

# TEMPORAL AND SPATIAL DIFFERENCES IN EMISSION OF NITROGEN AND PHOSPHORUS FROM POLISH TERRITORY TO THE BALTIC SEA

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#### INTRODUCTION

The Baltic Sea is a particularly sensitive area subject to anthropogenic impact. The Baltic Sea is an inland sea with very little water exchange with the North Sea. The surface area of the Baltic Sea is about 0.415 million km<sup>2</sup> and it is approximately four times smaller than its catchment area (about 1.72 million km²). Fourteen countries are located within the Baltic Sea catchment area and the overall population amounts to ca. 85 million people. In majority, these countries are highly urbanized and industrialized, and have intensive agricultural activity. These conditions stimulate strong anthropogenic pressure demonstrated by the dissipation of large amounts of nutrients which are transported by water in riverine outflow (diffuse losses and point sources discharges), or by air (in the form of precipitation) to the Baltic Sea. Among these substances nitrogen (N) and phosphorus (P) compounds have been considered of a particular importance, as their excess causes a deterioration of water quality and adverse changes in marine ecosystem functioning. Modern studies call for a holistic approach in specifying causes of perturbations in any ecosystem functioning and in interpreting the present or foreseeing the future consequences of such perturbations. It is evident in the light of recent studies, presented also in the monograph, that from the prospective of the Baltic ecosystem eutrophication not only excessive loads of nitrogen and phosphorus compounds delivered in riverine outflow must be given attention but also large-scale changes such as a decline in frequency of inflows of saline waters to the Baltic Sea or a decline in dissolved silicon concentrations (DSi), a third, after N and P, an extremely important player in the Baltic ecosystem functioning.

It is obvious that protection of the Baltic Sea ecosystem must be rooted in protection of inland waters as majority N and P reaches the Baltic Sea via riverine outflow. In the whole catchment area of the Baltic Sea, measures are taken to reduce land-based pollution. These activities are connected with implementation of the European Union (EU) Directives (e.g. the Framework Water Directive, the Urban Waste Water Treatment Directive, and the Nitrate Directive) or with realization of obligations arising from the Helsinki Commission (HELCOM) declarations. The activities performed by HELCOM are primarily undertaken within the framework of the Helsinki Convention, signed in Helsinki in April 1992 by all the states bordering on the Baltic Sea, and the European Community. After ratification, the Convention entered into force on 17 January 2000 (it was ratified by Poland in 1999). The Convention covers the entire Baltic Sea area, including inland waters as well as the water of the sea itself and the seabed. One of the recent HELCOM programs is the HELCOM Baltic Sea Action Plan which is an ambitious program aiming at restoring the good ecological status of the Baltic marine environment by 2021. The new strategy is a crucial stepping-stone for wider and more efficient actions to combat the continuing deterioration of the marine environment resulting from human activities.

Our country has a special place in the group of fourteen countries located in the catchment of the Baltic Sea due to its large proportion of the total catchment area

(approx. 18%), a very large share in the agricultural land area (ca. 50%), and the total population (approx. 45%). In Poland, the land used for agricultural purposes occupies approximately 60% of the total area, and the number of livestock exceeds 7 million Livestock Units. In 2000, contribution of Poland to overall loads of N and P reaching the Baltic Sea constituted 26% and 37% for total nitrogen (TN) and total phosphorus (TP), respectively. We are aware of these high percentages of nutrient discharges, but we wish to make aware the reader of this monograph of the fact that the problem of the contribution of a particular country to polluting the Baltic Sea is very complex. It requires the analysis from the prospective of (i) land cover/use, geomorphology, climate, population, (ii) changes that have taken place in the economy of some Baltic states, Poland included, during the transition period.

Poland's economy has undergone a profound transition from a centrally planned to a market economy since 1989. This transition has led to major institutional and economic structural changes over the last two decades. Reforms initiated in the early 1990s provided opportunities to revise and implement environmental management and legislation, and to achieve greater integration of environmental concerns into other policies. The changes, which took place in Polish economy during the transition period, have not had the same spatial and temporal dynamics, and that has been reflected in different spatial/temporal N and P emission to the river basins and consequently different response of Polish rivers to changed pressures in the river basins. The temporal and spatial variability in nutrient emission into the Vistula and Oder Rivers, draining majority of Polish territory, is very extensively referred to natural and anthropogenic factors. The latter cover spatially/temporarily diversified structural changes in agricultural sector and handling of the wastewaters, and spatially/temporarily diversified agricultural activity in our country.

The problem of N and P diffuse losses is currently the subject of many research programs, both domestic and foreign. There are many differences, and even extreme opinions, concerning environmental impact assessment of broadly defined rural economy on water quality. It is largely due to methodological difficulties associated with the estimation of numerous complex factors that determine the processes affecting nutrient emission from farmland to the Baltic Sea. Therefore, there is an urgent need for reliable, comprehensive assessment of the share of agriculture in the pollution of the Baltic Sea. However, one should be extremely cautious while commenting the share of agricultural sector in overall emission of N and P. At a significant decrease in N and P loads from point sources, the relative contribution of diffuse sources has increased during the transition period in Poland. However, that does not imply that we are facing increased N, P loads discharged by Polish rivers into the Baltic Sea. On the contrary, the flow normalized loads of N (nitrates included) and P constituents, discharged by the Vistula and Oder River into the Baltic Sea, have shown steady, considerable, and statistically significant declines in 1988-2011. It is an additional proof that a holistic approach is badly needed in evaluation of contribution of Polish agriculture to overall loads of N and P reaching the Baltic Sea.

An attempt has been made to provide the reader with a comprehensive set of observational and reference data, which may be valuable for further studies aiming

at mitigation of diffuse nutrient emission. Many of the presented data cover the transition period in Poland (24 years) but there are also numerous data, which cover the former economic/political system. The issues raised in the monograph also allow addressing a number of fragmentary studies, which usually unilaterally and in a very simplified way have exaggerated the risks posed by agriculture in Poland. Apart from the overall scientific value, all the conclusions arising from the presented results, may be of great help for the decision makers in Poland dealing with environment protection issues, on both the local (at three levels of the administrative division of the country) and the central level (Ministry of Agriculture and Rural Development, Ministry of the Environment). Very comprehensive material presented in this monograph, focusing on reduced pressures on natural environment in Poland during the transition period and response of Polish rivers in terms of declining N and P loads introduced to the Baltic Sea, can serve as the reference material in official contacts with the European Union (EU) and the Helsinki Commission (HELCOM) representatives. We address this monograph to non-governmental and governmental bodies dealing with agriculture and environment, agricultural advisers, and all people interested in the interdisciplinary science concerning the environment. The intention of the authors was to prepare a thematic monograph presenting in a comprehensive manner complex natural and economic conditions that affect the outflow of nitrogen and phosphorus from the territory of Poland to the Baltic Sea. The study is a compendium of current knowledge in the form of a textbook on the cycling of nitrogen and phosphorus in the environment, which can be also used for teaching purposes at universities.

The authors wish to thank all those who have made creative contributions to the publication of the book, both in the field of agriculture and oceanography, as well as in other disciplines.

Janusz Igras D.Sc. Marianna Pastuszak Ph.D.

DESCRIPTION OF THE BALTIC SEA CATCHMENT AREA - FOCUS ON THE POLISH SUBCATCHMENT

MARIANNA PASTUSZAK

# 1. DESCRIPTION OF THE BALTIC SEA CATCHMENT AREA – FOCUS ON THE POLISH SUB-CATCHMENT

#### Marianna Pastuszak

#### 1.1. Land cover/use in the Baltic catchment area

The Baltic Sea is a shallow brackish sea with only a limited water exchange with the world ocean through the Danish Straits. This landlocked intra-continental sea consists of several basins of different depth, which are connected by sills. Although the Baltic Sea is a shallow sea, the morphology of the sea floor is as diverse as that of the coast line. Among the more outstanding morphological features in the Baltic Sea are the various forms of deeps – depressions and troughs (trenches). The depths of the existing depressions are, however, rather modest: the depth of the Gotland Deep (east of Gotland) is 245 m. The Gdańsk depression in the southeastern Baltic Proper is only 116 m deep. The Landsort Deep, north of Gotland, is the deepest place in the Baltic Proper with the depth of 459 m. Despite several considerable deeps, the mean depth of various parts of the Baltic Sea are rather modest: the Baltic Proper is 65 m, the Bothnian Sea 68 m, the Bothnian Bay 43 m deep (Winterhalter et al., 1981; Fig. 1.1).

The Baltic Sea has a longitudinal extension of more than 1500 km and a latitudinal extension of about 650 km. It consists of a series of basins of which the Gulf of Bothnia (often divided into three sub-basins i.e. the Bothnian Bay, the Bothnian Sea, and less frequently marked on charts, the Archipelago Sea), the Gulf of Finland, the Gulf of Riga, and the central part of the sea called the Baltic Proper are the main water bodies. The Belt Sea, including the Danish Straits and the Sound, form together with the Kattegat the transition zone of the Baltic Sea with the Atlantic Ocean (Figs. 1.1, 1.2; Ehlin, 1981; Majewski and Lauer, 1994; Lass and Matthäus, 2008).

Due to a substantial longitudinal extension, the drainage basin also varies greatly with respect to climatic conditions, with long winters with snow and ice in the north, and short winters with less frequent snow in the south. Even the amount of precipitation varies, and the highest amounts fall in the western areas, especially in the mountains (Ehlin, 1981). The brackish Baltic Sea is located within the belt of westerlies of mid-latitudes, just in the transition zone between maritime and continental influence. Such a location causes that the region is exposed to so-called regime shifts which reflect abrupt changes between continental and maritime climate modes, describing the predominance of different weather types on the interannual scale (Hagen and Feistel, 2008).

Fig. 1.1 Catchment area of the Baltic Sea; the Vistula and Oder catchments (Poland) shown in different colors (red dots indicate lowermost river monitoring stations) (source: map prepared and kindly made available for this monograph by the *Coalition Clean Baltic*)

In addition to natural variability in climate, global warming has been observed during the past century. In the Baltic Sea region, the warming trend has been reflected in a decrease in the number of very cold days during winter as well as a decrease in the duration of the ice cover and its thickness in many rivers and lakes, particularly in the eastern and southeastern Baltic Sea basin. In addition, the length of the frost-free seasons has increased and an increasing length of the growing season in the Baltic Sea basin has been observed during this period, especially during the last 30 years (HELCOM, 2011).

The catchment area of the Baltic Sea (1 720 270 km²) is 4.3 times as large as the area of the sea itself (415 266 km²). The catchment area of the Baltic Sea is geographically highly diversified. The high mountains, the forested terrains, and the wetlands are characteristic for the Swedish part of the catchment; vast areas with lakes and forests are typical for the Finnish and Russian parts of the catchment, while very extensive agricultural land is characteristic for the Polish part of the Baltic catchment (Figs. from 1.2 to 1.5).

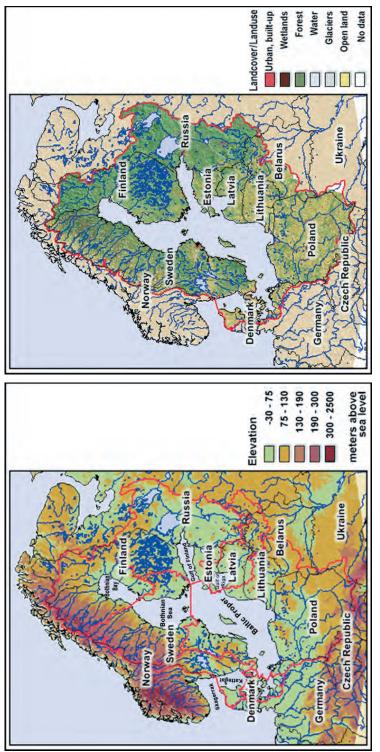
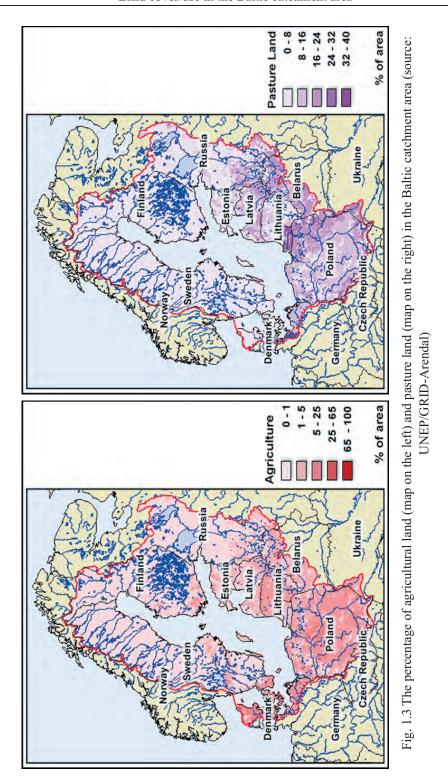


Fig. 1.2 Topography (map on the left; the red line indicates the catchment areas of particular Baltic sub-regions) and land cover/land use of the Baltic catchment area (map on the right) (source: UNEP/GRID-Arendal)



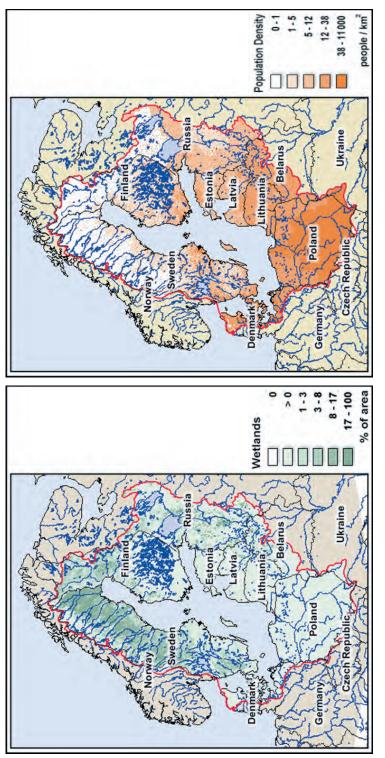


Fig. 1.4 The percentage of wetlands in the Baltic catchment area (map on left) and population density in the Baltic catchment area (map on the right) (source: UNEP/GRID-Arendal)

The Baltic catchment is inhabited by ca. 85 million people, and of that 38 million live in Poland (HELCOM, 2001, 2004). The population density in the entire Baltic catchment is spatially diversified (Fig. 1.4) and it ranges from a very low number in Sweden (on average 21 persons per km²) to the highest ones in Poland (122 persons per km²) and Denmark (158 persons per km²) (HELCOM, 2011). In Poland, about 62% of population lives in urban zones, while the remaining percentage of people inhabits the rural areas (GUS, 1991-2009).

The Polish part of the Baltic catchment (i) belongs to four largest catchments in the Baltic basin, (ii) is similar, by its size, to the Russian and the Finnish parts of the Baltic catchment, and (iii) is by ca. 30% smaller than the largest Swedish catchment (Fig. 1. 5). The area covered by agricultural land in Poland constitutes over 50% of the overall agricultural land area in the entire Baltic catchment. Finland, Sweden, and Russia have in their catchments much larger forested and inland waters (lakes) areas than Poland; forests in Finland cover ca. 60% of the Finnish catchment area. Over 25% of the Swedish catchment is occupied by mountains and that is a distinguishing feature in the Baltic catchment. The urban area in Poland is the largest one in the Baltic basin, and that in turn is directly related to the population figure; 45% of the entire Baltic basin population inhabits territory of Poland (HELCOM, 2004).

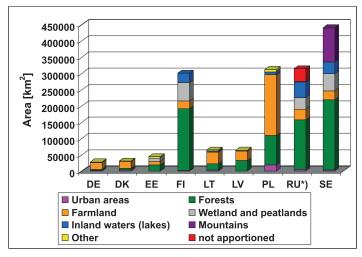


Fig. 1.5 Land cover/land use of the Baltic catchment area in the year 2000 in particular countries; abbreviations used for the Baltic countries – see to Chapter 12; (source of data: HELCOM, 2004)

<sup>\*) 23700</sup> km² and 15000 km² of the area in Russia belong to the catchment area of the Gulf of Riga and the Baltic Proper, respectively; for these areas the percentage of land cover/land use is not specified in the HELCOM elaboration

#### 1.2. Polish part of the Baltic catchment area

Almost all of Polish territory (99.7%) belongs to the catchment area of the Baltic Proper (Figs. 1.2, 1.6). Most of the land belongs to the large drainage basins of the Vistula River (194,424 km², with 168,699 km² within Polish borders, constituting ca. 54% of Polish territory) and the Oder River (118,861 km², with 106,056 km² within Polish borders, constituting ca. 34% of Polish territory). Small rivers, carrying their waters directly to the Baltic Sea, drain the remaining, relatively large area (11% of Polish territory) (HELCOM, 2004). Only 0.8% of Polish territory belongs to the Nemunas drainage area, 0.2% - to the catchment of the Black Sea, and 0.1% - to the catchment of the North Sea (Encyklopedia Geograficzna Świata, Polska, 1997). About 96.1% of the Polish catchment area of the Baltic Proper is monitored hydrologically and hydrochemically (HELCOM, 2004).

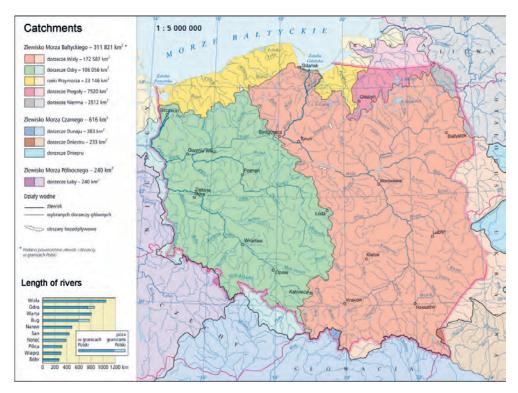


Fig. 1.6 Catchments of the Vistula (Polish: Wisła), Oder (Polish: Odra), Pomeranian rivers (Polish: rzeki Przymorza), and other rivers draining territory of Poland (source: map elaborated and kindly made available for this monograph by *Demart S.A.*, *Poland*)

With surface area of 31.268 million ha (312 683 km<sup>2</sup>), Poland ranks among Europe's larger countries. It lies in Central Europe, between the Baltic Sea and Carpathian Mountains. With the average height of 173 m, as compared to the European average of 330 m above the sea level (m.a.s.l.), Poland is a largely lowland country. As much as 75% of Polish territory has an elevation below 200 m.a.s.l., 16.3% has an elevation in the range 200-300 m.a.s.l., while the remaining 8.7% of the land occupies the terrains elevated above 300 m.a.s.l. (within this percentage the terrains above 500-1000 m.a.s.l. account for 2.9%) (GUS, 2007a, b). Nearly 87% of the entire Polish area has a land slope below 3° (Chapter 2). However, it is worth pointing that the lowland in Poland has a hilly character and that is related to activity of glaciers in the past; only central part of the country has a typical lowland character. About 2.6% of the entire surface area in Poland is covered by over 9000 (<1ha) rather shallow lakes whose average depth is <20 m. These lakes are mainly situated in the Pomeranian (Polish: Pojezierze Pomorskie) and the Mazurian (Polish: Pojezierze Mazurskie) Lake Districts (northern Poland) (Fig. 1.7; Encyklopedia Geograficzna Świata, Polska, 1997).

Poland has highly variable soils, without clearly marked regional types. Polish soils are characterized by low content of colloids, clay minerals, and humic substances (Chapter 2). The greatest area is covered by podzol and pseudopodzol types, followed by the less widely distributed brown-earth soils, which are richer in nutrients. In the south, there are extensive areas of fertile loess-based soils. The rendzinas, formed on limestone rocks, are a unique type. The alluvial soils of the river valleys and the peaty swamps soils found in the lake area and in poorly drained valleys are also distinctive (Terelak et al., 2000). Poland has poor natural conditions for agricultural production as sandy formations (20% of particles less than 0.2 mm in diameter) occupy about 50% of the total area, while very acid and acid soils cover almost 50% of the agricultural land. As much as 21% of agricultural land, mainly arable land, and 8% of forested areas are imperiled with soil erosion. Appropriate agro-technical and land reclamation measures are necessary for the improvement of these soils characterized by light granulometric composition, low content of colloids, loamy minerals and organic compounds. The hydro-physical properties of soils, i.e. water retention and water permeability in both saturated and unsaturated zones are of great importance as they not only shape soil water balance but also decide on the conditions for plant growth, development and yield. They also determine water availability for the plant root system and the transfer of water with dissolved chemical compounds, e.g. nutrients, into deeper layers (Walczak et al., 2002; for details: see to Chapter 2).

Poland's climate is moderate i.e., intermediate between maritime and continental climates. The geographical location of the country and the landform features are two the most important factors determining climate in Poland. Location of the country in moderate climatic latitudes causes that polar air masses predominate, but due to

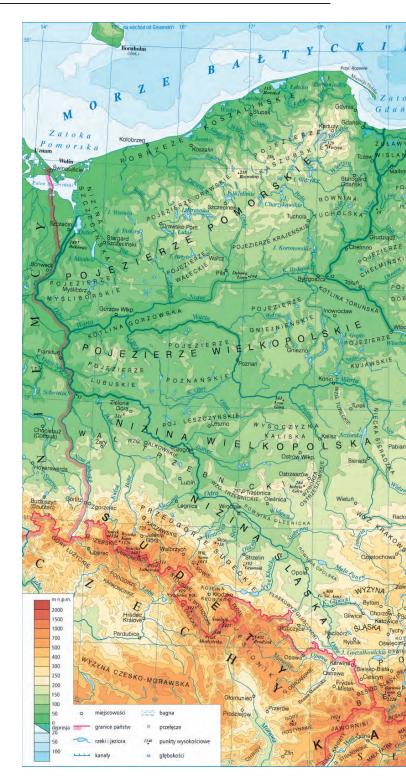
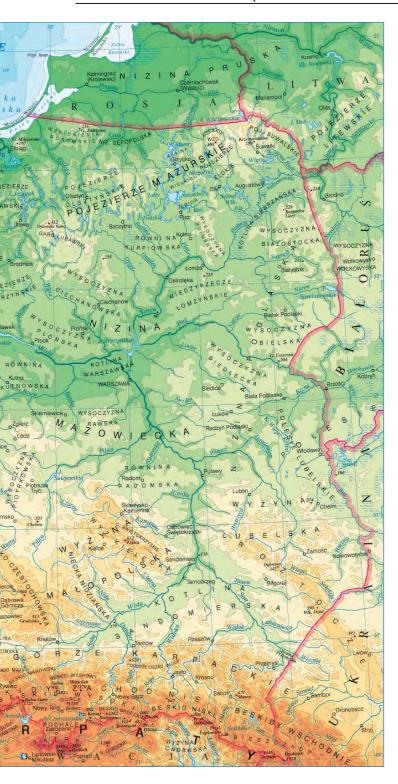


Fig. 1.7 Topographic map of Poland (source: map elaborated and kindly made available for this monograph by *Demart S.A., Poland*)



prevailing western (oceanic) air circulation the percentage contribution of maritime air masses prevails over the continental one (46% and 38%). The latitudinal pattern of terrain forms in Europe favors transport of wet air masses from above the ocean to Poland; Poland receives 75% of atmospheric fronts from the western direction. The maritime-continental character of climate in Poland generates great variability in weather conditions and the changes may take place from one day to the next, as well as from one year to the next. The features of the continental climate strengthen in the south-western direction, and that finds its reflection in increase in amplitude in the annual air temperature, as well as in precipitation patterns (Andrzejewski et al., 2009; Fig. 1.8). Poland finds itself in the zone of atmospheric fronts, and as a result the fairly wet and mild winters, with average monthly temperature of around 0°C, alternate with severe and dry winters, with average monthly temperature of -10°C. A similar variation in air temperature and precipitation occurs in the summer season, especially during the vegetation period. Hot and dry summers, with less than 20 mm of rain in June, July, and August, may alternate with cold and wet summers, with a monthly rainfall up to 150 mm or even 200 mm. Annual isotherms range between 6.5°C and 8.5°C; average temperatures in January and June range from -1°C to -5°C, and from 17°C to 19°C, respectively. Average monthly amplitudes of temperature range between 19°C in the west and 22°C in the east. The longitudinal pattern of isotherms in January clearly indicates strengthening of continental climate as moving towards the east; the latitudinal pattern of isotherms in July points to impact of the cooling effect in northern Poland and that is related to closeness of the Baltic Sea (Andrzejewski et al., 2009; Fig. 1.8).

Rainfalls are related to the lie of the land and land exposure. The highest annual rainfalls are observed in the mountains and in the uplands (above 600 mm), while the lowest values are noted in the lowland of Poland (400-500 mm). The maximum rainfalls receive the regions situated in uplands overlooking the prevailing winds, e.g. Pomeranian and Mazurian Lake District in the north (above 600 mm) and the highest parts of Polish mountains (above 1000 mm). The coastal areas in Poland receive lower rainfalls than the neighboring lake districts and that results from different weather conditions forcing the convection and consequently the precipitation in the lake area. The sums of annual rainfalls show great variability, its values reaching even 250% in particular months. On the annual scale, precipitation in summer is considerably higher than that in winter. That difference is strengthened spatially, being two times greater in the south-eastern than in the north-western Poland (Andrzejewski et al., 2009; Fig. 1.8). During the growing season potential evapotranspiration in most of the country exceeds precipitation. Vegetation period is rather short, on average 220 days; only in south-western part of the country it exceeds 230 days. The physiography and agro-climate are presented in detail in Chapter 2 of this monograph.

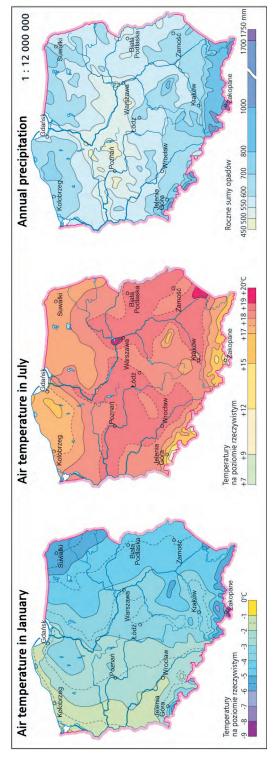


Fig. 1.8 Average air temperature in January (left) and July (middle), and average annual precipitation in Poland (right) (source: maps elaborated and kindly made available for this monograph by Demart S.A., Poland)

#### 1.3. Discharges of water and nutrients into the Baltic Sea

## Riverine water discharges and a large- scale water circulation in the Baltic Sea

The overall volume of the Baltic Sea water amounts to 21 547 km<sup>3</sup>; the volume of riverine water, annually supplying the sea, constitutes ca. 2% (428 km<sup>3</sup>) of the Baltic volume. The Baltic Sea is fed by about 250 rivers. The combined average inter-annual water flow rate of all the Baltic catchment rivers amounts to 15 190 m<sup>3</sup>s<sup>-1</sup>, which gives 497 km<sup>3</sup>yr<sup>-1</sup>. Neva, Vistula, Nemunas, Daugava, Oder, Göta älv., and Kemijoki are the largest rivers feeding the Baltic Sea (Table 1.1; HELCOM, 2004). The main rivers in the Polish part of the Baltic Proper catchment area are the Vistula, which flows into the Gulf of Gdańsk, and the Oder, which flows into the Pomeranian Bay. The long term (1951-1990) flow rates in the Vistula and Oder Rivers are equal to 1081 m<sup>3</sup>s<sup>-1</sup> and 574 m<sup>3</sup>s<sup>-1</sup>, respectively (Table 1.1; Fal et al., 2000).

Table 1.1 Long-term average water flows in seven largest rivers feeding the Baltic Sea (source: HELCOM, 2004)

River	Neva	Vistula	Nemunas	Daugava	Oder	Göta älv.	Kemijoki	Total
Flow [m <sup>3</sup> s <sup>-1</sup> ]	2488	1081	664	637	574	572	553	6569
Period	1859- 1988	1951- 1990	1811-1995	1881- 1914 1924- 2000	1951- 1990	1961- 1990	1961- 1990	
Length [km]	741)	1047	937	1020	854	902)	600	

<sup>1)</sup> Length up to Ladoga Lake; 2) length up to Vänern Lake

Like other landlocked seas in humid regions at temperate latitudes, the Baltic Sea has a positive water balance, which in turn determines the basic hydrographic and ecological properties of the sea. These properties encompass: estuarine circulation, the deepwater formation and ventilation, stratification, and the nutrient balance. Outflow of brackish surface water and inflow of saline water combined with upwelling and vertical mixing of saline bottom water with brackish surface water closes the estuarine circulation. The salt balance in the Baltic is maintained by advection of salty North Sea water by both intermittent barotropic and baroclinic inflows. In general, there is an outflow of low saline water in the surface layer, while compensation current transports higher saline water in the deep layer into the Baltic

Sea. The mean Baltic Sea salinity is strongly related to large-scale atmospheric variability and the accumulated freshwater inflow (Elken and Matthäus, 2006; Meier et al., 2006; Lass and Matthäus, 2008; Fig. 1.9).

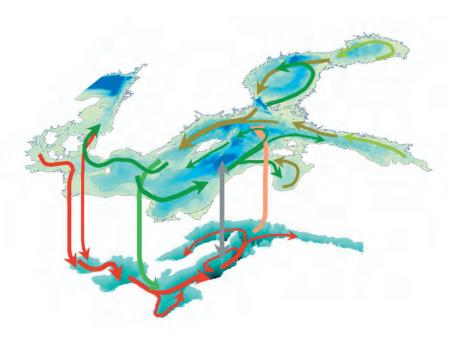


Fig. 1.9 A schematic illustration of the large-scale water circulation in the Baltic Sea; the dark green and red arrows denote the surface and bottom layer circulation, respectively; the light green and beige arrows show entrainment; the gray arrow denotes diffusion (source: Elken and Matthäus, 2006)

Water exchange with the North Sea through the Sound and the Belt Sea is highly variable in direction and magnitude. The deeper deep water of the Baltic Proper is replaced *via* episodic inflows of larger volumes (100-200 km³) of highly saline (17-25 PSU - Practical Salinity Units) and oxygen-rich water; these are termed major Baltic inflows. Most major inflows occur between October and February. Although major Baltic inflows had occurred fairly regularly until mid-1970s, their frequency and intensity changed after that and only a few major events have occurred since then (Elken and Matthäus, 2006; Lass and Matthäus, 2008; Hansson et al., 2011; Fig. 1.10). The decrease in inflows can most likely be connected with variations in atmospheric conditions and increased zonal circulation, which result in both more precipitation and increased river runoff (Feistel et al., 2008). Long periods of easterly winds, which is needed to lower the sea level in the Baltic Sea to initiate an inflow, have been absent and the prevailing winds remained westerly during most winters. Steady westerly winds and increased freshwater supply keep the sea level high in the Baltic Sea which prevents inflows. As the outflow of low saline water from the Baltic

Sea increases the salinity in the Kattegat decreases. Owing to that, when inflows do occur, the salinity of inflowing water is too low. Hence, the water is not dense enough to renew the bottom water (Meier and Kauker, 2003).

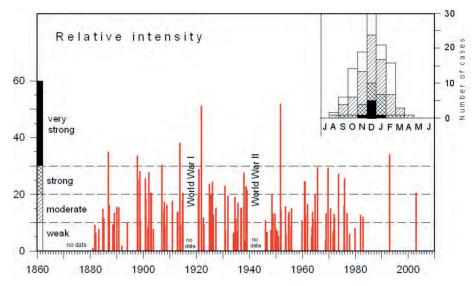


Fig. 1.10 Major Baltic inflows between 1880 and 2005 and their seasonal distribution (upper right) shown in terms of their relative intensity [source: Matthäus and Franck, 1992; Fischer and Matthäus, 1996; supplemented and updated by BALTEX Assessment of Climate Change for the Baltic Sea basin (BACC); graph obtained from HELCOM (2007b)]

Based on analyzed long-term oxygen data (1960-2011) a distinct regime shift has been identified by Hansson et al. (2011). As stated further by these authors, during the first regime, 1960 to 1999, hypoxia affected large areas and volumes, while anoxic conditions affected only minor deep areas. After the regime shift in 1999, both the spatial extent and volume of hypoxia and anoxia have been elevated to levels never recorded before (Fig. 1.11). Further increase in the extent and volume of anoxic conditions can enhance the eutrophication of the Baltic Sea, due to released phosphorus from the sediments that previously have been oxygenated (Nehring, 1987; Graca and Bolałek, 1998; Savchuk, 2005; Graca et al., 2006; Łukawska – Matuszewska and Burska, 2011).

About 70% of river runoff enters the Gulfs of Bothnia, Finland, and Riga, representing the major source of freshwater to the Baltic Sea and controlling the salinity in the Baltic surface water. Spatially diversified river water runoff together with pathways/extent of the saline inflowing water, propagating from the western towards the central basins of the Baltic Sea, cause that the surface salinity in the Baltic Sea changes from ca. 20 PSU in the Kattegat, through ca. 7 PSU along the Polish coast, to ca. 2 PSU in the Gulf of Bothnia and Gulf of Finland (Lass and Matthäus, 2008; Table 1.2). In spring, when the freshet water outflow is at its maximum, the

salinity in the eastern part of the Gulf of Finland may drop down zero (Ehlin, 1981; Kullenberg, 1981). Overall, the runoff is governed by precipitation and evaporation over land and inland water bodies as well as changes in stored precipitation as snow and ice on land and in lakes or groundwater. In all subregions of the Baltic Sea, a strong seasonal, annual and decadal variability can be identified (HELCOM, 2011). Longer periods with wet and dry conditions characterize the runoff patterns. The 1970s was a fairly dry period as compared with the 1980s and 1990s (HELCOM, 2011).

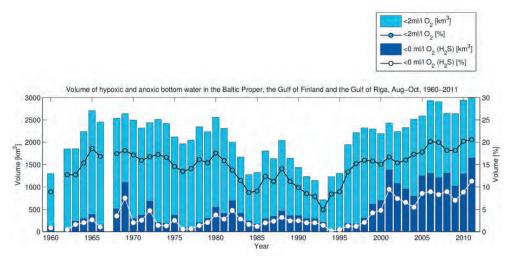


Fig. 1.11 Volume of deep Baltic water (Baltic Proper, Gulf of Finland, and Gulf of Riga) remaining under hypoxia and anoxia in 1960-2011 (source: Hansson et al., 2011)

Table 1.2 Catchment areas of particular sub-regions of the Baltic Sea and water inflows to these sub-regions in the year 2000 (source: HELCOM, 2005; Majewski and Lauer, 1994)

Sub-region	Surface area [km²]	Water inflow [106m³yr¹]
Bothnian Bay	260675	155480
Bothnian Sea	220765	124150
Archipelago Sea	9000	3840
Gulf of Finland	413100	107340
Gulf of Riga	127840	28750
Baltic Proper	574545	115580
Belt Sea	27365	6670
Kattegat	86980	42380
Sum:	1720270	584190

In the central Baltic Proper, the water column is permanently stratified, with the fresher surface water (salinity 6-8 PSU) separated from the deeper, more saline water (salinity 10-14 PSU) by a halocline (at 50-70 m depth) characterized by a significant vertical salinity gradient. In summer, a thermocline develops at round 25-30 m depth, separating the warm upper layer from the cold intermediate water. A strong permanent halocline and a thermocline considerably prevent vertical circulation and, consequently ventilation of the bottom waters all the year round (Lass and Matthäus, 2008).

#### Nutrient discharges

There are three sources of nutrients reaching the Baltic Sea: the riverine load (encompassing the diffuse emission + atmospheric deposition, the point sources, and the natural background i.e. losses from unmanaged land, and the proportion of nutrient losses from managed land that would occur irrespective of agricultural activities), the direct discharges from point sources, and the atmospheric deposition to the sea (Fig. 1.12). The proportion of natural background load varies considerably among countries, but it constitutes on average 16% of the total phosphorus load and somewhat higher for nitrogen. Sweden has recently corrected its share of N background loads (it is now on the level of about 50%) and that is the highest value in the Baltic basin; Finland and Poland have also declared correction in their N background loads but the specific numbers are not given in PLC-5 (HELCOM, 2011). Natural background losses in Poland, reported in PLC-4 (HELCOM, 2004) amounted to ca. 17% of the total P load and ca. 20% of the total N load.

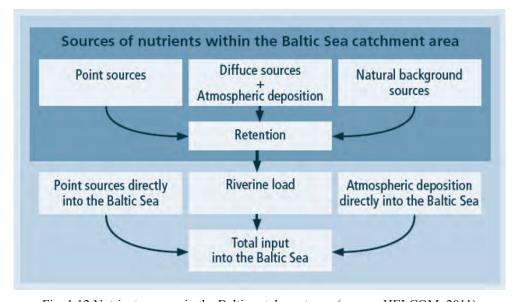


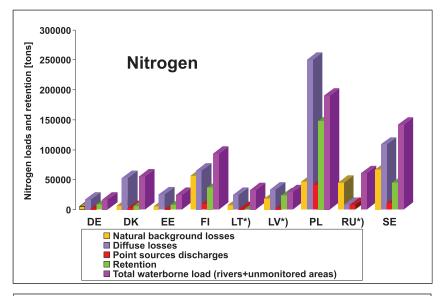
Fig. 1.12 Nutrient sources in the Baltic catchment area (source: HELCOM, 2011)

It is estimated that about 75% total nitrogen (TN) load and 95-99% of total phosphorus (TP) load are discharged to the Baltic Sea in riverine outflow; 25% of TN and 1-5% of TP originates from atmosphere. In 2000, the monitored rivers were responsible for 77% of TN and TP loads that reached the Baltic Sea; the overall contribution of unmonitored rivers and coastal areas amounted to 17% for TN, and 15% for TP; municipal agglomerations as well as industrial plants and fish processing plants, situated along the coast, were responsible for the remaining 6% of TN and 8% of TP loads supplying the Baltic Sea (HELCOM, 2004).

The source apportionment of nitrogen and phosphorus losses into inland surface waters, made for all the Baltic countries (HELCOM, 2004), shows that the respective contribution of nitrogen from diffuse sources, point sources, and natural background constituted 62%, 18%, and 20% in Poland in 2000; the respective contribution of phosphorus from diffuse sources, point sources, and natural background constituted 54%, 29%, and 17%. Within the discharges of nutrients from point sources, contribution of waste water treatment plants (WWTPs) was in Poland of uppermost importance as it constituted ca. 92% of both N and P loads; contribution of industrial discharges constituted ca. 8% of both N and P loads.

The modeling studies (MONERIS), which allow to estimate the percentage contribution of particular pathways in N and P emission to the river basins, showed that in 1995-2008, the combined contribution of only tile drainage and groundwater to N emission into the Vistula and Oder basins amounted to ca. 70%, while contribution of point sources reached 11-12%. Point sources, erosion, overland flow, and urban systems were found the most important P pathways in both basins, with a higher percentage contribution of point sources in the Oder basin (Kowalkowski et al., 2012; see to Chapter 8).

In 2000, the total waterborne (riverine + coastal areas, and direct point and diffuse sources) nitrogen and phosphorus loads entering the Baltic Sea amounted to 706,000 tones and 31,800 tones, respectively. Contribution of Polish rivers to overall N and P riverine load reaching the Baltic Sea is considerable. In the year 2000, the Vistula, discharging its water into the Gulf of Gdańsk, introduced 117,000 tons of TN and 7,500 tons of TP, while the Oder, inflowing into the Pomeranian Bay, discharged 53,000 tons of TN and 3,700 tons of TP. Contribution of Poland to overall N and P loads discharged into the Baltic Sea constituted 26% and 37% of total nitrogen (TN) and total phosphorus (TP), respectively (HELCOM, 2004). The total waterborne nitrogen and phosphorus, presented in Fig. 1.13, was obtained by summing up nitrogen and phosphorus originating from the diffuse outflow, from the natural background, and the point sources, and then by subtracting the retention. Retention of nutrients is defined as the removal of nitrogen and phosphorus in surface waters or river systems, including adjoining lakes and the flooding of river valleys. Retention calculations are necessary to enable the quantification of discharges/ losses of nutrients to marine areas from land-based sources. It is also necessary to have figures on N and P retention to compare and validate the figures on nutrient discharges/losses from land-based sources based on measurements at the river mouth (HELCOM, 2011).



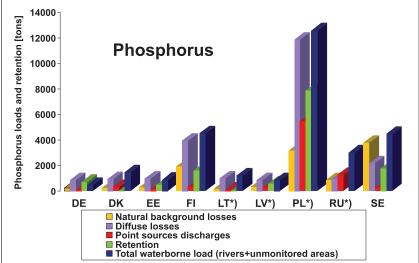


Fig. 1.13 Contribution of the Baltic countries to total annual loads of nitrogen and phosphorus originating from the riverine outflow and non-monitored zones; abbreviations used for the Baltic countries - see to Chapter 12 (source of data: HELCOM, 2004)

LT, LV\*) data concern the territory of Latvia and Lithuania exclusively; PL\*) Polish point sources

– the results are taken from the reports, and the diffuse outflow includes also point sources not
covered by the reports; RU\*) lack of retention for the Russian data

Nitrogen and phosphorus compounds are essential nutrients in crop/animal production, but on the other hand, the unbalanced use of mineral and natural fertilizers may result in enhanced emission of N and P from agricultural land to river networks and then to larger water reservoirs causing their eutrophication (HELCOM, 2006; Håkanson and Bryhn, 2008). Though both N and P are responsible for eutrophication, phosphorus is perceived as the element playing a more important role in this respect, as there are some algae which are capable of taking up N from the atmosphere (Schindler, 1977; Sharpley, 1995; Carpenter et al., 1998; Stal et al., 2003).

It is obvious that not entire pools of nitrogen and phosphorus discharged into river basins reach the coastal zones through the riverine outflow. Rivers do not act as "inert pipelines", transporting N and P from land to the coastal zone. It is worth mentioning that river systems consist of not only main rivers and the networks of their tributaries, but they also encompass flow-through-lakes, riparian zones, floodcontrol reservoirs and inland parts of estuaries. Processes, such as denitrification, organic matter burial in sediments, sediment sorption, and plant and microbial uptake can remove N and P from the river network, and thus affect the amounts of N and P that are transported by rivers to coastal ecosystems (Billen et al., 1991; Van Bremen et al., 2002). These processes in turn depend on nutrient concentrations, sediment properties, flow rate thus water residence time, and land use (e.g. Howarth et al., 1996; Nixon et al, 1996). Modeling studies, carried out by Seitzinger et al. (2002) in 16 drainage networks in the eastern U.S., show that 37% to 76% of N input to these rivers is removed during transport through the river networks. Approximately half of that is removed in 1st through 4th order streams (see to Fig. 1.14) which account for 90% of the total stream length. The other half is removed in 5th and higher order rivers, which account for only about 10% of the total stream length.

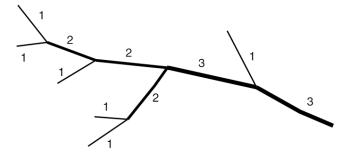


Fig. 1.14 Diagram showing the Strahler stream order (source: Strahler, 1957)

The proportion of N removed from all streams in the watersheds (37-76%) is considerably higher than the proportion of N input to an individual reach that is removed in the reach (generally <20%) because of the cumulative effect of continued nitrogen removal along the entire flow path in downstream reaches (Seitzinger et al., 2002). Van Breemen et al. (2002) constructed N budgets for sixteen large watersheds in the northeastern U.S.A., mainly forested (48-87%) and widely varying with

respect to population density and land use. The outcome showed that of the total storage and losses in the watersheds, about half of the N is lost in gaseous form, largely by denitrification.

The estimates of N and P retention in river networks (lakes, rivers) in the Baltic catchment countries in the year 2000 show that Poland outdistances all the other Baltic States. Over 50% of the overall N and P retention takes place in Polish river systems (HELCOM, 2004; Fig 1.15). Polish rivers belong to the least regulated ones in the entire Baltic region, and in majority they have grass/bushes overgrown river banks. It is well documented in international bibliography that all these features contribute to a long residence time favoring effective nutrient removal from the system on the way of biogeochemical processes (Nixon et al., 1996; Behrendt et al., 1999, 2005 a, b; Dannowski et al., 2002; Vagstad et al., 2004; Grizetti et al., 2005; Pastuszak et al., 2005; Voss et al., 2005, 2010; Lepistö et al., 2006; see also to Chapters 8, 9, and 10).

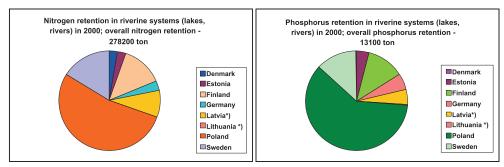
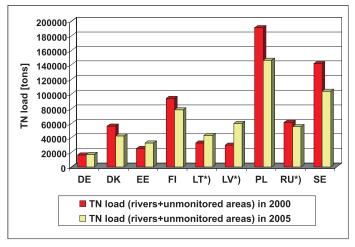


Fig. 1.15 Nitrogen and phosphorus retention in riverine systems (rivers and lakes) in particular Baltic countries (for Russia – retention was not estimated) (source: HELCOM, 2004)

\*) in the case of Latvia and Lithuania the retentions were estimated only for the territories of these countries.

Though the loads of N and P discharged from Polish territory are still the highest in the Baltic catchment (Fig. 1.16), it is clear that changes in Polish economy during the transition period, as well as implementation of nutrient mitigation measures after joining the European Union in 2004, resulted in reduced pressure on natural environment in Poland. The reduced N and P emission into the river basins (Kowalkowski et al., 2012) resulted in statistically significant declines in nutrient concentrations and loads at the lowermost river monitoring stations on the Vistula and Oder River (Pastuszak et al., 2012) (see to Chapters 8 and 9). Among the main causes of declined N and P emission to river basins in Poland there should be mentioned: (i) reduced pressure on natural environment from agricultural sector, expressed by considerably dropping N and P surplus, (ii) modernization of old and construction of a huge number of very efficient WWTPs, and (iii) closure of obsolete factories (see to Chapters 3, 4, 8, and 9).



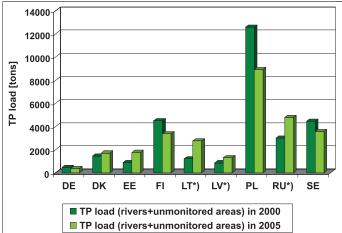


Fig. 1.16 Total annual loads of nitrogen and phosphorus originating from the riverine outflow and the non-monitored zones in the years 2000 and 2005; abbreviations used for the Baltic countries - see to Chapter 12; (source: HELCOM, 2004, 2007a)

") data for the year 2000 refer only to the territory of Latvia and Lithuania; for the year 2005 HELCOM (2007a) does not specify the territories for which the Latvian and Lithuanian data are given, so, these data may encompass parts of the catchment areas beyond the borderlines of these countries; data for the year 2005 for Russia are not complete

#### 1.4. Pollution hot spots in the Baltic basin – changes in 1999-2006

Nitrogen and phosphorus delivered to the Baltic Sea in riverine outflow originate mainly from agriculture and point sources. The Baltic Sea Joint Comprehensive Action Program (HELCOM, 2009a, b) aims to facilitate the implementation of pollution reduction measures at the most polluted sites in the Baltic Sea catchment area. According to these reports a total of 79 hot spots and sub-hot spots now remain on the list, following the deletion of 83 of the earlier indentified 162 hot spots/sub-hot spots. As many as 29 hot spots were eliminated in Poland (Fig. 1.17) and these changes resulted from the vast modernization of the existing and the construction of new WWTPs (particularly steadily growing number of tertiary WWTPs), closure of obsolete factories and modernization of the remaining ones, and introduction of clean technologies.

Huuska and Forsius (2002) provide an overview of industrial hot spots in the entire Baltic catchment [situation for the year 2000, thus earlier than that presented by HELCOM (2009a, b)]. Fourteen factories, situated in the Oder and Vistula basins, are covered by this very detailed report which describes the situation in every single plant which was a direct threat for natural environment of the Baltic Sea. The authors conclude that overall volume of waste water discharges from the hot spots to the environment have been considerably reduced in Poland over the past years, and the amount of organic matter expressed as an average BOD<sub>5</sub>, as well as average N and P loads decreased by 45%, 24% and 50%, respectively.

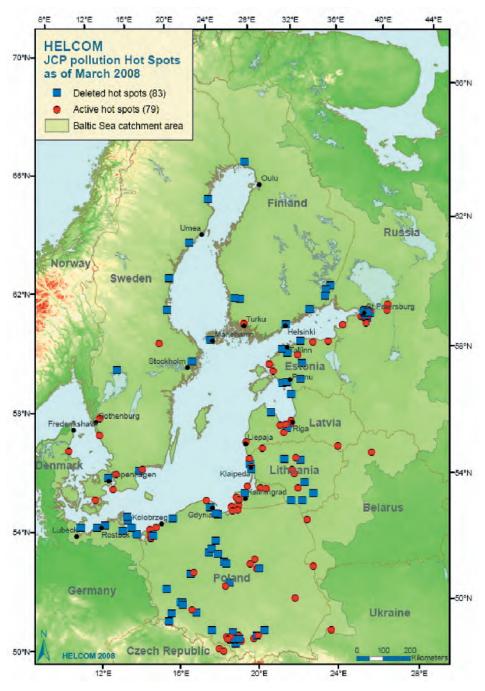


Fig. 1.17 Pollution hot spots in the Baltic catchment area (source: HELCOM, 2009b)

#### References

- Andrzejewski, R., Baranowski, M., Ciołkosz, A., Harbin, Z., Jagielak, J., Kleczkowski, A., Nowicki, M., Olecka, A., Piotrowska, H., Rykowski, K., Ryszkowski, L., Sadowski, M., Walewski, A., Wiśniewski, R., Witek, T., 2009. Stan Środowiska w Polsce. Państwowy Inspektorat Ochrony Środowiska i Centrum Informacji o Środowisku UNEP/GRID-Warszawa. 14 chapters. http://www.gridw.pl/raport pl/index.htm [Accessed on 02 June 2009].
- Behrendt, H., Kornmilch, M., Korol, R., Strońska, M., Pagenkopf, W.-G., 1999. Point and diffuse nutrient emissions and transport in the Odra basin and its main tributaries. Acta hydrochim. Hydrobiol., 27:274-281.
- Behrendt, H., Opitz, D., Korol, R., Strońska, M., 2005a. Changes of the nutrient loads of the Odra River during the last century – their causes and consequences. ICID 21st European Regional Conference, 15-19 May 2005, Frankfurt (Oder) and Słubice – Germany and Poland. 9 pp.
- Behrendt, H., Dannowski, R., Deumlich, D., Doležal, F., Kajewski, I., Klir, J., Kornmilch, M., Korol, R., Łabędzki, L., Makom, E., Mioduszewski, W., Opitz, D., Steidl, J., Strońska, M., Tippl, M., Zdanowicz, A., 2005b. Nutrient and heavy metals in the Odra River system. Emissions from point and diffuse sources, their loads, and scenario calculations on possible changes. Weißensee Verlag ökologie, 353 pp.
- Billen, G., Lancelot, C., Meybeck, M., 1991. N, P and Si retention along the aquatic continuum from land to ocean. [in:] Mantoura, R.F.C., Martin, J.M., Wollast, R. (eds.), Ocean Margin Processes in Global Change. Dahlem Workshop Reports, Wiley, pp. 19-44.
- Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., Smith, V.H., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Appl., 8:559-568.
- Dannowski, R., Steidl, J., Mioduszewski, W., Kajewski, I., 2002. GIS-based distributed analysis of subsurface nitrogen flow in the Odra basin. J. Water Land Dev., 6:91-104.
- Elken, J., Matthäus, W., 2006. Baltic Sea Oceanography [in:] BALTEX Assessment of climate change for the Baltic Sea basin (BACC). Annex A 1.1, von Storch, H. (ed.), Springer, Berlin.
- Ehlin, U., 1981. Hydrology of the Baltic Sea [in:] Voipio, A. (ed.), The Baltic Sea, Elsevier Scientific Publishing Company, Amsterdam-Oxford-New York, pp. 123-134.
- Encyklopedia Geograficzna Świata, Polska, Tom X, 1997. OPRES, Kraków, 431 pp.
- Fal, B., Bogdanowicz, E., Czernuszenko, W., Dobrzyńska, I., Koczyńska, A., 2000. Przepływy charakterystyczne głównych rzek polskich w latach 1951-1995.

References 41

- Materiały Badawcze, Seria: Hydrologia i Oceanologia, Instytut Meteorologii i Gospodarki Wodnej, Warszawa, No. 26, 137 pp.
- Feistel, H., Nausch, G., Wasmund, N. (eds.), 2008. State and Evolution of the Baltic Sea, 1952-2005: A detailed 50-Year Survey of Meteorology and Climate, Physics, Chemistry, Biology, and Marine Environment, ISBN:978-0-471-97968-5. 702 pp.
- Fischer, H., Matthäus, W., 1996. The importance of the Drogden Sill in the Sound for major Baltic inflows. J.Mar. Sys., 9:137–157.
- Graca, B., Bolałek, J., 1998. Forms of phosphorus in sediments from the Gulf of Gdańsk. App. Geochem.,13:319-327.
- Graca, B., Witek, Z., Burska, D., Białkowska, I., Łukawska-Matuszewska, K., Bolałek, J., 2006. Pore-water phosphate and ammonia below the permanent halocline in the south-eastern Baltic Sea and their benthic fluxes under anoxic conditions, J. Mar. Sys., 63:141-154.
- Grizetti, B., Bouraoui, F., De Marsily, G., Bidoglio, G., 2005. A statistical method for source apportionment of riverine nitrogen loads. J. Hydrol., 304:302-315.
- GUS (Central Statistical Office). Ochrona Środowiska. Annuals issued in 1991-2009, Warszawa, Poland.
- GUS (Central Statistical Office). Mały Rocznik Statystyczny Polski, 2007(a), Warszawa, Poland.
- GUS (Central Statistical Office). Ochrona Środowiska, 2007(b), Warszawa, Poland.
- Hagen, E., Feistel, R., 2008. Baltic climate change. [in:] Feistel, R., Nausch, G., Wasmund, N. (eds.), State and Evolution of the Baltic Sea, 1952-2005; A detailed 50-year survey of meteorology and climate, physics, chemistry, biology, and marine environment. Wiley Interscience, A. John Wiley & Sons, Inc. Publication, pp. 93-120.
- Håkanson, L., Bryhn, A.C., 2008. Eutrophication in the Baltic Sea; Present situation,
   Nutrient transport, Processes, Remedial strategies. Environmental Science
   and Engineering; Subseries: Environmental Science. Springer-Verlag Berlin,
   Heidelberg, 261 pp.
- Hansson, M., Andersson, L., Axe, P., 2011. Areal Extent and Volume of Anoxia and Hypoxia in the Baltic Sea, 1960-2011. SMHI, Report Oceanography No. 42, 63 pp.
- HELCOM, 2001. Environment of the Baltic Sea area 1944-1998. Baltic Sea Environ. Proc. No. 82A.
- HELCOM, 2004. The Fourth Baltic Sea Pollution Load Compilation (PLC-4). Baltic Marine Environ. Protection Com. Proc. No. 93.
- HELCOM, 2005. Nutrient pollution to the Baltic Sea in 2000. Baltic Sea Environ. Proc. No. 100.
- HELCOM, 2006. Eutrophication in the Baltic Sea, Draft HELCOM Thematic Assessment in 2006, Helsinki, Finland, 7 March 2006. 29 pp.

- HELCOM, 2007a. Towards a Baltic Unaffected by eutrophication, HELCOM Overview 2007. HELCOM Ministerial Meeting, Kraków, Poland.
- HELCOM, 2007b. Climate Change in the Baltic Sea Area. HELCOM Thematic Assessment in 2007. Baltic Sea Environ. Proc. No. 111.
- HELCOM, 2009a. Baltic facts and figures. (http://www.helcom.fi/environment2/nature/en GB/facts/) [Accessed on 02 June 2009].
- HELCOM, 2009b. HELCOM JCP pollution Hot Spots as for March 2008. (http://www.helcom.fi/projects/jcp/hotspots/en\_GB/hotspots/) [Accessed on 02 June 2009].
- HELCOM, 2011. Fifth Baltic Sea Pollution Load Compilation (PLC-5). Baltic Sea Environ. No. 128.
- Howarth, R.W., Billen, G., Swaney, D., Townsend, A., Jaworski, N., Lajtha, K., Downing, J.A., Elmgren, R., Caraco, N., Jordan, T., Berendse, F., Freney, J., Kundeyarov, V., Murdoch, P., Zhao-Liang, Z., 1996. Regional nitrogen budgets and riverine N, P fluxes for the drainages to the North Atlantic Ocean: Natural and human influence. Biogeochemistry, 35:75-139.
- Huuska, P., Forsius, K., 2002. Review of progress at industrial hot spots. The Finnish Environment, Environmental Protection, Finnish Environment Institute No. 576, pp. 1-78.
- Kowalkowski, T., Pastuszak, M., Igras, J., Buszewski, B., 2012. Differences in emission of nitrogen and phosphorus into the Oder and Vistula basins in 1995-2008 Natural and anthropogenic causes (MONERIS model). J. Mar. Syst. 89:48-60.
- Kullenberg, G., 1981. Physical Oceanography [in:] Voipio, A. (ed.) The Baltic Sea, Elsevier Scientific Publishing Company, Amsterdam-Oxford-New York, pp. 135-181.
- Lass, H-U., Matthäus, W., 2008. General Oceanography of the Baltic Sea, [in: Feistel, R., Nausch, G., Wasmund, N. (eds.), State and Evolution of the Baltic Sea, 1952-2005; A detailed 50-year survey of meteorology and climate, physics, chemistry, biology, and marine environment. Wiley Interscience, A. John Wiley & Sons, Inc. Publication, pp. 5-43.
- Lepistö, A., Granlund, K., Kortelainen, P., Räike, A., 2006. Nitrogen in river basin: Sources, retention in the surface waters and peatlands, and fluxes to estuaries in Finland. Sci. Total Environ., 365:238-259.
- Łukawska-Matuszewska, K., Burska, D., 2011. Phosphate exchange across the sediment-water interface under oxic and hypoxic/anoxic conditions in the southern Baltic Sea, Oceanol. Hydrobiol. Stud. 40 (2), 57-71.
- Majewski, A., Lauer, Z. (eds.), 1994. Atlas Morza Bałtyckiego. Instytut Meteorologii i Gospodarki Wodnej, Warszawa, 214 pp.
- Matthäus, W., Franck, H., 1992. Characteristics of major Baltic inflows a statistical analysis. Cont. Shelf Res., 12:1375–1400.

References 43

- Meier, H.E., Kauker, F., 2003. Modeling decadal variability of the Baltic Sea: 2. role of freshwater inflows and large-scale atmospheric circulation for salinity. J. Geophys. Res. 108:C11, 3368.
- Meier, H.E., Feistel, R., Piechura, J., Arneborg, L., Burchard, H., Fiekas, V., Golenko, N., Kuzmina, N., Mohrholz, V., Nohr,. C., Paka, V.T., Seellschopp, J., Stips, A., Zhurbas, V., 2006. Ventilation of the Baltic Sea deep water: a brief review of present knowledge from observation and models. Oceanologia, 48(S):133-164.
- Nehring, D., 1987. Temporal Variations of Phosphate and Inorganic Nitrogen Compounds in Central Baltic Deep Waters. Limnol. Oceanogr., 32(2):494-499.
- Nixon, S.W., Ammerman, J.W., Atkinson, L.P., Berounsky, V.M., Billen, G., Boicourt, W.C., Boynton, W.R., Church, T.W., Diroto, D.M., Elmgren, R., Garber, J.H., Giblin, A.E., Jahnke, R.A., Owens, N.J.P., Pilson, W.E.Q., Seitzinger, S.P., 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. Biogeochemistry, 35:141-180.
- Pastuszak, M., Stålnacke, P., Pawlikowski, K., Witek, Z. 2012. Response of Polish rivers (Vistula, Oder) to reduced pressure from point sources and agriculture during the transition period (1988-2008). J. Mar. Syst., 94:157-173.
- Pastuszak, M., Witek, Z., Nagel, K., Wielgat, M., Grelowski, A., 2005. Role of the Oder estuary (southern Baltic) in transformation of the riverine material. J. Mar. Syst., 57(1-2):30-54.
- Savchuk, O., 2005. Resolving the Baltic Sea into seven sub-basins: N and P budgets for 1991-1999. J. Mar. Syst. 56:1-15.
- Schindler, D.W., 1977. Evolution of phosphorus limitation in lakes. Science, 195:260-262.
- Seitzinger, S.P., Styles, R.V., Boyer, E.W., Alexander, R.B., Billen, G., Howarth, R.W., Mayer, B., Van Breemen, N., 2002. Nitrogen retention in rivers: model development and application to watersheds in the northeastern U.S.A. Biogeochemistry, 57/58:199-237.
- Sharpley, A.N., 1995. Soil phosphorus dynamics: agronomic and environmental impacts. Ecol. Eng., 5, pp. 261-279.
- Stal, L., Albertano, P., Bergman, B., Bröckel, K., Gallon, J., Hayes, P.K., Sivonen, K., Walsby, A.E., 2003. BASIC: Baltic Sea cyanobacteria. An investigation of the structure and dynamics of water blooms of cyanobacteria in the Baltic Sea responses to changing environment. Cont. Shelf Res., 23:1695-1714.
- Strahler, A. N., 1957. Quantitative analyses of watershed geomorphology. Transactions American Geophysical Union. Vol. 38, No.6, pp. 913-920.
- Terelak, H., Krasowicz, S., Stuczyński, T., 2000. Środowisko glebowe Polski i racjonalne użytkowanie rolniczej przestrzeni produkcyjnej (Polish soil environment and rational use of agricultural productive space) Pamiętnik Puławski, Puławy. 120/II pp. 455-467 (in Polish).

- UNEP/GRID-Arendal, Baltic Environmental Atlas, Baltic Sea Drainage Basin GIS, Maps and Statistics Database: http://maps.grida.no/baltic/ [Accessed on 02 June 2009].
- Vagstad, N., Stålnacke, P., Andersen, H-E., Deelstra, J., Jansons, V., Kyllmar, K., Loigu, E., Rekolainen, S., Tumas, R., 2004. Regional variations in diffuse nitrogen losses from agriculture in the Nordic and Baltic regions. Hydrol. Earth Syst. Sc., 8(4):651-662.
- Van Breemen, N., Boyer, E.W., Goodale, C.L., Jaworski, N.A., Paustian, K., Seitzinger, S.P., Lajtha, K., Mayer, B., Van Dam, D., Howarth, R.W., Nadelhoffer, K.J, Eve, M., Billen, G., 2002. Where did all the nitrogen go? Fate of nitrogen inputs to large watersheds in the northern U.S.A., Biogeochemistry, 57/58:267-293.
- Voss, M., Liskow, I., Pastuszak, M., Rűß, D., Schulte, U., Dippner, J.W., 2005. Riverine discharge into coastal bay: A stable isotope study in the Gulf of Gdańsk, Baltic Sea. J. Mar. Syst., 57:127-145.
- Voss, M., Deutsch, B., Liskow, I., Pastuszak, M., Schulte, U., Sitek, S., 2010. Nitrogen retention in the Szczecin Lagoon, Baltic Sea. Isotopes in Environmental & Health Studies Vol. 46, Issue 3, pp. 355-369.
- Walczak, R., Ostrowski, J., Witkowska-Walczak, B., Sławiński, C., 2002. Spatial characteristic of hydro-physical properties in arable mineral soils in Poland as illustrated by filed water capacity (FWC). Int. Agrophysics, 16:151-159.
- Winterhalter, T., Flodén, T., Ignatius, H., Axberg, S., Niemistö, L., 1981. Geology of the Baltic Sea [in:] Voipio, A. (ed.), The Baltic Sea, Elsevier Scientific Publishing Company, Amsterdam-Oxford-New York, pp. 1-121.

AGRICULTURAL
CHARACTERISTICS OF THE
TERRITORY OF POLAND

STANISŁAW KRASOWICZ TADEUSZ GÓRSKI KRYSTYNA BUDZYŃSKA JERZY KOPIŃSKI

# 2. AGRICULTURAL CHARACTERISTICS OF THE TERRITORY OF POLAND

Stanisław Krasowicz, Tadeusz Górski, Krystyna Budzyńska, Jerzy Kopiński

### 2.1. Outline of physiography of Polish territory

The territory of Poland is characterized by great physiographic diversity, with occurrence of all the major types of landscapes, from mountains, foothills, through the highlands to the lowlands. Hypsometric diversity is also considerable since denivelations are over 2500 m (from 2499 above the sea level - Rysy in Tatra Mountains to 1.8 m below the sea level in the village of Raczki Elbląskie in Żuławy Wiślane (northern Poland) in the gmina of Elbląg (gmina - the smallest unit in administrative division of the country). However, Polish average elevation above the sea level is only 173 m and it is much lower than the average elevation found in Europe (287 m). Polish landscape is dominated by lowlands, and the height of 200 m above sea level is their upper limit. Lowlands occupy more than 75% of the country's surface, and within this percentage the lowlands at an altitude of 100 m constitute more than 25%. This provides favourable conditions for agricultural production. Even in lowlands the landscape of our country is diversified both in terms of relief and land use. The surface of Poland has a slope in the direction from the southeast to northwest, and terrain relief forms latitudinal belts.

Most of the Polish territory was formed as a result of Pleistocene glaciations. The first glaciation of the relatively small range (the glaciation of the Narew) occurred in the early Pleistocene, but the main southern-Polish and central-Polish glaciations occurred in the middle Pleistocene and it can be divided into several sub-periods. According to the division made by Lindner (see to: Harasimiuk and Rodzoś, 2004) it is now assumed that in our country there were seven ice ages in total (Figs. 2.1, 2.2).

The northern part of Poland, covered by the last glaciation, is characterized by a very large diversity of the surface. Glacier stagnation lines are marked by moraine sequences. They separate hilly, rolling, and flat areas of young-glacial relief with various post-glacial forms such as intramoraine depressions, proglacial gutters, kames, eskers, and drumlins. Many depressions are currently filled with lake water. In some places absolute heights even reach up to 100 m. There are also small flat outwash plains. The landscape of this part of Poland is the least transformed after the continental glacier retreated.

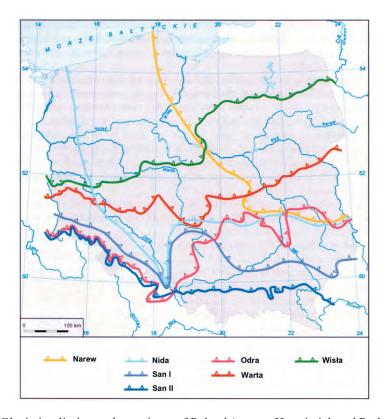


Fig. 2.1 Glaciation limits on the territory of Poland (source: Harasimiuk and Rodzoś, 2004)

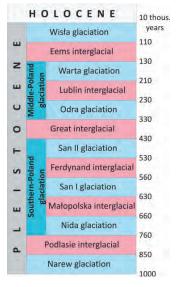


Fig. 2.2 Glaciations sequence on the territory of Poland (source: Harasimiuk and Rodzoś, 2004)

Old-glacial relief extends further south down to the uplands belt. The Wielkopolska, Mazowiecka, Śląska, and Podlaska Lowlands are characterized by typical old-glacial relief. It was strongly modified by periglacial processes that took place in a cold climate on the foreground of the continental glacier (Richling and Ostaszewska, 2005). Convex relief forms were softened and concave relief forms were partly filled. Wide valleys with flat bottoms, gentle slopes and latitudinal course are characteristic elements of lowland relief (Photo 2.1).



Photo 2.1 Swamps in the Polesie National Park (photo by K. Budzyńska)

The upland belt is characterised by a much greater degree of diversification of the terrain relief. This is due to greater altitudes and the occurrence of surface rocks of varying resistance. Altitudes here range from 100 to over 600 m above the sea level.

Within the Jurassic limestone deposition of the Kraków-Częstochowa Upland there are characteristic karst forms appearing as deep valleys with steep slopes and individual rocks protruding above the surface.

In the loess formations of the southern and south-eastern part of the Upland many picturesque gorges were formed, particularly in the vicinity of Sandomierz and Opatów. Height differences on the Lublin Upland and Roztocze reach up to 100 m. The surface is covered with loess formations in which a very dense network of ravines was formed. The densest network of ravines in Poland is on the Nałęczów Plateau, where it even reaches up to several km  $\cdot$  km² (Photo 2.2; for geographical names see to Fig 1.7 in Chapter 1).



Photo 2.2 Loess gorge on the Nałęczów Plateau (photo by K. Budzyńska)

In the south of Poland there are mountainous regions with small areas of high-mountain relief. It is the most diversified part of Poland in terms of terrain relief. Sudetes Mountains are characterised by fault-block and fold reliefs where individual fault blocks are separated by tectonic valleys and depressions. The Carpathians consist of a series of mountain ranges separated by deep valleys and low-lying mountain passes.

The glacier receded from the territory of Poland approximately 13 thousand years BC at the beginning of Holocene, and during this period - over the last 10 thousand years - today's Baltic Sea has been formed.

Terrain relief of Poland is mainly the effect of the influence of endogenous forces and climate change in the geological past. Differentiation of the surface relief can be characterised with sufficient precision, based on terrain slope gradients. It is an objective and uniform evaluation for the whole country (Fig. 2.3; Table 2.1). In terms of administrative units the largest area of land with slope gradients from 0 to 1°, i.e. flat, is in Mazowieckie, Wielkopolskie, Łódzkie, and Kujawsko-Pomorskie voivodeships (Table 2.1; location of voivodeships – see to Fig. 4.4 in Chapter 4). Land with slope gradients greater than 3°, occupies a large area of Małopolskie, Podkarpackie, Świętokrzyskie, and Śląskie voivodeships. Land with slope gradients greater than 15° occupies the smallest area in Poland and it is used as arable land

only occasionally. Most areas with slopes greater than 3° occur in Małopolskie voivodeship. In general, almost 84% of Polish territory is characterized by average slope gradients of less than 3°. In such areas, the threat of erosion and associated surface runoffs of nutrients is small.

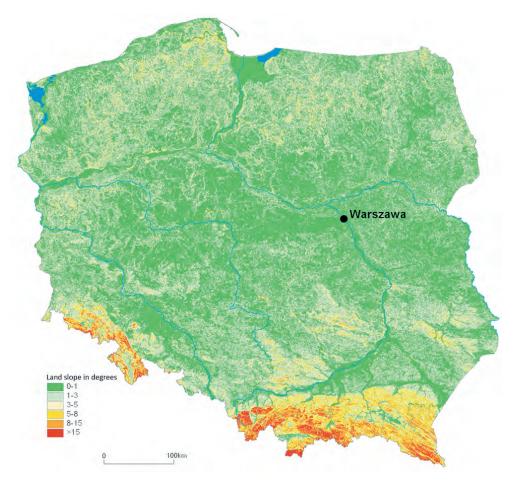


Fig. 2.3 Differentiation of terrain slope gradients in Poland (gradients calculated from Shuttle Radar Topography Mission data) with a resolution of approximately 90 m x 90 m (source: Budzyńska and Gawrysiak, unpublished materials)

Table 2.1 Percentage of area by terrain slope gradients (source: Budzyńska and Gawrysiak, own study)

Voivodoshin!)	Terrain slope gradients in degrees										
Voivodeship <sup>1)</sup>	0-1	1-3	3-5	5-8	8-15	>15					
DLN	39.04	34.91	11.10	6.37	6.44	2.14					
KUJ	57.50	34.14	6.46	1.61	0.28	0.01					
LUB	49.59	40.98	7.39	1.70	0.33	0.01					
LUS	42.34	43.75	11.12	2.51	0.28	0.00					
LOD	59.55	35.75	4.15	0.45	0.10	0.00					
MLP	18.29	23.56	15.82	16.17	18.45	7.71					
MAZ	62.24	33.64	3.70	0.40	0.02	0.00					
OPL	49.64	40.11	8.52	1.45	0.25	0.03					
PDK	29.71	28.89	13.07	13.09	12.60	2.64					
PDL	48.48	43.68	6.60	1.15	0.09	0.00					
POM	38.70	43.10	12.52	4.55	1.11	0.02					
SLS	32.12	44.61	10.54	3.83	5.16	3.74					
SWT	32.63	49.17	13.08	4.00	1.09	0.03					
WAM	37.37	47.61	11.40	3.19	0.43	0.00					
WLP	61.31	31.46	6.06	1.06	0.11	0.00					
ZAP	41.51	44.29	10.91	2.91	0.38	0.00					
POLAND	45.98	38.20	8.92	3.60	2.49	0.81					

<sup>1)</sup> abbreviations for voivodeships are explained in Chapter 12

The Quaternary Pleistocene and Holocene formations on land surface occupy over 90% of the territory of Poland and they constitute the most important group of soil parent rocks (Fig. 2.4). These formations are present throughout the Polish Lowlands, the Sandomierz and Oświęcim Basin, the Kraków-Częstochowa Upland, the Nida Basin, the Lublin Upland, and the Sandomierz Upland (for geographical names see to Fig. 1.7 in Chapter 1). Boulder clays are the most common Pleistocene bottom-glacial sediments. Their thickness is usually about 25-100 m, but in some places it exceeds 200 m. Boulder clays present large regional differences depending on age. These are deposits containing different granulometric fractions, ranking from silty parts to gravel and stones. Older clays from the Oder (Odra in Polish) glaciation are usually sandy on top. Boulder clays are the parent rocks for Luvisols, Cambisols, and Gleysols. Within the area of the last glaciation marginal sediments, varved clays, occur and Gleysols developed on them. In the northern part of Poland fluvioglacial outwash formations with loose or loamy sand graining were deposited and Podzols developed on them. Dune sands occur in different parts of Poland. These are Pleistocene inland dunes and Holocene seaside dunes. Loess formations occur on the Lublin Upland, Roztocze, the Małopolska Upland, and the Carpathian and Sudetic foreland (for geographical names see to Fig. 1.7 in Chapter 1). Their thickness varies from a few to about 30 meters. Luvisols, Cambisols, Phaeozems developed on loess formations. A characteristic feature of these formations is a large susceptibility to erosion. In the northern part of Poland large areas are occupied by wetlands (approximately 7.4%) and peat lands (approximately 7.7%). In the central part of the country such formations occupy 6.0% and 3.2% of the area, respectively, while in the southern part they are virtually non-existent (Fig. 2.4).

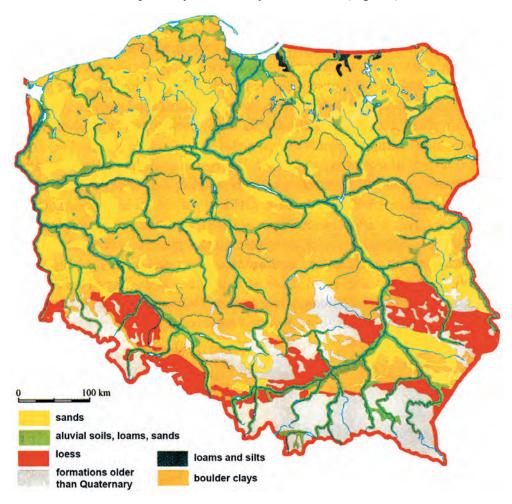


Fig. 2.4 Differentiation of superficial deposits in Poland (source: Harasimiuk and Rodzoś, 2004)

In the area of the Małopolska Upland and the Lublin Upland Jurassic, Cretaceous and Tertiary limestone occur, and various rendzinas (Rendzinas, Leptosols) have developed on them. In the area of the Sudetes the igneous, metamorphic and sedimentary rocks occur and Cambisols and Lithosols have developed on them. The Carpathians are built of Carpathian flysch - sandstones, shales, Tertiary conglomerates, and Cretaceous limestone. Mainly Cambisols, Luvisols, and Lithosols have developed on them (Uziak and Klimowicz, 2000).

River network in Poland formed as a result of terrain relief development in the Tertiary in the southern part, and the Quaternary in the northern part of the country. The current network was formed in the late Pleistocene and Holocene, after complete withdrawal of the continental glacier (Encyklopedia Geograficzna Świata, 1997). In hydrographic terms, almost the entire area of the country lies in the Baltic Sea drainage basin (97.3%), 54% of which accounts for of the Vistula (Wisła in Polish) basin, and nearly 34% for the Oder basin (Atlas Polski, 2001; Chapter 1). Major rivers have a characteristic meridional arrangement, only certain sections of their flow go in the latitudinal direction. This is due to glacial activity. The asymmetry of the Vistula and Oder river basins is characteristic in this respect. The proportion of the left basin to the right is 27:73 for the Vistula, and 30:70 for the Oder, respectively. In practice, almost the entire eastern part of the country is drained to the Vistula River, while the western to the Oder River. The density of the river system on the territory of Poland is highly variable (Fig. 2.5). It is very dense in the Carpathians and Sudetes. This is due to high rainfall and diversified relief, as well as to poor permeability of the bedrock. In the uplands the river network is very thin. This is caused by a large infiltration of rain water in the fractured and karsted surface and deep-lying underground water table. Very thin network also occurs in areas covered with sandy tracks. Within the Polish Lowland the network is dense in places where the surface is impermeable. In terms of the administrative system, Dolnośląskie, Małopolskie, and Podkarpackie voivodeships are characterized by the densest network of rivers, whereas Zachodniopomorskie, Pomorskie, and Kujawsko-Pomorskie voivoideships by the thinnest one (Fig. 2.5; Table 2.2).

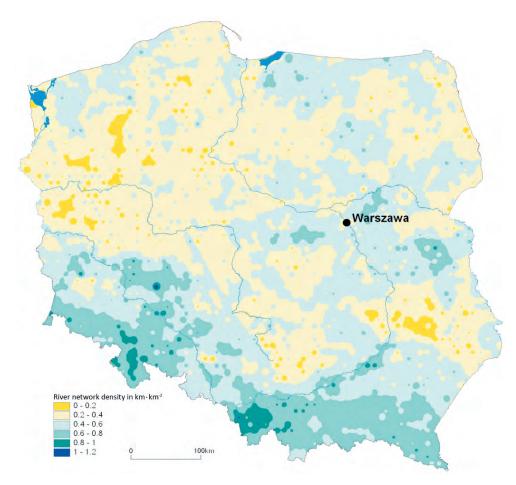


Fig. 2.5 The density of river network in Poland (the density calculated in hexagonal boxes with an area of 100 km²) (source: Budzyńska and Gawrysiak unpublished own delaboration)

Table 2.2 The density of river network in voivodeships in km · km<sup>-2</sup> (source: Budzyńska and Gawrysiak unpublished own delaboration)

Voivodeship	DLN	KUJ	LUB	TOS	TOD	MLP	MAZ	OPL	PDK	PDL	POM	STS	SWT	WAM	WLP	ZAP	Poland
km·km <sup>-2</sup>	0.62	0.34	0.39	0.36	0.39	09.0	0.43	0.56	0.57	0.38	0.35	0.54	0.41	0.42	0.35	0.34	0.43

Outflow is one of the major features of the river system. Rivers of the Beskidy Mountains are characterised by considerable variability of the outflow, which is caused by large height differences and a relatively low retention capacity of flysch rocks. High variability of flows is characteristic for the rivers of the Central Polish Lowlands. Upland rivers display small variation of flows. The most balanced flows have the rivers of the Pomeranian and Mazurian Lake Districts (for geographical names see to Fig. 1.7 in Chapter 1). Human interference in the form of regulation of river beds has a very big impact on the flows (Fig. 2.6). Not regulated rivers cause a significant slowdown of water outflow, thus increase water residence time, and therefore promote retention of phosphorus as well as denitrification of oxidized nitrogen compounds. This significantly reduces the discharges of nitrogen and phosphorus compounds into the main Polish rivers and then into the Baltic Sea (Chapter 1).





Fig. 2.6 Regulated (a) and unregulated (b) rivers (source: http://maps.google.com, 2008)

In addition to rivers, lakes hold certain quantity of surface water. Total number of lakes in Poland exceeds 9,000 and they occupy about 1% of the country's surface, but the distribution of lakes is very uneven (Fig. 2.7). Most of the lakes (about 72% of total number) are located in the Mazurian and the Pomeranian Lake Districts, whereas the remaining 18% are in the Wielkopolska and Kujawy Lake Districts (see to Fig. 1.7 in Chapter 1). Most lakes are shallow and subject to the processes of eutrophication and overgrowing, as well as silting up. This leads to the disappearance of the lakes, and in the recent years the process has significantly accelerated.

Groundwater resources are very important for the national economy, including agriculture. Most of the Polish territory, especially the Polish Lowlands, has, however, little or no groundwater resources (Fig. 2.7). In this area there are also the majority of cones of depression caused by mining activity or by drawing water to supply urban areas. A schematic distribution of groundwater is presented in more detail in Chapter 6.

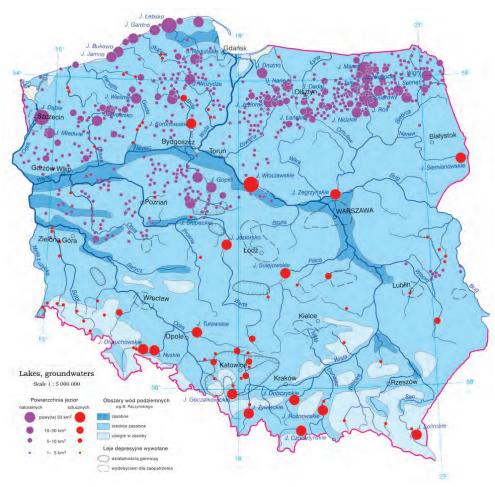


Fig. 2.7 Lakes and underground water in Poland (source: Encyklopedia Geograficzna Świata, 1997 - by permission of Nowa Era sp. z o. o. Wrocław)

# 2.2. Agroclimate of Poland

Poland lies in the zone of colliding influences of a continental climate with relatively dry summers and cold winters, with a moderate climate with Atlantic influences, and this situation creates very stable conditions for agricultural production. Average annual air temperature ranges from 6.0°C to 8.8°C. The length of thermal growing season averages about 220 days and only in the south-west of the country exceeds 230 days. Average yearly precipitation amounts to 500-600 mm in the lowlands, 600-700 mm in the uplands, and exceeds 1000 mm in the mountains. Central Poland (Mazowsze, Wielkopolska, Kujawy) belongs to the regions with the lowest rainfall in Europe, where annual rainfall does not exceed 550 mm (see also

to Chapter 1). Three factors have profound influence on the climate of any place in Poland, i.e. latitude, distance from the Atlantic Ocean, and absolute height. Latitude determines the access to solar radiation, and therefore annual cycle of mass and energy flows in ecosystems. The inflow of humid air of oceanic origin, which is quite frequent due to western circulation prevailing in the area, increases average annual temperature and reduces annual and diurnal temperature variations, as well as exerts a strong influence on the intensity of radiation and amount of rainfall. These two geographical factors shape general climate gradients (especially the thermal ones) in Poland, which get arranged along the north-northeast line, with some seasonal modifications. Absolute height determines air pressure and thermal air currents according to the vertical temperature distribution in free atmosphere, and consequently the relative humidity, and affects solar exposure depending on the optical mass of the atmosphere which decreases with height.

The role of these factors is clear to such an extent, that Polish climate (and agroclimate) from analytical perspective can be described as a function of three geographical coordinates, longitude, latitude, and height above sea level. However, regional and local descriptions need to take into account meso- and topoclimatic peculiarities, which are modelled by various factors that are limited in scope. On a regional scale the Baltic Sea plays a special role, and its measurable impact can reach tens of kilometres; similarly mountains and hills of lake districts of the Central Uplands, which modify rainfall patterns over large areas. On a local scale the specific influence of the terrain cover and relief, relative heights and exposure of the slopes, urban development, as well as major bodies of water cannot be ignored (Górski and Zaliwski, 2002).

To a certain extent anthropogenic air pollution plays a role in the spatial distribution of climatic elements, especially of clouds and insolation. The range of air pollution can vary from several kilometres zone around a single emitter, to the entire region, such as Upper Silesia. In the vast stretches of south-western parts of the country (Górski and Górska, 1998) a clear reduction in insolation (i.e. the number of hours of direct solar exposure) has been found, which in some part can be attributed to industrial pollution immission from abroad. In the years 1961-1995 the annual average insolation in Zgorzelec could be determined as amounting to 1 380 hours, while in Legnica to 1 540 hours, and in Kalisz to 1 600 hours. In the central and eastern-central Poland mean annual insolation typically exceeds 1 650 hours, while in the lake districts it drops below 1 600 hours. Quantitative measurements of solar radiation in Poland are not numerous enough to enable to present the characteristics for all regions. Of the seven stations operating in the years 1961-1995 (Bogdańska and Podogrocki, 2000), the highest values were measured at Kasprowy Wierch (3 839 MJ · m<sup>-2</sup>) and in Kołobrzeg (3 829 MJ · m<sup>-2</sup>), and the lowest in Suwałki (3 528 MJ · m<sup>-2</sup>). The months of the growing season (April - October) account for approximately 85% of the annual value of insolation. It can be assumed that the land used for agricultural purposes in Poland during this period receives about 3.1

GJ m<sup>-2</sup> of radiant energy and the spatial distribution does not differ much from the distribution of insolation.

The average temperature of the year determines overall characteristics of the thermal conditions. In Poland, as elsewhere in Europe, an upward trend in temperature is clearly visible (Górski, 2007). The values shown in Fig. 2.8 are based on measurement data from the years 1941-1990 and the trends observed since the seventh decade of the twentieth century are extrapolated over the period 2001-2010. These trends include the increase in the average temperature (0.3°C per decade) and a reduction of annual amplitude and phase shift in favour of the spring. Temperature variation in the twenty first century (until 2008) confirms the validity of the extrapolation.

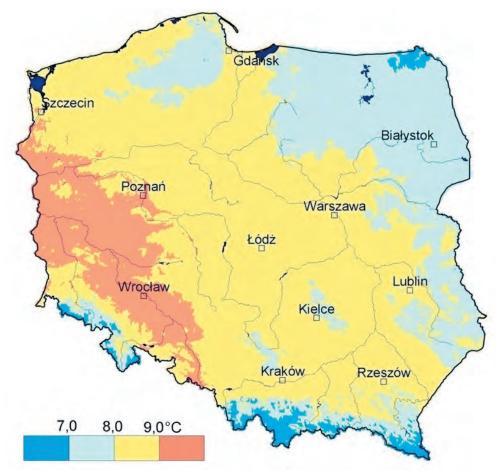


Fig. 2.8 Average annual air temperature (extrapolation from the years 1941-1990 over the decade 2001 to 2010) (source: Górski, 2005)

Lower Silesian Lowland is characterized by the highest temperature in Poland, and in the vicinity of Opole, Legnica, and Wrocław average temperature reaches 9.5°C (of course it is higher in the cities). The lowest average temperature (below 7°C), excluding the mountains, occurs in the northern part of the Suwałki Lake District (near Wiżajny). In the Carpathians, the average temperature is reduced on average by about 0.5°C per 100 m elevation, in the Sudetes by about 0.55°C, but with considerable topoclimatic influences. In summer, the warmest regions are the Central Lowlands, and the Sandomierz Basin and there the average July temperature exceeds 19°C. However, winter isotherms run meridionally. In the coldest region (Suwałki Lake District), the average January temperature drops below -3.5°C, whereas in the warmest regions (the Lower Oder and around the Pomeranian Bay) it has a positive value.

The derivative of the annual course of temperature is the length of climatic growing season (Fig. 2.9), and it is assumed that it is determined by dates when normal temperature crosses the threshold of 5°C. Thus, the spatial distribution of duration of this period resembles the temperature distribution pattern. Average growing season in the Suwałki Lake District lasts approximately 200 days, while in Lower Silesia is by over 40 days longer. The important feature of agroclimate is the length of farming and frost-free periods.



Fig. 2.9 Average length of growing season (extrapolation over the decade: the years 2001-2010) (source: Kozyra and Górski, 2004)

The spatial distribution of precipitation (Fig. 2.10) is determined primarily by the topography of the area. The average amount of rainfall increases with absolute height, at least up to 2000 m above the sea level, where it exceeds 1600 mm per year. However, the exposition of slopes and distance from terrain barriers is also of significant importance. Slopes exposed to rain-carrying westerly winds usually receive more precipitation than the eastern slopes. In the shadow of hills, even with the relative heights of only 100 - 150 m, usually areas of reduced rainfall in relation to macroscale gradients extend (Górski, 2006). Rain shadows (Woś, 1999) are clearly identifiable on the south and east of the Pomeranian Lake District. On the windward side the average annual rainfall reaches 800 mm (in the vicinity of Polanów), while not exceeding 550 mm in the Powiśle. In Kujawy and along the central part of the Noteć River the rainfall does not reach 500 mm. Similar effects can be observed in the valleys of Sandomierz, Nowy Targ, and Kłodzko, and in many other places, although weaker, yet still distinct.

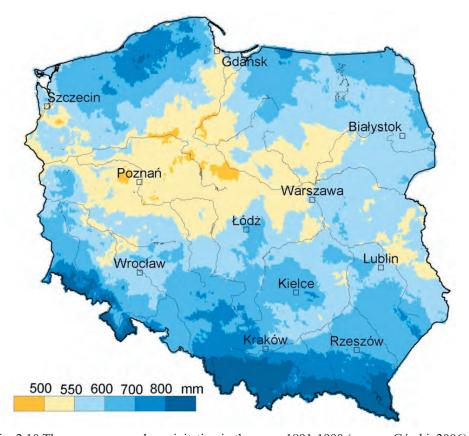


Fig. 2.10 The average annual precipitation in the years 1891-1990 (source: Górski, 2006)

Within the annual cycle the daily maximum rainfall usually occurs in July, (in some coastal areas in August), while the minimum in March. Actual values (not averaged) show considerable variability both within a year and between years. Agricultural droughts, as it seems more and more frequent in recent years due to correlation of rainless periods with increased evapotranspiration (Górski, 2007), and excessive summer rainfall, causing flooding of fields, are a consequence of this variability. The ratio of winter half year precipitation (November - April) to annual precipitation is particularly high in the west (Fig. 2.11), for example, in Szczecin; rainfall during this half year amounts to 43% of the annual total, whereas in Lublin it reaches 34%, in Świeradów - 42%, and in Nowy Targ - 32%.

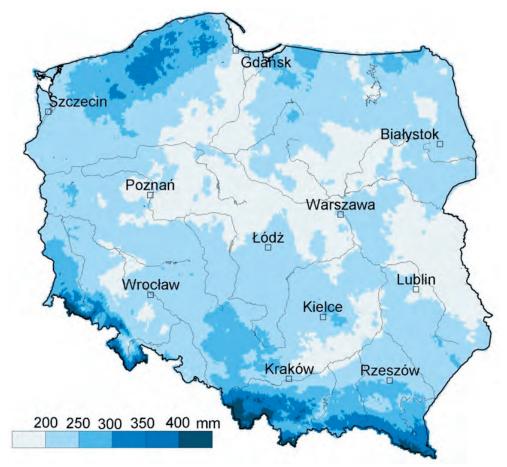


Fig. 2.11 The average precipitation in the half year November-April (in the years 1891-1990) (source: Górski, 2006)

Therefore, it can be concluded that the leaching of nutrients from soil during the winter and early spring in western Poland is particularly intense, especially since the vast majority of rainfall comes in the form of rain, while the snow cover, stopping seepage and water runoff, lasts there for a much shorter period of time than in the east (Fig. 2.12).

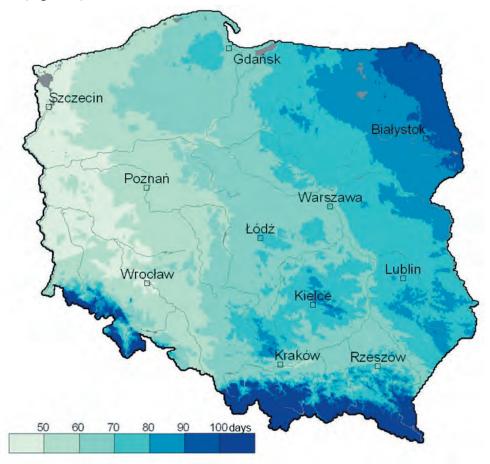


Fig. 2.12 The average annual number of days with snow cover (in the years 1955-1981) (source: Górski and Zaliwski, 2002)

The above-mentioned (including these that were not mentioned) climatic factors must be taken into account in all agro-climatic syntheses that consider climate as a factor in agricultural production. Since the relationships between the plant and its environment are typically nonlinear and non-monotonic, individual elements characterizing the weather and climate cannot be determined only by the mean values, because the far from the average values are particularly interesting. Therefore, the type of statistical distributions should be formally defined, or at least the frequency of cases in different ranges of values should be used. Empirical weather/yield

functions may constitute a basis for the assessment of individual regions. Because climatic requirements of crops are different, each synthetic evaluation of agroclimate must include assumptions about the structure of crops, as well as about the relative value of crops. The agroclimatic bonitation of the country developed by IUNG-PIB (Górski and Górska, 1998; Kozyra and Górski, 2004) took into account nine different crops. The resulting bonitation index decreases from the southwest to the northeast (Fig. 2.13), similarly to the length of the growing season, with some modifications necessitated by moisture conditions.

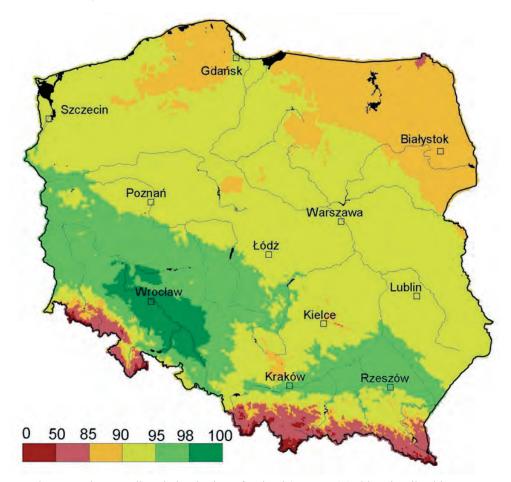


Fig. 2.13 The agroclimatic bonitation of Poland (source: Górski and Zaliwski, 2002; Kozyra and Górski, 2004)

In the vicinity of Oława (western Poland) the agroclimatic bonitation by assumption has the value of "100". In the Suwałki Lake District (south-eastern Poland) it drops to "85", which means 15 percent reduction (compared to the optimal region) of the average yield for climatic reasons. In the mountains e.g. at an altitude of 800 m above the sea level in the Sudetes the bonitation index drops to "50", while

at about 900 m in the Carpathian Mountains and above these altitudes it quickly tends towards zero. The systematization of connection between plants and their environment requires the distinction of two aspects of development: the speed of development, which involves the ability to go through the entire life cycle, and weight gain, which determines the yield. Climatic factors have almost exclusive role in controlling the length of development phases, but their countrywide role in the forming of bonitation of agricultural habitats (which defines long-term yield) is much smaller than the role of the soil environment, with the exception of mountain areas. Climatic factors have also evident, although very complex, influence on the dispersion of nutrients from agriculture into the environment. This occurs both directly by leaching of nitrates and phosphates, as well as by escaping of gas nitrogen products into the atmosphere, and indirectly by increasing or decreasing the expected crop yields and thus the amount of nutrients taken up by plants. As it was already mentioned, in the south-western part of the country the amount and distribution of rainfall promotes leaching of nutrients to groundwater. However, in this part of Poland higher crop yields are achieved (due to better insolation and a longer growing season); therefore the uptake of nutrients from the soil and fertilizers is higher, which partially prevents their dispersion. In the north-eastern part of Poland agroclimatic conditions are worse, and rainfall higher than the average in the country, which should theoretically increase the dispersion of nutrients. However, long-lying snow cover and the shift of rainfall proportions to the growing season limit the potential losses of nutrients through their leaching from the soil.

# 2.3. Rural and agricultural areas

Rural areas cover approximately 29.7 million hectares, which represents more than 95% of the total area of Poland (about 31.1 million hectares). Rural areas are inhabited by approximately 14.9 million people, i.e. almost 39% of the total population of our country. The share of rural population is significantly varied regionally, from 22% in the Silesian region to 58.7% in the voivodeship of Podkarpackie. The number of villages, constituting separate village administrative units, amounts to approximately 41.9 10³, and about 15% of the villages have less than 100 inhabitants, whereas 66% of the villages have a population ranging from 100 to 500 inhabitants. The average population density in rural areas is small and does not exceed 50 persons per 1 km². This indicates a very significant dispersion of the households in these areas and problems with providing them with appropriate technical infrastructure, which can have a direct impact on water pollution by nutrients. Only part of the total rural population is employed in agriculture. This is indicated by the share of people working in agriculture, which in relation to the total number of employed persons amounts to 17.3%.

In Poland, there are migration processes that have significant impact on the situation of rural areas. Since 2000 the observed influx of people from cities to rural areas has been slightly larger than the outflow of population from rural to urban areas (Bański, 2005). There is a new category of rural residents who live in the country or run their businesses there, and as a rule they represent a wealthy part of the population. These people usually settle in areas around big cities and along major transport routes. Rural areas located near urban agglomerations (especially large ones) have a higher level of development compared to other areas. The condition of technical and social infrastructure has been improving there along with the level of environmental awareness. This also concerns rural population whose level of education has been steadily improving. Nevertheless, as much as 34% of rural population finished only primary education. The situation of this population has been aggravated by severe unemployment problem. The registered unemployment rate in rural areas is about 9.1%; the hidden unemployment is assessed at 1.6 million people, while nearly 70% of population works part-time on small farms. The share of people working in agriculture has been decreasing at a slow pace, but with generally high levels of employment in this sector of economy. In certain regions of Poland (mainly in the east), there is a problem of the lack of successors on farms and depopulation of rural areas. Of the total area of Poland agricultural land occupies nearly 18.9 million hectares, i.e. 60.4% of the surface. The area of well cultivated agricultural land amounts to about 15.4 million hectares (about 49% of the country), and the remaining land is used for non-agricultural purposes, mainly for rural infrastructure. Poland is one of the countries with the largest share of agricultural land in the total area of the country. The average global share of agricultural area is less than 36%. Private sector farms, which dominate in agriculture, use more than 13.9 million ha of agricultural land, i.e. 90.3%. In 2011, approximately 2.2 million farms with an area of over 0.1 hectare operated in Poland, including 1.5 million farms with an area of more than 1 hectare (Fig. 2.14; Table 2.3). The average general area of the farm, in the group of farms with an area of more than 1 hectare, has been steadily increasing and now it amounts to 9.8 ha (GUS, 2011a). Polish agriculture is dominated by small farms, of 1-5 ha (Fig. 2.14). They constitute over 55% of the total number of farms, but hold only about 20% of agricultural land. Farms with an area over 20 ha (their number amounts to 120 · 10<sup>3</sup>) constitute only 5.7% of the total number of farms but use 47% of agricultural land. The largest fragmentation of individual farms is observed in southern and south-eastern part of the country. In northern Poland agrarian structure is more advantageous (Krasowicz and Kopiński, 2006).

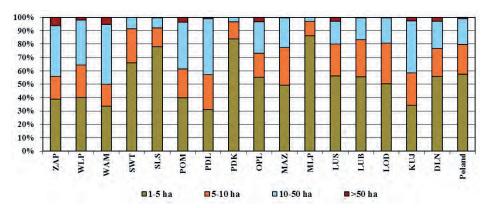


Fig. 2.14 The share of farms in the area groups (%) (source: own calculations based on GUS, 2011a data)

Table 2.3 Agrarian structures of farms with an area of over 1 ha by area groups in 2010 (source: own calculations based on GUS, 2011a data)

Voivodeship	Number of farms	Hectars of agricultural land per	The share of farms in the area groups [%]							
	[thous.]	farm	1-2 ha	2-5 ha	5-10 ha	10-50 ha	> 50 ha			
DLN	63	15.0	22.2	30.2	20.6	22.2	4.8			
KUJ	68	15.9	11.8	20.6	25.0	39.7	4.4			
LUB	190	7.3	17.9	35.8	27.9	17.4	0.7			
LUS	24	18.9	25.0	25.0	16.7	20.8	8.3			
LOD	134	7.4	16.4	32.8	30.6	20.1	0.5			
MLP	163	3.8	38.7	45.4	12.3	3.3	0.2			
MAZ	238	8.4	15.5	31.5	28.2	23.5	0.8			
OPL	29	18.1	17.2	27.6	20.7	27.6	6.9			
PDK	145	4.4	37.2	45.5	13.8	4.1	0.5			
PDL	86	12.4	9.3	20.9	25.6	43.0	1.5			
POM	43	18.7	14.0	23.3	23.3	34.9	4.7			
SLS	77	5.5	40.3	37.7	14.3	7.8	0.9			
SWT	103	5.2	24.3	42.7	24.3	9.7	0.3			
WAM	44	23.7	13.6	20.5	18.2	47.7	6.8			
WLP	124	14.4	15.3	23.4	24.2	33.9	2.4			
ZAP	32	29.8	15.6	25.0	18.8	31.3	9.4			
Poland	1563	9.8	21.9	33.3	22.5	20.5	1.7			

In the structure of land use, arable land and permanent grassland represent the highest percentage (Table 2.4). In terms of the share of arable land, Poland especially stands out from other European countries, where the share is usually much smaller.

Particularly large proportion of arable land is in the voivodeships of Kujawsko-Pomorskie, Opolskie, and Wielkopolskie in the central and western Poland, which are characterized by the highest intensity and efficiency of agricultural production. High proportion of permanent agricultural land is characteristic for voivodeships of Małopolskie and Podkarpackie, which are located in the southern Poland, and the voivodeships of Podlaskie and Warmińsko-Mazurskie, that are located in northeastern Poland in the area called the "green lungs" of Poland. The structure of land use has a very strong impact on diffuse nutrient losses. As results from the review of findings of Hatfield and Follett (2008) studies, the concentration of nitrates in open waters is proportional to the share of arable land in the studied catchment areas. The same review demonstrates that the amount of nitrate leaching from the soil is much greater under arable land compared to grassland. Flood-meadows near water courses are also a natural filter for nitrogen and phosphorus carried by surface or subsurface transport from the above-lying arable land (see also to Chapters 8 and 9).

Table 2.4 Area and structure of agricultural land in 2011 (source: own calculations based on GUS, 2011a data)

	Agricultural land										
Voivode- ship		Arable land		Permanent crops		Permanent grassland		Other		Share in the country	
Simp	ha·10 <sup>3</sup>	%	ha·10 <sup>3</sup>	%	ha·10 <sup>3</sup>	%	ha·10 <sup>3</sup>	%	ha·10 <sup>3</sup>	%	[%]
DLN	952	100	742	78.0	11	1.2	139	14.6	58	6.1	6.2
KUJ	1056	100	912	86.3	11	1.0	112	10.6	20	1.9	6.8
LUB	1453	100	1100	75.7	73	5.0	234	16.1	37	2.5	9.4
LUS	492	100	351	71.5	7	1.5	110	22.3	22	4.5	3.2
LOD	998	100	775	77.7	38	3.8	153	15.3	29	2.9	6.5
MLP	683	100	355	51.9	16	2.4	251	36.7	54	7.9	4.4
MAZ	2071	100	1248	60.3	109	5.3	614	29.7	96	4.6	13.4
OPL	536	100	469	87.5	1	0.2	41	7.6	23	4.3	3.5
PDK	690	100	375	54.4	16	2.4	203	29.5	86	12.5	4.5
PDL	1063	100	624	58.7	6	0.5	404	38.0	27	2.6	6.9
POM	746	100	597	80.0	6	0.8	124	16.6	18	2.4	4.8
SLS	446	100	304	68.1	4	1.0	92	20.7	44	9.8	2.9
SWT	535	100	351	65.7	36	6.7	106	19.8	40	7.4	3.5
WAM	1052	100	703	66.9	5	0.5	323	30.7	20	1.9	6.8
WLP	1790	100	1498	83.7	24	1.4	243	13.6	22	1.2	11.6
ZAP	879	100	639	72.7	27	3.1	143	16.2	69	7.9	5.7
Poland	15442	100	11044	71.5	390	2.5	3291	21.3	662	4.3	100

In Poland, agriculture is the economic sector of great importance and it has a decisive influence on the socio-economic situation of rural population, the natural environment, the landscape structure, and biodiversity of the country. However, the

impact of agriculture on macroeconomic indicators, including in particular the size of the Gross Domestic Product (GDP), is relatively small. In 2010, gross domestic product per one inhabitant of rural areas amounted to PLN 37 064, and the share of agriculture in GDP amounted to 3.8%. Poorly developed rural infrastructure is a major barrier to the development of agricultural and non-agricultural functions of rural areas. This applies to the condition of rural roads, rural water supply and sewage disposal, appliances, machinery and tools, and especially the condition of the buildings for livestock. Many existing hard-surfaced roads need upgrading and repair, and the access roads to agricultural land and forests are mostly cart-roads. Although approximately 90% of villages already use tap water (including about 8% only partially), still only about 24.8% of villages are equipped with a sewage system (including about 5% only partially) (see to Chapter 8). Rural water infrastructure has been presented in more detail in Chapter 6 of the monograph. In 2002, there were about 1.5 million tractors and 152 thousand combine harvesters on Polish farms. According to Wójcicki (2011), in quantitative terms, Polish agriculture is sufficiently equipped with means of agriculture mechanization. Alarming is the age and wear and tear of machinery and tractors and the resulting technological gap separating Polish agriculture from agriculture of leading countries in Western Europe. There is a concern that in the next 10 years, a number of farms in Poland will not be able to recreate and modernize their machine parks. Also, the technical condition and the standard of large part of livestock buildings are low. Almost 50% of these buildings were built before 1960 and now they do not meet modern zootechnical requirements. This also refers to equipping the farms with manure plates and tanks for storing liquid manure, though the situation is steadily improving (Chapters 5 and 6).

The varied terrain relief and diversity of soil and climate conditions make Poland the country of a great diversity of habitats and natural landscapes. On Polish territory there are about 265 types of plant associations half of them being related to agricultural areas, and 32.5% of the country is covered by nature conservation (Faber, 2001). Production potential of Polish agriculture, despite the high proportion of very poor and poor soils, is significant. However, the degree of utilization of this potential is low and has considerable regional variations. The low exploitation of production potential is due to acidification and low soil fertility, limited application of mineral fertilizers and plant protection products, and too little use of certified seed and planting material. A characteristic feature of Polish agriculture, despite the ongoing changes, is also small scale of commodity production and its dispersion. However, both natural conditions and low input production technologies make Poland a country capable of producing healthy, safe food, and the degree of environmental risk is relatively low.

#### 2.4. Agricultural production space and its use

Regional differentiation of the potential of the Polish agricultural production space is due to the spatial variability of terrain relief, soil cover and rainfall, as well as temperature. As early as in the 1970s the Valuation of Agricultural Production Space System (VAPSS) was developed in IUNG-PIB on the basis of quantitative relationship between the yield and quality of habitat and climate (Stuczyński et al., 2007). The VAPSS that has been used since then includes four static indicators to assess individual elements of the habitat and they are as follows: the quality and suitability of soils, the soil moisture, the terrain relief, and the agroclimate. The valuation of natural and soil conditions that has been developed with the use of statistical analysis methods has been aggregated to the level of gminas and voivodeships in order to calculate the overall Agricultural Production Space Valuation Index (APSV index) as a measure of the productive potential of the habitat. The weights assigned in the evaluation to each factor are a reflection of their importance in shaping the yield. In the valuation of agricultural production space the soil conditions are of particular importance. Approximately 70% of the observed variability of yields can be explained by the function of soil quality and suitability index. The influence of other factors is much smaller and it amounts to a total of about 30%. The share of partial agroclimate index, covering the whole complex of climatic factors, is within the range of 1-15 points, the water conditions index is within the range of 1-5 points, while the terrain relief index is within the range of 0.1-5 points. Currently, having numerical information layers, characterizing particular features of the habitat, the valuation index can be calculated for any area such as a geodesic precinct, a drainage basin, functional regions, etc.

In Poland, the average value of APSV index amounts to 66.6, but it reveals considerable regional variation (Table 2.5). The biggest limitations to crop production occur in areas with values of less than 52 points. These include both typical mountain terrain within which the limitations are mainly due to terrain relief and climate, and the lowlands, where the fundamental limitations are associated with low water capacity and limited natural abundance of soil nutrients. The largest clusters of areas of little use for agricultural purposes are in Podlaskie, Mazowieckie, and Pomorskie voivodeships. Podlaskie voivodeship has the lowest valuation index in Poland amounting to 55.0 points. Low quality of production space puts limits not only on the selection of crops and on crop yields, but it also has several adverse consequences in the economic and environmental dimensions, as it potentially leads to setting-aside of agricultural land and degradation of the landscape. Light soils with high permeability and low retention developed from sand are highly susceptible to soil drought. This phenomenon is particularly severe in areas where the ground water level is below the range of the root system of plants and the capillary ascent has no practical significance. Under these conditions, the amount and distribution of precipitation during the growing season and the amount of water retained in the

soil profile by capillary forces determine the yield. The ability to retain water in soil profile depends on the soil texture; the amount of water corresponding to the field water capacity (FWC) in the soil profile developed from strong loamy sand is almost double compared with the soil developed from loose sand, and the water capacity of the soil developed from heavy clay is almost three times greater. These factors also have a very strong impact on nutrient leaching.

Table 2.5 The bonitation index and Agricultural Production Space Valuation Index (APSV index) in Poland by voivodeships (source: Stuczyński et al., 2007)

		Bonitation	index		Agricultural	
Voivodeship	Quality and agricultural suitability of soils	Agrocli- mate	Terrain relief	Water conditions	Production Space Valuation Index (APSV index)	
DLN	56.9	10.4	3.8	3.8	74.9	
KUJ	54.4	9.2	4.0	3.4	71.0	
LUB	55.8	10.6	4.0	3.8	74.1	
LUS	43.6	11.6	4.3	2.7	62.3	
LOD	43.2	11.5	4.4	2.8	61.9	
MLP	53.6	9.3	2.4	4.0	69.3	
MAZ	43.1	9.7	4.1	3.0	59.9	
OPL	60.5	13.2	4.1	3.6	81.4	
PDK	52.7	10.7	3.0	4.0	70.4	
PDL	41.0	7.5	3.7	2.8	55.0	
POM	50.6	8.5	3.7	3.4	66.2	
SLS	46.8	11.2	3.6	2.6	64.2	
SWT	52.2	10.6	3.1	3.5	69.3	
WAM	51.1	8.1	3.4	3.4	66.0	
WLP	46.4	11.2	4.4	2.8	64.8	
ZAP	50.0	9.8	4.0	3.6	67.5	
Poland	49.5	9.9	3.9	3.3	66.6	

Soil quality exerts the strongest influence on the variation of bonitation index. The process of soil formation, with its direction and intensity determined by such factors as: water conditions, terrain relief, vegetation, climatic conditions, soil parent rocks, human activities, etc., caused the formation of a large number of soil typological units in the country. The soil science classification distinguishes 35 types and 78 subtypes of soil with marked differences in chemical properties, physical and physicochemical properties (Fig. 2.15).

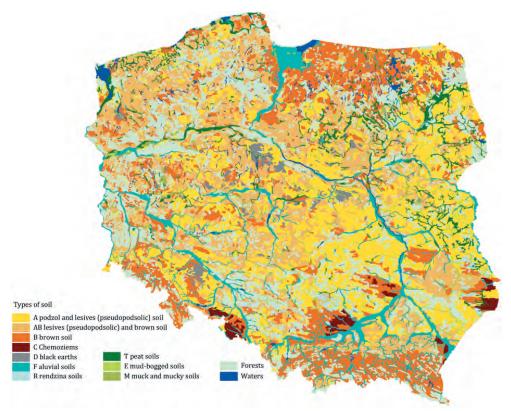


Fig. 2.15 The main types of soils in Poland based on soil-agricultural map at a scale of 1:500 000 (source: Witek, 1979)

The largest areas are covered with podzol soils and brown soils belonging to the type of podzols and rusty soils, acid brown soils, proper brown soils, and lessive soils. Podzol soils developed mainly from sandy formations under conditions of intensive washing and leaching of mineral components from surface levels to deeper levels. These are naturally acid and very acid soils, low in humus and mineral components, and with weak buffering properties. They are also susceptible to leaching and surface runoffs of mineral nitrogen and phosphorus compounds. Large areas of the country are covered by brown soils mainly represented by proper brown soils, acid brown soils, and lessive soils (washed). These soils are characterized by much smaller movement of nutrients from upper to deeper levels of the soil profile than in podzol soils. Field cultivation improves properties of the soils, and they become medium, and sometimes even good quality agricultural land. Good or very good soils i.e. chernozems, black earths, rendzinas, and alluvial soils cover relatively small area of the country.

The average quality of Polish soils is relatively low. This is due mainly to soil parent rock type (Table 2.6). Over 70% of Polish soils were developed mainly from Pleistocene boulder clay and sand, intensively washed out and sorted by glacial

waters. More than 28% of the surface soil was developed from loose sand and gravel and loamy sand. If we add part of the soils developed from clayey sands on loose sand or loamy sand, some light and very light alluvial soils, shallow and skeletal rendzina soils, and soils in mountain areas, then it will turn out that more than 40% of Polish soils are characterized by low quality and agricultural suitability (Lekan and Terelak, 1997).

Table 2.6 Soil parent rocks in Poland (source: Terelak et al., 2000)

Soil parent rocks	Area [thous. ha]	Share in the total soil area [%]	Share in the total agricultural land area [%]	Share in the arable land area [%]
Gravels	88.4	0.9	0.5	0.6
Light and slightly loamy sands	4262.0	34.6	24.8	27.8
Clayey sand	2476.4	10.2	12.4	16.2
Light loams	2562.5	15.8	18.8	16.7
Medium-heavy and heavy loams	1970.1	9.6	13.2	12.8
Clays	92.4	0.8	1.0	0.6
Loess	1395.4	3.5	4.8	9.1
Silts of water origin	739.4	4.2	4.6	4.8
Alluvial soils	787.7	4.7	5.8	5.2
Rendzina soils	235.0	1.1	1.6	1.6
Peat, peat earth	114.4	8.5	9.6	0.7
Massive rocks of various origin	599.1	6.1	3.9	3.9

Granulometric composition of soils (texture) and its variation in the soil profile determine the ability of soil to store water and mineral components, and therefore its fertility and productivity. The firmness of soil determines the field water capacity, the content of available water in soil and of easily available water (Table 2.7). The increase in firmness of the soil increases its ability to store these forms of water and thus reduces its infiltration in the soil profile. Thus, the leaching of nutrients is reduced. Sorption properties of soils depend mainly on the content of colloids and humus in the soil, its granulometric and mineralogical composition, and reaction. The index of sorption properties of soils is sorption capacity determining their ability to store ions. With the increase of sorption capacity of soils the abundance of mineral components and soil buffering capacity also increase. This allows intensifying the fertilization without fear of adverse consequences for the soil environment. Light

granulometric composition of soils in Poland, low content of colloids, clay minerals and humus in the soils, and their considerably high acidity, result in low, differing significantly from the optimal, values of sorption capacity (15-20 cmol +/kg of soil) and soil sorption complex saturation with basic cations (> 80%).

Table 2.7 Water	capacity of	mineral	soils in	mm	at 0-100	cm	layer	(source:	Terelak
et al., 2000)									

Granulometric composition	Field water capacity	Available water	Easily available water	
Light sand	110	92	45	
Slightly loamy sand	145	117	60	
Light loamy sand	175	138	70	
Heavy loamy sand	210	155	80	
Light loam	270	185	90	
Medium-heavy loam	320	200	100	
Heavy loam	400	240	120	
Clay	460	220	110	
Very fine sand	300	200	100	
Silt loam	360	244	120	

The classification of soils by agronomic categories is very useful for the purposes of agrochemical research and evaluation of susceptibility of soils to the processes of movement of water and soluble mineral compounds. Soil granulometric composition, or more specifically, the share of the so-called floatable parts of < 0.02 mm, is the basis for defining agronomic soil categories. This classification distinguishes the following categories of soils: very light soils (up to 10% of particles of <0.02 mm), light soils (11-20% of particles of <0.02 mm), medium-heavy soils (21-35% of particles of <0.02 mm), and heavy soils (over 35% of particles of <0.02 mm). The share of soils belonging to different agronomic categories greatly varies between the regions of the country (Table 2.8).

Table 2.8 The share of soils by agronomic categories and ranges of humus content (source: Stuczyński et al., 2007)

Voivode- ship	Perce	_	soils in agregories [%]	Percentage of soils in humus content classes [%]				
	Very light	Light	Medium- heavy	Heavy	Low	Average	High	Very high
DLN	9.3	16.3	30.1	44.4	4.1	24.6	41.7	29.5
KUJ	21.2	48.6	28.2	2.0	11.6	58.0	17.2	13.2
LUB	12.2	34.6	47.2	6.0	4.4	55.4	21.6	18.6

Voivode-	Perce		soils in agrogories [%]	onomic	Percentage of soils in humus content classes [%]				
ship	Very light	Light	Medium- heavy	Heavy	Low	Average	High	Very high	
LUS	33.8	38.4	22.9	4.9	3.9	43.7	28.0	24.4	
LOD	37.4	50.4	12.0	0.1	2.7	59.2	24.5	13.6	
MLP	3.8	9.5	47.6	39.1	11.7	44.9	31.8	11.6	
MAZ	35.5	45.5	17.5	1.4	12.5	51.6	21.0	14.9	
OPL	6.9	22.3	40.9	30.0	1.5	39.3	44.5	14.7	
PDK	13.9	29.1	22.6	34.4	8.2	32.8	44.9	14.0	
PDL	26.5	38.8	32.7	2.0	2.5	55.2	36.3	6.0	
POM	22.8	37.5	25.8	13.9	3.6	29.3	36.3	30.9	
SLS	23.7	21.6	33.3	21.4	4.5	30.5	45.1	19.8	
SWT	25.5	16.8	43.9	13.9	17.3	42.3	30.4	10.1	
WAM	17.6	25.6	48.7	8.1	3.0	50.2	28.4	18.4	
WLP	38.0	48.2	13.4	0.3	14.1	55.1	21.9	8.9	
ZAP	20.3	50.0	27.5	2.3	6.5	42.2	33.4	17.9	
Poland	23.4	36.1	29.4	11.1	7.6	47.1	29.3	16.0	

The amount of organic matter in soils is a key indicator of their quality, determining the physical and chemical properties of soils, such as sorption and buffering capacities, as well as biological processes that are important for the functioning of the habitat, and are known as biological activity. High humus content in soils is a factor that stabilizes their structure, reduces their susceptibility to consolidation and degradation by water erosion and wind. It is important to keep resources of soil humus not only because of the maintenance of productive functions of soils, but also because of the role of soils in sequestration (binding) of carbon dioxide from the atmosphere, contributing to reducing the greenhouse effect. The natural diversity of humus content in soils is determined by granulometric composition, location and water regime. Light soils located in higher areas beyond the reach of groundwater, have a lower content of humus then firm soils with precipitation-ground dependent type of water regime. Hydrogenic soils developed in water-dependent habitats, such as black earths and peat soils which are characterized by the highest content of organic matter. Among the most significant anthropogenic factors that affect the content of organic matter in soil there should be listed: the type of land use (i.e. agriculture, meadows, and forests), the agricultural intensification, the crop selection, and the level of organic fertilization.

The results of determination of soil fertility of agricultural land in Poland indicate a wide variation of humus content (Table 2.8). According to the classification used in Poland humus content of <1.0% is considered low, the content of 1.1-2.0% is considered average, of 2.1-3.0% is considered high, and that of >3.0% is very high. According to the criteria adopted by international conventions, humus content

below 3.5% (approximately 2% C<sub>org.</sub>) is treated as a symptom of desertification. Under these terms, 89% of the acreage of Polish soils used for agriculture should be categorized as soils with low content of organic matter and considered as being at risk of drought. Obviously this is a consequence of the specificity of Polish soils, with a large proportion of soils developed from sands and light soils with low water content, which in a natural way are the conditions that determine the accumulation of humus. In recent years, a preliminary analysis of the trend of changes in the humus content in soils on the basis of repeated studies of standard profiles was performed. Studies have shown a strong trend of decline in the humus content, mainly in soils initially rich in organic matter. The decrease in organic matter is associated with the change of soil water regimes, more intensive use of soil, and presence of drainage network. In contrast, over the past 30 years in a large part of the light soils there has been an increase in humus content associated with an increased level of fertilization and increased quantity of crop residues.

Significant threat to the quality of soils in Poland and to their resistance to the loss of mineral nitrogen and phosphorus compounds is also associated with the phenomenon of water erosion. The level of surface water erosion threat to soils depends on the slope of the ground, the susceptibility of soils to surface runoffs, and the amount of annual precipitation. Studies showed that about 29% of the country, including 21% of agricultural land, mainly arable land, and about 8% of forests are threatened by water erosion, including 4% by severe water erosion, 11% by moderate erosion, and 14% by slight water erosion. The largest share of soils at risk of surface water erosion occurs in the voivodeships of Małopolskie and Podkarpackie and the need for protection against erosion is very urgent there (see to Chapter 8). Water erosion is a major problem in the voivodeships of Śląskie, Świętokrzyskie, Lubelskie, Dolnoślaskie, Pomorskie, and Zachodniopomorskie, which have been classified at the second degree level of urgency for anti-erosion protection. On flatlands of six other voivodeships of Lubuskie, Łódzkie, Mazowieckie, Opolskie, Wielkopolske, and Podlaskie erosion occurs only on a few percent of the total area. The real threat of water erosion of soils in Poland is much smaller than the potential risks due to the fragmented structure of land use. Assuming continued exclusion from the use of arable land for afforestation, orchards, and permanent grassland with the soil protection function, further reduction of the extent and intensity of both water erosion and wind erosion should be expected.

An important factor limiting the quality of soils that is not recognized directly in the valuation of agricultural production space is their acidity. More than 50% of the total area of soils has a very acidic and acidic pH. Keeping this situation in the long run will lead to activation of aluminium and trace metals in the environment, reduction of mineral compounds uptake by plants, and consequently to increasing the risk of nutrients leaching into the aquatic environment.

Suitability of agricultural production space in the country is characterized by soil-agricultural complexes grouping together various types of soil with approximate properties and similar use. Therefore, they are habitat types of soils suitable for cultivation of certain plants or plant groups with similar requirements. In total, 13 complexes of arable land, 9 of which relate to flatlands, and 4 to mountain areas, were distinguished. Different soil complexes have been grouped by their suitability for cereals production and therefore by the group of plants dominant in the structure of crops (Table 2.9). Very good and good soils that do not pose restrictions on the selection of cultivated cereals account for nearly 50%, and medium soils, where cultivation of wheat is associated with considerable risk, account for about 16%. The share of poor soils is about 23%, and 11.6% are very poor. The weakest soils, due to very low productivity, will probably be excluded from agricultural use in future.

Table 2.9 Area of soil quality groups of arable land and permanent grasslands (source: Terelak et al., 2000)

	Soil	Area of agricu	Area of agricultural land				
Group of soils	suitability complex	[thous. ha]	[%]	Available cereal yield [t · ha <sup>-1</sup> ] <sup>1)</sup>			
	F	Arable lands					
Very good	1, 2, 10	3387	24.0	6.08			
Good	3, 4, 8, 11	3628	24.8	5.16			
Medium	5	2244	15.9	4.57			
Weak	6, 9, 12	3190	22.7	3.43			
Very weak	7, 13	1637	11.6	2.76			
Total		14086	100.0	X			
	Perm	anent grasslands	S				
Very good and good	1pg	73	1.8	X			
Medium	2pg	2458	60.5	X			
Weak and very weak	3pg	1532	37.7	X			
Total		4063	100.0	X			

<sup>1)</sup> increased by 20% compared to the yield obtained in the experiments of the 1990s

As a function of agroclimate and soil conditions the unit production potential of agriculture in Poland is not too large and is lower than the potential of most Western European countries. However, the global agricultural production potential is significant due to the large agricultural area representing about 11% of agricultural land area in the 25 European Union countries with the domination of arable land, and because of the large labour force available in agriculture. Intrinsically not large, the unit production potential of agriculture in Poland is also not fully utilized as indicates the comparison of potential and actual yields of cereals, treated as indicator plants, due to a very large proportion of the sown area (Table 2.10).

Table 2.10 Present (average from the years 2001-2010) and potential<sup>1)</sup> cereal yields in Poland and yield potential utilization<sup>2)</sup> (source: own study based on GUS, 2001-2011 data)

Voivodeship	Actual yield [dt <sup>.</sup> ha <sup>-1</sup> ]	Potential yield <sup>1)</sup> [dt·ha <sup>-1</sup> ]	Utilization <sup>2)</sup> [%]
DLN	41.2	60.0	68.7
KUJ	34.6	52.8	65.5
LUB	29.2	57.0	51.2
LUS	30.2	49.2	61.5
LOD	27.8	48.6	57.2
MLP	31.0	54.0	57.3
MAZ	26.5	46.8	56.6
OPL	46.6	62.4	74.7
PDK	30.1	56.4	53.4
PDL	25.9	45.0	57.5
POM	33.0	51.6	63.9
SLS	33.9	50.4	67.2
SWT	26.6	54.0	49.3
WAM	32.3	52.8	61.3
WLP	34.4	49.2	70.0
ZAP	34.8	53.4	65.1
Poland	32.0	51.6	62.1

<sup>&</sup>lt;sup>1)</sup> potential yields obtained in experiments on comparing the productivity of agricultural soil suitability complexes carried out in the 1980's (increased by 20%); yields in the voivodeships include the percentage of soils classified as agricultural soil suitability complexes,

Cereals yield potential, calculated on the basis of agricultural soil suitability complexes, is realized in Poland at the level of approximately 62%. Realization of this potential to an extent clearly higher than the average for the country occurs in the voivodeships of Kujawsko-Pomorskie, Opolskie, Śląskie, and Wielkopolskie. It should be emphasized that the degree of realization of yield potential is relatively independent of the size of yield potential. The size of actual cereal yields depends on a number of factors both natural and agricultural, as indicated by the cluster analysis (Table 2.11).

<sup>2)</sup> the ratio of the actual yield to the potential yield

Table 2.11 Regional conditions for differentiation of actual (in the years 2001-2010) and potential cereals yields in Poland (source: own calculations based on GUS, 2001-2011 data)

Voivodeships in clusters	Potential cereals yield [dt·ha-1]	Actual cereals yield [dt·ha-1]	Realiza-tion of the potential [%]	APSV index [pts.]	Annual precipita- tion [mm]	NPK cosumption [kg·ha <sup>-1</sup> ]	Negative soil fertility bonitation <sup>1)</sup>
1. DLN, OPL, SLS, MLP	56.7	38.2	67.3	72.5	780	110.8	42.4
2. ZAP, POM, LUS, WLP, KUJ	51.2	33.4	65.2	66.4	586	128.3	37.8
3.WAM, LUB, SWT, PDK	55.1	29.6	53.7	70.0	638	86.9	48.7
<b>4.</b> LOD, MAZ, PDL	46.8	26.7	57.1	58.9	563	97.7	58.1

<sup>&</sup>lt;sup>1)</sup> The sum of the share of highly acidic soils and soils with very low content of P, K, Mg, and acidic soils low in P, K, Mg, and half of the share of slightly acidic soils with an average content of P, K, Mg

The lowest cereals yields are obtained in voivodeships of the cluster 4 (Łódzkie, Mazowieckie, and Podlaskie), which is justified by poor soil and climatic conditions, poor soil fertility and relatively low consumption of mineral fertilizers (Fig. 2.16). Small cereals yields are also obtained in the voivodeships of cluster 3 (Warmińsko-Mazurskie, Lubelskie, Świętokrzyskie, and Podkarpackie), as despite their substantially better natural conditions, agrotechnology is neglected there. In both of these clusters of voivodeship the degree of realization of the potential is the smallest in the country, despite the fact that the potential in the voivodeships of cluster 3 is much greater than that in the voivodeships of cluster 4.



Fig. 2.16 Clusters of voivodeships according to the cereal yields (source: Krasowicz own study)

## 2.5. Current status and prospects for crop production development

Crop output is the primary sector of Polish agriculture. In 2010, its value accounted for 37.4% of the total market output (GUS, 2011b). The efficiency of crop production, expressed as the yield of selected plants or the conversion yield in units of grain, is an important criterion for assessing the level of agricultural development and a measure of agricultural culture (Krasowicz, 2002). The ratio of actually obtained yield per hectare to achievable (potential) yield is a measure of the use of agricultural production space (Fotyma and Krasowicz, 2001).

The level and structure of crop production is a reflection of climate and soil as well as economic and organizational conditions (Klepacki, 2001). Its characteristic feature is the temporal and regional differentiation of crop structure, yield per hectare, and total output. Differentiation of the harvest of main crops in years is derived from changes in crop area and yield. The dynamics of sown areas, yield, and production of main crops is shown in Table 2.12.

Table 2.12 Dynamics of changes in sown areas, as well as yields and harvests of main crops in Poland 2000-2010 (source: own calculations based on GUS, 2001-2011 data)

Crops				Ye	ars			
	2000	2002	2004	2006	2007	2008	2009	2010
Sown area [ha · 10 <sup>3</sup> ]	12408	10764	11285	11465	11456	11631	11615	10878
Cereals								
Area [ha·10³]	8814	8294	8376	8379	8400	8599	8583	7638
[%]	100	94	95	95	95	98	97	87
Yield [dt·ha-1]	25.3	32.4	35.4	26.0	32.5	32.2	34.8	35.6
[%]	100	128	140	103	128	127	138	141
Harvests [t·10 <sup>6</sup> ]	22.3	26.9	29.6	21.8	27.1	27.7	29.8	27.2
[%]	100	121	133	98	122	124	134	122
Potatoes								
Area [ha·10³]	1251	803	713	597	570	549	508	401
[%]	100	64	57	48	46	44	41	32
Yield [dt·ha-1]	194	193	196	150	207	191	191	211
[%]	100	99	101	77	107	98	98	109
Harvests [t·10 <sup>6</sup> ]	24.2	15.5	14.0	9.0	11.8	10.5	9.7	8.5
[%]	100	64	58	37	49	43	40	35
Sugar beet								
Area [ha·10³]	333	303	297	262	249	187	200	206
[%]	100	91	89	79	75	56	60	62
Yield [dt·ha-1]	394	443	428	438	513	465	543	483
[%]	100	112	109	111	130	118	138	123
Harvests [t·10 <sup>6</sup> ]	13.1	13.4	12.7	11.5	13.0	8.7	10.8	10.0
[%]	100	102	97	88	99	66	82	76
Rape								
Area [ha·10³]	437	439	538	624	797	771	810	946
[%]	100	100	123	143	182	176	185	216
Yield [dt·ha-1]	21.9	21.7	30.3	26.5	26.7	27.3	30.8	23.6
[%]	100	99	138	121	122	125	141	108
Harvests [t·10 <sup>6</sup> ]	1.0	0.9	1.6	1.7	2.1	2.1	2.5	2.2
[%]	100	90	160	170	210	210	250	220

This differentiation is determined, in addition to natural conditions, by organizational and economic factors. In recent years the impact of this group of conditions has significantly increased, which is associated with transformations that took place in Polish agriculture following the transition to market economy system (Kuś et al., 2001). Adaptation processes for complying with the EU requirements, challenges, and standards have also been of great importance. The total sown area in Poland is dominated by cereals, which now account for 73.2% of the area. Within the structure of this group of crops, winter cereals represent around 43%, and maize grown for grain about 4%. The share of the latter has been steadily increasing, which is associated with shifting its cultivation border to the north-east and the profitability of its production. The share of maize grown for grain and silage increased from about 2.5% of the sown area in 2000 to 6.4% in 2008-2010. Another plant, which also has been steadily increasing its share, is rape which currently accounts for about 9% of the sown area. The share of potatoes and sugar beets has been very significantly and steadily decreasing in recent years. The share of fodder crops, including perennial legumes and their mixtures with grasses, is small and currently accounts for about 4% in the crop structure. According to estimates, winter catch crops, treated as cover crops in the agri-environment schemes are sown on about 740·10<sup>3</sup> ha, which represents about 6% of the total area of field crops. Of the total arable land (10878·10<sup>3</sup> ha in 2010; see to Table 2.4) 10428·10<sup>3</sup> ha (Table 2.12) is sown, and the rest (450·10<sup>3</sup> ha) are set-aside and fallow land. Such a structure of use of arable land has specific environmental consequences. The so-called "green fields" limiting the size of the losses of nitrate in the winter, (winter cereals, rape, perennial legumes and cover crops), occupy slightly more than 50% of the sown area, which, considering the specificity of soil and climatic conditions of our country, seems by far not sufficient. Decrease in the surface of plants traditionally fertilized with natural fertilizer results in the use of very large doses of fertilizer on decreasing number of fields. Finally, the share of plants that exhaust organic matter from soil (root crops, maize, cereals) is large, therefore, the decrease of humus in soil occurs in the whole country. Idle lands, fallows, and other lands which are not used for agricultural purposes are not fertilized with natural or mineral fertilizers. The majority of these lands remain under plant cover, and very simply they may be counted as "green fields".

The structure of crops shows large regional differences (Fig.2.17; Table 2.13). In regions with a high fragmentation of farms (the voivodeships of Małopolskie and Podkarpackie), usually focused on subsistence of farming families, potatoes have a larger share in the crop structure, with a lower than the country's average share of cereals. The quality of soils and their agricultural suitability determine, inter alia, the structure of crop species and cereal yields. However, the pricing conditions have caused expansion of wheat and barley cultivation on land earmarked for rye. The share of sugar beets and rape in the sown area is much more differentiated in regions than that of cereals. Nearly 78% of the domestic sugar beet growing areas are concentrated in six voivodeships (Dolnośląskie, Kujawsko-Pomorskie,

Lubelskie, Mazowieckie, Opolskie, and Wielkopolskie). A similar concentration is shown in the cultivation of rape. More than 78% of rape growing areas are located in seven voivodeships (Dolnośląskie, Kujawsko-Pomorskie, Opolskie, Pomorskie, Warmińsko-Mazurskie, Wielkopolskie, and Zachodniopomorskie). In the Podlaskie voivodeship, despite the country's highest share of permanent grassland, the high proportion of forage grown on arable land is also apparent. One of the reasons is the poor quality of permanent grasslands, and also widespread in the region cultivation of maize for silage, which is an important source of energy feed for cattle.

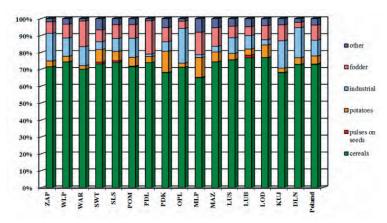


Fig. 2.17 Cropping pattern in voivodeships in 2010 (source: own calculations based on GUS, 2001-2011 data)

Table 2.13 Cropping structure by crop groups in 2010 (source: own calculations based on GUS, 2001-2011 data)

Voivode-	Cereals				I	ndustria	.1	sdo	SC
	gu 1		s and ds			Inclu	iding	crops	crops
ship	T <sub>C</sub> Inch	Pulses at seeds	Potatoes	Potal Total		Sugar beets	Fodder	Other	
DLN	70.9	35.9	0.9	3.2	20.5	17.7	2.7	2.4	2.0
KUJ	66.2	21.2	1.4	2.1	18.4	14.0	4.3	8.5	3.3
LUB	78.7	25.7	3.0	2.8	8.5	4.3	3.3	3.9	3.2
LUS	73.3	20.0	2.4	1.9	14.4	13.8	0.3	5.4	2.7
LOD	79.0	12.3	1.6	5.8	3.8	2.9	0.9	6.5	3.4
MLP	69.1	28.8	1.6	11.9	2.9	1.8	0.5	7.4	7.1
MAZ	76.5	10.5	1.8	4.5	5.9	3.9	1.0	8.2	4.1
OPL	71.1	32.7	0.5	1.9	22.5	19.3	3.2	3.2	0.9

	Cer	Cereals			I	ndustria	1	sd	SC
Voivode-	ng t s and		lses and seeds	Potatoes		Inclu	ıding	r cro	crop
ship	Total	Including wheat	Pulses seed Potato		Potar		Sugar beets	Fodder crops	Other crops
PDK	73.2	30.2	1.2	11.1	7.2	5.2	1.5	4.5	2.8
PDL	77.1	6.2	1.9	2.9	1.6	1.4	0.0	15.8	0.8
POM	71.5	23.9	2.7	3.7	14.7	12.9	1.7	5.4	2.0
SLS	79.4	24.3	1.0	4.4	8.2	7.6	0.6	5.0	1.9
SWT	74.8	21.1	3.6	6.2	3.9	1.8	1.6	5.3	6.2
WAM	72.4	24.2	2.6	1.8	12.3	11.6	0.6	9.4	1.5
WLP	73.4	14.2	1.2	2.7	12.4	9.4	2.9	8.0	2.3
ZAP	64.3	25.2	2.1	2.3	19.5	17.6	1.8	6.5	5.3
Poland	73.3	20.5	1.8	3.7	11.2	9.1	2.0	6.9	3.0

Regional differentiation of crop production is the result of historical circumstances, even dating back to the period of the partitions. The western part of the country is characterized by a higher average farm size, lower fragmentation of land, more opportunities for application of new technologies and higher crop yields, larger share of the so-called quality species such as wheat and barley, larger scale of production and its increased marketability (Jaśkiewicz, 2004). At the same time in the western and northern Poland, there is a clear specialization of agriculture in crop production, mainly in the cultivation of cereals and rape, with a prominent reduction of livestock production (cattle). Therefore, there is a regression in permanent grasslands management as some of them are not used.

Units of grain are still used as a synthetic measure of crop production. Global crop output in units of grain per 1 ha of agricultural land in the best way characterizes regional differences in the use of agricultural production space (Table 2.14) in the country. As results from data presented in this table, high-efficiency plant production, expressed in units of grain, was determined not only by natural conditions. In 2010 crop production in Lubelskie voivodeship, in spite of relatively good natural conditions (3<sup>rd</sup> place in the country), was at a level below the national average. At the same time the voivodeship was characterized by a relatively intense structure of crops, with a relatively low intensity of farming, assessed in a simplified manner by the use of mineral fertilizers in kg NPK per 1 ha of agricultural land. Opolskie voivodeship obtained the largest crop production per hectare, and although characterized by the best in the country natural conditions (APSV index), also demonstrated the largest consumption of mineral fertilizers and high share of intensive species (wheat, barley, sugar beet, rape). In contrast, the Kujawsko-Pomorskie and Wielkopolskie

voivodeships used their high crop production as the basis for the development of animal production. In the group of voivodeships focusing on livestock production, there was also Podlaskie voivodeship, characterized by the highest stocking density per 100 ha of agricultural land and specializing in the production of milk. However, the low quality of agricultural production space, a high share of permanent grassland, and relatively low mineral fertilization, are the main reasons for not the highest yields per 1 ha of agricultural land in this voivodeship.

Table 2.14 Average conversion yield (grain units per 1 ha of agricultural land) in 2010 in relation to the natural and organization-economic conditions of agriculture; APSV index - Agricultural Production Space Valuation Index; LU – livestock units; AL – agricultural land (source: own calculations based on GUS, 1999-2012 data)

Voivodeship	Average conversion yield	APSV index by IUNG-PIB	Share of permanent grassland [%]	Average individual farm's area [ha]	Livestock density [LU·100 ha¹ AL]	NPK Consumption [kg·ha <sup>-1</sup> AL] <sup>1)</sup>	Employed in agriculture [persons·100 ha <sup>-1</sup> AL] <sup>2)</sup>
DLN	48.1	74.9	14.8	12.4	16.7	152.9	7.5
KUJ	44.7	71.0	13.1	15.9	54.1	166.2	9.2
LUB	38.0	74.1	16.3	8.2	30.5	105.7	17.2
LUS	38.3	62.3	21.3	15.3	28.3	111.3	5.9
LOD	37.0	61.9	16.1	8.2	53.6	125.0	16.8
MLP	32.4	69.3	37.7	4.5	37.5	63.6	31.6
MAZ	32.6	59.9	26.1	9.5	52.8	96.2	14.6
OPL	53.8	81.4	8.8	13.7	33.2	196.9	7.8
PDK	36.3	70.4	30.7	4.8	25.0	57.9	24.9
PDL	31.8	55.0	38.0	14.5	74.3	97.6	10.5
POM	42.8	66.2	16.6	16.8	35.4	129.6	7.2
SLS	41.4	64.2	19.8	6.0	39.3	107.4	16.8
SWT	32.8	69.3	20.8	5.9	37.3	84.5	23.5
WAM	38.4	66.0	31.9	21.7	53.7	114.9	5.8
WLP	43.7	64.8	13.4	13.1	69.8	158.7	10.6
ZAP	43.5	67.5	15.8	21.4	17.0	123.0	4.1
Poland	39.5	66.6	21.2	9.8	44.8	119.7	12.9

<sup>&</sup>lt;sup>1)</sup> Average from the years 2009-2011, <sup>2)</sup> data for the year 2006

Economic and organizational conditions also determine the structure of market agricultural output (Table 2.15). Voivodeships characterized by intensive livestock production, Podlaskie, Wielkopolskie, and Warmińsko-Mazurskie have the lowest share of crop production in market agricultural output. However, this share exceeds 60% in the voivodeships of Dolnośląskie, Zachodniopomorskie, and Opolskie. Detailed analysis of the structure of commodity crop production, confirms specialization of western and northern voivodeships in the production of cereals and industrial crops. In the voivodeships of Dolnoślaskie and Opolskie the share of these two groups of plants in market agricultural production exceeds 55%, and in Pomorskie and Zachodniopomorskie by far exceeds 30%. However, in the voivodeships of Lubelskie, Łódzkie, Małopolskie, Mazowieckie, and Świętokrzyskie fruits and vegetables have a significant share in the structure of market agricultural output. In Lubelskie and Świetokrzyskie their share exceeds 31%. This confirms the specialization of these regions in horticultural and vegetable production, which is also related to the average size of farms and a large number of people employed in agriculture per 100 ha of agricultural land. The largest share of potatoes in the structure of agricultural production is characteristic for Łódzkie, Pomorskie, and Mazowieckie voivodeships. This shows clearly that potatoes commercial cultivation is concentrated in selected regions, that are not distinguished by the highest share of potatoes in the crop structure, since this is rather due to the fragmentation of individual farms and subsistence production (potatoes are treated more as a vegetable).

Table 2.15 Structure of commercial agricultural production in terms of value (%) in 2009 (source: GUS, 2011c)

			200	09 (Con	stant pr	ices in 20	008)			
	Crop output				Livestock output					
*** 1 1.		I	ncludir	ıg			Including			
Voivodeship	Total	Cereals	Industrial	Potatoes	Total	Cattle for slaughter	Pigs for slaughter	Poultry for slaughter	Cows' milk	
DLN	70.8	38.3	19.8	2.1	29.2	2.5	5.1	7.7	6.4	
KUJ	45.4	13.9	16.1	1.7	54.6	4.4	18.9	8.4	19.9	
LUB	56.2	12.4	8.2	2.6	43.8	4.7	13.3	5.1	15.1	
LUS	53.8	19.8	12.4	1.6	46.2	2.0	7.6	22.2	8.8	
LOD	45.3	5.6	2.2	11.7	54.7	6.6	17.8	8.8	17.1	
MLP	44.8	7.1	2.0	3.6	55.2	11.4	11.6	7.9	14.7	
MAZ	46.2	10.9	2.1	6.2	53.8	5.5	8.5	11.5	21.8	
OPL	60.1	34.5	19.6	0.9	39.9	2.6	12.5	7.5	13.5	
PDK	36.4	12.2	6.6	1.0	63.6	4.6	13.4	11.2	23.1	

			200	09 (Con	estant prices in 2008)					
		Crop	output		Livestock output					
		Including				Including				
Voivodeship	Total	Cereals	Industrial	Potatoes	Total	Cattle for slaughter	Pigs for slaughter	Poultry for slaughter	Cows' milk	
PDL	11.2	5.4	0.7	1.8	88.8	7.9	9.8	8.4	57.4	
POM	48.3	22.2	10.6	7.5	51.7	3.1	21.6	10.1	12.1	
SLS	36.6	12.7	4.5	2.9	63.4	7.3	14.3	16.8	13.0	
SWT	52.3	9.3	3.6	2.7	47.7	6.0	11.6	8.2	16.2	
WAM	29.9	17.3	7.1	0.9	70.1	3.9	11.3	20.5	31.2	
WLP	29.6	8.0	9.1	1.3	70.4	5.9	24.6	11.6	16.3	
ZAP	63.0	34.1	15.4	5.0	37.0	1.9	9.6	14.3	7.0	
Poland	42.1	13.2	8.5	3.9	57.9	5.4	13.9	11.3	19.6	

Growing of crops for energy purposes is a new issue in the scale of development of agriculture in Poland. One of the trends is to convert part of the harvest of traditionally grown crops (cereals, oilseed rape, and sugar beets) to biofuels, and to use it for special production of crops biomass for energy generation from its combustion. The third direction is the acquisition of biogas by anaerobic digestion of livestock manure, and biomass of by-products, and even of the main plant. Biofuel development strategy adopted in the EU countries, including Poland, requires an analysis of natural, economic, and organizational conditions of the use of domestic raw material base for production of bioethanol and biodiesel (Nowacki, 2007). The choice of different types of plants in each country should be decided mainly on the basis of local climatic and soil conditions, production costs, unit output of alcohol or biodiesel yield per 1 ha, the yield potential, and stability of plant species. However, the competitiveness of other markets is important, including food and fodder markets, determining the country's food self-sufficiency. Plants from which bioethanol and biodiesel may be obtained are included in the so-called main crops for feed, direct human consumption, and for industrial processing. Therefore, precise harvest management balances of these plants are needed (Nowacki, 2007).

The balance of cereal consumption in the country is now variable, showing a deficit in the years of crop failure, and some surpluses in the years which are favourable for their production. The research performed by IUNG-PIB (Krasowicz, 2007; Kuś et al., 2006) shows that the prospect of the average yield of cereals within the limits of 3.8-3.9 t per ha and domestic grain production at the level of 29-30·10<sup>6</sup> tons, i.e. 1-2·10<sup>6</sup> tons above current consumption, is realistic. Under this

assumption, it is possible to cover consumption, feed, and industrial needs, and to use 1-1.5·10<sup>6</sup> tons of grain for the production of bioethanol. However, this requires increased investment in economically viable intensification of production, including use of mineral fertilizers and agricultural limestone. The increase in consumption of fertilizers, especially nitrogen and phosphorus fertilizers means of course increasing the pressure of the fertilizer industry and agriculture on the environment.

Sugar beet harvest is now fully converted to sugar, but in some years there are surpluses of this product. This creates a capacity to produce bioethanol. The species for which supply exceeds current market demand is potato. Partial use of the surplus potatoes for processing into ethanol is very interesting both for the distillery industry and consumers alike. According to Nowacki (2007), initiation of a base of plant energy raw materials, without endangering the food supply in Poland, requires a new philosophy in the approach to the technology their production. Quantitative technology will be replaced by qualitative technology, which aims to maximize the yield and energy from 1 ha, while reducing the cost of cultivation. Biological progress may be of significant importance, generating varieties of low-cost cultivation. Modern high-starch potatoes, characterized by low costs of cultivation and high yields of ethanol per unit of surface, are the confirmation of this thesis.

Also, the production of biomass for solid biofuels will continuously require intensification of main crops cultivation, improvement of agrotechnology, and rationalization of soil use in agriculture. In biomass production development scenarios (Dolniak, 2006) it was assumed that the production of biomass for solid biofuels will be allocated mainly on inferior soil, the so-called marginal land, land currently setaside or fallows, and on soil polluted mainly by heavy metals, unsuitable for growing crops for consumption and feed. However, yields from plantation production are usually lower than experimental yields. Moreover, production of biomass for solid fuels in worse habitat conditions may be ineffective in economic and energy output terms. These aspects should be taken into consideration in forecasting the demand of land for production of biofuels. According to Grzybek (2008) the total land demand for biofuel production, following the assumptions, must amount to approximately 800·10<sup>3</sup> ha in 2010 and 1500·10<sup>3</sup> ha in 2020. Some of this land is currently used for food production. Maintaining the current level of consumption, while using a part of the crops for energy purposes, will result in the competition for land as a factor influencing the production of biofuels.

Environmental consequences of cultivating crops for energy purposes are currently not possible to estimate. Plants grown for production of bioethanol and biodiesel are the main crops, and the way they are utilised does exert environmental pressure. Plants intended to produce biomass for combustion are now grown in marginal areas (except straw), and there are several scenarios which provide for further developments in this field.

## 2.6. Current status and prospects for development of livestock production

In Poland, livestock output is the dominant sector in the structure of agricultural production. In recent years its share in the market agricultural outputs has been declining, but still exceeds 55%. The production of animals for slaughter (meat) and milk is predominant (Table 2.16). The large variation in the profitability of livestock production, caused by fluctuations in prices of animal products and feed, contributes to fluctuations of stocks of all livestock species. The strength of livestock population is an important indicator for assessment of the intensity of agricultural production and is well diversified regionally. The level and scale of livestock production also determine the amount of manure and nutrients available. Natural fertilizers, in addition to mineral fertilizers, are the primary factors in determining yields, exerting positive influence on plant growth and development, and enriching the soil with organic matter. However, excessive use of fertilizers, particularly natural, creates certain environmental threat.

Table 2.16 Share of animal output in the structure of market output (%) in Poland in the years 2001-2010 (source: GUS, 2011c)

Specification	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Cattle for slaughter	5.1	4.7	4.6	5.1	8.0	6.6	6.1	5.4	5.4	5.4
Pigs for slaughter	25.1	23.3	21.5	20.9	26.6	18.7	19.7	14.4	13.9	13.8
Poultry for slaughter	8.7	9.1	9.6	9.6	5.5	8.9	10.1	11.4	11.3	11.1
Hen eggs	4.2	4.7	5.0	4.7	3.1	4.8	5.1	5.1	5.9	5.8
Cow's milk	18.8	18.2	18.0	18.1	16.1	18.1	20.0	20.5	19.6	18.0
Animal output - total	63.2	61.2	60.0	59.6	60.6	58.1	63.1	58.5	57.9	55.8

The introduction of market economy has launched adjustment processes in agricultural production. Changes in the structure of this production were also related to changes in livestock population and production, livestock output, and milk yield. The processes of concentration and specialization of production have also been progressing. Changes in the prices of raw materials and products of animal origin, resulting from the supply and demand relationship had decisive influence on these developments. Supply and demand are derived from the income of the population and the needs and tastes of consumers. Trade liberalization and increasing globalization often enhance the dynamics of these changes.

The general tendency observed in the years 1990-2010 was an increase in meat consumption, with large variations between years and significant changes in the structure. According to GUS (2001, 2011b) in the years 1997 to 2010 the balance of meat and pluck/giblets consumption increased to 74.3 kg per person. Existing relationships of prices and consumer food preferences in particular stimulated the demand for poultry meat, and to a lesser degree, for pork. There has been significant, approximately two-fold, increase in consumption of poultry (from 12.5 kg to 24.8 kg), with approximately 19% increase in consumption of pork meat (from 35.7 kg to 42.6 kg). In the same period beef consumption decreased four times (from 8.4 kg to 2.4 kg). During the past 12 years the annual consumption of milk has declined from 198 litres per person (including processed milk products, but without butter) to 189 litres per person. Annual butter consumption remained at a similar level of 4.3-4.4 kg per person. With the reduction of the rural population self-supply with milk and its products, the demand for dairy products has been increasing. Consequently, the quota on dairy production established for Poland and amounting to 9380·10<sup>3</sup> tons, including 9142·10<sup>3</sup> tons for dairy industry, and approximately 238·10<sup>3</sup> tons for direct sales (subsistence of rural population), was insufficient in 2007. In Poland, the milk yield per cow reached 4,487 l in 2010, and over the last 10 years it has been increasing at an annual rate of about 2%. After accession to the EU, there has been considerable improvement in the profitability of milk production. However, currently with the national milk production limit having been increased by 5% since 2009, Poland will have a limit of 10.055 million tons in 2014. The situation may change dramatically after possible removal of quotas in 2015. Not without significance is the fact that milk production in Poland is dominated by individual farms, with the trend of increasing the concentration of livestock population in large-scale farms.

After the introduction of market economy in 1989/90, the population of all species of livestock declined. Only since 2000, especially after Polish accession to the EU and the introduction of milk production limits, there has been some stabilization of both livestock population and livestock production. However, the processes of specialization and concentration of production, necessitated by increasing competition, have been clearly outlined. Over the last 8 years there has been a significant increase in cattle and pigs in area groups of farms over 50 ha of agricultural land (Table 2.17). However, livestock and livestock production fluctuations are high due to the situation of product market prices, (including global competition and trade liberalization), changes in livestock production costs, environmental requirements concerning production, changes in weather (e.g. droughts) and cyclical changes (the so-called hog cycle).

Area of		Ca	ttle		Pigs				
agricultural	2002		2010		2002		2010		
lands [ha]	Heads·10 <sup>3</sup>	[%]							
1 – 2	121	2.2	50.8	0.9	255	1.4	118.4	0.8	
2 – 5	521	9.4	303.3	5.3	1135	6.1	750.9	4.9	
5 – 10	1079	19.5	839.8	14.6	3255	17.5	2246.6	14.7	
10 – 15	1034	18.7	982.8	17.1	3396	18.2	2263.8	14.8	
15 – 20	752	13.6	806.4	14.0	2369	12.7	1659.4	10.9	
20 – 50	1294	23.4	1807.1	31.4	4469	24.0	3740.0	24.5	
Above 50	670	12.1	937.2	16.3	3565	19.2	4342.9	28.4	
Total	5533	100	5761	100	18629	100	15278 1	100	

Table 2.17 Number of cattle and pigs by agricultural land area groups (source: GUS, 2003, 2011a)

Livestock density is an important measure of the intensity of agricultural production. Polish agriculture is characterized by considerable territorial differentiation of stocking density (Table 2.18). Recently the average livestock density in Poland has amounted to 0.44-0.45 LU ha<sup>-1</sup> of agricultural land (including horses). The highest livestock density appears in Podlaskie and Wielkopolskie voivodeships (around 0.68-0.78 LU ha<sup>-1</sup> of agricultural land). The lowest livestock density is observed in Dolnośląskie, Lubuskie, and Zachodniopomorskie voivodeships (western Poland) (approx. 0.15-0.29 LU ha<sup>-1</sup> of agricultural land). Moreover, in Poland regional disparities in terms of production orientation can be observed. In Wielkopolskie and Kujawsko-Pomorskie voivodeships pig rearing dominates, whereas the Podlaskie, Mazowieckie, and Warmińsko-Mazurskie voivodeships are characterized by the highest stocking density of cattle (dairy cows) (Fig. 2.18).

Table 2.18 Livestock density in Poland in  $LU^{1)}\cdot 100$  ha<sup>-1</sup> of agricultural land in the years 2002-2011 (source: own calculations on the basis of GUS, 1999-2012 data)

Voivodeship	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
DLN	19.7	18.5	17.0	18.5	17.7	17.9	18.2	17.1	17.9	15.1
KUJ	51.5	53.2	52.1	53.6	56.3	54.1	51.1	54.8	55.3	52.2
LUB	36.9	39.8	34.3	37.5	37.0	34.9	32.7	29.6	31.0	31.0
LUS	26.4	25.1	21.9	25.0	23.5	24.5	29.3	28.6	27.1	29.2
LOD	48.9	53.2	48.7	48.7	49.7	50.6	51.5	51.9	52.7	56.2
MLP	47.0	49.7	47.3	47.9	48.6	45.6	42.6	39.4	37.9	35.1
MAZ	47.7	51.7	52.4	51.6	52.9	51.3	54.5	50.4	53.5	54.6

Voivodeship	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
OPL	34.7	35.0	33.1	33.5	32.0	32.5	31.7	31.2	33.1	35.4
PDK	35.0	36.7	33.4	32.2	29.6	30.5	30.1	27.9	24.9	22.1
PDL	59.4	67.0	61.1	64.6	67.5	67.9	70.4	72.6	71.4	78.8
POM	33.6	35.9	34.2	35.9	35.7	37.5	37.8	35.2	37.5	33.4
SLS	38.4	39.3	38.2	36.2	36.9	38.7	43.4	39.1	42.0	36.8
SWT	41.0	40.3	35.9	41.6	42.3	39.7	39.2	37.4	37.7	36.7
WAM	41.4	41.8	42.4	47.4	49.2	48.2	52.5	53.0	54.4	53.6
WLP	61.9	62.3	58.7	65.0	68.4	67.8	69.6	68.4	72.4	68.7
ZAP	18.9	18.5	17.6	15.9	16.1	17.3	17.8	15.7	18.7	16.6
Poland	42.5	44.3	42.0	44.0	44.8	44.5	45.3	44.1	45.5	44.9

<sup>1)</sup> LU – livestock unit according to the definition of the Ministry of Agriculture and Rural Development (MRiRW) based on the annex to the Regulation of the Council of Ministers dated of 9 November 2004 (Dz. U. Nr 257, item. 2573, 2004)

Note: In the conversion of livestock population into livestock units (LU) the following coefficients (multipliers) are used: calves aged up to 0.5 year - 0.15, calves aged 0.5 - 1year - 0.3, bovine animals aged 1 - 2 yrs - 0.8, heifers, dairy cows - 1.0, other cattle -1.4, piglets - 0.02, pigs - 0.07, fattening pigs - 0.14, sows - 0.35, boars - 0.4, sheeps, goats - 0.1, adult horses - 1.2, young horses - 0.3, layers, broilers, ducks - 0.004, geese - 0.008, turkeys - 0.024.

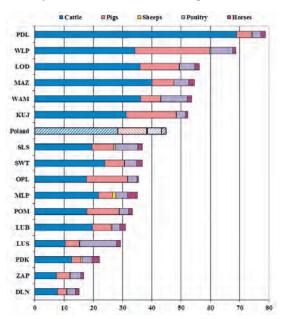


Fig. 2.18 Livestock density structure (LU per 100 ha of agricultural land) in Poland as a whole and in voivodeships in 2011 (source: own calculations based on GUS, 1999-2012 data)

In recent years strong ongoing trends of concentration and specialization of production of milk and livestock have been evident in Poland. However, the pace of these changes is different in each voivodeship. In the years following Polish accession to the EU cow population increased generally only in the voivodeships with the highest stocking density of cattle. Pig population dropped quite considerably across the country (with the exception of Wielkopolskie voivodeship). The previous decline in livestock populations was observed in the western voivodeships, and that indicated the shift to crop production (mainly cereals and oilseed rape), whereas the current, quite significant reduction in stocking density (by about 30-40%), has been observed in Podkarpackie and Małopolskie voivodeships. The restoration of livestock population is a difficult and long-lasting process, and perhaps in today's highly competitive environment not feasible at all. The scale of the problem is evidenced by the annual production value of livestock commodities in Poland, which, according to GUS (2011b) was estimated at PLN 33,241 million (cow's milk production at PLN 10,691 million, pigs at PLN 8,191 million, poultry at PLN 6, 631 million, cattle for slaughter at PLN 3,589 million).

The degree of concentration of livestock production is indicated by the number and size of livestock herds. The average herd of cows in Poland currently has 6.1 heads, while in 2007 it had only 3 heads. In 2011, only 20.2% of dairy farms had a herd of more than 10 cows, and 56.6% of the farms had 1-2 cows (Table 2.19).

Table 2.19 Share of agricultural farms by scale of cattle breeding in 2011 (source: GUS, 1999-2012)

Maine de alrie		Percentage of c	ow breeding far	ms
Voivodeship	1-2 heads	3-4 heads	5-9 heads	Above 10 heads
DLN	60.8	14.6	12.9	11.7
KUJ	52.8	15.3	8.4	23.5
LUB	74.3	8.9	5.7	11.1
LUS	52.6	11.7	11.0	24.7
LOD	48.5	15.2	15.6	20.7
MLP	82.6	8.9	5.2	3.3
MAZ	39.7	13.5	15.9	30.9
OPL	61.3	8.0	8.3	22.4
PDK	86.4	8.7	2.9	2.0
PDL	28.2	7.8	22.4	41.6
POM	59.9	11.4	10.5	18.2
SLS	63.8	18.0	11.1	7.1
SWT	72.9	14.5	7.5	5.1
WAM	15.9	15.6	21.4	47.1

Vaivadashin	Percentage of cow breeding farms							
Voivodeship	1-2 heads	3-4 heads	5-9 heads	Above 10 heads				
WLP	49.9	49.9 9.9		27.3				
ZAP	48.6	17.0	12.6	21.8				
Poland	56.6	11.6	11.6	20.2				

In recent years, however, there is a tendency towards concentration of milk production, contributing to the increase in milk yield of cows. Average yield of milk from one cow in 2000 was 3,668 litres, while in 2006 it amounted to 4,200 litres, and in 2010 increased to 4,487 litres (Table 2.20). The dynamics of changes in milk yield of cows was, however, strongly differentiated regionally. More than 50% of farms produced milk exclusively for their own use, selling only seasonal surpluses to neighbours or local markets.

Table 2.20 Average yield of milk from one cow in the years 2000, 2006, and 2010 and the dynamics of its changes (source: own calculations based on GUS, 2011c)

Voivodeship	Average yiel	d of milk from	n one cow in	Dynamics (%) year 2000 = 100%			
vorvodeship	2000	2006	2010	Change in 2006	Change in 2010		
DLN	4054	4675	4069	115.3	100.4		
KUJ	3798	4408	4683	116.1	123.3		
LUB	3660	3987	4078	108.9	111.4		
LUS	3978	4505	4244	113.2	106.7		
LOD	4066	4250	4215	104.5	103.7		
MLP	3274	3024	3140	92.4	95.9		
MAZ	3366	4085	5216	121.4	155.0		
OPL	4414	5416	6109	122.7	138.4		
PDK	3393	3444	3581	101.5	105.5		
PDL	3426	4286	4105	125.1	119.8		
POM	4113	4153	4096	101.0	99.6		
SLS	4260	4109	4425	96.4	103.9		
SWT	3443	3620	4412	105.1	128.1		
WAM	3603	4330	4549	120.1	126.3		
WLP	4034	5016	4767	124.3	118.2		
ZAP	4092	4481	4575	109.5	111.8		
Poland	3668	4200	4487	114.5	122.3		

Similar tendency towards concentration can also be seen in pig production but only less than 16% of farms maintained herds with more than 50 animals (Table 2.21).

Table 2.21 The structure of agricultural farms by pig breeding scale in 2011 (source: GUS, 1999-2012)

		Share o	of pig breeding	g farms	
Voivodeship	1-2 heads	3-4 heads	5-9 heads	10-49 heads	More than 50 heads
DLN	23.0	15.4	12.8	41.0	7.8
KUJ	6.7	5.6	8.2	50.6	28.9
LUB	30.9	20.5	10.9	32.6	5.1
LUS	11.5	6.0	7.4	61.1	14.0
LOD	11.4	4.4	15.1	55.6	13.5
MLP	39.2	6.9	17.0	32.3	4.6
MAZ	12.1	11.5	17.0	47.3	12.1
OPL	8.1	4.3	8.1	47.1	32.4
PDK	57.0	9.3	10.1	21.1	2.5
PDL	26.0	18.8	20.7	28.5	6.0
POM	7.2	6.0	16.9	45.8	24.1
SLS	18.4	12.8	8.1	47.8	12.9
SWT	21.8	9.1	15.0	49.3	4.8
WAM	16.1	7.1	7.9	34.8	34.1
WLP	6.2	3.8	6.4	48.7	34.9
ZAP	10.2	4.8	17.7	50.4	16.9
Poland	19.7	10.0	12.4	42.2	15.7

The economic prospects of livestock production development are a complex issue because of numerous rapidly changing conditions. The forecasted livestock population in 2020 was based on statistical calculations (mean, median figures over the past 10 years i.e. from 1998 to 2007), and on the trend analysis which take into account the definitive assumptions made by the Ministry of Agriculture in the Strategy for Sustainable Rural Development, Agriculture and Fisheries for 2011-2020 (Strategia..., 2012). Although the forecast for 2020 is long-term, yet due to the turnaround of business conditions it is difficult, especially after Polish accession to the EU in 2004, to base forecasts on data series longer than 10 years. Arrangements concerning the final shape of the future Common Agricultural Policy (CAP) after 2013 are unknown. Forecast of animal production in Poland in 2020 against the background of the current state is presented in Table 2.22. Dairy cow population was assumed at a level of the average from the last five years. This is

conditioned by the possibility of increase in milk production capacity (limits) until the year 2015. In the long term, it can be expected that the milk quota system will be abolished. This additional production will be obtained by increasing the annual yield of milk, and its growth rate is estimated at 2% per year. The population of heifers in calf was determined according to its average share (median) in the structure of herds in the years 2002-2011. The population of other categories of cattle was calculated on the basis of average levels in the years 2002-2011 (median), with some corrections, i.e. an increase in calves aged up to 1 year by 6.5%, and young cattle aged 1 year to 2 years by 20% up to the year 2020. The population of cattle for fattening aged over 2 years by 2020 should increase by 20%. This is due to the dependence of complementary area payments on stocking density of animals fed with the use of grazing system. These changes will force a large proportion of farms to close certain branches of production or to shift to extensive herding to produce meat. The demand for beef is expected to be maintained.

Table 2.22 Livestock population (in thous. of heads) in Poland (year average) over the years 2002-2011 and the prognosis for the year 2020; UAA – utilized agricultural area (source: own calculations based on GUS, 1999-2012 data)

Description	2002	2005	2006	2007	2008	2009	2010	2011	Forecast for 2020
Total cattle	5532	5483	5606	5696	5757	5700	5761	5762	5880
Calves aged up to 1 year	1384	1425	1428	1473	1502	1472	1463	1481	1540
Heifers aged from 1 to 2 years	1083	978	1040	1072	1102	1204	1273	1300	1295
Cattle aged over 2 years	3065	3080	3138	3151	3153	3025	3024	2981	3045
Heifers in calf	192	285	315	365	346	337	255	245	310
Dairy cows	2851	2752	2775	2727	2733	2606	2657	2626	2670
Cattle for fattening and other	22	43	49	60	73	82	112	110	65
Total pigs	18629	18112	18881	18129	15425	14279	15278	13509	14260
Piglets weighing up to 20 kg	6517	6042	6127	5695	4708	4457	4408	3948	4240

Description	2002	2005	2006	2007	2008	2009	2010	2011	Forecast for 2020
Piglets weighing 20 - 50 kg	5319	4557	4887	4722	4214	3834	4671	3738	4100
Fattening pigs weighing over 50 kg	4826	5655	5962	5896	5103	4578	4747	4612	4600
Pigs, (including)	1967	1859	1905	1814	1401	1410	1452	1210	1320
Boars	49	45	48	47	34	36	25	33	35
Sows	1918	1813	1856	1767	1367	1374	1427	1177	1285
Total sheep, goats, (including)	538	458	431	476	460	405	385	363	425
Sheep	345	316	301	332	324	286	268	251	315
Goats	193	141	130	144	136	119	117	112	110
Total poultry, (including)	125272	101976	94777	100065	145496	140826	174963	143557	155550
Broilers	61658	41635	38562	41781	78063	74733	102657	80482	86330
Laying hens	51759	51153	47746	49509	50724	49396	52374	47059	51870
Ducks	3695	3290	2544	2857	5082	4593	4693	3837	4700
Turkeys	5766	3829	4049	4010	7745	8065	10156	8458	9100
Geese	2394	2068	1876	1907	3881	4039	5083	3720	3550
Horses	330	312	307	329	325	298	264	254	320
LU/100 ha UAA	42.5	44.0	44.8	44.5	45.3	44.1	45.5	44.9	47.5

The population of pigs should not essentially differ from the levels of the last seven years. Slightly downward trend of about 10% over the next 10 years, contingent upon, inter alia, expected deterioration in the relative profitability of production, i.e. higher increase in feed prices than in livestock prices (due to increased competition on the markets for grain and pork), should be taken into account. It should be noted that the pork market is not covered by the regulations of the CAP, and the market changes significantly depend on the situation (competition) on global markets. This refers primarily to emerging demand-supply relationships in countries such as China, India, and Russia.

Minor changes are expected in relation to the population of sheep. This is due to the marginalization of the importance of wool production in Poland and the need to shift to meat production. Polish accession to the EU has not caused a significant increase in export capacity of mutton, which, given the lack of tradition of mutton consumption in Poland, does not allow to formulate optimistic forecasts. As far as goats are concerned, their population is expected to be reduced by 25%.

The population of horses should stabilize or even slightly increase. In Poland the number of horses used as a pulling force steadily decreases. Some farms may consider professional production of horsemeat which has virtually unlimited possibilities of selling in European markets. However, real chances for increasing the population of horses should be mainly seen in the expansion of leisure and sporting use of horses.

At the same time, in the forecast for the year 2020, referring to the average (median) from the years 1998-2007, it was assumed that the average annual population of laying hens and broilers will be maintained and the population of turkeys will increase by 13%, whereas the population of geese and ducks will decrease by 13%. The situation and opportunities of the poultry industry to a large extent depend on market prices of feed and prices on competitive pork and beef markets. Changes in the poultry population will be also shaped by consumers' income situation and changes of their dietary preferences.

Livestock production forecast is presented here in general outline. Its scope and certain simplification is the result of incomplete information about the future shape of economic phenomena. The forecast results from the assumed scenario of phenomena, but is limited by available forecasting information resources. Nevertheless, it allows estimating the condition of livestock production in 2020 which may be useful in scenarios focusing on the impact of agriculture on the environment.

## 2.7. The condition of farmers and agriculture in Poland after the accession to the European Union

The Institute of Agricultural and Food Economics (IAFE-NRI) Warsaw provides a systematic analysis of the economic condition of farmers and agriculture in Poland. The analysis presented in this chapter of the monograph is based on the material published by the Institute.

The level of income in agriculture should be considered in two aspects. The first relates to the production function of agriculture. The appropriate level of income is necessary for agricultural development, reproduction, and the modernization of farms to meet the demands of market competition. The second aspect relates to consumption, and more broadly to the level and living standard of farm (rural) families. According to Zegar (2008), the situation in the development of personal income of farm families clearly has been changing. In the past, the only (or main) source of income was farm income, i.e. the income generated by the farm. For several years now a phenomenon of raising revenue from outside the farm has been growing. Therefore, the income that is not directly related to agricultural production

is transferred to farms. Also transfers of funds resulting from the implementation of national policies concerning rural areas and agriculture and changing the relationship of agricultural production and agricultural income currently play an important role in shaping the agricultural income.

The structure of personal income in rural households is the main prerequisite for classifying and distinguishing types of households. GUS (2008) data indicate that farmers' households constitute only about 25% of all farms in the countryside. In this group of households the income from agriculture (farm income) is the predominant source of income for the farmer and his family. IAFE-NRI studies (Zegar, 2008) assume that the share of farm income in this group exceeds 50%. Other farms are auxiliary farms, having other non-agricultural main source of income, and family farm businesses. The "real" farmers account for 62% of agricultural land, 65% of arable land, 78% of livestock, 71% of standard gross margin, 48% cost of labour, as well as for 29% of those working in private farming.

The political transformation resulted in a clear worsening of the problem of income in agriculture and reduced the real income of the farming population. During the period of 1989-1992 agricultural income decreased to approximately 40% of revenues in 1989. The second phase of the decline in farm income occurred in the years 1996-1999. The reduction in agricultural income took place despite an increase in agricultural production, which could not compensate the fall in prices caused by increased supply and imports of agri-food products. Polish accession to the European Union and the inclusion of the agricultural sector in the mechanisms of the CAP has radically changed the income situation in agriculture. New funding streams have appeared.

The indicators characterizing the dynamics of total nominal and real income of households and farm households are presented in Table 2.23. Gross income stream available to the sub-sector of farm households in 1995-2006 was lower compared to the whole household sector. The inclusion of Polish agriculture in the mechanisms of the CAP, in particular starting direct payments, resulted in improvement of farm households' income situation. The increase in gross income of these households in 2004-2006 was higher than in the entire household sector; however, the distance from the previous years has not yet been eliminated.

Table 2.23 Indices of nominal and real gross income in total number of households and in farm households (source: Zegar, 2008)

Year	(Preced	ominal ding year = 100)	Real (Preceding year = 100)		Nominal (1995=100)		Real (1995=100)	
	Total	Farmers	Total	Farmers	Total	Farmers	Total	Farmers
1995	135.6	144.5	106.0	114.1	100.0	100.0	100.0	100.0

Year	(Preced	ominal ling year = 100)	Real (Preceding year = 100)		Nominal (1995=100)		Real (1995=100)	
	Total	Farmers	Total	Farmers	Total	Farmers	Total	Farmers
1996	125.6	109.7	104.8	90.9	125.6	116.7	104.8	96.7
1997	123.1	104.4	107.1	91.7	154.6	130.4	112.2	94.8
1998	117.2	106.9	104.6	96.5	181.2	138.9	117.4	91.2
1999	109.7	98.0	102.2	91.7	198.8	136.1	120.0	83.7
2000	111.0	105.0	101.0	94.8	220.7	142.9	121.2	79.3
2001	107.8	108.1	102.3	103.3	237.9	154.5	124.0	82.0
2002	102.3	95.7	100.4	94.4	243.4	147.8	124.5	77.4
2003	101.9	100.0	101.1	99.5	248.0	147.8	125.9	77.0
2004	106.6	120.6	102.4	106.0	264.3	178.3	128.9	81.6
2005	103.8	106.8	101.7	104.6	274.4	190.4	131.1	85.4
2006	104.9	107.3	103.9	106.8	287.8	204.3	136.2	91.2

The real income of farm households in 2006 was by 8.8% lower as compared to that in 1995, while in total number of households it was higher by 36.2% (Table 2.23). In the year 2007, which was favourable for agriculture, the income in total number of households increased by 44% and in farm households only by 6% as compared to 1995. Despite the generally positive changes in the development of income, the ratio of farmers' income to the income of total number of households throughout the period 2003-2006 was unfavourable for farmers.

The gross value added (GVA) of the agricultural sector increased by 23.6% and the income of farmers (agricultural enterprises) by 23.2% in 2007, as compared to the values in the preceding year (Table 2.24). The research of Woś (2007) shows that the growth of the value of economic categories in 2007 was associated with the improvement by 7.7% of agricultural price scissors and with an increase in the volume of global production of private farms by 5.9%. However, the action of both these factors on such a scale can be non-recurrent and therefore, conclusions about the systematic improvement of the relationship of agricultural prices cannot be drawn on that basis. The situation occurring in 2008 has clearly proved it.

Table 2.24 Basic production-economic indicators of the agricultural sector in 1998-2007 in billions of PLN, in current prices (Analysis of the production-economic situation of agriculture and food industry (source: Woś, annuals 2005, 2006, and 2007; www.rer.ierigz.waw.pl)

	Clobal	Intermediate	Chara valua	Income o	f farmers <sup>1)</sup>
Year	Year Global Ir production co		Gross value added	Current prices	Fixed prices <sup>2)</sup>
1998	48.8	28.6	20.2	11.3	11.3
1999	45.9	28.0	17.9	8.4	7.8
2000	50.0	31.1	18.9	9.3	7.9
2001	54.6	32.6	22.0	11.7	9.3
2002	51.6	32.1	19.5	9.3	7.3
2003	51.8	33.3	18.5	8.5	6.7
2004	64.6	37.6	27.0	20.5	15.6
2005	64.0	37.4	26.6	20.8	15.5
2006	63.0	37.6	25.4	21.0	15.5
2007	76.4	45.0	31.4	25.9	18.7

<sup>1)</sup> the so-called agricultural business income (paid and unpaid work, without wage labour costs),

Farms are very diverse in terms of area, which clearly affects the level and structure of disposable income of their owners (Table 2.25). As the farm size increases the rate of increase in disposable income of their owners also grows. This indirectly indicates benefits of the inclusion of the agriculture in the mechanisms of the Common Agricultural Policy. However, only farms larger than 15 ha derive more than 50% of income from agricultural production. The share of this group of farms has positively changed over the years 2003-2006.

Table 2.25 The average monthly disposable income per person in farms according to their size in PLN in 2003, 2005 and 2006 (source: Zegar, 2008)

Groups		2003			2005			2006	
Groups by area in ha	Total (T)	From farm (F)	F/T (%)	Total (T)	From farm (F)	F/T (%)	Total (T)	From farm (F)	F/T (%)
Total	498	139	27.8	562	189	33.8	634	223	35.1
1-5	506	48.4	9.6	523	52.0	9.9	589	77.2	13.1
5-10	442	124	28.0	498	158	31.7	565	172	30.4

<sup>&</sup>lt;sup>2)</sup> including inflation rate.

Cmayma		2003			2005			2006	
Groups by area in ha	Total (T)	From farm (F)	F/T (%)	Total (T)	From farm (F)	F/T (%)	Total (T)	From farm (F)	F/T (%)
10-15	457	200	43.7	544	245	45.0	633	319	50.5
15-20	552	314	56.9	594	363	61.1	719	418	58.1
≥ 20	630	414	65.7	893	682	76.4	919	677	73.6

Sources of disposable income are quite different in total number of households and in farm households (Table 2.26). The income from employment certainly predominates in total number of households, whereas in farm households the income from the farm is dominant. However, it is interesting that social benefits are a more significant source of income in total number of households, than in farm households.

Table 2.26 Sources of disposable income of households in total (TH) and in farm households<sup>1)</sup> (FH) in the years 2003 - 2006 (source: Zegar, 2008)

Sources	2003		2004		2005		2006	
Sources	TH	FH	TH	FH	TH	FH	TH	FH
Total income	100	100	100	100	100	100	100	100
Wage labour	45.1	0.1	45.5	0.1	46.0	0.2	47.5	0.2
Farm	3.8	68.6	4.1	72.8	4.5	74.7	4.6	76.5
Self-employment	7.8	1.5	8.0	1.8	8.1	1.6	8.5	1.4
Social benefits <sup>1)</sup>	36.2	24.8	35.5	22.4	34.9	20.4	33.5	18.0

<sup>1)</sup> including social security benefits

There are major differences in disposable income between socio-economic groups (Table 2.27). Net monthly income per household is lower, and per person significantly lower in the farmers' group in comparison with paid employees, and even more lower in comparison with those who are self-employed (Table 2.27). Also retired employees reach higher income per capita than farmers. The differences in income per capita are due to, inter alia, varied family sizes in households of each socio-occupational group. The households of farmers and of the so-called farmer-workers (peasant farmers working in factories) have more family members than in other occupational groups.

Table 2.27 Net monthly income of households by occupational groups (in PLN) (source: Czapiński and Panek, 2007)

Description	Pe	r househo	old	Per person			
Description	2003	2005	2007	2003	2005	2007	
Total	1886	2122	2399	676	790	894	
Employed	2193	2510	2791	684	822	906	
Farmers	1656	1953	2491	403	504	583	
Farmer-workers	2191	2321	2607	492	572	627	
Pensioners and retired	1522	1653	1799	739	824	916	
Self-employed	2593	3277	3875	782	1074	1308	
Other unearned income	969	1154	1158	371	414	513	

The parity of disposable income of farmers in relation to employees in 1995-2000 underwent a progressive and significant deterioration (Table 2.28). Since 2001 the parity has been quite systematically improving. Only in 2006 the income of farmers reached parity with the level of mid-1990s of the last century. Nevertheless, even in 2007, farmers' income was lower than the income of employees. The research of Zegar (2008) shows that still about 23% of households of this group of farmers is below the statutory poverty threshold and the situation of about 10% place them below the minimum of existence.

Table 2.28 The monthly disposable income per employed person (in PLN) and parity income for farmers in 1995-2007 (source: Zegar, 2008)

Year	Employed	Farmers	Farmers/employed
1995	544	477	87.6
1996	719	566	78.7
1997	832	637	76.6
1998	981	677	69.0
1999	1081	646	59.8
2000	1197	741	61.9
2001	1210	815	67.3
2002	1238	953	77.0
2003	1371	838	61.2
2004	1426	1007	70.6
2005	1475	1196	81.1
2006	1539	1318	85.6
20071)	1700	1638	96.0

<sup>1)</sup> estimates made assuming that labour inputs (number of employed) have not changed

Polish accession to the European Union has created new opportunities for agriculture and rural development. After the accession the aid for agriculture had a significant share in the income of farmers, as in the 15 countries of the former European Union (Fig. 2.19). Therefore, a new significant instrument for revenue shaping and the development of agriculture has appeared in the form of transfers resulting from the mechanisms of the Common Agricultural Policy.

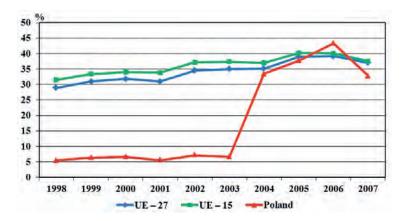


Fig. 2.19 Subsidies on products and production in the income of farmers in % (source: Zegar, 2008)

However, in the future, primarily the internal transformation of agriculture should play an important role in the revenue policy. The key issue in terms of shaping the agricultural income is a need for changes leading to the concentration of land and production, as factors that increase the competitiveness of Polish agriculture. The elimination of backwardness in economic and civilization development of rural areas and the reduction of regional disparities are also needed. Regional differentiation of economic condition of agriculture and rural areas is significant. The division of Poland into Poland A (west of the Vistula river) and Poland B (east of the Vistula) is clearly visible. This division is reflected, and even enhanced in the economic evaluation of agricultural production (Krasowicz and Kopiński, 2006). There is also a strong variation of economic condition of farms depending on the area, type of production (specialization of production), the intensity of farming, and the strength of relationships with the market. Various functions such as manufacturing, environmental, social, cultural, and the function of providing rural areas inhabitants with a decent standard of living, require an investment and innovation. Polish accession to the European Union has significantly increased funds to finance the development of agriculture and rural development and to improve revenues. However, rural areas do not generate sufficient own funds to finance the necessary and desired investment and farming modernization processes. This problem also applies to large-area farms, which are strongly associated with the market.

The inclusion of Polish agriculture in the mechanisms of the Common Agricultural Policy made it possible to achieve real income levels of the mid-nineties of the twentieth century, and also to somewhat shorten the distance between farmers and the general population due to the level of income. Nevertheless, this does not mean that the situation can be assessed as being explicitly positive. Still there is disparity to the disadvantage of farmers on labour charges, as well as on personal income. As before, the extent of poverty in households (families) of farmers is significantly higher than in other social groups. Moreover, it is expected that the income impulse produced by the accession, in particular due to direct subsidies, will wane. The transfers focused on rural development and modernization of farms will gain more importance. The efficiency of utilization of these transfers and direct subsidies will be the primary determinant of the ability to improve the efficiency of farms, the pace and scale of structural transformations in agriculture and rural development. It will also be decisive for the possibilities of reducing the adverse impacts of agriculture on the environment.

## References

- Atlas Polski. 2001. Modela, R., (ed.), t. 1, Oficyna Wydawnicza FOGRA, Kraków.
- Bański, J., 2005. Przestrzenny wymiar współczesnych procesów na wsi. Studia obszarów wiejskich. Warszawa. pp. 123-131.
- Bogdańska, B., Podogrocki, J., 2000. Zmienność całkowitego promieniowania słonecznego na obszarze Polski w okresie 1961-1995. Mat. Badawcze IMGW, Seria Meteorologia, Nr. 3.
- Czapiński, J., Panek, T., (eds), 2007. Diagnoza społeczna. Rada Monitoringu Społecznego, Warszawa. 367 pp.
- Dolniak, P., 2006. Biopaliwa w Unii Europejskiej. Fermer. 4:14-16.
- Dz. U. Nr 257, item. 2573, 2004. Rozporządzenie rady Ministrów z dnia 9 listopada 2004 r. w sprawie określenia rodzajów przedsięwzięć mogących znacząco oddziaływać na środowisko oraz szczegółowych uwarunkowań związanych z kwalifikowaniem przedsięwzięcia do sporządzania raportu o oddziaływaniu na środowisko.
- Encyklopedia Geograficzna Świata, Polska, Tom X, 1997. OPRES, Kraków, 431 pp.
- Faber, A., 2001. Bioróżnorodność w krajobrazie rolniczym Polski. Biul. Form. IUNG-PIB, Puławy, 15:4-9.
- Fotyma, M., Krasowicz, S., 2001. Potencjalna produkcyjność gleb gruntów ornych Polski w ujęciu regionalnym. Pam. Puł., vol. 124:99-108.
- Górski, T., 2005. Model średniej temperatury powietrza w Polsce. Acta Agrophysica, 125:73-83.
- Górski, T., 2006. Klimatologiczny model sum opadów atmosferycznych w Polsce. [in:] Migała, K., Ropuszyński, P. (eds.), Współczesna meteorologia i klimatologia

- w geografii i ochronie środowiska. P.T. Geogr., Wrocław, pp. 43-57.
- Górski, T., 2007. Changes in Poland's agroclimatic conditions over the last century. Papers on Global Change. IGBP PAS, 14:55-67.
- Górski, T., Górska, K., 1998. An algorithm for evaluating the cycle of sunshine duration in Poland. Proc. 2<sup>nd</sup> ISES-Europe Solar Congress, Portorož. Book of Proceedings I., 1.4:1-6.
- Górski, T., Zaliwski, A., 2002. Model agroklimatu Polski. Pam. Puł., Puławy, 130:251-260.
- Grzybek, A., 2008. Ziemia jako czynnik warunkujący produkcję biopaliw. Problemy Inżynierii Rolniczej. IBMER, Warszawa, 1(59):63-70.
- GUS (Central Statistical Office), 1999-2012. Użytkowanie gruntów, powierzchnia zasiewów i pogłowie zwierząt gospodarskich w 1998 2011. Warszawa, Poland.
- GUS (Central Statistical Office), 2001. Rocznik Statystyczny Rzeczpospolitej Polskiej. Warszawa, Poland.
- GUS (Central Statistical Office), 2003. Użytkowanie gruntów, powierzchnia zasiewów i pogłowie zwierząt gospodarskich w 2002 r. Warszawa, Poland.
- GUS (Central Statistical Office), 2008. Charakterystyka gospodarstw rolnych w 2007 r. Warszawa, Poland.
- GUS (Central Statistical Office), 2001-2011. Produkcja upraw rolnych i ogrodniczych w 2000-2010 roku. Warszawa, Poland.
- GUS (Central Statistical Office), 2011a. Użytkowanie gruntów. Powszechny Spis Rolny. Warszawa, Poland.
- GUS (Central Statistical Office), 2011b. Rocznik Statystyczny Rzeczpospolitej Polskiej. Warszawa, Poland.
- GUS (Central Statistical Office), 2011c. Rocznik Statystyczny Województw Warszawa, Poland.
- Hatfield, J.L., Follett, R.F., (eds.), 2008. Nitrogen in the Environment (second edition): Sources, Problems and Management. Academic Press, 702 pp.
- Harasimiuk, K., Rodzoś, J., 2004. Geografia Polski. Wyd. UMCS, Lublin. 387 pp.
- Jaśkiewicz, B., 2004. Organizacyjno-ekonomiczne uwarunkowania produkcji zbóż jakościowych w różnych regionach Polski. Pam. Puł., vol. 137, pp. 59-70.
- Klepacki, B., (ed.), 2001. Procesy dostosowawcze produkcji roślinnej w Polsce w kontekście integracji z Unią Europejską. SGGW, Warszawa, 287 pp.
- Kozyra, J., Górski, T., 2004. Wpływ zmian klimatu na uprawę roślin w Polsce. (in:] Klimat –Środowisko Człowiek, Polski Klub Ekologiczny, Wrocław. pp. 41-50.
- Krasowicz, S., 2002. Produkcja roślinna na ziemiach polskich w XIX i XX w. Pam. Puł. vol.130(1):11-31.
- Krasowicz, S., 2007. Możliwość zwiększenia produkcji zbóż w Polsce. Wyd. Wieś Jutra.

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- Krasowicz, S., Kopiński, J., 2006. Wpływ warunków przyrodniczych i organizacyjnoekonomicznych na regionalne zróżnicowanie rolnictwa w Polsce. Raporty IUNG-PIB Puławy, vol. 3, pp. 81-99.
- Kuś, J., Faber, A., Madej, J., 2006. Przewidywane kierunki zmian w produkcji roślinnej w ujęciu regionalnym. [in:] Regionalne zróżnicowanie produkcji rolniczej w Polsce Raporty IUNG-PIB, Puławy, 3:195-210.
- Kuś, J., Jończyk, K., Kamińska, M., 2001. latach 1988-1998. Pam. Puł. vol. 124, pp. 263-271.
- Lekan, S., Terelak, H., 1997. Zróżnicowanie środowiska glebowo-rolniczego Polski. Mat. Konf. Nauk. nt. "Ochrona i wykorzystanie rolniczej przestrzeni produkcyjnej Polski, Puławy, Sesja I i II, pp. 7-21.
- Maps showing regulated and unregulated rivers: http://maps.google.com [Accessed in 2008].
- Nowacki, W., 2007. Przyrodnicze i ekonomiczne uwarunkowania wykorzystania krajowej bazy surowcowej do produkcji bioetanolu. Rocz.Nauk. Vol. IX, part 1, pp. 338-342.
- Production-economic situation of agriculture and food industry: www.rer.ierigz\_waw.pl [Accessed in 2010].
- Richling, A., Ostaszewska, K., 2005. Geografia Fizyczna Polski. PWN, Warszawa.
- Stuczyński, T., Kozyra, J., Łopatka, A., Siebielec, G., Jadczyszyn, T., Koza, P., Doroszewski, A., Wawer, R., Nowocień, E., 2007. Przyrodnicze uwarunkowania produkcji rolniczej w Polsce. [in:] Współczesne uwarunkowania organizacji produkcji w gospodarstwach rolniczych. Studia i Raporty IUNG-PIB, Puławy, 7:77-115.
- Strategia Zrównoważonego Rozwoju Wsi, Rolnictwa i Rybactwa na lata 2012-2020. Ministerstwo Rolnictwa i Rozwoju Wsi. Warszawa, 2012, 156 pp.
- Terelak, H., Krasowicz, S., Stuczyński, T., 2000. Środowisko glebowe Polski i racjonalne użytkowanie rolniczej przestrzeni produkcyjnej. Pam. Puł. Vol. 120/II, pp. 455-469.
- Uziak, S., Klimowicz, Z., 2000. Elementy geografii gleb i gleboznawstwa, Wydawnictwo UMCS, Lublin.
- Witek, T., 1979. Wpływ jakości gleb na plonowanie roślin uprawnych. Zesz. Probl. Nauk Rol., 224:35-47.
- Woś, A., 1999. Klimat Polski. Wyd. Nauk. PWN. Warszawa.
- Woś, A., (ed.), Analiza produkcyjno-ekonomicznej sytuacji rolnictwa i gospodarki żywnościowej (years 2005, 2006, 2007). IERiGŻ, Warszawa.
- Wójcicki, Z., 2011. Projektowanie modernizacji rodzinnych gospodarstw rolnych. Probl. Inż. Roln. ITP., KTR PAN, PTIR, Falenty, 2(72):5-16.
- Zegar, J.S., 2008. Dochody w rolnictwie w okresie transformacji i integracji europejskiej. IERiGŻ, Warszawa.

NITROGEN UTILIZATION
AND DIFFUSE LOSSES IN
AGRICULTURAL CROP

MARIUSZ FOTYMA JANUSZ IGRAS JERZY KOPIŃSKI

**PRODUCTION** 

# 3. NITROGEN UTILIZATION AND DIFFUSE LOSSES IN AGRICULTURAL CROP PRODUCTION

Mariusz Fotyma, Janusz Igras, Jerzy Kopiński

#### 3.1. Nitrogen cycle in agricultural systems

Carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and phosphorus (P) are the elements of life as an essential part of the biomass and participate in all basic metabolic processes of plants, animals, and humans. Nitrogen in its molecular or ionic form is a constituent of the lithosphere, hydrosphere, atmosphere, and biosphere. The atmosphere in approximately 78% consists of nitrogen, and its resources are estimated at about  $4 \cdot 10^{15}$  tons  $N_2$  with the renewal time of approximately 50 years. Resources of nitrogen in plant biomass on land, and in soil are estimated at 3.5  $\cdot$   $10^{11}$  tons N with the renewal time of approximately 50 years, and at 9.5  $\cdot$   $10^{11}$  tons N with the renewal time of approximately 2000 years, respectively. The natural nitrogen cycle between the atmosphere and the lithosphere includes the inflow from the atmosphere through chemical and biological  $N_2$  fixing rated at around  $10^7$  tons N per year and the outflow from the lithosphere in the form of gaseous products of denitrification that is estimated at approximately  $1.47 \cdot 10^8$  tons N per year. The inflow into the lithosphere should include nitrogen contained in mineral fertilizers estimated at around 85 million tons of N per year (Hatfield and Follett, 2008).

Soil forming part of the lithosphere is the product of processes occurring at the interface of the atmosphere, hydrosphere, and biosphere. For this reason, and given the importance of soil for life processes, soil should be treated as an element of the biosphere. The concentration of nitrogen in soil varies from 3 to 30 g N · kg<sup>-1</sup>, and in plants it amounts to about 15 g N · kg<sup>-1</sup>, while in human and animal bodies it reaches approximately 80 g N · kg<sup>-1</sup> (Jolankai, 2004). Concentration of nitrogen in terrestrial hydrosphere is very variable and generally does not exceed 15 mg N · dm<sup>-3</sup>. The primary source of nitrogen is atmospheric nitrogen which occurs almost exclusively in the form of molecular N2, which is inaccessible for higher plants. Reduction or oxidation of atmospheric nitrogen occurs as a result of lightning discharges, biological binding by free-living and symbiotic bacteria, and in the chemical synthesis processes performed in fertilizer factories. In Poland, lightning discharges deliver from 1 to 10 kg N · ha<sup>-1</sup> · year<sup>-1</sup> of nitrogen in the form of ammonium or nitrate, and biological fixation is rated at about 7 - 10 kg N · ha<sup>-1</sup> · year<sup>-1</sup>. However, both processes do not satisfy even half of nitrogen demand of agriculture and only after mastering the process of ammonia synthesis (Haber-Bosch method) in the early twentieth century, nitrogen in fixed forms ceased to be limiting factor for food production in the world. Nitrogen is a very mobile element due to its presence at as many as five levels of valence, both in gaseous and ionic forms (Thornton, 1998; Table 3. 1).

Oxidation level	Compound	Form	Significance
-3	NH <sub>3</sub>	Gaseous	Toxic for living organisms
-3	NH <sub>4</sub> <sup>+</sup>	Ionic	It occurs in soils and sewage sludge, in equilibrium with NH <sub>3</sub> , it is the source of nitrogen for plants
0	$N_2$	Gaseous	Neutral form, mainly in the atmosphere
+1	N <sub>2</sub> O	Gaseous	Source of acid rain, destroys the ozone layer
+2	NO	Gaseous	Acid rain precursor
+3	NO <sub>2</sub> -	Ionic	Transitional form in biological processes, toxic for living organisms
+4	NO <sub>2</sub>	Gaseous	Acid rain precursor
+5	NO <sub>3</sub>	Ionic	The basic form in plant nutrition and environmental risk

Table 3.1 Nitrogen forms and their importance for the environment and living organisms (source: Thornton, 1998)

Nitrogen is an essential component of DNA, RNA and proteins in organisms living on earth. Nitrogen cycle in the atmosphere, biosphere and geosphere is shown in Fig. 3.1.

Nitrogen in the form of gas is largely unavailable to plants and animals due to the type of chemical bond in N<sub>2</sub>. Gaseous form of nitrogen must, therefore, first be processed into a more chemically available form such as ammonium (NH<sub>4</sub><sup>+</sup>), nitrate (NO<sub>3</sub><sup>-</sup>), or organic nitrogen, such as urea (NH<sub>2</sub>)<sub>2</sub>CO. Similarly to the global carbon cycle, nitrogen cycle consists of many N reservoirs and of many processes through which the exchange between these reservoirs takes place. There are eight important processes in the nitrogen cycle and they are as follows: 1) uptake of nitrogen from the atmosphere (called symbiotic fixation), 2) the uptake of ammonium and nitrates from the soil and water (called plant uptake), 3) ammonification, 4) nitrification, 5) denitrification, 6) nitrate immobilization, 7) nitrate leaching from the soil, 8) release of NH<sub>3</sub>, N<sub>2</sub>, N<sub>2</sub>O to the atmosphere through denitrification and volatilization from animal and poultry farms and from manure that is applied to soil and stored (O'Neill, 1997; Kurvits and Marta, 1998; Misselbrook et al., 2000; Sommer and Hutchings, 2001; Krupa, 2003; Sommer et al., 2003; Webb et al., 2005; Balsari et al., 2007; Desjardins et al., 2007; Erisman et al., 2007).

There exists biological and high-energy gaseous nitrogen fixation:  $N_2 \Rightarrow NH_3 \Rightarrow R-NH_2$ , i.e. processing of atmospheric nitrogen into a form that is assimilable by plants. Biological fixing is performed by (i) bacteria such as e.g. *Rhizobium* or

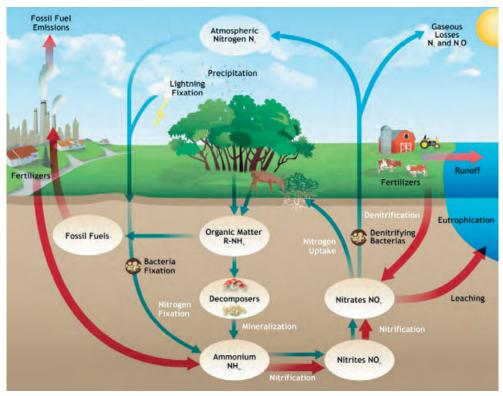


Fig. 3.1 Nitrogen cycle; the blue arrows show the natural elements of the nitrogen cycle; the red arrows represent nitrogen entering the cycle through human activities (source: http://landscapeforlife.org/give\_back/3c.php)

Frankia Azospirillum, living in symbiosis with leguminous plants and other plants, and feeding the plants with ammonium or glutamine, in exchange for carbohydrates, (ii) by root nodules of non-leguminous plants, (iii) by free-living anaerobic bacteria, (iv) by blue-green algae. High-energy fixation - small amounts of nitrogen are fixed by lightening discharges. Most of plants take up nitrogen through root systems and/ or shoots in the form of ammonium and nitrate ions, and then convert them into amino acids from which proteins are built; NO<sub>3</sub> and/or NH<sub>4</sub> ⇒R-NH<sub>2</sub>. These ions are present in the soil as a result of saprogenic processes, and the operation of freeliving nitrogen bacteria. Almost all organisms can use ammonium for biosynthesis, and the reduced form of N is preferred in the reactions of biosynthesis (Azam et al., 1993). From the energy point of view NH4<sup>+</sup> ions are the preferred source of nitrogen as nitrate requires energy expensive reduction before its embedding into an amino acid. However, the nitrification process is seen as the main process in the transformation of NH<sub>4</sub><sup>+</sup> in soil (Robertson, 1997), where NH<sub>4</sub><sup>+</sup> is usually present in low concentrations as compared to the concentrations of NO<sub>3</sub>. The process of ammonium generation (NH<sub>4</sub><sup>+</sup>) from the decomposition of nitrogen-containing organic

compounds by microorganisms R-NH<sub>2</sub>⇒NH<sub>4</sub> is called ammonification, and it occurs during saprogenic processes carried out by specialized bacteria and fungi. Also animals participate in the secondary generation of ammonium by the decomposition of urea, one of the basic products of their metabolism. The process equivalent to ammonification is the immobilization of nitrate and processing nitrate into organic matter in soil. This process requires enzymatic catalysis of soil microorganisms (Recous and Mary, 1990; Kissel et al., 1977; Puri and Ashman, 1999; Bernston and Aber, 2000; Dail et al., 2001; Burger and Jackson, 2003; Erisman et al., 2007). The ammonia/ammonium occurring in the environment, either by fixing from the atmosphere or by ammonification, is converted to nitrate ions by nitrifying bacteria. In a great simplification the nitrification process consists in the oxidation of ammonium to nitrite and nitrate ions  $NH_4^+ \Rightarrow NO_3^- \Rightarrow NO_3^-$ . Denitrification is the process of converting excess nitrate from nitrification to nitrogen gas. It is carried out by a number of microorganisms, mainly living in water, such as Pseudomonas fluorescens bacteria; denitrification occurs under anaerobic conditions: NO₃ ⇒NO₃ ⇒NO⇒N<sub>2</sub>O⇒N<sub>2</sub>. Two very important processes cannot be ignored here, i.e. the ammonia volatilization from the soil to the atmosphere and the leaching of mobile nitrate from soil and its transfer to surface waters and further into the sea. The volatilization of ammonia from soil occurs as soon as NH, appears close to soil surface (Nelson, 1982). Losses of ammonia from soil can range from 3 to 50%, depending on soil texture and type of added fertilizer. Volatilization increases with increasing soil pH, as well as with the intensification of evaporative conditions, i.e. high temperature and winds (Sommer et al., 2003). Microorganisms, particularly bacteria, play a key role in primary nitrogen metabolism, and among the factors that affect the rate of bacterial processes, the temperature, humidity, and the abundance of a particular reservoir should be mentioned (Krupa, 2003; Sommer et al., 2003). Webb et al. (2005) estimated that approximately 75% of European NH<sub>3</sub> emissions come from livestock production. According to the authors, these emissions occur at all stages of production - starting in the livestock buildings, through natural fertilizer storage and application to soil, up to the deposition of animal excreta on pastures.

The introduction of mineral fertilizers in the early twentieth century significantly increased the productivity of agricultural sector, followed by the increase in livestock population; there also occurred changes in land use and management. These facts, along with industrialization and greenhouse gas emissions from both the agricultural sector and industry, have contributed to environmental degradation on a global scale. This degradation is due to unbalanced use of mineral and natural fertilizers in agriculture and neglect in the industrial sector (contaminated waste water, emissions into the atmosphere), and is a result of nitrogen emissions from agriculture and industry into rivers, lakes and eventually into the sea, including the emission of nitrogen oxides, sulphur and methane into the atmosphere. Research of Oenema et al. (2007), conducted for the 27 EU member states and focused on the management

of manure and losses of nutrients from this source to the environment shows that, firstly, about 65% of the total amount of N excreted by livestock was stored for a certain period before it was added to the soil, and secondly - up to 52% of N excreted by farm animals on the premises was efficiently processed by plants. These authors further concluded that nearly 30% of N excreted by farm animals on the premises was lost in storage, including about 19% of NH<sub>3</sub>, and 7% of NO and N<sub>2</sub>O that was emitted to the atmosphere and approximately 4% was lost due to the leaching and outflow. Another 19% of N excreted by animals was emitted into the atmosphere in the form of NH<sub>3</sub> after the addition of manure to the soil. The spread of N losses from manure and slurry storage was significant for the 24 EU member states as it amounted to 19.5-35%. Fernández et al. (1999) estimated that in 1996 the amount of ammonia that was emitted into the atmosphere from Danish pig farms reached 16,000 tons.

#### 3.2. Production and consumption of nitrogen mineral fertilizers

Poland, with the production capacity of approximately 1.7 million tons of N, is the largest producer of nitrogen fertilizers in the EU countries and produces approximately 17% of the total amount of these fertilizers in the European Community. The production capacity of each of the other major producers, France, Holland, and Germany reaches around 1 million tons of N (Igras and Biskupski, 2011).

In Poland 10 chemical plants produce mineral fertilizers and intermediate products on a large scale. These are: Anwil S.A., ZAK S.A., Zakłady Azotowe "Puławy" S.A. (Photo 3.1), Azoty Tarnów, Zakłady Chemiczne "Police" S.A., Gdańskie Zakłady Nawozów Fosforowych "Fosfory" Sp. z o.o., Zakłady Chemiczne "Luvena" S.A., Zakłady Chemiczne "Siarkopol" Tarnobrzeg Sp. z o.o., Fosfan S.A. and Zakłady Chemiczne "Alwernia" S.A. The first five plants produce nitrogen fertilizers, which are as follows: ammonium nitrate fertilizers (Anwil S.A., ZAK S.A., Zakłady Azotowe "Puławy" S.A. and Azoty Tarnów), urea (ZAK S.A., Zakłady Azotowe "Puławy" S.A., Azoty Tarnów, ZCh "Police" S.A.) and ammonium sulphate (Zakłady Azotowe "Puławy" S.A., Azoty Tarnów, ZCh "Police" S.A.) (Fig. 3.2). Coke plants produce additional 100-200 thousand tons of ammonium sulphate per year. The group of nitrogen fertilizers should also include calcium nitrite, magnesium nitrate, and sodium nitrate. Solid and liquid fertilizers, with the above-mentioned nitrates being their main component, are produced by ZCh "Złotniki" SA, ZCh Alwernia SA, ZAK SA, Azoty Tarnów and Zakłady Chemiczne "Organika-Sarzyna" SA (Igras and Biskupski, 2011).



Photo 3.1 Nitrogen Works (Zakłady Azotowe) "Puławy" (photo by S. Kłak)



Fig. 3.2 Location of nitrogen works in Poland (source: Igras and Biskupski, 2011)

Production capacity of Polish fertilizer plants exceeds the needs of domestic agriculture. This situation forces domestic fertilizer producers to expand their product mix and to improve quality of their products. It should be noted that domestic fertilizer industry has significantly raised the quality of its products in recent years and currently nitrogen fertilizers (as well as other types of fertilizers) manufactured in the country meet the quality requirements applicable in the EU. Nevertheless, in the coming years, fertilizer plants will be forced to proceed with their development following changes in legal regulations relating to fertilizers (Igras and Biskupski, 2011).

Over the last years, solid fertilizers containing ammonium nitrate have been of particular interest to the various administrative bodies. This is because they are used for terrorist purposes in many places in the world. The EU has decided to introduce marketing restrictions concerning fertilizers containing ammonium nitrate. As a result of these restrictions only nitrogen fertilizers with a maximum content of 16% of ammonium nitrate will be allowed for the free trade (temporarily, until 2014 - 20% is allowed). The fertilizers of the existing compositions will be available in the licensed trade, and of those the most commonly used types of fertilizers are ammonium nitrate and nitro-chalk. These regulations created a situation in which industrial plants producing ammonium nitrate are forced to seek new technological solutions, if they intend to maintain their existing production capacity. It can be assumed that a large part of ammonium nitrate and nitro-chalk fertilizers will be sold to professional buyers (licensed trade), but some part of the existing buyers will be forced to switch to the use of fertilizers that will be available in the free trade (Igras and Biskupski, 2011).

Solid nitrate fertilizers produced currently in our country (ammonium nitrate based) contain 27.0% N (nitro-chalk produced by Azoty Tarnów and Anwil, and N-S fertilizer produced by Anwil), 27.5% N (nitro-chalk from ZAK and N-S fertilizer from ZAK), 34.5% N (ammonium nitrate from ZA Puławy and Anwil), 32% N (saltpetre from ZAK and Azoty Tarnów), 30% N (saltpetre from Azoty Tarnów), and 26% N, including 14.6% N with NH $_4$ NO $_3$  (ASN from Azoty Tarnów) (Igras and Biskupski, 2011).

Export of fertilizers is required to exploit the full production capacity of fertilizer plants, because their domestic consumption is currently around 1 million tons N (Igras and Biskupski, 2011) (Table 3.2). Although the use of fertilizers recently has been slowly growing, yet it is still unlikely to exceed 60% of the production capacity of fertilizer plants by 2020.

Balance item	Thousands of tons N	Explanation
Total production in the country including: for domestic market for export	1339 1046 287	According to the Polish Chamber of Chemical Industry
Import trade	220	
Consumption in agriculture	1027	According to GUS (2009-2011b)

Table 3.2 Balance of fertilizer nitrogen in Poland in 2011 year (source: Igras and Biskupski, 2011)

Nitrogen fertilizers production structure is dominated by ammonium nitrate and urea, two most popular and most frequently purchased nitrogen fertilizers (Table 3.3). The solution of urea and ammonium nitrate (UAN) has been increasingly popular, and in recent years its production has increased several times. The largest producer and exporter of UAN is Zakłady Azotowe Puławy.

Table 3.3 Assortment of nitrogen fertilizers produced in Poland in 2010 (source: Annual Report, 2010)

Fertilizer type	Production (by weight of fertilizer) [thous. tons of N]	Share [%]	Production (by weight of pure component) [thous. tons of N]	Share [%]
Nitro-chalk	908	22	247	18
Ammonium nitrate	1562	38	526	39
Urea	928	23	427	32
Nitrogen sulphuric fertilizers	671	17	139	11
Total	4069	100	1339	100

Significant amounts of nitrogen are supplied in the form of compound fertilizers. NO and NPK compound fertilizers are produced by Zakłady Chemiczne Police and mixed fertilizers by Zakłady Chemiczne "Luvena" S.A. and Zakłady Chemiczne "Siarkopol" Tarnobrzeg Sp. z o.o. For mixed fertilizers, the latter uses nitrogen fertilizers produced in one of the five plants of chemical synthesis. In the coming years it is not envisioned to significantly expand the nitrogen fertilizers production sector because the existing factories have sufficient production capacity. Instead, changes in the assortment of fertilizers should be expected aiming towards a reduction in the production of ammonium nitrate with nitrogen content above 28% in favour of nitro-chalk or saltpetre-urea-solution (SUS). At present SUS production is beneficial both for chemical plants, because of the easy and relatively inexpensive technological modernization required for its manufacturing, and for agriculture, as

the research clearly shows that production and economic efficiency of nitrogen unit in this fertilizer has the highest value. However, SUS domestic consumption growth will depend on the development of logistics, and above all on the increasing number of SUS handling centres and tanks for storage (Igras and Biskupski, 2011).

The consumption of nitrogen fertilizers in Poland from the mid 1990s of last century has been showing an upward trend (Table 3.4; Fig. 3.3) and this trend is opposite to that observed in the EU-15 (Fig. 3.4). As a result of these opposing processes the consumption of nitrogen fertilizer per 1 ha of agricultural land (excluding set-aside and fallow land) in Poland currently has reached the average level of EU-15. Of course, among the "old" Union member states with intensive agricultural production the unit consumption of nitrogen fertilizers is much higher than the consumption in Poland.

Table 3.4 Consumption of nitrogen fertilizers in Poland in the last 15 years (source: GUS, 1991-2011)

Consumption	1995	1997	2000	2002	2005	2007	2008	2009	2010	2011
[thous. tons]	836	852	861	862	895	1056	1142	1095	1027	1091
[kg N·ha-1]	46.6	47.6	48.4	51.0	56.4	65.3	73.2	70.1	70.6	74.1

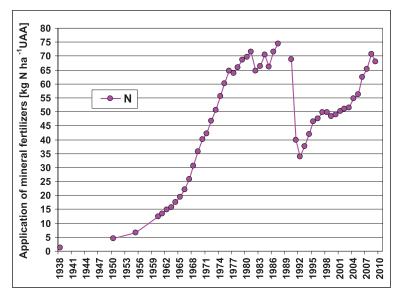
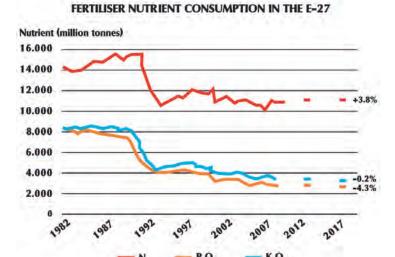


Fig. 3.3 Consumption of nitrogen fertilizers in Poland in the years 1938-2009; UAA – utilized agricultural area (source: graph was prepared and made available by Pastuszak, NMFRI, Gdynia - based on GUS, 1960-2003; 1991-2011 data)



## Fig. 3.4 Dynamics of fertilizer consumption in EU countries (million tons) (source: EFMA, 2009)

Nitrogen fertilizer consumption structure is slightly different from the earlier described structure of production. The consumption of nitrogen fertilizers is dominated by urea and ammonium nitrate (Table 3.5), which together constitute over 60% of the total weight of the fertilizers. However, the share of nitrogen in the form of compound fertilizers is fairly constant and does not exceed 12-13%. As results from a comparison of the data contained in Tables 3.3 and 3.4, almost all the ammonium sulphate produced, and a significant part of the solution of ammonium nitrate, is earmarked for export, while the whole production of nitro-chalk is consumed in the country. In recent years the use of ammonium sulphate and ammonium nitrate solutions, specially ammonium nitrate, urea and SUS has been growing as a result of the improvement of the economic situation of agriculture and the development of new techniques of fertilizers transport, storage and application.

Consumption of nitrogen fertilizers in Poland is regionally differentiated, which is associated primarily with the intensity of agricultural production (Fig. 3.5). Most fertilizers are consumed in the western and north- and south-western regions of the country, and the least in the eastern and central Poland. In the voivodeship of Opolskie (south-western Poland) the consumption of nitrogen fertilizers reaches up to 120 kg N  $\cdot$  ha<sup>-1</sup> of agricultural land. In Kujawsko-Pomorskie and Dolnośląskie voivodeship (central and western Poland) the consumption of nitrogen fertilizers has reached or even exceeded the average level of European Union (EU) countries and amounted up to over 90 kg N  $\cdot$  ha<sup>-1</sup>. The consumption of nitrogen fertilizers is smallest in the eastern and central Poland, where the intensity of agricultural production is lowest, and does not exceed 60 kg N  $\cdot$  ha<sup>-1</sup>.

Table 3.5 Structure of nitrogen fertilizers consumption in Poland in thousand tons N and in % (source: Igras and Kopiński, 2007; GUS, 2009-2011b)

Years	Unit	Ammonium sulphate	Urea	Ammonium nitrate	Calcium ammonium nitrate	Urea and Ammonium nitrate solutions	Ammonium phosphate	NPK	Total amount of nitrogen fertilizers
2004/05-	[thous. tons]	22	260	326	170	40	22	90	930
2006/07	[%]	2.4	28.0	35.0	18.3	4.3	2.4	9.7	100
2007/08-	[thous. tons]	31	314	384	202	51	26	109	1116
2009/10	[%]	2.8	28.1	34.4	18.1	4.5	2.3	9.8	100

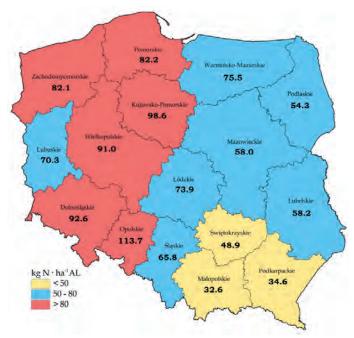


Fig. 3.5 Regional diversification of nitrogen fertilizers consumption in Poland in 2009-2011 years; AL – agricultural land (source: graph based on GUS, 2006-2011; 2009-2011b data)

#### 3.3. Productivity of nitrogen fertilizers

Cereals have the largest share in the crop structure in most European countries. For this reason, the comparison of consumption and productivity of fertilizers was made taking into account this group of plants. Further considerations relate to the assessment of average nitrogen fertilizer consumption for cereals in 2008-2010 in the EU. The data were calculated on the basis of EFMA (2011) research.

The average consumption of nitrogen fertilizers for cereals in the EU amounts to approximately  $100~kg~N \cdot ha^{\text{-}1}$  of cereal crop. The range of average doses of nitrogen fertilizers is very wide and oscillates from about  $40~kg~N \cdot ha^{\text{-}1}$  in Romania and Cyprus to nearly  $160~kg~N \cdot ha^{\text{-}1}$  of cereal crops in Great Britain. There is a fairly close correlation (R = 0.72) between the consumption of nitrogen fertilizers and yields of cereals. The analysis shows that below the lower confidence interval of the simple linear regression are South-European countries with unfavourable conditions for crop production, such as Spain, Italy, Portugal, Cyprus, and North-European countries - Estonia and Lithuania (Fig. 3.6), and among these countries there is also the Czech Republic. In these countries the achieved cereals yields are lower than could be expected on the basis of the consumption of nitrogen fertilizers.

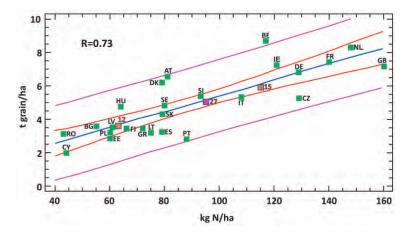


Fig. 3.6 Relation between nitrogen rates and the yield of cereals in UE countries in the years 2008–2010; abbreviations used for countries – see to Chapter 12) (source: own elaboration on the basis of EFMA, 2011 data)

Austria, Belgium, Denmark, and Hungary are above the upper confidence interval and these are countries with a high livestock density and large production of natural fertilizers. These countries achieve high grain yields with relatively low consumption of nitrogen fertilizers. Poland is close to the average (simple linear regression) and small yield of cereals in our country may result from very small doses of nitrogen fertilizers applied to these plants. The average unit consumption of nitrogen fertilizers in the EU countries is about 2.1 kg N per 100 kg of cereal

grain and this is also the approximate mineral nutrient uptake in cereal production in Poland. Spain, Greece, Cyprus, Estonia, and Lithuania have large nitrogen unit inputs, whereas in Austria, Belgium, and Denmark nitrogen is applied very sparingly (Fig. 3.7). Poland is in the group of countries with low cereal yields. Lower yields are obtained only in Romania, Estonia, and Cyprus. In Poland, about 70 kg N is applied and that gives the producing yields of about 3.3 tons of grain per hectare and the average uptake of about 2 kg N per 100 kg of grain (the value that is very close to the average of other EU countries). This value is also very close to the average nitrogen content in 100 kg of grain, which is about 1.9 kg N (Karklins, 2001).

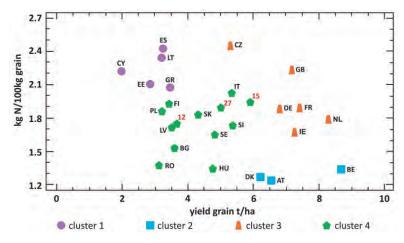


Fig. 3.7 Clusters of EU countries according to the yield of cereals and N input per 100 kg of grain in the years 2008 – 2010; abbreviations used for countries – see to Chapter 12) (source: calculations made by Fotyma on the basis of EFMA, 2011 data)

The productivity of nitrogen applied for cereals can also be calculated using various dosages of fertilizers and cereal yields at regional level. Data concerning the consumption of nitrogen fertilizers per 1 ha of agricultural land are available at regional level (Table 3.6), whereas there is no data regarding the distribution of fertilizers for each type or group of plants, including cereals. To obtain approximate data, the nitrogen fertilization preference coefficient for cereals was used. The preference coefficient is the ratio of consumption of fertilizers per 1 ha of cereal crops to their consumption per 1 ha of agricultural land. In 7 EU countries, including Poland, the preference coefficient was close to the value of 1.1 (Fotyma et al., 2001). It was assumed that the preference coefficient shows no regional variation and that 1 ha of cereal crops in Poland consumes 10% more nitrogen than 1 ha of agricultural land with other plants (Table 3.6). Apart from doses of nitrogen fertilizers, yields of cereals are affected by natural conditions and other agronomic factors. Agricultural Production Space Valuation Index (APSVI) and the share of highly acidic soils were adopted as a measure of diversity of natural conditions, whereas the consumption

of nitrogen in natural fertilizers and the share of cereals in the crop structure were adopted as a measure of other agronomic factors.

Table 3.6 The basic data concerning cereal production in Poland in the years 2008-2010; APSV Index - Agricultural Production Space Valuation Index; UAA – utilized agricultural area (source: GUS, 2009-2011a; GUS, 2009-2011b; Igras, 2008; Lipiński, 2005; Stuczyński et al., 2000)

Voivodeship	Share of cereals in sown pattern [%]	Yield of cereals [t · ha <sup>-1</sup> ]	kg N · ha <sup>-1</sup> area of cereals	kg N·ha <sup>-1</sup> UAA in natural fertilizers	APSVI	Share of acid and very acid soils [%]
1*	2*	3*	4*	5*	6*	7*
DLN	72.6	4.32	93.3	11.9	74.9	48.7
KUJ	67.6	3.60	100.9	34.4	71.0	32.6
LUB	78.7	3.17	59.0	20.9	74.1	50.9
LUS	75.1	3.27	74.0	18.3	62.3	46.7
LOD	78.4	3.02	73.9	37.1	61.9	68.7
MLP	65.9	3.24	32.8	26.7	69.3	61.7
MAZ	75.6	2.79	60.0	36.7	59.9	62.6
OPL	73.0	5.06	103.0	22.2	81.4	32.7
PDK	71.3	3.19	34.9	20.3	70.4	66.3
PDL	75.0	2.76	53.3	49.0	55.0	67.2
POM	72.4	3.48	78.7	23.9	66.2	53.7
SLS	77.6	3.49	63.4	30.6	64.2	53.1
SWT	74.6	2.87	51.7	26.9	69.3	42.0
WAM	70.8	3.67	75.9	33.7	66.0	59.0
WLP	74.4	3.59	89.6	46.5	64.8	42.1
ZAP	69.9	3.83	81.5	12.4	67.5	49.7
Poland	73.7	3.41	71.3	30.7	67.4	52.4

<sup>1\* –</sup> abbreviations used for voivodeships – see to Chapter 12; 2\* – GUS, (2009-2011a); 3\* – own calculations by J. Kopiński; 4\* – increased by 10% (own calculations by J. Kopiński), 5\* – own calculations by J. Kopiński; 6\* – Agricultural Production Space Valuation Index (soil and climate) (Stuczyński et al., 2000); 7\* – Lipiński (2005).

There is a fairly close correlation (R = 0.69) between the consumption of nitrogen fertilizers and yields of cereals (Fig. 3.8). Below the lower confidence interval of the simple linear regression are the voivodeships of Lubuskie, Łódzkie, Podlaskie, and

Mazowieckie. These voivodeships have unfavourable natural conditions for cereal production. The average Agricultural Production Space Valuation Index is lower in these voivodeships, while soil acidification index is higher than the country's average. The voivodeships of Dolnośląskie and Opolskie remain above the upper confidence interval. These voivodeships achieve high grain yields with relatively low consumption of nitrogen fertilizers and they have very favourable natural conditions for cereal production. The average consumption of nitrogen to produce 100 kg of grain in Poland is 1.9 kg N; therefore it is very similar to the consumption in EU countries and coincides exactly with the average nitrogen content in cereal grains. The voivodeships of Małopolskie and Podkarpackie are characterised by very low mineral nutrient uptake (approx. 1.1 kg N · dt<sup>-1</sup> of cereals), but the yields obtained there are among the lowest in the country. Mineral nutrient uptake exceeding 2 kg N · dt<sup>-1</sup> of cereals is observed in the voivodeships of Łódzkie and Warmińsko-Mazurskie, which indicates wasteful nitrogen management.

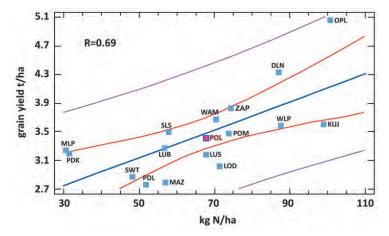


Fig 3.8 Relation between nitrogen rates and the yield of cereals in voivodeships in Poland in the years 2008-2010 (shortenings used for voivodeships – see to Chapter 12) (source: GUS, 2009-2011a, b)

In conclusion of the discussion on the productivity of nitrogen it can be therefore assumed that to achieve increase in grain yield by 100 kg per ha at least 2 kg N  $\cdot$  ha<sup>-1</sup> should be additionally applied. In order to increase cereal yields to about 5 tons of grain per hectare the dose of fertilizers in this group of plants needs to be increased by approximately 30 kg N  $\cdot$  ha, that is by about 50% compared to the doses currently applied. If no significant changes occur in the crop structure and cereals fertilization preference coefficient remains at the level of 1.1 it means that about 85 kg N  $\cdot$  ha  $^{-1}$  will be needed to apply to agricultural land used for growing crops (excluding fallows and idle land).

#### 3.4. Consumption of nitrogen in mineral fertilizers

Contrary to mineral fertilizers whose consumption is quite accurately recorded, the evaluation of the amount of nitrogen supplied to agriculture in the form of natural fertilizers (manure, slurry, and liquid manure) must be based on estimates supported by specific models. At the level of NUTS-1 and NUTS-2 [NUTS-1 - calculations at the national level, NUTS-2 calculations at the level of regions (voivodeships) - according to the classification of the EU] two basic methods may be distinguished. In both, the starting point is the knowledge of stocking density in generic and age groups.

In the first method the number of animals is converted into Livestock Units (LU) and the production of natural fertilizer (especially manure) per a single LU is estimated (below conversion coefficients used for the conversion of livestock population into livestock units according to the annex to the Regulation of the Council of Ministers of 9 November 2004 (Dz. U. Nr 257, poz. 2573, 2004) (Fig. 3.9).

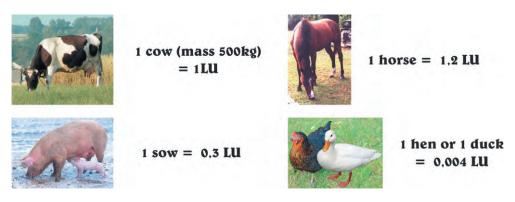


Fig. 3.9 Livestock Units (LU) conversion coefficients (source: Dz. U. Nr 257, poz. 2573, 2004)

Then the mass of manure that was calculated in this way is multiplied by a standard amount of nitrogen in the manure and the result is the amount of nitrogen in natural fertilizers. These calculations refer to the "mature manure" in the form in which the manure is delivered to the field, and therefore does not include losses of nitrogen in the process of collection and storage of natural fertilizers. The relevant calculations, made at NUTS-2 level are presented in Table 3.7.

Table 3.7 Production of organic fertilizers in Poland in 2008-2011; AL – agricultural land; LU – livestock units; UAA – utilized agricultural area (source: own calculations by Kopiński based on GUS, 2006-2011 data)

	Aı	·ea	Anii	mals	of sti	zation raw on tter	Total	produc	tion	Pre	oductio manui	
Voivode-ships*)	UAA [thous. ha]	AL [thous. ha]	Livestock population [thous. LU]	Livestock load [LU·ha¹ UAA]	[thous. t]	[kg·LU·1]	Manure [thous. t]	Liquid manure [thous. m³]	Slurry [thous. m³]	[t·ha-1 UAA]	[t·ha-l AL]	[t·LU-1]
DLN	903	755	164	0.17	300	1833	1648	227	131	1.8	2.2	9.7
KUJ	1070	943	583	0.54	300	1833	6390	1128	610	6.0	6.8	10.5
LUB	1466	1155	480	0.31	300	1833	5156	868	498	3.5	4.5	10.5
LUS	451	341	139	0.28	300	1833	1097	126	81	2.4	3.2	8.2
LOD	1029	827	573	0.54	300	1833	6310	1077	614	6.1	7.6	10.7
MLP	644	392	269	0.38	300	1833	2879	438	258	4.5	7.3	10.5
MAZ	2015	1367	1136	0.53	300	1833	12312	2177	1239	6.1	9.0	10.6
OPL	536	483	181	0.33	300	1833	2021	307	184	3.8	4.2	10.6
PDK	654	424	195	0.25	300	1833	2098	292	185	3.2	4.9	10.6
PDL	1080	676	823	0.74	300	1833	9387	1656	973	8.7	13.9	11.4
POM	737	604	280	0.35	300	1833	2972	460	265	4.0	4.9	10.2
SLS	412	314	182	0.39	300	1833	1939	253	160	4.7	6.2	10.3
SWT	525	377	216	0.37	300	1833	2300	371	218	4.4	6.1	10.3
WAM	967	661	538	0.54	300	1833	5491	792	516	5.7	8.3	10.3
WLP	1775	1515	1258	0.70	300	1833	13683	2179	1210	7.7	9.0	10.3
ZAP	865	698	165	0.17	300	1833	1581	257	137	1.8	2.3	9.2
POLAND	15129	11532	7180	0.45	300	1833	77160	12716	7280	5.1	6.7	10.4

<sup>\*)</sup> abbreviations for voivodeships are explained in Chapter 12

The average annual production of manure for the whole country is estimated at 5.1 tons · ha-1 of agricultural land and 10.4 tons · LU-1 (Table 3.7). The standard content of nitrogen in organic fertilizers amounts to 5.5 kg N · t<sup>-1</sup> of manure, 3.5 kg N · t<sup>-1</sup> of liquid manure, and 4.5 kg N · t<sup>-1</sup> of slurry (Maćkowiak and Żebrowski, 2000). This means that approximately 28.1 kg N · ha-1 is brought in with the manure, and around 2.2 kg N · ha<sup>-1</sup> in the slurry, which in total amounts to approximately 33.2 kg N · ha<sup>-1</sup> of well cultivated agricultural land. This represents approximately 32% of nitrogen delivered in mineral and natural fertilizers. One LU excretes about 53 kg of nitrogen in the form of manure, 6.7 kg of nitrogen in the form of liquid manure, and 3.0 kg of nitrogen in the form of slurry, which in total amounts to 62.8 kg N · LU<sup>-1</sup>. However, estimates of the global amount of nitrogen in natural fertilizers differ depending on the method of their calculation. The estimate based on consumption of fertilizers per hectare (30.7 kg N · ha<sup>-1</sup> of agricultural land) gives the global amount of 464 thousand tons N (per 15.1 million ha of well cultivated agricultural land), and the estimate based on the number of LUs gives a global amount of 451 thousand tons N (obtained from 7 million LU).

In Poland, the size and conditions of animal production are regionally diversified (Fig. 5.3 in Chapter 5). The production volume of each type of manure is determined mainly by the structure of livestock population, livestock density, and the breeding system. Livestock density of cows and milk production is significantly correlated with permanent grasslands, and thus indirectly depends on the structure of ownership of land and natural conditions. On the other hand, the density of pigs, highly capital-intensive type of production, is positively correlated with the share of cereals in the crop structure, the main source of fodder for this group of animals. In 2009-2011, the average density of livestock in Poland amounted to 0.45 LU · ha<sup>-1</sup> of well cultivated agricultural land. The highest livestock density is found in voivodeships of Podlaskie and Wielkopolskie, while the lowest is observed in voivodeships in western Poland: Dolnośląskie, Lubuskie, and Zachodniopomorskie. In the latter voivodeships the average dose of manure does not exceed 2.5 t · ha<sup>-1</sup> of agricultural land and is three times lower than in the voivodeships with the highest stocking density.

In the second method, the amount of nitrogen supplied in natural fertilizers is estimated by SFOM model (Standard Figures Organic Manure) developed in Denmark (Jadczyszyn et al., 2000; Fotyma et al., 2001). The algorithm of this model begins with the amount of nitrogen in urine and faeces, excreted by different types of animals, supplemented by the amount of the component in the straw used as bedding in cowsheds with bedding (with a distinction between deep and shallow litter cowsheds), and then nitrogen losses occurring in the production process and storage of natural fertilizers are estimated (Fig. 3.10). The final result of the model is the amount of nitrogen in "mature" natural fertilizers that are ready to be applied on the field.

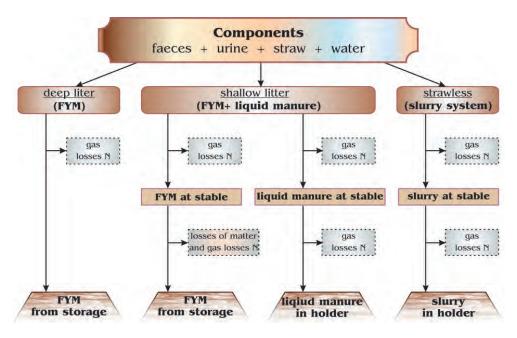


Fig. 3.10 SFOM model diagram (source: Fotyma et al., 2001)

In SFOM model, the nitrogen (and other components) calculations are made separately for 3 main animal husbandry systems, in deep cowsheds, shallow litter cowsheds, and litterless cowsheds. This is related to the type of produced organic fertilizers, i.e. manure in litter cowsheds (with deep and shallow litter), liquid manure in shallow litter cowsheds, and slurry in litterless cowsheds. For the calculation at NUTS-2 level, due to the lack of reliable data, it is assumed that about 12% of the livestock is kept in deep cowsheds and about 7% in litterless cowsheds that produce slurry. This is a fundamental difference in comparison to Western European countries, where deep cowsheds are practically non-existent, and most of the livestock is kept in litterless cowsheds. These conditions have extensive environmental implications, because due to the high content of labile forms of nitrogen (at least 50% of N in the ammonium form NH<sub>4</sub><sup>+</sup>) slurry is considered to be potentially dangerous fertilizer. The calculations of the amount of nitrogen in natural fertilizers are shown in Table 3.8. The results of calculations of nitrogen made with both methods are fairly consistent. SFOM model, however, creates much greater possibilities for interpretation and allows insight into the processes occurring after the excretion of manure until the delivery of "mature" manure to the field.

•			
Method		Indicator	
Method	kg N • ha-1	kg N · LU <sup>-1</sup>	% N in manure
"LU" model	28.1	63.3	0.46
"SFOM" model	28.7	65.9	0.49

Table 3.8 Selected synthetic indicators of the amount of nitrogen in natural fertilizers calculated by two methods (source: Kopiński and Madej, 2006)

The amount of nitrogen in natural fertilizers calculated according to this model applies only to the current structure of herds and general proportions of the husbandry systems (12% in deep cowsheds, 81% in shallow litter cowsheds (Photo 3.2) and 7% in slurry cowsheds). For readers interested in making their own calculations the amounts of net nitrogen ready to be exported to the field in natural fertilizers excreted by different types of animals are given in Table 3.9, though still taking into account the above listed proportions of the husbandry systems. Therefore, these values should not be used in the calculation for farms that use a single, well-defined livestock husbandry system.



Photo 3.2 Shallow litter cowshed (photo by B. Wróbel)

Table 3.9 The amount of nitrogen in "mature" organic fertilizers from different animals, with recognition of proportion of different types of cowsheds (shallow, deep, slurry) (source: own calculations on the basis of data by: Kopiński and Madej, 2006; Igras and Kopiński, 2007; Kopiński and Tujaka, 2009)

Total Cattle	kg N · head-1 · year-1	Total Pigs	kg N · head-1 · year-1	Other animals	kg N · head -1 · year -1
Calves < 0.5 yr.	9.75	Sows - total	18.60	Sheep and Goats - total	6.57
Female Cattle 0.5-1 yrs	21.74	Pigs 20 - 30 kg	5.89	Foals < 0.5 yr.	10.09
Male Cattle 0.5-1 yrs	22.22	Pigs 20 - 50 kg	7.12	Horses - total	30.56
Female Cattle 1-2 yrs	38.55	Porks 30 - 70 kg	11.36	Layers	0.52
Male Cattle 1-2 yrs	38.87	Fattening Pigs (porks) > 50 kg	12.14	Broilers	0.31
Heifers > 2 yrs	46.90	Fattening Pigs 70 - 110 kg	12.52	Turkeys	1.07
Bulls > 2 yrs	54.88			Geese	1.06
Dairy Cows - total	71.23			Ducks	0.95

### 3.5. The plants' use of nitrogen from mineral and organic fertilizers

For both the economic and the methodological reasons the majority of studies focus on what happens with nitrogen from mineral fertilizers. The utilization of nitrogen from mineral fertilizers may be measured by differential or isotopic methods. Both methods require accurate filed or vegetation research experiments (Table 3.10).

Table 3.10 Comparison of methods for determining the use of nitrogen from fertilizers (source: Gaj, 2008)

Method	Nitrogen utilization formula	Explanation of symbols in the formulas
Differential	$W_{R} = (U_{N} - U_{0})/N$	$U_N$ – nitrogen uptake by plants in the fertilized area, $U_0$ – nitrogen uptake by plants in the control area, $N$ – nitrogen dose
Isotopic	$W_{R} = TN_{f}/N_{a} \cdot 100$	${ m TN_f}$ - amount of nitrogen from fertilizer enriched with ${ m N^{15}}$ taken up in yield, ${ m N_a}$ - the amount of nitrogen in the fertilizer enriched with ${ m N^{15}}$

For practical purposes (e.g. fertilizer advisory services) the differential method is commonly used, but nitrogen utilization measured by this method is often referred to as apparent. This method involves the so called priming effect of nitrogen contained in fertilizers consisting in stimulating nitrogen uptake from the soil. The utilization of nitrogen is dependent on several factors, of which the most important are the size and manner of application of doses of fertilizers, soil moisture and temperature, species and even variety of plants. In multiannual crop rotation field experiments with different doses of nitrogen the average utilization of this component from the optimal dose was as follows: 65% for wheat, with a coefficient of variance of 41.3%, 48% for corn with a coefficient of variance of 37.3%, 36% for rape with a coefficient of variance of 26.5%, and 67% for barley with a coefficient of variance of 39.9% (Fotyma et al., 2007).

It is even more difficult to determine the utilization of nitrogen from organic fertilizers. Natural fertilizers contain all the minerals necessary for plants and separating the effect of one of them is methodologically very difficult. Moreover, a significant part of the nitrogen in natural fertilizers, - even most of it in the main form of organic fertilizer, i.e. the manure - is in the form of organic connections that are not directly available to plants.

The nitrogen from organic compounds enters the nitrogen cycle described in the first subchapter and is released over a longer period of time as a result of soil organic matter mineralization processes. Therefore, short-term and long-term production effects of natural fertilizers are distinguished. Currently adopted method of short-term (nutritive) effects valuation, and in practice of the evaluation of the effects of activity of mineral nitrogen contained in these fertilizers, is the determination of the so-called N Fertilizer Replacement Value (NFRV). NFRV is a factor, by which the total nitrogen content in manure should be multiplied to get the amount of the so-called acting nitrogen - operational equivalent of an appropriate amount of nitrogen in mineral fertilizers. The description and method of determining the value of NFRV can be found in the study of Fotyma and Filipiak (2006). NFRV values are highly variable depending on the type and timing of manure application, soil properties, weather conditions and species of cultivated plants. Indicative NFRV values are given according to Schroeder (2005) in Table 3.11.

Table 3.11 Indicative NFRV values depending on the type manure (source: Schroeder, 2005)

Type of fertilizer		ct as per time of f the fertilizer	Long-term effect as per time of application of the fertilizer		
	Autumn	Spring	Autumn	Spring	
Liquid manure	0.1 - 0.2 $0.5 - 0.9$		0.1 - 0.2	0.5 - 0.9	
Slurry	0.1 - 0.3	0.3 - 0.7	0.3 - 0.4	0.4 - 0.8	
Manure	0.1 - 0.3	0.2 - 0.4	0.4 - 0.6	0.6 - 0.7	

NFRV values must not be synonymous with the coefficient of utilization of nitrogen from manure. NFRV value = 0.3 (e.g. from, manure) just means that 100 kg N contained in manure has the same fertilizing effect as 30 kg N contained in mineral fertilizers. It should be remembered that 30 kg N in mineral fertilizers would not be used 100%.

Therefore, in reality, the utilization of nitrogen from organic fertilizers (especially manure) by plants is very low, which is of great environmental consequences. The amount of nitrogen that is not utilised by plants enters the nitrogen cycle in agricultural systems and that is associated with potentially large losses as a result of the volatilization of gaseous forms of nitrogen and N leaching.

#### 3.6. Content of mineral forms of nitrogen in soil

Almost all soil nitrogen occurs in the soil organic matter. Nitrogen in the mineral form (ions  $NH_4^+$  and  $NO_3^-$ ) described in brief as  $N_{min}$  constitutes only a few percent of the total amount of this component. However, this is the most mobile, directly available to plants and easy to determine form of nitrogen. Information on  $N_{\min}$ during early spring and late autumn is particularly interesting. The nitrogen content in spring allows for more precise dose levels of nitrogen fertilizer, and the nitrogen content in autumn is very important because of possible threats to the environment caused by excess nitrate. The  $N_{\min}$  difference of content in the soil profile between autumn and spring can be used to assess the magnitude of nitrogen losses through leaching of this component from the soil. In 1997, to the order of the Ministry of Agriculture and Rural Development, chemical and agricultural stations began monitoring the content of soil mineral nitrogen and have been continuing it until now. Approximately 5,000 monitoring points were selected all over Poland where in spring and autumn samples from 0-90 cm soil profile divided into 3 layers at every 30 cm are regularly taken. The contents of ammonium and nitrate forms of nitrogen is determined in the soil samples and converted into the N<sub>min</sub> content expressed in each layer and in the whole soil profile. The results of these studies were published in the form of two large syntheses (Fotyma et al., 2004) and their summary will be presented here. The content of mineral nitrogen in soil demonstrates very high spatial and seasonal variability, and the distribution of concentration greatly deviates from the normal distribution. For this reason, the median (rather than the arithmetic mean) was adopted as a measure of the average value, and as a measure of dispersion the percentiles distribution (instead of the average standard deviation). The explanation of this way of presentation of monitoring studies results is given in Chapter 4 of this monograph.

The factor that most strongly differentiates the content of mineral nitrogen in soil is its granulometric composition, and in practice the agronomic category (Tables 3.12 and 3.13).

Table 3.12 Content and distribution of mineral nitrogen content in 0-90 cm soil profile belonging to different agronomic categories (average values for the years 1997 - 2005) (source: Fotyma and Fotyma, 2006)

Percentiles range	$N_{_{min}}$ content in soil in autumn [kg $\cdot$ ha $^{ ext{-}1}$ ]				$N_{min}$ content in soil in spring [kg · ha <sup>-1</sup> ]			
	Very light	Light	Medium	Heavy	Very light	Light	Medium	Heavy
Number of samples	10095	13917	14848	7586	10142	14217	15143	7662
0-20 %	up to 49	up to 56	up to 60	up to 59	up to 40	up to 51	up to 59	up to 62
21-40 %	50 - 69	57 - 78	61 - 84	60 - 84	41 - 55	52 - 70	60 - 81	63 - 84
41-60 %	70 - 90	79 - 103	85 - 113	85 - 113	56 - 74	71 - 92	82 - 106	85 - 111
61-80 %	91 - 127	104-146	114-161	114-159	75-103	93-126	107-147	112-153
81-100 %	up to 128	up to 147	up to 162	up to 160	up to 104	up to 127	up to 148	up to 154
Median	79	89	97	98	64	81	93	97

Table 3.13 Content and distribution of nitrate nitrogen content in 0-90 cm soil profile belonging to different agronomic categories (average values for the years 1997 - 2005) (source: Fotyma and Fotyma, 2006)

Percentiles range	NO <sub>3</sub> -N content in soil in autumn [kg • ha <sup>-1</sup> ]				NO <sub>3</sub> -N content in soil in spring [kg · ha <sup>-1</sup> ]			
	Very light	Light	Medium	Heavy	Very light	Light	Medium	Heavy
Number of samples	10275	14227	15061	7582	10243	14296	15066	7562
0-20 %	up to 27	up to 34	up to 37	up to 40	up to 17	up to 26	up to 34	up to 38
21-40 %	28 - 44	35 - 54	38 - 59	41 - 62	18 - 28	27 - 42	35 - 54	39 - 60
41-60 %	45 - 63	55 - 76	60 - 86	63 - 90	29 - 42	43 - 61	55 - 77	61 - 84
61-80 %	64 - 93	77-114	87-130	91-133	43 - 66	62 - 90	78 - 113	85 - 122
81-100 %	up to 93	up to 115	up to 131	up to 134	up to 66	up to 90	up to 114	up to 123
Median	53	64	72	75	34	51	64	71

An analysis of the data presented in Tables 3.12 and 3.13 allows drawing several important conclusions:

- N<sub>min</sub> content of mineral nitrogen and of forming its part NO<sub>3</sub>-N nitrogen increases in the direction from very light to heavy soils,
- The difference between the content of nitrogen in very light and heavy soils is much greater in spring than in autumn,
- The content of mineral nitrogen, especially nitrate nitrogen, is higher in autumn than in spring,
- The difference in the content of nitrogen between autumn and spring periods is significantly higher in very light soils than in heavy soils.

It can be therefore assumed that the difference in the content of nitrate nitrogen, as the most mobile of mineral nitrogen forms, between autumn and spring periods corresponds to the loss of this component through leaching from 0-90 cm soil profile during winter. The estimated amount of nitrate nitrogen leached from 1 ha of soil amounts to 19 kg NO<sub>3</sub>-N from very light soils, 13 kg NO<sub>3</sub>-N from light soils, 8 kg NO<sub>3</sub>-N from medium soils and 4 kg NO<sub>3</sub>-N from heavy soils (Table 3.14). In Poland very light soils occupy 23.4%, light soils 36.1%, medium soils 29.4%, and heavy soils 11.1% of the agricultural area (Stuczyński, personal communication). The average weighted losses of nitrate in Poland due to leaching can therefore be estimated at approximately 12 kg NO<sub>3</sub>-N from 1 ha of agricultural land, or about 190 thousand tons NO<sub>3</sub>-N from the entire area of agricultural land, which currently stands at about 16 million ha.

The decisive factor in nitrate losses during the period of autumn - spring is nitrate content in soil during autumn. The higher nitrate content, the greater is the loss of nitrate in winter. There is a significant relationship between the granulometric composition (agronomic category) of soil and nitrate losses in autumn. As results from the following regression equations the effect of the content of nitrates in the autumn on their losses from 0-90 cm soil profile is greater in lighter soils than in heavier soils (Fig. 3.11).

```
Very light soils: y = -17.276 + 0,6443 N_j; R = 0.68
Light soils: y = -25.662 + 0,6005 N_j; R = 0.65
Medium-heavy soils: y = -24.668 + 0,4710 N_j; R = 0.47
Heavy soils: y = -28.643 + 0,4098 N_j; R = 0.40
```

Where: y = nitrate losses in the period autumn – spring in kg NO<sub>3</sub>-N · ha<sup>-1</sup>, N<sub>1</sub> = nitrate content in the 0-90 cm soil profile in autumn in kg NO<sub>3</sub>-N · ha<sup>-1</sup>

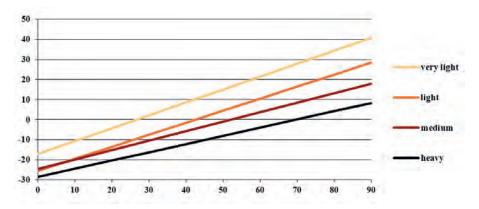


Fig. 3.11 Losses of nitrate in soil, depending on the agronomic category of the soil (source: Fotyma and Fotyma, 2006)

#### 3.7. Nitrate concentrations in soil water

Soil water is present in the unsaturated zone, in which it is maintained by capillary forces, and in the saturated zone, where it is maintained by gravity forces. The first type of water is referred to as soil solution and is found in 0-90 cm soil profile, and the other type of water is referred to as groundwater and is below 90 cm. Groundwater is located within the drainage system and because of the manner of its uptake is also known as drain water. A more detailed classification of types of groundwater is given in Chapter 6 of the monograph.

The so far discussion focused on the difference in nitrate content during autumn and winter, describing it in simplification as losses of this form of nitrogen out of 0-90 cm soil profile. Losses of nitrate may occur as a result of denitrification (in the form gaseous compounds) and as nitrate leaching from soil by excess rain water (Fig. 3.1). In monitoring studies the separation of these two types of losses of nitrate is of course impossible. It may be only assumed that the loss of nitrate in winter is associated mainly with its leaching, because at low temperatures, soil denitrification, being a microbial process, is very limited. In designating areas vulnerable to nitrate pollution the amount of these compounds leached from the soil is not as much important as their concentration in the groundwater. This concentration can be theoretically calculated based on knowledge of the losses of nitrate and water seepage through the soil profile, according to the formula:

Losses of nitrate, depending on the agronomic category of soil, were given in the previous subchapter. The amount of water percolating beyond the 0-90 cm soil profile is much more difficult to calculate, or in fact to estimate. The amount of percolated water depends on three factors: field water capacity (FWC), the degree of soil saturation with water at the beginning of winter, and the amount of rainfall in winter. Field water capacity of soil depends to a decisive extent on its granulometric composition (agronomic category). In very general terms it can be assumed that field water capacity of 0 - 30 cm layer of very light soils is about 40 mm, of light soils about 55 mm, of medium soils approximately 85 mm and of heavy soils approximately 130 mm (Fotyma et al., 2005). Based on water content in soils and losses of nitrate during the period autumn - spring nitrate concentrations in groundwater at 90-120 cm soil layer, where drainage systems are located, were simulated. It was assumed that this layer is always saturated with water to a full field water capacity (FWC), and that the total amount of nitrate subject to losses in winter moves into this layer of soil. A modified formula was used for the simulation:

Concentration mg NO<sub>3</sub>-N · dm<sup>-3</sup> = (losses kg NO<sub>3</sub>-N · ha<sup>-1</sup>/amount of water mm in 90-120 cm soil layer) · 100

The outcome of calculation of nitrate concentrations in groundwater for soils classified into particular agronomic categories is shown in Table 3.14.

Table 3.14 Simulation of nitrate concentration	in groundwater	depending on soil
texture (source: Fotyma et al., 2004)		

Soil category	Loss of nitrate in winter period [kg NO <sub>3</sub> -N · ha <sup>-1</sup> ]	Water capacity of 90-120 cm layer in [mm]	Nitrate concentration in groundwater [mg NO <sub>3</sub> -N·dm <sup>-3</sup> ]		
Very light	19	40	$19/40 \cdot 100 = 47.5$		
Light	13	55	$13/55 \cdot 100 = 23.6$		
Medium-heavy	8	85	8/85 · 100 =9.4		
Heavy	4	130	$4/130 \cdot 100 = 3.1$		
On the average, including the effect of soil category	12	-	23		

Simulated nitrate concentration is greatest in the groundwater of light soils, which results both from increased nitrate losses and low water holding capacity of these soils. Knowing the share of soils belonging to each category in each voivodeship the average water capacity and simulated nitrate concentrations in groundwater in these voivodeships were calculated.

In 1998 monitoring studies on the chemical composition of soil and groundwater were started in about 700 test farms, which are located all over Poland (Fig. 3.12). These studies have been continued to date.



Fig. 3.12 Location of sampling points on test farms (source: Igras, 2004)

In each farm 2-3 water sampling points have been located, so the number of samples greatly exceeds the number of test farms. Water samples have been collected from the drains, drainage ditches and water wells or piezometers, in autumn and spring. Unfortunately, monitoring of both parameters, i.e. of the content of mineral nitrogen in soil and of concentrations of nitrate (and other components) in water until 2005 were carried out independently and the checkpoints did not correspond. Methodological details and results of monitoring of soil and groundwater in the years 1999-2002 are presented in the works of Igras (2004, 2006). In this Chapter only the average concentrations of nitrate in drainage waters in different voivodeships are given in order to include them in cluster analysis and make a comparison with simulated concentrations in groundwater at a depth of 90-120 cm. The relevant data are given in Table 3.19 (column 5) in subchapter 3.9. A comparison of data in columns 4 and 5 of this table shows that the nitrate concentrations in drainage water are several times lower than the simulated concentrations in groundwater at the same depth at which drainage systems are located. This may be partly due to diverse representativeness of samples and completely different methodological approaches applied in the systems for monitoring soil and water, but the main reason are processes of self-purification of soil water and groundwater in their flow upwards from soil waters (up to 90 cm), through groundwater, drainage waters, water in drainage ditches to surface

waters - rivers and lakes. Process of denitrification (Fig. 3.1), leading to release of nitrogen gas, plays an important role. Denitrification process occurs under anaerobic conditions and is mainly of microbiological character; therefore it is dependent on carbon sources and temperature. Smaller, but significant losses of nitrogen gas also occur during the process of nitrification, in which the intermediate product is nitrite ion NO<sub>2</sub><sup>-</sup>. The differences of nitrate concentrations in drainage waters and waters in open ditches (Igras, 2004) are a direct evidence of the size of the process. However, there was significant correlation between nitrate concentrations in drainage waters and simulated concentrations in the groundwater at a depth of 90-120 cm, which proves the correctness of the methodology. The interdependence of the two types of concentrations is presented by the linear regression equation:

Concentration in drainage waters = 1.7827 + 0.0945 x simulated concentrations in groundwater, R = 0.69

It arises from the above equation, extrapolated beyond the scope of simulated concentrations calculated in own studies, that only with the simulated concentration in groundwater of approximately 100 mg  $NO_3$ -N · dm<sup>-3</sup> the nitrate concentration in drains may exceed the critical level set by Nitrates Directive (11.3 mg  $NO_3$ -N · dm<sup>-3</sup>). However, simulated nitrate concentrations in groundwater at the depth of 90-120 cm did not exceed the critical level in any of the voivodeships.

#### 3.8. Nitrogen balance in the EU and in Poland

In national (NUTS-1) and regional (NUTS-2) studies usually the method of balancing the components "on the soil surface" is used, which is officially recommended and binding for nitrogen in the OECD countries (OECD, 2005). In this method, the intake side includes the amount of the component in mineral and natural fertilizers and the amount of the component introduced with seeds and planting material, including biological fixation and nitrogen deposits from the atmosphere. Since 2002, this balance has been defined as the gross balance. Since 2009 the methodology of nitrogen and phosphorus balance calculation has also been adopted by OECD, Eurostat (2007) and Kopiński (2007) (Fig. 3.13).

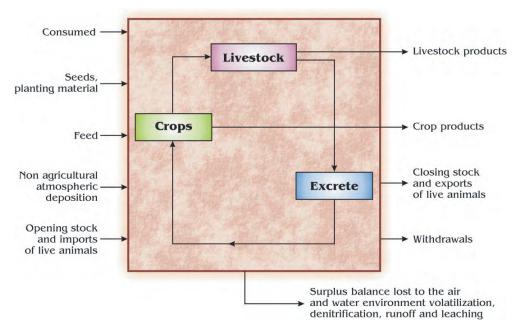


Fig. 3.13 Balance elements "on the soil surface" (source: own elaboration on the basis of OECD, 2005; Eurostat, 2009 http://ec.europa.eu/eurostat/product?code=aei\_pr\_gnb&langu age=en&mode=view)

With the unified methodology it is possible to compare the balance and efficiency of nitrogen utilization between countries and to determine the dynamics of changes in different years (Fig. 3.14 and 3.15).

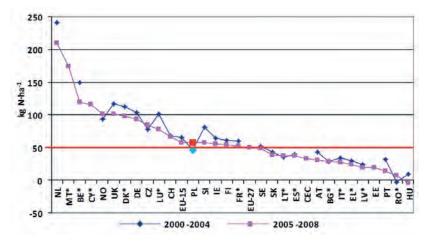


Fig. 3.14 Nitrogen balance in the UE countries in the years 2000-2004 and 2005-2008; abbreviations for countries see to Chapter 12 (source: Eurostat, 2009 http://ec.europa.eu/eurostat/product?code=aei\_pr\_gnb&language=en&mode=view)

The average balance of nitrogen for 27 EU countries is  $50 \text{ kg N} \cdot \text{ha}^{-1}$ . Such a low average value of the balance is due to the fact that many countries that have been recently admitted to the EU have extensive agriculture with low consumption of mineral fertilizers. The figure also indicates that in recent years the nitrogen balance has been reduced in most European countries. Poland has N balance comparable to the "old" EU-15 and higher than the average of the EU-27. However, in recent years the value of nitrogen balance in Poland has increased due to a large extent to the increase in crop production intensity measured by the use of nitrogen fertilizers (Fig. 3.16; Kopiński and Tujaka, 2010).

The average utilization of nitrogen in the EU-27 countries in 2004-2008, calculated as the ratio of outflow to inflow, amounted to 61%. During this period, Poland with the N utilisation of 54% remained below the average. Very high nitrogen utilisation takes place in Portugal, Romania, and Hungary (78-100%). In the Netherlands and Norway, Cyprus, and Malta nitrogen utilization is below 50% (Fig. 3.15).

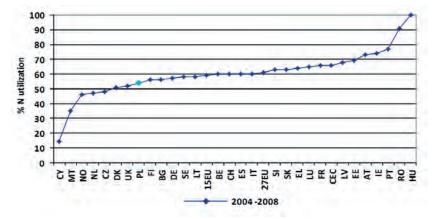


Fig. 3.15 Nitrogen utilization in % in UE countries in 2004-2008; abbreviations for countries see to Chapter 12 (source: Eurostat, 2009 http://ec.europa.eu/eurostat/product?code=aei\_pr\_gnb&language=en&mode=view)

Changes in nitrogen balance in Poland in the last 26 years show three characteristic periods (Fig. 3.16). The first lasting to the 1990, the second covering the nineties, after the initiation of economic and political system reforms in the country, and the third connected with the accession of Poland to the EU. As a result, in the last three years nitrogen surplus in Poland has risen to  $58.4 \, \text{kg N} \cdot \text{ha}^{-1}$  of agricultural land, with an average annual growth estimated at around 2.3 kg N · ha<sup>-1</sup> of agricultural land. This is a negative phenomenon indicating the increase of potential adverse impact of intensive agricultural production on the environment (Kopiński and Tujaka, 2010). Values of nitrogen balance in voivodeships and in the entire Poland are presented in Tables 3.15 and 3.16.

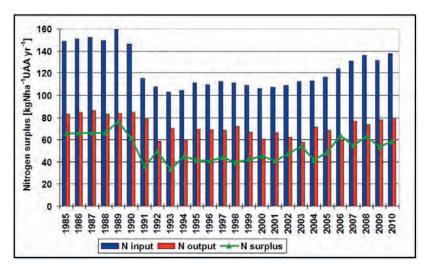


Fig. 3.16 Long term development of nitrogen balance in Polish agriculture; UAA – utilized agricultural area (source: own calculations by Kopiński based on GUS, 2006-2011; 2009-2011a; 2009-2011b data)

Table 3.15 Nitrogen balance in voivodeships of Poland in the years 2008-2010; abbreviations for voivodeships see to Chapter 12; UAA – utilized agricultural area (source: own calculations by dr. J. Kopiński based on GUS, 2006-2011; 2009-2011a; 2009-2011b data)

	Thous. tons			kg	Efficiency		
Voivodeships	Total inputs	Total outputs	Balance	Total inputs	Total outputs	Balance	of N use <sup>1)</sup> [%]
DLN	121	72	49	133.3	79.3	54.0	59.5
KUJ	184	93	91	169.9	85.5	84.4	50.3
LUB	166	100	66	111.7	67.0	44.7	60.0
LUS	55	28	28	124.0	62.2	61.7	50.2
LOD	150	76	75	143.3	72.3	71.0	50.5
MLP	61	46	15	93.4	70.8	22.6	75.8
MAZ	264	146	118	129.8	71.8	58.0	55.3
OPL	84	53	31	154.4	96.7	57.7	62.6
PDK	57	43	15	85.3	63.2	22.1	74.1
PDL	148	97	51	135.1	88.2	46.9	65.3
POM	100	55	44	134.5	74.4	60.1	55.3
SLS	53	31	22	126.9	74.7	52.1	58.9
SWT	60	35	24	111.0	65.7	45.3	59.2
WAM	137	80	57	144.6	84.4	60.2	58.4

	Thous. tons			kg	Efficiency		
Voivodeships	Total inputs	Total outputs	Balance	Total inputs	Total outputs	Balance	of N use <sup>1)</sup> [%]
WLP	314	153	161	176.6	86.2	90.4	48.8
ZAP	108	63	45	121.7	70.9	50.8	58.3
POLAND	2060	1168	892	135.0	76.5	58.4	56.7

<sup>1)</sup> Efficiency of N use=Total outputs/Total inputs ·100

Table 3.16 Nitrogen balance elements in voivodeships of Poland in the years 2008-2010 in kg N  $\cdot$  ha<sup>-1</sup> UAA; UAA - utilized agricultural area; abbreviations for voivodeships see to Chapter 12 (source: own calculations based on GUS, 2006-2011; 2009-2011a; 2009-2011b data)

Voivodeships	$N_{\rm mf}^{-1)}$	N <sub>of</sub> <sup>2)</sup>	N <sub>is</sub> <sup>3)</sup>	N <sub>sym</sub> <sup>4)</sup>	N <sub>atm</sub> <sup>5)</sup>	N <sub>in</sub> <sup>6)</sup>	N <sub>out</sub> <sup>7)</sup>	Balance 8)
DLN	93.3	15.5	2.5	5.0	17.0	133.3	79.3	54.0
KUJ	100.9	43.1	2.5	6.3	17.0	169.9	85.5	84.4
LUB	59.0	26.6	2.7	6.5	17.0	111.7	67.0	44.7
LUS	74.0	25.1	2.1	5.7	17.0	124.0	62.2	61.7
LOD	73.9	44.2	2.7	5.5	17.0	143.3	72.3	71.0
MLP	32.8	35.3	2.0	6.3	17.0	93.4	70.8	22.6
MAZ	60.0	44.9	2.2	5.8	17.0	129.8	71.8	58.0
OPL	103.0	26.8	2.6	5.0	17.0	154.4	96.7	57.7
PDK	34.9	26.0	2.2	5.2	17.0	85.3	63.2	22.1
PDL	53.3	57.3	1.9	5.6	17.0	135.1	88.2	46.9
POM	78.7	30.1	2.6	6.2	17.0	134.5	74.4	60.1
SLS	63.4	38.6	2.3	5.6	17.0	126.9	74.7	52.1
SWT	51.7	32.8	2.4	7.1	17.0	111.0	65.7	45.3
WAM	75.9	42.9	2.1	6.7	17.0	144.6	84.4	60.2
WLP	89.6	61.3	2.6	6.1	17.0	176.6	86.2	90.4
ZAP	81.5	14.5	2.4	6.2	17.0	121.7	70.9	50.8
POLAND	71.3	38.3	2.4	5.9	17.0	135.0	76.5	58.5

 $<sup>^{1)}</sup>$   $N_{mf}-N$  in mineral fertilizers,  $^{2)}$   $N_{of}-N$  in organic fertilizers,  $^{3)}$   $N_{is}-$  nitrogen in seeds,

On the nitrogen inflow side mineral fertilizers are the essential item followed by organic fertilizers (ca. 80% in total) (Table 3.16). Other sources are largely based on estimates, and especially deposits of nitrogen from the atmosphere seem to be overestimated. Total inflow of nitrogen to the surface of the "farm Poland" in the years 2008-2010 averaged to about 2060 thousand tons N, or approximately 135 kg N  $\cdot$  ha<sup>-1</sup> of well cultivated agricultural land (AL). Of this amount approximately

 $<sup>^{4)}</sup>$   $N_{sym}^{m}$  – nitrogen fixed by symbiotic bacteria,  $^{5)}$   $N_{atm}$  – deposits of nitrogen from the atmosphere,

 $<sup>^{6)}</sup>$   $N_{in}^{-}$  - total N input,  $^{7)}$   $N_{out}$  – total N output,  $^{8)}$  N balance  $N_{in}$  –  $N_{out}$ 

1,170 thousands tons N outflows from the fields with crop yields, that is about 77 kg N·ha<sup>-1</sup> of agricultural land. Therefore, gross nitrogen balance calculated in this way amounts to approximately 892 thousand tons N and to about 58.4 kg N · ha<sup>-1</sup> AL. It should be noted that the highest increase in nitrogen balance as a result of a significant increase in intensity of production, occurred mainly in the voivodeships at the forefront of the rate of consumption of nitrogen in mineral fertilizers, i.e. Kujawsko-Pomorskie, Wielkopolskie, Dolnośląskie, and Opolskie. At the same time in these voivodeships there was a significant decrease in the efficiency of nitrogen utilisation within the range from 5 to 15%.

Nitrogen balance calculated using "on the soil surface" method creates quite optimistic picture of the management of this component in Europe and in Poland. Although nitrogen balance in our country is positive, but it is in compliance with good European standards, just like the level of utilization of this component by plants. However, the issue of nitrogen balance should be also considered from the perspective of global amounts of nitrogen dispersed into soil and aquatic environments, and to the atmosphere. As far as methodology is concerned, the method of "nitrogen balance at the farm gate" and systemic balances, which track the flow of excess mineral components, are used. However, preparation of such balances in the scales larger than the farm is difficult due to lack of available data, and their results may be subject to significant errors.

The balance drawn up "at the farm gate" on the intake side takes into account the amount of nitrogen flowing into the farm from the outside in the form of mineral fertilizers and industrial feed, including nitrogen contained in atmospheric precipitation and biologically fixed (Fig. 3.17).

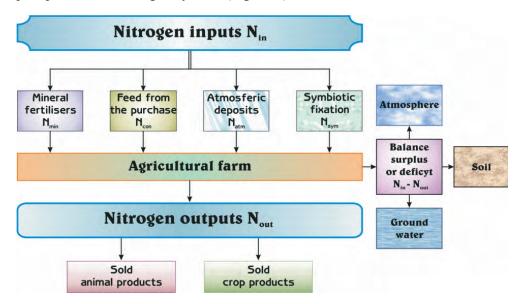


Fig. 3.17 Balance elements at the "farm gate" (source: OECD, Eurostat, 2007)

On the output side the balance takes into account the amount of nitrogen flowing out of the farm in the form of commodities of plant and animal origin. Components contained in natural fertilizers, seeds and seeding material are not taken into account as they circle within the farm.

In further discussion the entire Polish territory is treated as one farm, for which the components balance "at the farm gate" was drawn up. In the years 2008-2010 about 1065 thousand tons N in the form of mineral fertilizers was brought into the "farm Poland" (Table 3.15). This amount is measurable and fully reliable. Less certain is the amount of nitrogen in the atmospheric precipitation (255 thousand tons N) and the amount of nitrogen fixed by symbiotic bacteria (89 thousand tons N). The intake side does not include the amount of nitrogen bound by free-living bacteria, since the estimates presented by different authors are very divergent. The most difficult is the estimation of amounts of components supplied in the form of imported animal feed (Table 3.17). The inflow of nitrogen in feed is significant and reaches about 225 thousand tons N which represents approximately 25% of the amount applied in mineral fertilizers. The total supply of nitrogen in fertilizers, atmospheric precipitation, symbiotically fixed and in animal feed can be estimated at about 1 380 thousand tons N.

Table 3.17 The amount of mineral components in feed imported by the "farm Poland" in the years 2003-2007 (source: Rynek pasz, 2008; Normy żywienia, 1993)

Product	Immont [th over town]	Nitrogen		
Product	Import [thous. tons]	[kg N • t <sup>-1</sup> ]	[thous. tons N]	
Maize	304	16.6	5.05	
Cereals	275	19.7	5.42	
Bran	180	27.2	64	
Soybean meal	1696	80.0	136	
Rapeseed meal	188	64.0	12	
Fishmeal	16	139.0	2.22	
Leguminous plants	20	35.7	0.71	
Total	2 679	382.2	225	

It is also very difficult to estimate the quantity of nitrogen in plant and animal products which are sold by the "farm Poland". The sales volume must include the domestic market and exported products. The estimation of nitrogen in the products (commodities) purchased from farms in the years 2004 - 2007 is presented in Table 3.18.

Other

Total

Product	Purchase [thous. tons N]	Purchase [kg N·t <sup>-1</sup> ]	Gross outflow <sup>1)</sup> [thous. tons N]	Net outflow <sup>2)</sup> [thous. tons N]
Cereals	7152	18.6	133	85.8
Potatoes	1125	3.5	4	4.0
Beet	12072	1.8	22	3.2
Rape	1641	33.5	55	40.5
Vegetables	1211	2.3	3	2.5
Fruits	1166	1.5	2	1.5
Livestock	3913	32	125	94.0
Milk	8288	5.6	46	5.6
Eggs (million pieces)	920	1.21	1	1.0
Wool	268	30.7	8	6.0

Table 3.18 Estimate of components in plant and animal products purchased from the "farm Poland" in the years 2004-2007 (source: GUS, 2007, 2008)

19

418

11.4

255.5

The gross outflow of nitrogen from the "farm Poland" is estimated at about 418 thousand tons N (Table 3.18). The amount is clearly overestimated as the total nitrogen uptake with crop yields do not exceed 1168 thousand tons N (Table 3.15). Part of gross nitrogen content of the products or commodities remains or returns to the "farm Poland" in the form of feed or waste and that is estimated at the level of about 40%. By correcting the amount of nitrogen remaining or returning to the "farm Poland" we get a net outflow of nitrogen from the "farm Poland" in the amount of about 256 thousand tons N (Table 3.18). This nitrogen enters the market as food products of plant and animal origin. When converted into per capita consumption of food produced in Poland (42 million inhabitants, including 4 million staying abroad) it gives approximately 6.0 kg N · year 1, which is nearly the double annual demand for nitrogen of an adult person (approximately 3.25 kg N · year · ) (DRI, 2005) Therefore, it should be assumed that some net nitrogen outflowing from the "farm Poland" goes beyond national borders in the form of exported agricultural products, and some part of it goes to garbage dumps as waste from the processing of agricultural products for food. Nitrogen contained in imported food and agricultural products sold in the domestic and foreign markets may be of no interest as it does not relate directly to agriculture. Of course, there are also large losses in manufacturing and consumption, but most of the lost nitrogen goes to garbage dumps and sewage sludge. These

<sup>&</sup>lt;sup>1)</sup> from multiplying the values in columns 2 and 3; <sup>2)</sup> after deduction of all or part of a product that remains at (returns to) the "farm Poland"

wastes are only minimally recycled (treated) in agriculture and therefore they are not included in the balance calculation.

The systemic approach aimed at defining the fate of the nitrogen dissipated from agriculture may also be applied in nitrogen balancing. The individual streams of nitrogen losses, which are estimated on the basis of scientific research, are components of the systemic balance. Nitrogen losses from agriculture occur as a result of emission of gaseous compounds of ammonia and nitrogen oxides, and of nitrate ions leaching.

According to Sosulski and Łabętowicz (2008) losses of ammonia from animal production in Poland are about 200 thousand tons of NH<sub>3</sub>, and from agricultural land about 40 thousand tons of NH<sub>3</sub>. Indeed, there is a big emission of ammonia which is estimated by the authors to amount to approximately 50 thousand tons NH<sub>2</sub>, but this quantity of the component is included in the balance at the intake side as nitrogen from atmospheric precipitation. Therefore, the most likely loss of nitrogen in the form of ammonia amounts to approximately 250 thousand tons of NH, and this is the approximate value of ammonia emissions from agriculture which is reported by Pietrzak (2006). Significant losses of nitrogen occur in the form of oxidized gaseous products, nitrogen oxides, N<sub>2</sub>O, NO<sub>2</sub> and elemental nitrogen N<sub>3</sub>. These products are formed in the processes of chemical and biological denitrification of nitrogen in soils, soil waters, and groundwater. Direct measurement of N<sub>2</sub> and NO<sub>3</sub> emissions is very difficult and requires the use of isotopic techniques. However, it is possible to directly measure the emissions of N<sub>2</sub>O, and given the importance of nitrous oxide as a greenhouse gas there are numerous publications on this subject (e.g. Hatfield and Follett, 2008; Sosulski and Łabętowicz, 2008). Following the studies of Pietrzak et al. (2002) it was assumed that the emissions of nitrous oxide from agricultural production space in Poland amount to approx. 48 thousand tons N. This is slightly more than is reported in GUS (2008) (approx. 34 thousand tons N<sub>2</sub>O-N), and to that matter Sosulski and Łabętowicz (2008) agree. The emissions of nitrous oxide remain in the defined (quite widely) proportion to the total emissions of gaseous nitrogen products. At the global scale the emissions of N<sub>2</sub>O amount to approximately 4.5% of total emissions of N<sub>2</sub> and NO<sub>3</sub> (Hatfield and Follett, 2008). In Poland the share of the total nitrous oxide emissions in total emissions of gaseous products of denitrification oscillates between 3 - 10% (Sapek, 1998). Finally Sosulski and Łabętowicz (2008) estimate the loss of nitrogen in the form of elemental nitrogen to about 480 thousand tons N, whereas Pietrzak et al. (2002) to about 600 thousand tons N. Therefore, all the authors assume the share of nitrous oxide emissions in total emissions of gaseous products of denitrification as being close to the upper value (8-9%). Given the lack of own research it was decided to calculate the total size of nitrogen losses through denitrification (N2, NO, and N2O) from the difference in nitrogen balance "at the farm gate" and the amount of leached nitrogen and nitrogen escaping in the form of ammonia, and gave a value of 780 thousand tons N.

Finally, the loss of nitrogen occurs in ionic form, when NO<sub>3</sub>-N is leached from agriculturally used soils. According to monitoring studies (see previous subchapter) on average about 12 kg N · ha-1 is leached from soils, and simulated nitrate concentrations in soil water at depths below 1 m reach 27 mg NO<sub>3</sub>- N· dm<sup>-3</sup>. Across the agricultural land in Poland, (about 16 million ha), nitrogen losses attributed to leaching to soil waters and groundwater amount to approximately 190 thousand tons N. Such a scale of the loss of nitrogen from agricultural land has been identified by Fotyma and Fotyma (2006) for the first time in a direct way for the whole country on the basis of monitoring results. The losses of nitrate leaching from farmsteads (piles of manure and silage) have to be added, and these losses were estimated by Sosulski and Łabętowicz (2008) as amounting to 30 thousand tons N. This gives a total loss of nitrogen in the form of nitrates transferred to soil and groundwater in the amount of about 220 thousand tons N. It is the first such a low estimate of nitrogen losses through leaching, as other authors give values of about 250 thousand tons N (Sosulski and Łabętowicz, 2008), 380 thousand tons N (Pietrzak et al, 2002), and even 480 thousand tons of N (Sapek et al., 2000). This amount, however, agrees with the figure given in the report of the University of Wageningen devoted to the evaluation of nitrate vulnerable zones (Assessment, 2007).

Another interesting method of nitrogen balancing, although related only to nitrogen from mineral fertilizers, was proposed by Galloway and Bowling (2002) (Fig. 3.18). According to the calculation made with the use of their method, of the 100 N atoms fixed in the form of fertilizers 6 atoms are lost in the process of production, transport and storage, whereas 94 atoms are introduced into soil-plant cycle. Of this quantity, 47 atoms (50%) are taken up by plants, and the rest is dispersed into the environment in the form of gaseous products (NH<sub>3</sub>, N<sub>2</sub>, NO<sub>x</sub>) or ionic (NO<sub>3</sub>-N leaching). Of the 47 N atoms incorporated in the nitrogenous compounds of plants, 31 atoms are contained in the final plant products, and the rest of them is subject to metabolic and harvest losses. Of the 31 nitrogen atoms contained in agricultural crops 5 atoms are lost in the agri-food industry, while the next 12 are lost in the final process of preparing food. Ultimately, only 14 of the 100 N atoms fixed in the form of fertilizers are incorporated in human proteins. This balance applies only to vegetarians, since in the plant-meat diet the final efficiency of nitrogen fixed in the form of fertilizers does not exceed 4% (4 of 100 atoms contained in fertilizers).

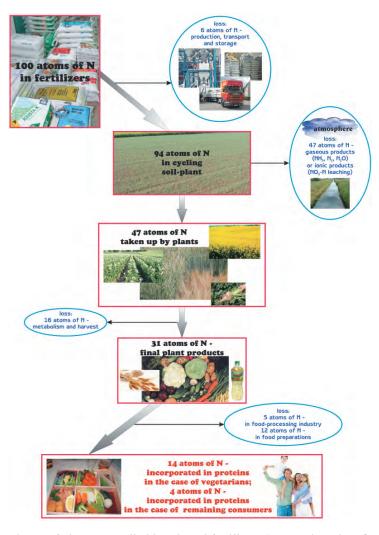


Fig. 3.18 Balance of nitrogen applied in mineral fertilizers (source: based on figures given by Galloway and Bowling, 2002)

The polarization processes taking place in Polish agriculture concerning, inter alia, the agrarian structure and the intensity of agricultural production, are also visible in the results of nitrogen balance, confirming nitrogen's important role as an indicator of the deepening of the existing regional agri-environmental diversity. The observed changes in nitrogen balance indicate that the increase in the intensity of agricultural production leads to lower production and economic efficiency of nitrogen utilisation, when it is not accompanied by corresponding modifications of the organizational and technological sphere of the production.

# 3.9. Territorial differentiation of environmental threats caused by excess of nitrogen

The territory of Poland is highly differentiated in terms of factors that determine the degree of nitrogen excess hazards. Factors that have been quantified in the previous subchapters are summarized in Table 3.19 and described under the table.

Table 3.19 Factors that affect the degree of nitrogen excess hazards in Polish regions (voivodeships) (NUTS-2) (source: Górski and Zaliwski, 2002; Igras, 2004; Kopiński and Tujaka, 2010)

Voivodeship	NO <sub>3</sub> -N [kg•ha <sup>-1</sup> ] in 0-90 cm soil profile in autumn <sup>1)</sup>	The difference in the content of NO <sub>3</sub> -N in 0-90 cm soil profile between autumn and spring [kg·ha <sup>-1</sup> ] <sup>2)</sup>	Concentrations of NO <sub>3</sub> –N [mg·dm <sup>-3</sup> ] in 90-120 cm soil profile in spring <sup>3)</sup>	NO <sub>3</sub> -N concentrations in drainage water [mg · dm <sup>-3</sup> ] <sup>4)</sup>	Rainfall OctMar. <sup>5)</sup> [mm]	Field water capacity (FWC) <sup>6)</sup> [mm]	Nitrogen balance [kg N•ha·l] 7)
DLS	87.9	18.5	19.1	3.53	241.4	289	18.7
KUJ	68.5	15.1	24.9	4.34	197.1	184	79.8
LUB	66.0	-3.1	-4.3	0.33	202.6	216	44.0
LUS	82.4	25.3	42.4	4.68	232.0	181	60.7
LOD	70.6	18.4	36.0	5.24	212.9	157	73.8
MLP	65.2	2.2	2.2	3.80	276.1	296	34.7
MAZ	55.9	4.4	8.1	4.82	199.0	166	44.6
OPL	72.0	16.4	18.3	1.87	228.1	267	43.3
PDK	64.0	5.2	6.1	1.17	259.0	256	22.4
PDL	38.0	11.9	19.2	4.07	213.4	187	44.5
POM	55.7	10.1	14.6	0.89	256.9	209	54.1
SLS	70.6	6.0	7.7	15.0	272.3	233	37.7
SWT	68.5	-3.7	-4.9	2.54	215.9	226	43.4
WAM	45.7	11.0	14.8	1.61	230.6	220	48.4
WLP	78.0	25.8	49.9	10.10	207.9	159	71.9
ZAP	73.3	27.2	44.7	4.13	263.9	185	50.2
Poland	66.5	11.9	18.7	4.26	231.8	214	46.7

<sup>&</sup>lt;sup>1)</sup> average (median) content of nitrate in 0-90 cm soil profile in autumn. Calculated from the data in Table 3.12 with recognition the percentage of soils in different textural classes; <sup>2)</sup> the difference in the content of nitrate in 0-90 cm soil profile between autumn and spring periods. Calculated from the data in Table 3.12; <sup>3)</sup> simulated concentration of nitrate in the soil water at the depth of 90-120 cm. Calculated from the data in Table 3.13; <sup>4)</sup> concentration of nitrate in the drainage water (Igras, 2004); <sup>5)</sup> average from 10 years rainfall in the period October to March (Górski and Zaliwski, 2002); <sup>6)</sup> field water capacity in 0-90 cm soil profile in mm. Calculated from the data in Table 3.13 with recognition the percentage of soils in different textural classes; <sup>7)</sup> nitrogen balance acc. to "soil surface" method (Table 3.16)

Using cluster analysis, areas with varying degrees of excess nitrogen hazard have been designated. All factors that significantly affect the diffusion of nitrogen into the environment were included as variables for cluster analysis. Cluster analysis was performed using Ward's method and voivodeships were divided into 2 groups (Table 3.20; Fig. 3.19) corresponding to the areas with different degrees of excess nitrogen threat.

Table 3.20 The division of voivodeships into clusters (source: Igras, 2004; Górski and Zaliwski, 2002)

Cluster (group)	Winter rainfall [mm]	FWC [mm]	Nitrogen balance [kg N•ha <sup>-1</sup> ]	Content of NO <sub>3</sub> -N, [kg·ha <sup>-1</sup> ] in 0-90 cm soil profile	Nitrogen losses in autumn - winter [kg N-NO <sub>3</sub> ·ha <sup>-1</sup> ] from 0-90 cm soil profile	Concentration of NO <sub>3</sub> -N [mg·dm <sup>-3</sup> ] in 90-120 cm soil profile	Concentration of NO <sub>3</sub> –N [mg·dm <sup>-3</sup> ] in drainage water
1. DLN, LUB, MLP, MAZ, OPL, PDK, PDL, POM, SLS, SWT, WAM	239	233	43	63	7.18	9.18	2.57
2. KUJ, LUS, LOD, WLP, ZAP	253	173	69	74	22.4	39.5	5.70

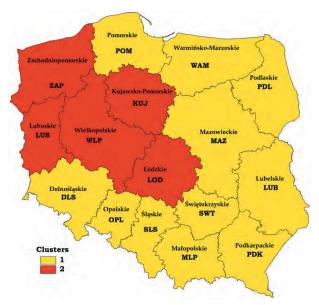


Fig. 3.19 Clusters of voivodeships according to potential threats for the environment from the excess of nitrates (source: Igras, 2004; Górski and Zaliwski, 2002)

The first group of voivodeships in which the loss of nitrogen and nitrate concentrations are lowest, is characterised by a relatively small excess of nitrogen and by soils with high water capacity. Winter precipitation in these provinces is smaller in comparison with the second cluster. It is worth noting that in the first cluster of voivodeships, the average concentration (expressed as a median) of nitrate in soil water, and in fact already in groundwater at a depth of 90-120 cm is just over 9 mg NO<sub>3</sub>-N· dm<sup>-3</sup>, and is smaller than the critical concentration defined by Nitrates Directive for drinking water (11.3 mg N· dm<sup>-3</sup>). The second cluster includes five voivodeships: Kujawsko-Pomorskie, Lubuskie, Łódzkie, Wielkopolskie and Zachodniopomorskie, where the simulated nitrate concentrations in groundwater and in drainage water are much higher than those reported in the first cluster. These voivodeships are characterized by much higher nitrogen balances and by soils with low water capacity, and in the years 1997 - 2005 winter precipitations were higher there than in the voivodeships from the first cluster. These voivodeships can be therefore considered an area where groundwater is particularly vulnerable to pollution by nitrates from diffuse agricultural sources. The majority of this area is located in the Oder River basin (Fig. 3.19; Table 3.21). However, the average concentrations of nitrates in drainage water in the area do not exceed the critical values as defined by the Nitrates Directive.

Table 3.21 The share of voivodeship's territories in the basins of Vistula, Oder, and Pomeranian rivers; abbreviations for voivodeships see to Chapter 12; (source: own elaboration based on GUS, 1991-2011 data; http://mapa.pf.pl/?gclid=CJ3Qkv2voLACFUPxzAodKk5WZg)

	Total area	% of the	% of the area in the basins of the rivers					
Voivodeship	[km <sup>2</sup> ]	Vistula	Oder	10 Pomeranian rivers				
DLN	19947		100					
KUJ	17972	75	25					
LUB	25122	100						
LUS	13988		100					
LOD	18219	51	49					
MLP	15183	100						
MAZ	35558	100						
OPL	9412		100					
PDK	17846	100						
PDL	20187	100						
POM	18310	47	4	49				
SLS	12333	44	56					
SWT	11710	100						

	Total area	% of the area in the basins of the rivers				
Voivodeship	[km <sup>2</sup> ]	Vistula	Oder	10 Pomeranian rivers		
WAM	24173	100				
WLP	29826		100			
ZAP	22892		52	48		
Poland	312679	55.7	32.9	9.3		

Weighted average values of the factors affecting the potential threat to the environment with excess nitrogen from agriculture were calculated for each river basin, and then divided into environmental (Table 3.22) and agronomic (Table 3.23) factors. Agronomic factors suggest greater susceptibility of the Oder basin to area losses of nutrients in comparison with those in the Vistula basin. The value of positive nitrogen balance is higher in the Oder basin, just as are the concentrations of nitrates in drainage water, and the simulated nitrate losses due to leaching. All these circumstances lead to a conclusion that unit nitrogen outflows from diffuse sources should be larger in the basin of the Oder River than in the basin of the Vistula River. This is confirmed by values of nutrient concentrations and loads recorded at the lowermost river monitoring stations in Kiezmark (Vistula) and in Krajnik Dolny (Oder) (Chapter 9). Pomeranian rivers basin should be more susceptible to territorial loss of nitrogen. It is evidenced by a greater proportion of arable land, the overwhelming predominance of poor soils (very light and light soils) with low field water capacity (FWC), and greater precipitation in the winter. The only environmental factor influencing the reduction of nitrogen outflow may be a high afforestation rate of the coastal area.

Table 3.22 Selected environmental factors influencing the losses of nitrogen compounds from the natural and diffuse sources to the groundwater and the open waters of the Baltic Sea (source: own calculations based on Górski and Zaliwski, 2002 data)

River basin	Arable land [%]	Forest land [%]	Grassland [%]	Very light and light soils [%]	Field water capacity of soils [mm]	Land with slope >5% [%]	River network [km·km²]	Winter rainfall [mm]
Vistula	39	29	12	56	210	8	0.43	224
Oder	43	31	8	63	205	5	0.43	230
Pomeranian rivers	48	37	7	66	196	4	0.34	260
Poland	41	30	10	59	207	7	0.43	228

Table 3.23 Selected agronomic factors influencing the losses of nitrogen compounds from the natural and diffuse sources to the groundwater and the open waters of the Baltic Sea (source: own calculations based on Fotyma and Fotyma, 2006; Kopiński and Madej, 2006)

River basin	N balance calculated using "on the soil surface" method for the years 2002-2005	NO <sub>3</sub> -N concentrations in drainage water [mg·dm <sup>-3</sup> ]	NO <sub>3</sub> -N losses from 0-90 cm soil profile [kg·ha <sup>-1</sup> ]	LU·100 ha¹	Crop yields in units of grain per ha
Vistula	40.0	3.52	6	50	31
Oder	52.5	6.05	21	47	39
Pomeranian rivers	48.2	3.20	20	29	36
Poland	46.7	4.26	12	46	34

The analysis carried out for the largest river basins in Poland is of a general nature, as they are internally diversified in terms of environmental and agronomic conditions. Analysis carried out at regional level (NUTS-2), within which the environmental and agronomic conditions are more homogeneous, can be more accurate. In the previous subchapter groups of voivodeships with different vulnerability to the area nitrogen losses to soil waters, groundwater and open waters were distinguished. Five voivodeships demonstrate higher vulnerability to area losses of nitrogen i.e. Kujawsko-Pomorskie, Lubuskie, Łódzkie, Wielkopolskie, and Zachodniopomorskie, where the simulated nitrate concentrations in groundwater and concentrations in drainage water are much higher than those reported in the remaining eleven voivodeships. These voivodeships are also characterized by a significantly higher nitrogen balance, and by soils with low field water capacity, and in recent years, winter precipitation was higher there than the precipitation in the other voivodeships. In these voivodeships soil waters, groundwater and surface waters are therefore potentially exposed to higher pollution by nitrates from the diffuse sources and in practice from agricultural sources. The voivodeships of Lubuskie and Wielkopolskie are entirely located in the basin of the Oder River, as well as almost half of the area of the voivodeship of Zachodniopomorskie. The majority of area of Kujawsko-Pomorskie voivodeship belongs to the Vistula River basin. Therefore, for a more precise delimitation of the river basins of the Vistula, Oder and Pomeranian rivers in terms of factors determining area nitrogen losses from agriculture to the Baltic Sea the data from smaller territorial units (counties, municipalities) should be analyzed. However, such data are mostly unavailable.

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#### References

- Annual Report, 2010. Chemical Industry in Poland. Polish Chemical Chambers.
- Assessment for the designation on Nitrate Vulnerable Zones in Poland, 2007. Report Wageningen: Alterra ss. 108 <a href="http://www.kzgw.gov.pl/630.html">http://www.kzgw.gov.pl/630.html</a> [Accessed in May 2012].
- Azam, F., Simmons, F.W., Mulvaney, R.L., 1993. Immobilization of ammonium and nitrate and their interaction with native N in three Illinois Mollisols. Biol. Fertil. Soils., 15:50-54.
- Balsari, P., Airoldi, G., Dinuccio, E., Gioelli, F., 2007. Ammonia emissions from farmyard manure heaps and slurry stores effect of environmental conditions and measuring methods. Biosystem Engineering, 97:456-463.
- Berntson, G.M., Aber, J.D., 2000. Fast nitrate immobilization in N saturated temperate forest soils. Soil Biology & Biogeochemistry, Vol. 32. No. 2:151-156.
- Burger, M., Jackson, L.E., 2003. Microbial immobilization of ammonium and nitrate in relation to ammonification and nitrification rates in organic and conventional cropping systems. Soil Biology & Biochemistry, 35:29-36.
- Dail, D.B., Davidson, E.A., Chorover, J., 2001. Rapid abiotic transformation of nitrate in an acid forest soil. Biogeochemistry, Vol. 54, No. 2:131-146.
- Desjardins, R.L., Sivakumar, M.V.K., de Kimpe, C., 2007. The contribution of agriculture to the state of climate: Workshop summary and recommendations. Agricultural and Forest Meteorology, 142:314-324.
- DRI, 2005. Dietary reference intakes for energy, carbohydrate, fiber, FAT, fatty AIDS, cholesterol, protein and amino AIDS. www/nap.edu. [Accessed in may 2012]
- Dz. U. z 2004 r. Nr 257, poz. 2573. Rozporządzenie Rady Ministrów z dnia 9 listopada 2004 r. w sprawie określenia rodzajów przedsięwzięć mogących znacząco oddziaływać na środowisko oraz szczegółowych uwarunkowań związanych z kwalifikowaniem przedsięwzięcia do sporządzenia raportu o oddziaływaniu na środowisko.
- EFMA, 2009. Modern agriculture feeds the world and helps protect the environment. Annual report 2008.
- EFMA, 2011. Forecast of Food Farming and Fertilizer Use 2011/2021. EFMA Annual Statistics and Forecast. 2011, vol. 1, 2. Executive Summary and Regional Data.
- Erisman, J.W., Bleeker, A., Galloway, J., Sutton, M.S., 2007. Reduced nitrogen in ecology and the environment. Environmental Pollution. 150:140-149.
- Eurostat, 2009. Gross nitrogen balance, 2000-2008 (kg N per ha agricultural land). http://ec.europa.eu/eurostat/product?code=aei\_pr\_gnb&language=en&mode=view [Accessed in May 2012].
- Eurostat map: http://mapa.pf.pl/?gclid=CJ3Qkv2voLACFUPxzAodKk5WZg [Accessed in May 2011].
- Fernández, J. A., Poulsen, H. D., Boisen, S., Rom, H. B., 1999. Nitrogen and

- phosphorus consumption, utilization and losses in pig production: Denmark. Livestock Production Science, 58:225-242.
- Fotyma, E., Fotyma, M., 2006. Normatywy zawartości azotu mineralnego w glebie i stężeń azotanów w roztworze glebowym gleb gruntów ornych w Polsce. Nawoży i Nawożenie Fertilizers and Fertilization 1(26):44-56.
- Fotyma, M., Filipiak, K., 2006. Produkcyjne skutki stosowania nawozów naturalnych. Nawoży i Nawożenie Fertilizers and Fertilization 4(29):97-110.
- Fotyma, E., Fotyma M., Igras J., 2005. Stężenie azotanów w wodzie glebowej jako wskaźnik stanu środowiska rolniczego. Fragmenta Agronomica. 4(88):19-36.
- Fotyma, M., Fotyma, E., Filipiak, K., 2007. Zastosowanie modelu QUADMOD do interpretacji wyników doświadczeń z nawożeniem azotem i modelowania potrzeb nawozowych roślin. Fragmenta Agronomica. 1:41-48.
- Fotyma, E., Fotyma M., Pietruch, Cz., 2004. Zawartość azotu mineralnego w glebach gruntów ornych w Polsce. Nawozy i Nawożenie Fertilizers and Fertilization. 3(20):11-54.
- Fotyma, M., Jadczyszyn, T., Pietruch, Cz., 2001. A decision support system for sustainable nutrient management on farm level: MACROBIL. Nawozy i Nawozenie Fertilizers and Fertilization 2(7):7-26.
- Galloway, J.N., Bowling, E.B., 2002. Reactive Nitrogen and The World: 200 Years of Change. AMBIO, Vol. 31, Issue 2:64-71.
- Gaj, R., 2008. Sustainable management of phosphorus in soil and plants in condition of intensive plant production. Fertilizers and Fertilization, 33,143pp.
- GUS (Central Statistical Office), Rocznik Statystyczny. Annuals issued in 1960-2003. Waszawa, Poland.
- GUS (Central Statistical Office), Ochrona Środowiska. Annuals issued in 1991-2011, Warszawa, Poland.
- GUS (Central Statistical Office), 2006-2011. Użytkowanie gruntów, powierzchnia zasiewów i pogłowie zwierząt gospodarskich w 2006, 2007, 2008, 2009, 2010 roku. Warszawa, Poland.
- GUS (Central Statistical Office), 2007. Środki produkcji w rolnictwie. Wyd. GUS, Warszawa, Poland.
- GUS (Central Statistical Office), 2008. Skup i ceny produktów rolnych w 2007 r. Wyd. GUS, Warszawa, Poland.
- GUS (Central Statistical Office), 2009-2011a. Produkcja upraw rolnych i ogrodniczych w 2009, 2010 i 2011 r. Warszawa, Poland.
- GUS (Central Statistical Office), 2009-2011b. Środki produkcji w rolnictwie w roku gospodarczym. Annual issued in 2008/2009, 2009/2010, 2010/2011. Warszawa, Poland.
- Górski, T., Zaliwski, A., 2002. Model agroklimatu Polski. Pam. Puł., Puławy, 130:251-260.
- Hatfield, J.L., Follett, R.F., (eds.), 2008. Nitrogen in the Environment (second edition): Sources, Problems and Management. Academic Press, 702 pp.

References 157

- Igras, J., 2004. Zawartość składników mineralnych w wodach drenarskich z użytków rolnych w Polsce. Monografie i Rozprawy Naukowe IUNG-PIB, No. 13, 123 pp.
- Igras, J., 2006. Stężenia składników mineralnych w wodach glebowo gruntowych w Polsce. Nawozy i Nawożenie Fertilizers and Fertilization 1(26):90-100.
- Igras, J., 2008. Ocena presji produkcji rolnej w zakresie stosowania nawozów naturalnych i mineralnych na środowisko. Maszynopis. pp. 19-43.
- Igras, J., Biskupski A., 2011. Aktualne tendencje w technologii wytwarzania nawozów azotowych oraz zużycie azotu z nawozów mineralnych w Polsce, Przemysł Chemiczny, t.90 (12):2128-2135.
- Igras, J., Kopiński, J., 2007. Zużycie nawozów mineralnych i naturalnych w układzie regionalnym. Studia i raporty IUNG-PIB. 5:107-116.
- Jadczyszyn, T., Maćkowiak, Cz., Kopiński, J., 2000. Model SFOM narzędziem symulacji ilości i jakości nawozów organicznych wytwarzanych w gospodarstwie. Pam. Puł. z. 120/I:169-175.
- Jolankai, M., 2004. Mineral and organic fertilizers w: Pollution processes in agrienvironment, a new approach. Ed. Lang, I., Jolankai, M., Komives, T. Akaprint Publishers, Hungary, pp. 39-50.
- Karklins, A., 2001. Model for the calculation of nutrient off take by crop. Nawozy i Nawożenie Fertilizers and Fertilization.1(6):63-74.
- Kissel, D.E., Smith, S.J., Hargrove, W.L., Dillow, D.W., 1977. Immobilization of fertilizer nitrate applied to a Swedish clay soil in the field. Soil. Sci. Soc. Am. J., 41:346-349.
- Kopiński, J., 2006. Bilans składników nawozowych w gospodarstwach rolnych, jako kryterium zrównoważonego gospodarowania. Raport IERiGŻ-PIB Programu Wieloletniego. Z badań nad rolnictwem społecznie zrównoważonym. IERiGŻ-PIB, Warszawa, 30:83-91.
- Kopiński, J., 2007. Bilans azotu brutto dla Polski i województw w latach 2000-2005. Studia i raporty IUNG-PIB. 5:117-132.
- Kopiński, J., Madej, A., 2006. Ilość azotu dostarczanego w nawozach naturalnych w zależności od obsady zwierząt. Nawozy i Nawożenie Fertilizers and Fertilization, 4(29): 36-75
- Kopiński, J., Tujaka, A., 2009. Bilans azotu, i fosforu w rolnictwie polskim. Water-Environment-Rural Areas, IMUZ, Falenty, t.9, z.4 (28) pp. 108-116.
- Kopiński, J., Tujaka, A., 2010. Bilans azotu, fosforu i potasu w rolnictwie polskim w latach 2005-2009. Nawozy i nawożenie Fertilizers and fertilization, 41:120-132.
- Krupa, S.V., 2003. Effects of atmospheric ammonia (NH<sub>3</sub>) on terrestrial vegetation: a review. Environmental Pollution, 124:179-221.
- Kurvits, T., Marta, T., 1998. Agricultural  $NH_3$  and  $NO_x$  emissions in Canada. Environmental Pollution, 102, S1:187-194.
- Lipiński, W., 2005. Odczyn gleb Polski. Nawozy i Nawożenie Fertilizers and

- Fertilization, 2(23):33-40.
- Maćkowiak, Cz., Żebrowski, J., 2000. Skład chemiczny obornika w Polsce. Nawozy i Nawożenie Fertilizers and Fertilization.4(5):119-130.
- Misselbrook, T.H., Van Der Weerden, T.J., Pain, B.F., Jarvis, S.C., Chambers, B.J., Smith, K.A., Philips, V.R., Demmers, T.G.M., 2000. Ammonia emission factors for UK agriculture. Atmospheric Environment, 34:871-880.
- Nelson, D.W., 1982. Gaseous losses of nitrogen other than through denitrification. [in:] Stevenson, F.J. (ed.), Nitrogen in agricultural Soils, American Society of Agronomy, Madison, WI, pp. 327-363.
- Nitrogen cycle: http://landscapeforlife.org/give\_back/3c.php [Accessed in May 2011].
- Normy żywienia bydła, owiec i kóz, 1993. Omnitech Press, Warszawa.
- OECD, 2005. OECD Nitrogen Balance Handbook. OECD publication service. Vol 4. Draft Report chapter 3. OECD. Paris.
- OECD, Eurostat, 2007. Gross nitrogen balance, handbook. October 2007. http://www.oecd.org/dataoecd/2/37/40820234.pdf
- O'Neill, P., 1997. Chemia Środowiska, Wydawnictwo Naukowe PWN, Warszawa-Wrocław, 308 pp.
- Oenema, O., Oudendag, D., Velthof, G.L., 2007. Nutrient losses from manure management in the European Union. Livestock Science, 112:261-272.
- Pietrzak, S., 2006. Metoda inwentaryzacji amoniaku ze źródeł rolniczych w Polsce i jej praktyczne zastosowanie. Woda Środowisko Obszary Wiejskie t.6.z.1:319-334.
- Pietrzak, S., Sapek, A., Oenema, O., 2002. Emisja podtlenku azotu (N<sub>2</sub>O) ze źródeł rolniczych w Polsce. Nawoży i Nawożenie Fertilizers and Fertilization. 1:135-147.
- Puri, G., Ashman, M.R., 1999. Microbial immobilization of <sup>15</sup>N-labelled ammonium and nitrate in a temperate woodland soil. Soil Biology and Biochemistry, Vol. 31, Issue 6, pp. 929-932.
- Recosus, S., Mary, B., 1990. Microbial immobilization of ammonium and nitrate in cultivated soils. Soil Biology and Biochemistry, Vol. 22, Issue 7, pp. 913-922.
- Robertson, P.G., 1997. Nitrogen use efficiency in row-crop agriculture: crop nitrogen use and soil nitrogen loss. [in:] Jackson, L.E., (ed.), Ecology and Agriculture, Academic Press, San Diego, pp. 347-365.
- Rynek pasz, 2008. Wyd. IERiGŻ-PIB, nr 23-24. Warszawa.
- Sapek, A., 1998. Emisja gazów cieplarnianych z rolnictwa. Zeszyte Edukacyjne IMUZ Falenty 5:17-26.
- Sapek, A., Sapek, B., Pietrzak, S., 2000. Rola produkcji zwierzęcej w rozpraszaniu składników nawozowych z rolnictwa do środowiska. [in:] Pietrzak. S. (ed.), Dobre praktyki w rolnictwie. Przysiek, 200:5-31.
- Schroeder, J. J., 2005. Manure as a suitable component of precise nitrogen nutrition. Proceedings IFS. 574, 32 pp.

References 159

- Sommer, S.G., Hutchings, N.J., 2001. Ammonia emission from field applied manure and its reduction invited paper. Europ. J. Agronomy, 15:1-15.
- Sommer, S.G., Génermont, S., Cellier, P., Hutchings, N.J., Olesen, J.E., Morvan, T., 2003. Porcesses controlling ammonia emission from livestock slurry in the field. Europ. J. Agronomy. 19:465-486.
- Sosulski, T., Łabętowicz, J., 2008. Oszacowanie rozpraszania azotu z rolnictwa polskiego do atmosfery oraz wód. Postępy Nauk Rolniczych, 3:3-19.
- Stuczyński, T., Budzyńska, K., Gawrysiak, L., Zalewski, A., 2000. Waloryzacja rolniczej przestrzeni produkcyjnej Polski. Biuletyn informacyjny IUNG. 12:4-17.
- Thornton, J.A., 1998. Assessment and control of nonpoint source pollution of aquatic ecosystems. Partenon Publ. Group, UNESCO, Paris.
- Webb, J., Menzi, H., Pain, B.F., Misselbrook, T.H., Dämmgen, U., Hendriks, H., Döhler, H., 2005. Managing ammonia emissions from livestock production in Europe. Environmental Pollution, 135:399-406.

4

PHOSPHORUS UTILIZATION AND DIFFUSE LOSSES IN AGRICULTURAL CROP PRODUCTION

JANUSZ IGRAS MARIUSZ FOTYMA

# 4. PHOSPHORUS UTILIZATION AND DIFFUSE LOSSES IN AGRICULTURAL CROP PRODUCTION

Janusz Igras, Mariusz Fotyma

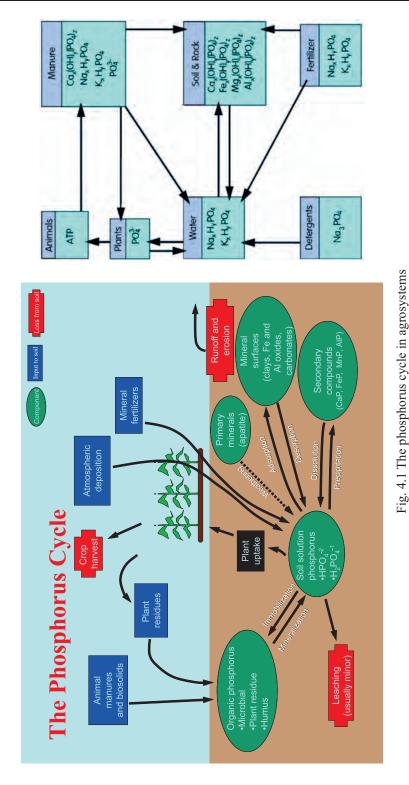
#### 4.1. Phosphorus cycle in agricultural systems

Phosphorus (P) is an essential element for plants and animals, because it is incorporated in the structure of DNA molecules, as well as in the structure of molecules which are energy carriers (ATP and ADP); it is also a component of fats and cell membranes. Likewise, phosphorus is indispensable for building bones of animals and humans. The movement of phosphorus in metabolic processes in plants and animals is fast, while its movement in soil or oceans is one of the slowest biogeochemical cycles. Phosphorus occurs in soil in organic and inorganic forms, it may be in dissolved forms (in very small amounts), or as embedded in minerals and organic material (Sharpley, 1995). Simplified phosphorus cycle in agrosystems is shown in Fig. 4.1.

Phosphorus losses to groundwater and surface waters may occur as a result of the processes of leaching or surface runoff with soil particles. As shown by the results of lysimeter studies, under sustainable farming conditions, phosphorus losses due to leaching are very small and insignificant from a practical point of view (Pondel et al., 1991; Sykut, 2000). After many years of using very high doses of fertilizers (especially natural fertilizers) soil buffering capacity in relation to phosphorus may be exceeded, therefore it should be taken into account that vertical movements of phosphorus compounds in soil profile and into groundwater may occur. As indicated in modelling studies (Chapter 8), contribution of groundwater too overall P emission to river basins reached only 6% in the Vistula and 11% in the Oder basin. These basins differ very much in agricultural activity, with more intensive agriculture in the Oder basin.

The major proportion of phosphorus transported from agricultural soils is generally in sediment-bound form, the remaining percentage constitutes dissolved P (molybdate reactive P) (Oenema and Roest, 1998; Sharpley, 2006). The sediment-bound phosphorus includes P associated with soil particles and organic material eroded during flow events and constitutes 60% to 90% of P transported in surface runoff from most cultivated land (Sharpley, 2006).

Phosphorus, like nitrogen (N), is one of the "elements of life", but its concentration in the biosphere is much lower than that of nitrogen. Total phosphorus content in soil is  $0.3 \cdot 10^3 - 1.5 \cdot 10^3$  mg P · kg<sup>-1</sup>, while in plants it generally does not exceed  $3 \cdot 10^3$  mg P · kg<sup>-1</sup>. Due to very low solubility of most phosphorus compounds the concentration of this element in soil solution is only 0.1 - 1.0 mg P · dm<sup>-3</sup> (Łabętowicz, 1995). The



components of soil is marked in green, P input to soil is marked in blue, P runoff is marked in red - left graph; simplified phosphorus cycle (sources: http://msucares.com/crops/soils/images/phosphorus.gif; http://www.alken-murray.com/Phosphorus.html; P pool in individual with detergents added - right graph)

phosphorus content in the atmosphere is insignificant. In mineral soils the majority of phosphorus is in the form of inorganic compounds, mainly in combination with calcium, aluminium, and iron (see to Fig. 9.16 in Chapter 9) whereas only a small P portion is in the form of organic compounds with varying degrees of humification. The multitude of phosphorus compounds in soil has no practical meaning in agricultural research, therefore, as a rule, only a few pools of phosphorus of varying availability to plants are distinguished. These pools are called fractions in the analytical procedure, and the very procedure is called soil phosphorus fractionation. The most commonly used methods of phosphorus fractionation are those developed by Chang-Jackson and Hedley (Levy and Schlesinger, 1999), with numerous modifications (Gaj, 2007).

In agrochemical research, the available phosphorus is determined, which is a sum of bioactive phosphorus and parts of mobile phosphorus. In Poland, for the determination of available phosphorus, the method of Egner - Riehm (Egner DL) is used (Egner et. al., 1960). The method consists in the extraction of soil samples with calcium lactate solution buffered to pH 3.5 by adding hydrochloric acid.

Classification of phosphorus pools in waters is different from P fractions in soils. The latter classification takes into account only the methods of separation and determination of individual pools of phosphorus. Phosphorus pools in soil solution are presented in Fig. 4.2.

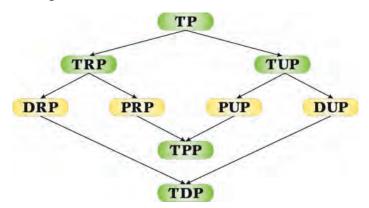


Fig. 4.2 Forms of phosphorus in soil solution; symbols used: TP – total phosphorus determined by wet combustion of the sample, TRP – total reactive phosphorus, (molybdenum, colorimetric method), TUP – total unreactive phosphorus (difference between TP and TRP), DRP-dissolved reactive phosphorus, PRP – particulate reactive phosphorus, PUP – particulate unreactive phosphorus, DUP – dissolved unreactive phosphorus, TPP – total particulate phosphorus, TDP – total dissolved phosphorus (source: Haygarth, 1997)

Although this monograph is not a methodical manual, the terms used in Fig. 4.2 require a few comments on the methodology of separation of phosphorus pools. Phosphorus that reacts with molybdenum blue can only be found in the form of phosphates forming coloured complex with this reagent, which is then determined colorimetrically. Unreactive phosphorus is the difference between TP, determined by wet combustion of the sample and the phosphorus that reacts with molybdenum blue. Particulate phosphorus is separated from dissolved phosphorus by filtration on a membrane filter with a mesh size of  $0.45~\mu m$ .

## 4.2. Production and consumption of mineral phosphorus fertilizers

Polish industry of phosphorus fertilizers has a production capacity of approximately 280,000 tons. Exclusively imported phosphorites are used for the production, while sulphuric acid is produced in the country. Currently, phosphorus fertilizers are produced in six factories: in "Police" Chemical Plant, "Fosfory" Phosphorous Fertilizer Plant in Gdańsk, in "Fosfan" Works in Szczecin, in "Luvena" and "Siarkopol" Chemical Plants in Tarnobrzeg. These plants currently produce more than 230,000 tons in the form of phosphorous fertilizers ( $P_2O_5$ ) (Igras, 2006). The production volume puts our country on one of the first, if not even on the first place (data from some countries are unavailable) among the European Union (EU) countries. Therefore, it is a similar position as in the production of nitrogen fertilizers. Similarly, as in the case of nitrogen fertilizers, the share of export in production volume amounts to approximately 40%. Only NP and NPK compound fertilizers are exported, and their major exporter is "Police" Chemical Plant.

NP, PK and NPK compound fertilizers predominate in the structure of production of phosphorous fertilizers. Total production of these fertilizers is around 1,700,000 tons by weight, most of which is produced by "Police" Chemical Plant. "Police" is also the sole producer of complex fertilizers, obtained by chemical synthesis of phosphorites, phosphoric acid, and ammonia, possibly with the addition of potassium salt. A small amount of multi-component fertilizers is imported by a company "Yara" Poland. "Luvena" Chemical Plant, and "Siarkopol" Chemical Plant in Tarnobrzeg are manufacturers of mixed fertilizers produced by plate granulation or crushing of the individual components (straight fertilizers). Single nutrient fertilizers such as single superphosphate or triple superphosphate have a much smaller share in the production of fertilizers. Superphosphates are produced mainly by "Luvena" Chemical Plant, "Siarkopol" Chemical Plant in Tarnobrzeg, "Police" Chemical Plant, "Fosfan" Works in Szczecin, and "Fosfory" Gdańsk. Currently superphosphate production does not exceed 350,000 tons (by weight of fertilizers), and almost all of the production is supplied in granular form.

Nitrogen and phosphorus fertilizer consumption in Poland was characterized by a significant increase in the 1970s and the 1980s (Fig. 4.3). Dramatic recession in

Polish economy on the turn of the 1980s and the 1990s hit also the agricultural sector and that was reflected in a huge drop in fertilizer application. Following a dramatic decrease a slow upward trend in fertilizer application has been observed since the middle of the last decade of the  $XX^{th}$  century. Currently the consumption of P fertilizers in Poland amounts to about 9.5 kg P  $\cdot$  ha  $^{-1}$  of agricultural land and it is approx. two time lower than in the 1980s.

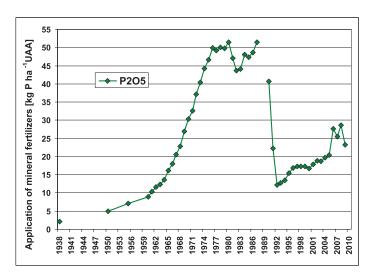


Fig. 4.3 Consumption of phosphorus fertilizers in Poland in the years 1938-2009; UAA – utilized agricultural area (source: graph was prepared and made available by Pastuszak, NMFRI, Gdynia - based on GUS, 1960-2003; 1991-2010 data)

The peak consumption of phosphorous fertilizers in the EU-15 took place at the beginning of the 1980s of the last century and therefore earlier than the peak consumption of nitrogen. Since then there has been a steady decline in the consumption of P fertilizers, clearly ahead of the decrease in the consumption of nitrogen fertilizers. Therefore, the ratio of N:P is steadily widening. The average consumption of phosphorous fertilizers for cereals in the EU-15 amounts to approximately 13 kg P  $\cdot$  ha<sup>-1</sup>, ranging from less than 9 kg P  $\cdot$  ha<sup>-1</sup> in Denmark, the Netherlands, and Sweden to over 17 kg P  $\cdot$  ha<sup>-1</sup> in Ireland, Italy, Spain, and Portugal. The consumption of phosphorous fertilizers for cereals in Poland is slightly smaller (about 12 kg P  $\cdot$  ha<sup>-1</sup>) than the average consumption in the EU countries (EFMA, 2006). In the EU-15, the average ratio of nitrogen to phosphorus in the fertilizers used for cereals is N:P = 1:0.13.

The consumption of phosphorus fertilizers in Poland shows territorial differentiation (Fig. 4.4), but not as large as the variation of nitrogen fertilizer consumption. The coefficient of variability of nitrogen fertilizers consumption is 28%, while the coefficient of variability of phosphorous fertilizers consumption amounts to only 15%.

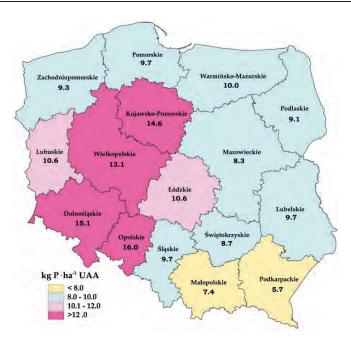


Fig. 4.4 Regional differentiation of phosphorus consumption in mineral fertilizers in 2009; UAA – utilized agricultural land (source: GUS, 2010)

# 4.3. Productiveness of phosphorus fertilizers

In the European Union (the EU-15), the average unit consumption of phosphorus fertilizers (at NUTS-1) to produce 100 kg of cereal grains is about 0.29 kg of P and it is fairly balanced among the EU-15 countries, except Spain and Portugal, where approximately 0.79 kg P per 100 kg of cereal grains is consumed. The calculations carried out for the "old" EU countries did not reveal any relationship between cereals yields and doses of phosphorus fertilizers. Also in Poland, there was no significant relationship between dosage amounts of phosphorus fertilizers and cereals yields at NUTS-2.

However, the issue of the impact of broadly understood fertilizer management on cereals yields should be viewed in the context of soil quality and the "delayed" effects of phosphorous fertilizers understood as "delayed" soil abundance of available forms of phosphorus. This approach was attempted by using cluster analysis (Fig. 4.5). Four clusters of voivodeships with varying yields of cereals were distinguished in the analysis. The analysis shows that Opolskie voivodeship, where the largest cereal yields of are achieved, constitutes a separate cluster. This region has the best soils in the country and favourable agro-climatic conditions. Although large doses of fertilizers, especially nitrogen fertilizers, are used in this voivodeship, soil negative bonitation index and phosphorus abundance indices are the lowest in the country.



Fig. 4.5 Clusters of voivodeships according to the cereals yield (source: Igras and Fotyma, own unpublished study)

The comparison of voivodeships in cluster 2 (Lubuskie, Śląskie, and Pomorskie) with voivodeships in cluster 3 (Łódzkie, Małopolskie, Mazowieckie, Podkarpackie, Podlaskie and Świętokrzyskie) makes it possible to assess economic impact of fertilizers management on cereals yields with the exclusion of soil quality factor (Table 4.1). With the same soil valuation index in the voivodeships grouped in cluster 2 cereals yields are almost 0.4 tons ha¹ higher than in the voivodeships from cluster 3. This is due to much higher doses of mineral fertilizers and much lower soil negative bonitation and soil fertility indices in the latter cluster.

The comparison of voivodeships from cluster 1 (Dolnośląskie, Kujawsko-Pomorskie, Lubelskie, Warmińsko-Mazurskie, Wielkopolskie, and Zachodniopomorskie) with voivodeships from cluster 2 provides evidence of the profound influence of soil quality and doses of nitrogen fertilizers on cereals yields.

Table 4.1 Cereals yields, the consumption of mineral fertilizers, and the chosen elements of the soil fertility in the individual cluster of voivodeships according to the data from years 2005 – 2009; abbreviations used for voivodeships – see to Chapter 12; (sources: GUS 2006a,b; 2007a,b; Igras and Lipiński, 2006; Witek and Górski, 1977)

Voivodeships	Cereals yield	NPK dose [kg]			APAVI <sup>1)</sup>	Negative bonitation index <sup>2)</sup>		
in the cluster	[kg]	N	$P_2O_5$	K <sub>2</sub> O	1 22 1 2 7 2	рН	P	K
1 DLN, KUJ, LUB, WAM, WLP, ZAP	3572	74.7	19.55	26.7	69.7	47.1	30.3	37.0
2 LUS, POM, SLS	3243	63.6	25.5	31.4	64.2	51.1	31.5	43.6
3 LOD, MLP, MAZ, PDK, PDL, SWT	2887	50.65	19.8	21.2	64.3	61.4	48.7	58.1
4 OPL	4830	74.9	25.5	40.9	81.4	32.7	26.1	34.1

<sup>&</sup>lt;sup>1)</sup> APAVI - Agricultural Production Area Valuation Index

Approximately 0.35 kg P is consumed in Poland to produce 100 kg of cereal grains. This value is slightly higher than the average for the EU-15. The average uptake of phosphorous with 100 kg of cereal grain yield amounts to 0.35 kg P, and with 100 kg of grain yield with the corresponding mass of straw it amounts to 0.52 kg P. Therefore, taking into consideration only grain yield it seems that current consumption of phosphorous fertilizers for cereals is sufficient for nutritional needs of this group of plants. However, such type of calculation should assume that the entire amount of phosphorus contained in cereal straw returns to soil in the form of ploughed up straw, manure (from sheds with bedding), or ash from the combustion of excess straw.

In conclusion of the discussion on the productivity of phosphorus it can be therefore assumed that to achieve increase in grain yield by 100 kg per hectare at least  $0.35 \text{ kg P} \cdot \text{ha}^{-1}$  should be additionally applied. In order to increase grain yields to about 5 tons of grain per hectare the dose of phosphorous fertilizers in this group of plants needs to be increased by approximately 5.2 kg P · ha<sup>-1</sup>, that is about by 40% compared to the doses currently applied. If no significant changes occur in the crop structure and cereals fertilization preference coefficient remains at the level of 1.1, about 14 kg P · ha <sup>-1</sup> would be needed to apply to agricultural land used for growing crops (excluding fallows and idle land). The N:P ratio would then amount to approximately 1:0.15.

<sup>&</sup>lt;sup>2)</sup> Total sum of soils exhibiting a very acid and acid reaction or very low and low content of available phosphorus and potassium

### 4.4. Production of manure and content of phosphorus in it

Contrary to mineral fertilizers whose consumption is quite accurately recorded, evaluation of the amount of phosphorus supplied to agriculture in the form of natural fertilizers (manure, slurry and liquid manure) is based on estimates supported by specific methods. At the level of NUTS-2 and NUTS-1 such methods can be divided into two main types. In both, the starting point is the knowledge of stocking density in generic and age groups.

In the first method, hereafter called the LU (Livestock Unit) method, the number of animals is converted into Livestock Units and the production of natural fertilizer (especially manure) per a single LU is estimated. Then the mass of manure that was calculated in this way is multiplied by a standard amount of phosphorus in the manure and the outcome gives the amount of phosphorus in natural fertilizers. These calculations refer to the "mature manure" in the form in which the manure is delivered to the field.

The average production of manure for the whole country is estimated at 5.0 tons  $\cdot$  ha $^{\!-1}$  of agricultural land and 11.4 tons  $\cdot$  LU $^{\!-1}$ . The standard content of phosphorus in manure amounts to 1.2 kg P  $\cdot$  t $^{\!-1}$  of manure, and in slurry it reaches 0.84 kg P  $\cdot$  t $^{\!-1}$  of slurry. Liquid manure contains only traces of phosphorus. This means that approximately 6.6 kg P  $\cdot$  ha $^{\!-1}$  of agricultural land is brought in with the manure, and around 0.4 kg P  $\cdot$  ha $^{\!-1}$  with the slurry. These amounts constitute ca. 43% of the total phosphorus brought in with mineral and natural fertilizers. Approximately 13.7 kg P and about 0.9 kg P are obtained from one LU in the form of manure and slurry, respectively.

The intensity of animal production in Poland is regionally differentiated. In 2002-2006, the average density of animals in Poland amounted to  $0.44~{\rm LU}\cdot{\rm ha^{-1}}$  of agricultural land. The highest density of animals appears in the voivodeships of Podlaskie (PDL) (around  $0.64~{\rm LU}\cdot{\rm ha^{-1}}$  of agricultural land) and Wielkopolskie (WLP) (around  $0.70~{\rm LU}\cdot{\rm ha^{-1}}$  of agricultural land). The lowest densities of animals have the voivodeships in western Poland: Dolnośląskie (DLN), Lubuskie (LUB), and Zachodniopomorskie (ZAP) (Chapter 5). In the latter three voivodeships the average dose of manure does not exceed 2 t  $\cdot{\rm ha^{-1}}$  of agricultural land and it is three times lower than in the voivodeships with the highest stocking density. The question of stocking density and size of herds is discussed in more detail in Chapter 5 of the monograph.

In the second method, the amount of phosphorus supplied in natural fertilizers is estimated by SFOM (Standard Figures Organic Manure) model developed in collaboration with the Danish Advisory Centre in Skejby (Fotyma et al., 2001; Jadczyszyn et al., 2000). The algorithm of this model begins with the amount of phosphorus in urine and faeces, excreted by different types of animals, supplemented by the amount of the component in the straw used as bedding in sheds with bedding

(with a distinction between deep and shallow sheds) (Fig. 4.6). In the next stage phosphorus losses occurring in the production and storage of natural fertilizers are estimated. The final result of the model is the amount of phosphorus in "mature" natural fertilizers that are ready to be applied on the field. SFOM model for phosphorus is much simpler than that for nitrogen (see to Chapter 3). The P model does not take into account phosphorus in the liquid manure, which, as already mentioned, is insignificant and there are no losses in gaseous form. The only source of loss may be surface runoffs or leaching of phosphorus from manure pits. With properly designed manure plates phosphorus losses are unlikely and they are generally not included in the calculation model. The coefficients used for calculations of the amount of phosphorus in natural fertilizers made by three methods are shown in Table 4.2.

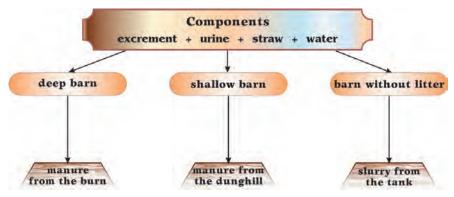


Fig. 4.6 SFOM (Standard Figures Organic Manure) model for phosphorus (source: Jadczyszyn et al., 2000)

Table 4.2 Selected coefficients of phosphorus in livestock fertilizers estimated by three methods (source: Igras and Fotyma own upublished data)

Method	Coefficient				
Method	kg P · ha-1	kg P·LU <sup>-1</sup>	% P in manure		
"LU" (Igras and Fotyma own upublished data)	6.5	14.9	0.12		
"SFOM" model (Fotyma et al., 2001; Jadczyszyn et al., 2000)	6.0	13.7	0.11		
The OECD gross balance (OECD, 1999)	7.1	16.3	-		

The results of calculations of phosphorus made by the "LU" and "SFOM" methods are quite consistent as it is shown by data presented in Table 4.2. SFOM model, however, creates much greater possibilities for interpretation and allows insight into the processes occurring after the excretion of manure until the delivery

of "mature" manure to the field. The amount of phosphorus in natural fertilizers calculated according to this model applies only to the current structure of herds and general proportions of the methods of maintaining them (12% in deep sheds, 81% in shallow sheds with bedding, and 7% in liquid manure sheds). For readers interested in making their own calculations the amounts of net phosphorus ready to be exported to the field in natural fertilizers excreted by different types of animals are given in Table 4.3, though still taking into account the above listed proportions of the methods of housing the animals. Therefore, these values should not be used in the calculation for farms that use a single, well-defined animal breeding system.

Table 4.3 The net amount of phosphorus in "manure livestock fertilizers" for groups of animals (source: Kopiński, unpublished data; Igras and Kopiński, 2007)

Cattle	kg P · head-1 · year-1	Pigs	kg P · head-1	Other animals	kg P · head-1 · year-1
Calves aged up to 0.5 year	1.50	Sows - total	6.90	Sheep, goats - total	1.30
Heifers aged from 0.5 to 1 year	3.31	Piglets weighing 20 - 30 kg	2.02	Foals aged up to 0.5 year	2.18
Young cattle aged from 0.5 to 1 year	3.31	Piglets weighing from 20 to 50 kg	2.42	Horses - total	6.55
Heifers aged from 1 to 2 years	6.40	Fattening pigs weighing 30 - 70 kg	3.83	Laying hens	0.13
Bulls for fattening aged from 1 to 2 years	6.34	Fattening pigs weighing over 50 kg	4.09	Broilers	0.07
Heifers in calf aged over 2 years	8.57	Fattening pigs weighing 70 - 110 kg	4.22	Turkeys	0.22
Bulls for fattening and stud bulls aged over 2 years	9.03		4.22	Geese	0.21
Dairy cows - total	12.14		4.22	Ducks	0.19

# 4.5. Plant utilization of phosphorus from mineral and natural fertilizers

The utilization of phosphorus from mineral fertilizers is measured by the differential and balance methods (Table 4.4). The isotopic method is not applied, because phosphorus isotopes are radioactive and have short half-life. In short-term field experiments the utilization of phosphorus is very small when measured by the differential method and does not exceed a few, and in special conditions, several percent. The unused amount of the component, however, is accumulated in the soil and supplies the pool of active and movable phosphorus and then the reserve pool. Phosphorus that is accumulated in soil is taken up by plants and clearly has an aftereffect. Therefore, with reference to phosphorus, the balance method was proposed, in which the entire amount of the component taken up from the area where phosphorus is applied is referred to its dose. The utilization of phosphorus calculated using this method reaches between ten and twenty or even more percent.

Table 4.4 The comparison of methods of estimated phosphorus utilization from fertilizers (source: Gaj, 2007)

Method	Phosphorus utilization formula	Explanation of symbols in the formulas
Differential	$W_R = [(U_P - U_0)/P] 100$	$U_p$ – phosphorus uptake by plants in the fertilized area, $U_0$ – phosphorus
Balance	$W_{R} = [U_{P}/P] 100$	uptake by plants in the control area, $P - \text{phosphorus}$ dose

The utilization of phosphorus from natural fertilizers (utilization of nitrogen - see to Chapter 3) is calculated using the indirect method by determining the equivalents of fertilizer P. Due to methodological difficulties, the research on this subject is scarce, therefore it is assumed now that the equivalent of phosphorus for natural fertilizers is 1, i.e. that 100 kg P applied in the form of manure or slurry has the same fertilizing effect as 100 kg P in mineral fertilizers. Similarly to nitrogen (Chapter 3), the reservation must be made that the value of P equivalent cannot be synonymous with the coefficient of phosphorus utilization from natural fertilizers. The utilization of phosphorus calculated using the differential method is in fact as small as the utilization of phosphorus from mineral fertilizers. However, considering the aftereffect of this component, the utilization of phosphorus from natural fertilizers may be greater than that from mineral fertilizers. Most of the phosphorus in natural fertilizers is in organic combinations, which gradually undergo mineralization process releasing phosphorus in forms that are available for plants.

## 4.6. Content of available forms of phosphorus in soil

Regardless of agronomic category of soil, five classes of available phosphorus content are distinguished: very low - up to 2.2 mg P  $\cdot$  kg<sup>-1</sup> of soil, low - 2.3 to 4.4 mg P  $\cdot$  kg<sup>-1</sup> of soil, medium - 4.5 to 8.8 mg P  $\cdot$  kg<sup>-1</sup> of soil, high – 8.9-17.5 mg P  $\cdot$  kg<sup>-1</sup> of soil and very high - from 17.6 mg P  $\cdot$  kg<sup>-1</sup> of soil. Table 4.5 presents the percentage of soils in phosphorus availability classes in particular voivodeships (NUTS level 2). The last column of this table contains the so-called positive bonitation index of phosphorus content in the soil. This index is the sum of the percentage of soils with very high and high content, and the percentage of soils with an average content of available phosphorus. Positive bonitation index is also illustrated in Fig. 4.7.

Table 4.5 Percentage of soils in the range of content of available phosphorus in the years 2005-2008 acc. to Central Agrochemical Laboratory; abbreviations used for voivodeships – see to Chapter 12 (source: Igras and Lipiński, 2006)

Voivodeship	Percen	Positive bonitation index				
voivouesinp	Very low	Low	Average	High	Very high	[%]
DLN	12.9	22.8	25.0	15.9	23.5	51.9
KUJ	4.2	17.8	23.6	18.7	35.8	66.3
LUB	12.6	30.0	28.0	17.1	12.1	43.3
LUS	3.4	18.9	31.6	23.2	22.9	61.9
LOD	8.5	29.7	27.4	14.5	19.9	48.1
MLP	31.5	25.6	16.2	9.4	17.4	34.8
MAZ	8.1	25.8	27.3	16.7	22.1	52.5
OPL	4.5	21.6	28.1	19.5	26.3	59.8
PDK	23.5	30.5	20.3	10.8	14.8	35.8
PDL	15.9	38.5	24.6	10.8	10.2	33.3
POM	4.7	21.7	27.5	18.6	27.6	59.9
SLS	17.3	28.8	21.9	12.3	19.7	43.0
SWT	26.0	29.1	17.0	10.0	17.9	36.5
WAM	7.5	28.1	28.0	17.1	19.3	50.4
WLP	3.0	16.4	27.0	23.3	30.3	67.1
ZAP	4.2	22.6	33.3	20.9	19.0	56.5
POLAND	9.5	24.0	26.1	17.4	23.0	53.4



Fig. 4.7 The index of positive bonitation of phosphorus content in the soil in voivodeships (data for the years 2003-2005) (source: Igras and Lipiński, 2006)

### 4.7. Phosphate concentrations in the tile drainage water

Soil waters are most exposed to agricultural anthropogenic impact because their chemical composition is affected mainly by the number and intensity of agrotechnical procedures performed on the production fields. These waters infiltrate directly through soil profile, and are supplied mainly from precipitation. They transfer nutrients primarily to surface waters, but also to subterranean and even deep subterranean waters. Therefore, the quality of these waters may be a potential indicator of area pollution from agricultural sources. Distribution and characterization of subsurface waters are discussed in more detail in Chapter 6. Phosphate concentrations in soil waters were evaluated in a control network of farms located in the system of hydrographic regions corresponding to second-order river basins. Statistical evaluation of the results was based on an analysis of the distribution of variable and the median as the average concentration of phosphates, because distributions of concentrations of components in waters or their contents in soils are predominantly skewed to the left. In most previous studies on the assessment of chemical composition of surface waters and groundwater, data sets were subjected to a very simplified statistical analysis, without examining the distributions of concentrations of the analyzed elements. In these works it was assumed "in advance" that the concentrations of nutrients in water are normally distributed, therefore, only the arithmetic mean concentration was reported - as a measure of the position of the average value and the minimum or maximum values of concentrations, and at times the standard deviation - as a

measure of variability of the studied population of results. The difference between these two approaches is illustrated in Fig. 4.8.

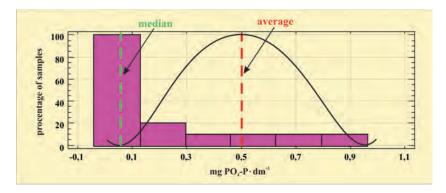


Fig. 4.8 The example of phosphates concentration distribution in drainage water (source: Igras, 2004)

A comparison of the results of analyses of the concentrations of phosphates in the water conducted according to commonly accepted method which assumes a normal distribution of these variables with the assessment based on the median and a range of expected concentrations is presented in Table 4.6. It is clear from this table that the median values are always lower than the arithmetic mean. Evaluation of the dispersion of results around the average value, based on an evaluation of the standard deviation or a range of values from minimum to maximum, varies considerably in relation to the expected ranges. The range of values from minimum to maximum covers 100% of the observations, thus it is much broader than the predicted values, covering 90% of the observations. In turn, the range of values within  $\pm$  limits of doubled standard deviation from the arithmetic mean is narrower than the expected range. This narrowing is done at the expense of "cutting out" low concentrations of the components and extending the range towards higher values. Water quality is therefore much "worse" according to an assessment based on the arithmetic mean than according to a real assessment, which takes into account the skew nature of the distribution of concentrations of analyzed components and the median value as the average measure of concentration (Fig. 4.8).

Table 4.6 Comparison of two ways of statistical analyses of water quality on the basis of estimation of phosphates concentration in mg · dm<sup>-3</sup> (source: Igras, 2004)

	Average	Median	$\pm 2 \cdot \text{standard}$ deviation <sup>1)</sup>	Min. – max. value	Predicted range <sup>2)</sup>
PO <sub>4</sub> -P	0.58	0.07	1.43 - 2.61	0.01 - 1.03	0.01-0.65

<sup>1)</sup> covers 95.5% of the results

<sup>&</sup>lt;sup>2)</sup> covers 90% of the results (the widest of the two sampling periods, the extent of predicted concentrations inupper limit rounded to integers)

As it results from the above discussion the correct statistical analysis is of great practical importance for the assessment of the actual value of nutrient concentrations in water. It is therefore proposed to harmonize the methodology for the statistical evaluation of water monitoring results assuming the following:

- the median as a measure of the average value of the component content in the water,
- the range of expected values as a measure of dispersion of the average value,
- quantile analysis to determine classes of nutrient concentrations in water.

In order to standardize the approach to assess regional differences in soil water quality in terms of the phosphates content at NUTS-2 level, their concentrations in water were extrapolated from the system of second-order river basins to the system of voivodeships (Fig. 4.9). The limits of classes of water quality proposed by Igras (2004) were used to assess water quality.

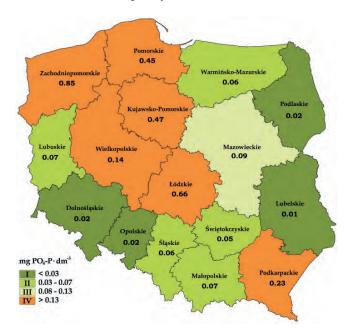


Fig. 4.9 Classes of water quality and average concentration of phosphates in groundwater in Poland in 1998-2002 (source: Igras, 2004)

Phosphate phosphorus content in soil water varies regionally (Fig. 4.9). Soil water in the north-western part of the country and in the voivodeships of Kujawsko-Pomorskie (KUJ), Łódzkie (LOD), Pomorskie (POM), and Zachodniopomorskie (ZAP) contain most phosphates; lower values are observed in Podkarpackie (PDK) and Wielkopolskie (WLP) voivodeships. The waters in this area are classified as Class IV water and particularly phosphate concentrations in KUJ, LOD, POM, and ZAP voivodeships exceed the acceptable content (Igras, 2004, 2007; Igras and Jadczyszyn,

2008). In accordance with the Regulation of the Minister of Environment on the criteria for designation of waters vulnerable to pollution from nitrogen compounds from agricultural sources, (Dz. U. No. 241, item 2093, 2002), the limit for the process of eutrophication shall be phosphate content equal to 0.7 mg PO<sub>4</sub>·dm<sup>-3</sup> (0.23 mg PO<sub>4</sub>-P·dm<sup>-3</sup>). In the voivodeships of eastern, south-eastern, and south-western Poland the phosphate concentration in water is low or very low and the threat with respect to water quality is negligible.

### 4.8. Phosphorus balance "on the soil surface"

In national (NUTS-1) and regional (NUTS-2) studies usually the method of balancing nitrogen and phosphorus "on the soil surface" is used, which is officially recommended and obligatory in the OECD countries (OECD, 1999). In this method, the input side includes the amount of N or P in mineral and natural fertilizers and the amount of N or P introduced with sowable and seed material, (which is very important and often overlooked); the output side – it is the amount of N or P taken out in the form of crops. With a uniform methodology it is possible to easily compare the phosphorus balance between countries (Fig. 4.10).

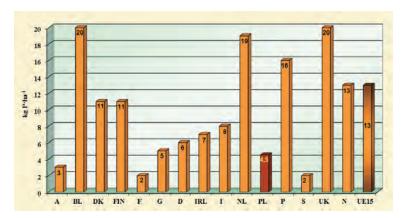


Fig. 4.10 Phosphorus balance in selected EU countries in 2002–2004 (kg P·ha¹); abbreviations of names of countries – see to Chapter 12; (source: OECD, 2008; the present number for Poland is higher than that in OECD documents, as in the mean time there were new OECD remommendations with respect to calculation of P surplus, and the Polish value has been recalculated accordingly)

The average balance of phosphorus for the 14 countries of the EU-15 is 13 kg P·ha<sup>-1</sup> and it has fallen by about 30% over the last decade. In 2002-2004, the balance of phosphorus in Poland gives the number of 4.5 kg P·ha<sup>-1</sup> and it is lower or much lower than in majority of the EU countries or Baltic countries. Across the agricultural area in Poland, (about 16 million ha), the phosphorus balance calculated "on the soil surface" amounts to approx. 96,000 tons (Table 4.7).

The balance of phosphorus in Poland reveals considerable regional variation (Table 4.7). The lowest balance values occur in Podkarpackie (PDK) and Zachodniopomorskie (ZAP) voivodeships, where large yields of crops are obtained with relatively low consumption of mineral and natural fertilizers. This indicates economical management of this component. However, disproportionately high in relation to crop yields obtained are the values of phosphorus balance found in the voivodeships of Wielkopolskie (WLP), Mazowieckie (MAZ), Kujawsko-Pomorskie (KUJ), and Łódzkie (LOD) (Table 4.7).

Table 4.7 Phosphorus balance for voivodeships in Poland in the years 2005-2009; abbreviations used for voivodeships – see to Chapter 12; (source: Kopiński and Tujaka, 2009, 2010)

Voivode-	В	Balance elements [thous. tons P]				Balance elements [kg P · ha <sup>-1</sup> of agricultural land]						
ship	$P_{\rm mf}^{-1}$	$P_{of}^{-2}$	$P_{\text{sm}}^{ 3}$	$P_{\text{atm}}^{ 4}$	P <sub>out</sub> <sup>5</sup>	Surplus <sup>6</sup>	P <sub>mf</sub>	P <sub>of</sub>	$P_{\rm sm}$	P <sub>atm</sub>	P <sub>out</sub>	Surplus
DLN	11.9	3,2	0.4	0.2	13.1	2.6	12.6	3.4	0.5	0.2	13.9	2.8
KUJ	15.2	9.7	0.5	0.2	16.4	9.3	14.3	9.2	0.5	0.2	15.5	8.7
LUB	17.2	8.1	0.8	0.3	18.4	8.0	11.3	5.3	0.5	0.2	12.1	5.2
LUS	5.5	2.8	0.2	0.1	4.8	3.8	11.8	6.0	0.4	0.2	10.3	8.2
LOD	13.4	8.7	0.6	0.2	13.9	9.0	12.3	8.0	0.5	0.2	12.8	8.3
MLP	6.0	4.7	0.3	0.2	8.7	2.5	8.8	6.9	0.4	0.2	12.7	3.6
MAZ	21.4	15.7	0.9	0.5	25.8	12.7	10.1	7.5	0.4	0.2	12.3	6.0
OPL	8.5	3.3	0.3	0.1	9.6	2.7	15.2	5.9	0.5	0.2	17.1	4.8
PDK	5.2	3.7	0.3	0.2	7.7	1.7	7.1	5.0	0.4	0.2	10.5	2.3
PDL	10.1	9.0	0.5	0.2	15.2	4.6	9.1	8.1	0.4	0.2	13.7	4.2
POM	8.7	4.8	0.4	0.2	9.7	4.4	11.5	6.4	0.5	0.2	12.7	5.8
SLS	4.9	3.2	0.2	0.1	5.7	2.7	10.9	7.2	0.4	0.2	12.7	6.1
SWT	5.9	3.6	0.3	0.1	6.8	3.1	10.6	6.4	0.5	0.2	12.2	5.5
WAM	9.4	7.8	0.4	0.2	12.4	5.4	9.8	8.1	0.4	0.2	12.9	5,6
WLP	24.1	24.2	0.9	0.4	27.5	22.1	13.5	13.6	0.5	0.2	15.5	12.4
ZAP	8.8	2.7	0.4	0.2	10.9	1.3	9.5	3.0	0.5	0.2	11.7	1.4
Poland	176.2	115.3	7.3	3.5	206.5	95.8	11.2	7.3	0.5	0.2	13.1	6.1

<sup>1) –</sup> Phosphorus in mineral fertilizers

<sup>&</sup>lt;sup>2)</sup> – Phosphorus in natural and organic fertilizers

<sup>3) –</sup> Phosphorus from other sources, primarily in sowable material

<sup>4) –</sup> Phosphorus from atmospheric deposition

<sup>&</sup>lt;sup>5)</sup> – Phosphorus taken out with crop yields

 $<sup>^{6)}</sup>$  – Phosphorus surplus =  $P_{mf} + P_{of} + P_{sm} + P_{atm} - P_{out}$ 

Phosphorus balance calculated using "on the soil surface" method creates quite optimistic picture of the management of these components in Europe and particularly in Poland. A considerable decrease in P surplus in Polish agriculture was observed in 1985-2010; it dropped from 17-18 kg P ha<sup>-1</sup> in the 1980s to values 3-4 kg P ha<sup>-1</sup> in 1993-2001 and below 5 kg P ha<sup>-1</sup> in 2009-2010 (Fig. 4.11). There was an increase in N and P surplus in 2006 (wet spring; Chapter 9) but that seems to be conditioned by poor yields in that year, thus low nutrient uptake by plants (Pikuła, 2010).

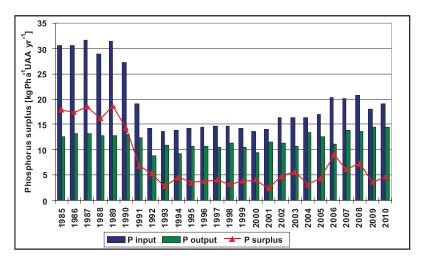


Fig. 4.11 Long term development of phosphorus balance in Polish agriculture; UAA – utilized agricultural area (source: graph prepared and made available by Kopiński, based on GUS, 1960-2003, 1991-2011 data)

## 4.9. Phosphorus balance "at the farm gate"

The issue of phosphorus balance should be also considered from the perspective of global amounts of phosphorus diffused into soil and aquatic environments. As far as methodology is concerned, the method of "Phosphorus balance at the farm gate" and systemic balances, which track the flow of excess nutrients, are used. Preparation of such balances in the scales larger than the farm (e.g. the regions and the whole country) is difficult due to lack of available data and their results may be subject to significant errors.

The balance drawn up "at the farm gate" on the intake side takes into account the amount of phosphorus flowing into the farm from the outside in the form of mineral fertilizers and industrial feed, and on the output side it takes into account the amount of the component flowing out of the farm in the form of commodities of plant and animal origin. Phosphorus in natural fertilizers is not included, because it circles within the farm.

In the years 2004-2006 about 137,000 tons of P (GUS, 2007a) in the form of mineral fertilizers was supplied in Poland. This amount is measurable and fully reliable. Much more difficult is the estimation of phosphorus supplied in the form of imported animal feed (Table 4.8). The inflow of phosphorus in feed in Poland is significant and reaches about 26,200 tons P which represents approximately 18% of the amount applied in mineral fertilizers. The total supply of phosphorus in fertilizers and animal feed can thus be estimated at about 163,000 tons P.

Table 4.8 The amount of phosphorus in imported food stuffs by the "farm Poland" in the years 2003-2007 (source: Igras and Fotyma, own unpublished study)

Product	Product imports	The amount of phosphorus			
Product	[tons]	[kg P ·t-1]	[thous. tons P]		
Maize	304	3.5	1.06		
Cereals	275	3.9	1.07		
Bran <sup>1)</sup>	180	12.8	2.30		
Soybean meal	1696	7.8	13.20		
Rapeseed meal	188	12.4	2.33		
Fishmeal	16	20.0	0.12		
Leguminous plants	20	4.6	0.09		
Feed additives <sup>2)</sup>	-	-	6.00		
Total	-	-	26.2		

<sup>1)</sup> mainly from domestic production

It is also very difficult to estimate the quantity of phosphorus in plant and animal products which are sold by the "farm Poland". The sales volume must include the domestic market and exported products. The estimation of phosphorus in the products (commodities) purchased from farms in the years 2004 - 2007 is presented in Table 4.9.

Table 4.9 Estimated amount of phosphorus in the products bought in 2004-2007 from the "farm Poland" (source: GUS, 2007b; Rynek pasz, 2008)

Product	Purchase [thous. tons]	Content of P [kg P · t <sup>1</sup> ]	Gross outflow <sup>1)</sup> [thous. tons]	Net outflow <sup>2)</sup> [thous. tons]
Cereals	7.15	3.5	25.03	15.02
Potatoes	1.12	0.6	0.67	0.50
Beet	12.07	0.4	4.83	0.50
Rape	1.64	7.8	12.80	8.96
Vegetables	1.21	0.5	0.61	0.50
Fruits	1.17	0.2	0.23	0.20

<sup>2)</sup> import of bran and 40% of imported wheat

Product	Purchase [thous. tons]	Content of P [kg P · t <sup>-1</sup> ]	Gross outflow <sup>1)</sup> [thous. tons]	Net outflow <sup>2)</sup> [thous. tons]
Livestock	3.91	10.5	41.06	32.90
Milk	8.28	1.0	8.28	6.63
Eggs (million pieces)	0.92	0.12	0.11	0.11
Wool	0.27	9.0	2.43	2.41
Other	-	-	4.90	2.94
Total	-	-	100.950	70.67

 $<sup>^{1)}</sup>$  from multiplying the values in columns 2 and 3,  $^{2)}$  after deduction of all or part of a product that remains at (returns to) the "farm Poland"

The gross outflow of phosphorus from the "farm Poland" is estimated at about 101,000 tons P (Table 4.9). The amount is clearly overestimated as the total phosphorus uptakes with crop yields do not exceed 206,500 tons P (Table 4.7). Part of gross phosphorus content of the products or commodities remains or returns to the "farm Poland" in the form of feed or waste. This quantity is estimated in Table 4.9 as amounting to about 30%. This approximately corresponds with the data of Sapek and Sapek (2002) who assumes that at least 40% of phosphorus in the products sold from the farm returns to the farm in the form of industrial feed (bran, pomace, spent grain, etc.). By introducing a correction for the amount of phosphorus remaining or returning to the farm we get a net outflow of phosphorus from the "farm Poland" in the amount of about 71,000 tons P (Table 4.9). This quantity still seems to be too high, because it amounts to approximately 1.8 kg P per capita per year in our country. Human nutritional requirements do not exceed 1 kg P per capita per year, which in the whole country gives about 38,000 tons P. However, it can be assumed that some net phosphorus outflowing from the "farm Poland" goes beyond national borders in the form of exported agricultural products, and some part of it goes to garbage dumps as waste from the processing of agricultural products for food.

Therefore, for further calculations "net outflow" of phosphorus was taken into consideration. The difference between the estimated inflow (101,000 tons) and outflow (71,000 tons) of phosphorus gives approx. 30,000 tons P and it should be recognized that this amount of phosphorus from agriculture is dispersed into the environment. This estimate highly accurately corresponds with the estimate given by Sapek (1998), by which the balance of phosphorus in Polish agriculture was positive and amounted to 106,000 tons P. The destiny of phosphorus in imported food and agricultural products sold in domestic and foreign markets may be of no interest, because it does not relate directly to agriculture. Of course, there are large losses in manufacturing and consumption, but most of the lost component goes to garbage dumps and sewage sludge. These wastes are only minimally turned back (recycled) to agriculture, and therefore they are not included in the balance calculation.

## 4.10. Phosphorus cycling in Polish agriculture

Flow of phosphorus in Polish agriculture, including the previously discussed P balance calculations "at the farm gate", is shown in Fig. 4.12. The values given earlier in the tables or in the text are marked in blue and should be treated as "definite". The values resulting from additional calculations are marked in red and should be treated as "simulated", and the method of their calculation is explained in the description below the picture.

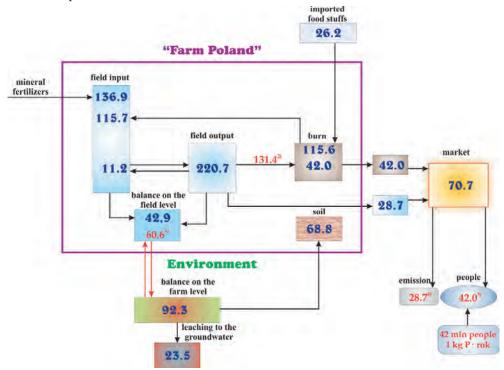


Fig. 4.12 Phosphorus cycle in Polish agriculture in thous. tons P (explanation in the text) (source: Igras and Fotyma, own unpublished study)

the balance of phosphorus calculated using the method "on the soil surface" was increased by 52.9 thousand tons as expected losses from the field (ploughed-in straw and other plant by-products). Therefore, the "outflow from the field" is calculated as the ratio of crop yield and elementary phosphorus content in the main products including the amount of by-product. A part of phosphorus is left behind on the field in the form of by-products;

<sup>&</sup>lt;sup>2)</sup> the amount of phosphorus in the roughage for animals is difficult to estimate directly, and so the simulation was done under the assumption that the amount of phosphorus in those products must cover phosphorus demand from "the stable", excluding the element quantity applied as concentrates;

<sup>&</sup>lt;sup>3)</sup> it is the estimated amount of phosphorus consumed by people. It was assumed that the total population consuming products from the "farm Poland" amounts to 42 million persons (38 million in the country and 4 million abroad), and the yearly demand of one person is 1.0 kg P;

<sup>&</sup>lt;sup>4)</sup> the amount of phosphorus lost in the processing of raw agricultural products into ready for consumption food stuffs.

Excess phosphorus in agriculture estimated as amounting in total to 92.3 thousand tons P enters the soil and is partly lost due to surface runoff and leaching, and partly accumulates in the soil in various forms. According to Sapek (1998), losses through leaching of phosphorus from the soil can be estimated at about 5.5 thousand tons P, and the losses due to surface runoffs at about 18 thousand tons P. The amount of 23.5 thousand tons P was assumed as a primary loss of phosphorus to soil and surface waters. It should not be forgotten though, that some part of phosphorus moving to surface waters is subject to retention in river systems (see to Chapters 8 and 9). It is assumed that the amount of phosphorus accumulated in the soil amounts to 68.8 thousand tons per year. This amount cannot be directly counted as losses of phosphorus, but when the buffering capacity of soil is exceeded the excess phosphorus can easily be subject to surface runoffs and leaching from the soil. It would be important to distinguish the forms of phosphorus in the amount accumulating in the soil. Most of the excess phosphorus probably accumulates in available forms, and according to monitoring studies conducted by chemical and agricultural monitoring stations, there has been a significant increase in content of available phosphorus in soils over the recent years. At monitoring sampling points the average increase in available phosphorus content was approx. 1.4 mg P · kg<sup>-1</sup> of soil per year (Jadczyszyn et al., 2009), which corresponds to an amount of about 4.2 kg P · ha<sup>-1</sup> · year<sup>-1</sup> (in the upper layer of the soil with the thickness profile of up to 20 cm). Referring these values to the whole area of agricultural land in Poland, the annual accumulation of phosphorus in available forms can be estimated at about 67 thousand tons P. That would constitute almost 100% of the total amount of phosphorus accumulating in soil. Data presented by Jadczyszyn et al. (2009) refer, however, only to farms equipped with monitoring points, and these farms are significantly better than the average with respect to agricultural practices. On most farms however, phosphorus balance shows a much smaller surplus, which for the whole Polish territory is estimated at 6.1 kg P · ha <sup>-1</sup>·yr<sup>-1</sup> in the period 2005-2009 (Table 4.7). If we assume that the entire amount of phosphorus is accumulated in the soil in a form that is available, it would give about 38 thousand tons of available P in the whole country, which represents approximately 55% of the total component accumulated in the soil.

# 4.11. Spatial differentiation of environmental threats caused by phosphorus excess

The analysis at river basin level presented in the previous chapter (Chapter 3; Tab. 3.22) shows that basins of the Vistula, the Oder, and the Pomeranian rivers differ quite significantly in terms of environmental conditions that may affect the size of the loss of nutrients into the Baltic Sea (Table 4.10). Theoretically, Pomeranian river basins should be more susceptible to diffuse loss of phosphorus compounds, as

evidenced by a greater proportion of arable land, the overwhelming predominance of very light and light soils - with low water holding capacity, and greater precipitation in the winter. In addition to the natural conditions also the agronomic factors should be taken into account. Out of these factors the higher average levels of phosphates in the water from drains and slightly higher amounts of available phosphorus in the soil suggest greater susceptibility of Pomeranian river basins to the loss of phosphorus compounds. On the other hand we have to keep in mind that contribution of P loads carried with the Pomeranian rivers to overall P loads introduced to the Baltic Sea in riverine outflow from Polish territory, is very small. The Vistula and Oder Rivers are responsible for the great majority of N and P loads (Chapters 8 and 9).

Table 4.10 Selected agronomic factors influencing the losses of phosphorus compounds from natural sources to the drainage and surface waters (source: Igras and Fotyma own study)

River basin	Phosphorus balance [kg P·ha <sup>1</sup> ] <sup>1)</sup>	The threat of erosion to the extent of> 5% [% of area] 2)	PO <sub>4</sub> -P concentrations in water from drains [mg·dm <sup>-3</sup> ] <sup>3)</sup>	Phosphorus positive bonitation index [% of area] 4)	Livestock density [LU·100 ha-1]	The intensity of crop production [crop unit·ha-1]
Vistula	3	8	0.15	46	50	31
Oder	2	5	0.23	58	47	39
Pomeranian rivers	3	4	0.67	58	29	36
Poland	2.5	7	0.21	51	46	34

<sup>&</sup>lt;sup>1)</sup> phosphorus balance calculated using "the soil surface" method, <sup>2)</sup> real water erosion threat by CorineLand Cover 2000 (Wawer and Nowocień, 2007); phosphorus losses are a consequence of the runoff, <sup>3)</sup> real phosphate concentrations in the drainage waters (at the depth lower than 100 cm); data from monitoring studies on the soil/ground-water quality carried out by IUNG-PIB Puławy, <sup>4)</sup> share of soils showing very high and high phosphorus content and 50% of the soils with the average content of phosphorus (data made available by the National Chemical-Agricultural Station in Warsaw)

The area specific emission of phosphorus into the Vistula and Oder River basins have been almost identical and for the last 10 years they have been amounting to about 38 kg P·km<sup>-2</sup>. The area specific emission of phosphorus into the Pomeranian river basins is the smallest and it is about 28 kg P·km<sup>-2</sup>. The lower values in the Pomeranian river basins may result from low share of areas threatened by erosion, a minor share of land with a slope of >5%, denser forest cover and reduced livestock density in the area of the basin (Chapter 2; see to Fig. 8.17 in Chapter 8).

Comparable area specific P emission into the two largest Polish river basins corroborates very well with the modelling studies (Chapter 8) which show that in the period 1995-2008 (i) erosion, tile drainage, and groundwater were the main paths of N emission to the Vistula and Oder basins, and N emission *via* these pathways reached 74% and 76% in the Vistula and Oder basin, respectively, (ii) P emission via these same three pathways amounted to 44% in both basins, (iii) the percentage contribution of these three and the four other N and P pathways was different in the river basins studied, and the full explanation is given in Chapter 8. Different N and P pathways, characterized by different transit time, therefore different natural nutrient retention, result in different river response with respect to spatial and temporal variability in nutrient concentrations monitored at the lowermost river monitoring stations; these issues are extensively discussed in Chapter 9.

Analysis of the diversity of environmental hazards caused by excess phosphorus in basins of the largest rivers in Poland is simplified because the basins are internally diversified in terms of natural conditions and agricultural practices (Chapters 8 and 9). Analysis carried out at regional level (NUTS-2), within which the environmental and agronomic conditions are more homogeneous, definitely can be more accurate. Between voivodeships, however, there is wide variation in terms of factors that determine the extent of excess phosphorus threats (Table 4.11).

Table 4.11 The factors influencing the extent of phosphorus potential threats in voivodeships (NUTS-2 level) in the years 2004-2006; abbreviations used for voivodeships – see to Chapter 12 (source: Igras and Fotyma, own study)

Voivodeship	Phosphorus positive bonitation index [%]	The threat of erosion to the extent of >5 [% of area]	The share of arable land in total area of voivodeship [%]	PO <sub>4</sub> -P concentrations in water from drains [mgP dm <sup>-3</sup> ]	Precipitation Oct. – Mar. [mm]	Field water capacity [mm]	Phosphorus balance [kg P ·ha <sup>-1</sup> ] <sup>1)</sup>
DLS	51.9	5.7	45.1	0.02	241	289	4.1
KUJ	66.3	7.6	56.0	0.47	197	184	8.0
LUB	43.3	12.3	53.0	0.01	202	216	3.7
LUS	61.9	2.3	29.4	0.07	232	181	6.4
LOD	48.1	2.6	54.4	0.66	213	157	6.7
MLP	34.8	26.8	35.5	0.07	276	296	1.7
MAZ	52.5	2.0	48.3	0.09	199	166	4.5
OPL	59.8	0.9	54.1	0.02	228	267	5.2
PDK	35.8	15.1	35.5	0.23	259	256	1.3
PDL	33.3	3.2	38.5	0.02	213	187	4.0

Voivodeship	Phosphorus positive bonitation index [%]	The threat of erosion to the extent of >5 [% of area]	The share of arable land in total area of voivodeship [%]	PO <sub>4</sub> -P concentrations in water from drains [mgP dm <sup>-3</sup> ]	Precipitation Oct. – Mar. [mm]	Field water capacity [mm]	Phosphorus balance [kg P ·ha-1]1)
POM	59.9	8.0	39.9	0.45	257	209	4.1
SLS	43.0	7.5	36.8	0.06	272	233	5.9
SWT	36.5	14.6	43.8	0.05	216	226	3.3
WAM	50.4	6.2	37.5	0.06	231	220	4.2
WLP	67.1	3.2	52.5	0.14	208	159	11.8
ZAP	56.5	5.0	38.0	0.85	264	185	1.0
Poland	53.4	7.1	40.6	0.07	232	206	5.2

<sup>1)</sup> calculations made for the years 2008-2010

Areas with varying degrees of excess phosphorus threats have been designated using cluster analysis. For this purpose a set of variables significantly affecting surface runoff and leaching of phosphorus was used (Table 4.12). Cluster analysis was performed using Ward method which allowed distinguishing two clusters of voivodeships corresponding to areas with varying degrees of phosphate excess and related threats (Fig. 4.13).

Table 4.12 Clusters of voivodeships according to the potential threats for the environment from the excess of phosphorus; abbreviations used for voivodeships – see to Chapter 12; (source: Igras and Fotyma, own study)

Cluster (group)	Positive bonitation index [%]	The share of arable land [%]	Field water capacity [mm]	Phosphorus balance [kg P·ha <sup>-1</sup> ]	Phosphorus concentration in water from drains [mg PO <sub>4</sub> -P·dm <sup>-3</sup> ]
1 DLS, LUB, MLP, OPL, PDK, PDL, SLS, SWT, WAM	43.2	42.2	243	1.08	0.06
2 KUJ, LUS, LOD, MAZ, POM, WLP, ZAP	58.9	45.5	177	4.04	0.39



Fig. 4.13 Regional differentiation of phosphorus threats in Poland (Igras and Fotyma, own study)

Phosphate concentration in water from drains is a direct indicator of the risk of excess phosphorus in the environment. As shown in Table 4.12, the average concentration of phosphate phosphorus in drainage water from the voivodeships of the second cluster is six times greater than in the voivodeships of the first cluster. It means that PO<sub>4</sub>-P concentrations exceed the upper range of concentrations considered hazardous because of the possibility of eutrophication of surface waters (Dz. U. No. 241, item 2093, 2002). Indirect indicators of phosphorus excess threats are also significantly different between the highlighted clusters of voivodeships. This refers particularly to positive bonitation of phosphorus content in the soil and its balance calculated using "on the soil surface method". Two of the indicators listed in Table 4.11, i.e. the threat of erosion and precipitation in the winter did not differ significantly between the distinguished clusters of voivodeships, and therefore have not been included in cluster analysis. In order to be able to carry out a more detailed analysis of losses and threats posed by phosphorus compounds, the data for smaller administrative units should be taken into account, but currently they are not available.

#### References

- Dz. U. Nr 241, poz. 2093, 2002. Rozporządzenie Ministra Środowiska w sprawie kryteriów wyznaczania wód wrażliwych na zanieczyszczenia związkami azotu ze źródeł rolniczych.
- EFMA, 2006. Forecast of food, farming and fertilizer use 2006-2016. Brussels.
- Egner, H., Riehm, H., Domingo, W.R., 1960. Untersuchungen über diechemische Bodenanalyse als Grundlage für die Beurteilung des Nahrstoffzustandes der Boden: II. Chemische Extraktionsmethoden zur Phosphor- und Kaliumbestimmung. Kungliga Lantbr.-Hogsk. Ann., Uppsala, 26:199–215.
- Fotyma, M., Jadczyszyn, T., Pietruch, Cz., 2001. A decision support system for sustainable nutrient management on farm level: MACROBIL. Nawozy i Nawożenie Fertilizers and Fertilization 2(7):7-26.
- Gaj, R., 2007. Zrównoważona gospodarka fosforem w glebie i roślinie w warunkach intensywnej produkcji roślinnej. Nawoży i Nawożenie Fertilizers, and Fertilization No. 33, 143 pp.
- GUS (Central Statistical Office), Rocznik Statystyczny. Annuals issued in 1960-2003. Waszawa, Poland.
- GUS (Central Statistical Office), Ochrona Środowiska. Annuals issued in 1991-2011, Warszawa, Poland.
- GUS (Central Statistical Office), 2006a. Użytkowanie gruntów, powierzchnia zasiewów i pogłowie zwierząt gospodarskich. Wyd. GUS, Warszawa, Poland.
- GUS (Central Statistical Office), 2006b. Środki produkcji w rolnictwie. Wyd. GUS, Warszawa, Poland.
- GUS (Central Statistical Office), 2007a. Użytkowanie gruntów, powierzchnia zasiewów i pogłowie zwierzat gospodarskich. Wyd. GUS, Warszawa, Poland.
- GUS (Central Statistical Office), 2007b. Środki produkcji w rolnictwie. Wyd. GUS, Warszawa, Poland.
- GUS (Central Statistical Office), 2009-2011. Produkcja upraw rolnych i ogrodniczych w 2009 r., 2010 r., 2011 r. Warszawa, Poland
- GUS (Central Statistical Office), 2010. Środki produkcji w rolnictwie. Wyd. GUS, Warszawa, Poland.
- Haygarth, Ph., 1997. Agriculture as a source of phosphorus transfer to water: Sources and pathways. Scope Newsletter. 21:3.
- Igras, J., 2004. Zawartość składników mineralnych w wodach drenarskich z użytków rolnych w Polsce. [in:] Monografie i rozprawy naukowe, 13:1-123.
- Igras, J., 2006. Potencjał polskiego przemysłu nawozowego na tle krajów Unii Europejskiej. Raporty IUNG-PIB, 2:9-25.
- Igras, J., 2007. Ocena jakości płytkich wód gruntowych w Polsce. Studia i Raporty IUNG-PIB, 5:49-54.
- Igras, J., Jadczyszyn, T., 2008. Zawartość azotanów i fosforanów w płytkich wodach gruntowych w Polsce. Problemy Inżynierii Rolniczej, 2(60):91-101.

References 191

- Igras, J., Kopiński, J., 2007. Zużycie nawozów mineralnych i naturalnych w układzie regionalnym. Studia i Raporty IUNG-PIB, 5:107-117.
- Igras, J., Lipiński, W., 2006. Regionalne zróżnicowanie stanu agrochemicznego gleb w Polsce. Raporty IUNG-PIB, Puławy, 3:71-79.
- Jadczyszyn, T., Maćkowiak, Cz., Kopiński, J., 2000. Model SFOM narzędziem symulacji ilości i jakości nawozów organicznych wytwarzanych w gospodarstwie. Pam. Puł. z. 120/I:169-175.
- Jadczyszyn, T., Filipiak, K., Igras, J., 2009. Ocena prognoza stanu agrochemicznego gleb w średnio intensywnych gospodarstwach rolnych. Studia i Raporty IUNG-PIB, Puławy, 14:175-185.
- Kopiński, J., Tujaka, A., 2009. Bilans azotu, i fosforu w rolnictwie polskim. Water-Environment-Rural Areas, IMUZ, Falenty, t.9, z.4 (28):108-116.
- Kopiński, J., Tujaka, A., 2010. Bilans azotu, fosforu i potasu w rolnictwie polskim w latach 2005-2009. Nawozy i nawożenie Fertilizers and fertilization, 41:120-132.
- Levy, E., Schlesinger, A.W., 1999. A comparison of fractionation methods for forms of phosphorus in soils. Biogeochemistry 47:25-48.
- Łabętowicz, J., 1995. Skład chemiczny roztworu glebowego w zróżnicowanych warunkach glebowych i nawozowych. Wyd. Fundacja "Rozwój SGGW", Warszawa, pp. 1-104.
- OECD (Organization for Economic Cooperation and Development), 1999. National Soil Surface Nutrient Balances: explanatory notes to interpret the data sheets. OECD Secretariat, Paris, 1999.
- OECD (Organization for Economic Cooperation and Development), 2008. Environmental Performance of Agriculture in OECD countries since 1990, Paris, France.
- Oenema, O., Roest, C.W., 1998. Nitrogen and phosphorus losses from agriculture into surface waters; the effects of policies and measures in the Netherlands. Wat. Sci. Tech., Vol. 37, No. 2:19-30.
- Pikuła, D., 2010. The yield of winter wheat depending on weather and nitrogen supply. Fertilizers and Fertilization. 41/2010:187-198.
- Phosphorus cycle: http://msucares.com/crops/soils/images/phosphorus.gif[Accessed in December 2011]; http://www.alken-murray.com/Phosphorus.html [Accessed in December 2011].
- Pondel, H., Ruszkowska, M., Sykut, S., Terelak, H., 1991. Wymywanie składników nawozowych z gleb w świetle badań prowadzonych przez Instytut Uprawy Nawożenia i Gleboznawstwa. Rocz. Gleb. T. XLII, 3/4:97-106.
- Rynek pasz, 2008. Wyd. IERiGŻ-PIB, nr 23-24. Warszawa.
- Sapek, A., 1998. Phosphorus cycle in Polish agriculture. [in:] Phosphorus in agriculture and water quality protection. IMUZ Falenty, pp. 8-18.
- Sapek, A., Sapek, B., 2002. Obieg i bilans fosforu w łańcuchu pokarmowym człowieka w Polsce. Nawozy i Nawożenie Fertilizers and Fertilization, 4

(13):105-123.

- Sharpley, A.N., 1995. Soil phosphorus dynamics: agronomic and environmental impact. Ecological engineering, 5:261-279.
- Sharpley, A.N., 2006. Agricultural Phosphorus management: Protecting Production and Water Quality. Lesson 34. Agricultural Research Service. Mid West Plan Service. Iowa State University, Ames, Iowa 50011-3080; http://www.lpes.org/Lessons/Lesson34/34\_Phosphorus\_Management.html. [Accessed in October 2009].
- Sykut, S., 2000. Wymywanie makroelementów z gleb w lizymetrach. Nawozy i Nawożenie, 4(5):18-26.
- Wawer, R., Nowocień, E., 2007. Aktualne zagrożenie erozją gleb w Polsce. Studia i Raporty IUNG-PIB, 5:157-168.
- Witek, T., Górski, T., 1977. Przyrodnicza bonitacja rolniczej przestrzeni produkcyjnejw Polsce. Wyd. Geologiczne, Warszawa.

5

NITROGEN AND PHOSPHORUS LOSSES FROM FARMS

STEFAN PIETRZAK

## 5. NITROGEN AND PHOSPHORUS LOSSES FROM FARMS

Stefan Pietrzak

### 5.1. Nitrogen and phosphorus flows and surpluses on the farms

The farm is a basic unit of organization and production in agriculture. The farm's production process is connected with inflows, outflows as well an internal cycling of nitrogen (N) and phosphorus (P) compounds (Fig. 5.1). On the input side we have: (i) purchased mineral fertilizers, (ii) less important with respect to quantity - organic feed, (iii) animals for breeding, (iv) sowable material, (v) atmospheric precipitation, (vi) assimilation of atmospheric nitrogen e.g. by symbiotic bacteria and free-living soil microorganisms. On the output side we have: (i) plant and animal products that are delivered to consumers or reach other agricultural producers or industry, (ii) N and P losses that get dispersed in the environment. Within the farm, certain amounts of N and P compounds circulate within a closed cycle soil—plant—animal—soil, but part of them leaves the closed system and goes up to the atmosphere or down due to leaching from soil.

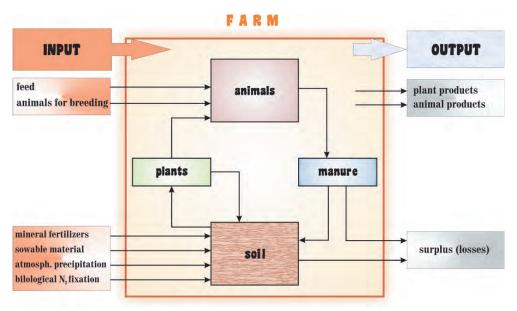


Fig. 5.1 Flow of nutrients on the farm (source: Oenema, 1999; graph modified)

The difference between all the farm's inputs and outputs gives a nutrient balance which is called the "Farm Gate Nutrient Balance". The N or P farm gate nutrient balance has usually a positive value. The N and P surplus constitutes a potential threat

for the environment as it may result in N and P accumulation in soil, N and P outflow to surface water and groundwater or loss to the atmosphere. Loss of nutrients form the agricultural system has negative economic effects such as reduction of production levels, greater investment in the means of production), and it imposes a threat to the environment, especially to water quality. Transport of N and P compounds into the water bodies takes places through a number of processes, such as:

- water and wind erosion (dissolved N, P forms and phosphorus compounds also adsorbed on soil particles) and subsurface runoff (mainly transporting nitrates NO<sub>3</sub>) from agricultural land,
- nitrate (NO<sub>3</sub>) washing out (infiltration) from farmland and farmsteads,
- emission of ammonia (NH<sub>3</sub>) from natural fertilizers and farmland soil fertilized with manure and then its precipitation from the atmosphere,
- emission of nitrogen oxides (II & IV) NO<sub>x</sub> (NO + NO<sub>2</sub>) from soil and manure and their precipitation from the atmosphere.

Excessive enrichment of surface waters with nitrogen and phosphorus results in eutrophication, defined by excessive phytoplankton growth and related consequences (e.g. diminishing water transparency, lack of oxygen in deep water reservoirs due to excessive phytoplankton production, declining recreational value of water bodies). Too high concentrations of nitrates make groundwater unsuitable for consumption by humans and animals. Ammonia emitted to the atmosphere is removed from the atmosphere along with dry and wet precipitation. Its deposition contributes to eutrophication of surface waters, soil acidification and increased leaching of nitrates from the soil into groundwater. Emission of nitrogen oxides (II & IV) released during microbiological soil processes indirectly contributes to acidification of aquatic ecosystems.

Among the different types of farms, the largest surpluses of nitrogen and phosphorus are found on farms oriented on livestock production and that has been documented by numerous studies conducted in Poland and abroad. The research studies carried out on 186 French farms showed that the N surplus on the farms with intensive production of pigs and poultry amounted to  $392-532 \text{ kg N} \cdot \text{ha} \cdot \text{yr}^{-1}$ ; on the farms producing only milk and beef livestock it amounted to  $152-256 \text{ kg N} \cdot \text{ha} \cdot \text{yr}^{-1}$ , whereas on the plant growing farms (cereals and root crops) it amounted only to  $28 \text{ kg N} \cdot \text{ha} \cdot \text{yr}^{-1}$  (Simon and Le Corre, 1992; Fig. 5.2)

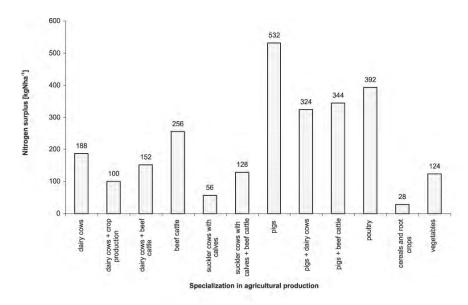


Fig. 5.2 Surplus of nitrogen on the farms of Northern France depending on the specialization of production (source: Simon and Le Corre, 1992; graph adapted)

In Polish agriculture the surplus of N and P generated in livestock farms is lower than in countries with highly developed agriculture, nevertheless it also reaches high values. This applies in particular to farms dedicated solely or mainly to pork production. In this type of farms from Wielkopolska region (WLP voivodeship – see to shortenings in Chapter 12), which is generally characterized by intensive agricultural activity, N and P annual surpluses amounted to 392 kg N  $\cdot$  ha<sup>-1</sup> and 96 kg P  $\cdot$  ha<sup>-1</sup>) (exclusively raising pigs), and to 219 kg N  $\cdot$  ha<sup>-1</sup> and 71 kg P  $\cdot$  ha<sup>-1</sup> (mainly raising pigs) (Table 5.1).

Table 5.1 Average annual surplus and the use of nitrogen and phosphorus in three pig farms in Wielkopolska region (data from Krajowe Centrum Doradztwa Rozwoju Rolnictwa i Obszarów Wiejskich Oddział, Oddział w Poznaniu) (source: Pietrzak, 2002)

	Profile of production on the farm							
Index	Pigs only <sup>1)</sup>		Mainly pigs <sup>2)</sup>		Pigs + plant production <sup>3)</sup>			
	N	P	N	P	N	P		
		Input [k	g · ha-1]					
Mineral fertilizers	67.8	21.1	123.6	43.8	102.7	22.1		
Feed mixtures and concentrates	321.2	111.2	85.9	28.1	35.3	11.6		
Feed grain	318.8	63.2	103.9	21.4	0.0	0.0		

	Profile of production on the farm							
Index	Pigs only <sup>1)</sup>		Mainly pigs <sup>2)</sup>		Pigs + plant production <sup>3)</sup>			
	N	P	N	P	N	P		
Sowable material	4.0	0.8	1.8	0.3	2.4	0.5		
Animals (stock animals)	1.5	0.6	1.4	0.2	0.4	0.1		
Free-living microorganisms	10.0	-	10.0	-	10.0	-		
Precipitation	18.0	-	18.0	0.0	18.0	-		
Total input [kg · ha <sup>-1</sup> ]	741.3	196.9	344.6	93.8	168.8	34.3		
		Output [l	kg · ha-1]					
Livestock pigs	256.6	45.4	91.2	16.1	29.8	5.3		
Manure	92.3	55.4	-	-	-	-		
Sugar beets	-	-	13.5	2.6	21.1	4.1		
Rape	-	-	20.8	4.0	-	-		
Sweet corn	-	-	-	-	4.5	0.9		
Cereals	-	-	-	-	9.5	1.9		
Total output [kg · ha-1]	348.9	100.8	125.5	22.7	64.9	12.2		
Surplus [kg · ha <sup>-1</sup> ]	392.4	96.1	219.1	71.1	103.9	22.1		
Efficiency [%]	47.1	51.2	36.4	24.2	38.4	35.6		
Size of the farm in hectares	13		38		119			

<sup>1)</sup> nutrients were taken away solely in livestock and natural fertilizers,

Generally, the annual surplus of N and P on cattle farms is smaller. The N and P surpluses on the levels of 123 kg N  $\cdot$  ha<sup>-1</sup> and 13 kg P  $\cdot$  ha<sup>-1</sup>, that have been found on three typical farms specializing in milk production in Podlasie region (PDL – see to shortenings in Chapter 12), where the stocking density is the highest in the country, may be considered representative for the cattle farms (Pietrzak, 2005; Table 5.2). In the analyzed farms, which were exclusively or mainly oriented towards production of pigs or milk and beef livestock, surpluses of N and P were higher than on farms with mixed production, and the greater was the share of crop production in the farm's total production, the lower were the surpluses of N and P. This confirms the rule that farms with mixed production exert much lower pressure on the environment than farms that are specialized in livestock production.

<sup>&</sup>lt;sup>2)</sup> more than 70% of nutrients were taken away in livestock,

<sup>&</sup>lt;sup>3)</sup> approximately 45% of nutrients were taken away in livestock and about 55% in plant products.

Table 5.2 Average annual surplus and the use of nitrogen and phosphorus in four cattle farms in Podlasie region (PDL – see to voivodeship shortenings in Chapter 12) (source: Pietrzak, 2005)

	Profile of production on the farm							
Specification	(Average five	oduction <sup>1)</sup> -year results of farms)	Dairy production + crop production (Average five-year results of one farm)					
	N P		N	P				
	Inp	out [kg · ha <sup>-1</sup> ]						
Mineral fertilizers	108.1	14.1	88.6	14.2				
Nutritive fodders	12.8	3.9	7.5	2.3				
Bulky feeds	4.7	0.5	1.8	0.2				
Straw	0.1	0.01	0.2	0.0				
Animals	-	-	0.2	0.1				
Fabaceae <sup>2)</sup>	2.3	-	3.9	-				
Free-living microorganisms	10.0	-	10.0	-				
Precipitation	10.6	-	10.6	-				
Total input	148.6	18.6	122.8	16.8				
	Out	put [kg · ha-1]						
Cereals	0.3	0.1	15.4	2.9				
Potatoes	0.6	0.1	1.1	0.2				
Sugar beets	-	-	8.8	1.8				
Milk	22.1	4.4	13.9	2.6				
Cattle for slaughter	3.0	1.0	1.6	0.4				
Total output	26.0	5.6	40.8	7.9				
Surplus [kg · ha <sup>-1</sup> ]	122.6	12.9	82.0	8.9				
Efficiency [%]	17.5	30.3	33.2	47.0				
Surplus [kg · m <sup>-3</sup> of milk]	29.3		31.1					

<sup>&</sup>lt;sup>1)</sup> farms from which nutrients were taken away solely in animal products, with some possibility of a very small share of plant products,

<sup>2)</sup> without fabaceae in meadow sward.

On livestock farms, the main factors affecting the size of the surplus are the purchased fertilizers, which are ultimately used for production of feed, and the purchased nutritive fodders. The latter are often brought to the farm in very large amounts, thus significant amounts of N and P inflow with them. On the analysed farms, which were dedicated exclusively or principally to the production of pigs, the amount of nitrogen and phosphorus brought in with industrial feed and feed grain exceeded the respective amount brought in with mineral fertilizers (Table 5.1). In animal feeding, only a small part of nutrients contained in the feed is processed into milk or meat. The unused amount is excreted by animals in the form of manure. Manure constitutes the biggest direct source of loss of nutrients in farming. This issue is discussed further in subsection 5.2 concerning the losses of nitrogen and phosphorus compounds from farms to groundwater, and in subsection 5.3 with reference to emissions of ammonia.

Along with the concentration and intensification of animal production, the fluxes of N and P on farms increase, and so do their surpluses, thus increasing the risk for the environment pollution, including deterioration of water quality. It has become particularly evident in areas with highly developed livestock production in Belgium, Denmark, Germany, France, Holland, Great Britain, and Italy, where considerable groundwater pollution by nitrates and eutrophication of surface waters occurred (Rude and Frederiksen, 1995).

In Poland, the average stocking density is low [0.45 Livestock Units (LU) · ha¹ in 2009-2011], which in general suggests that livestock production does not exert strong pressure on water resources. However, considering the problem in more detail, it should be noted that locally, in isolated areas, and in many spots, the impact of livestock production on water quality can be significant. There are many large scale livestock farms with intensive production, which emit significant loads of pollutants into the environment. The largest concentrations of such farms can be found in the following voivodeships: Wielkopolskie (WPL) (the production of pigs), Podlaskie (PDL) (milk production), but also in Mazowieckie (MAZ), Kujawsko-Pomorskie (KUJ), and Warmińsko-Mazurskie (WAM), and Łódzkie (LOD) (Fig. 5.3). The question of the distribution and concentration of animal production is discussed in more detail in Chapter 2 of the monograph.

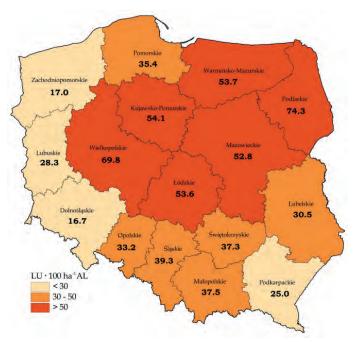


Fig. 5.3 Livestock density in LU per 1 ha of agricultural land in voivodeships in 2009-2011 (source: map prepared and made available for this monograph by Kopiński; map based on the data from: GUS, 2009-2011)

# 5.2. Contamination of soil and water on farms with nitrogen and phosphorus compounds originating from farms' point sources

The farm is a spot, in which a large part of the process of agricultural production, especially livestock production, takes place. Significant losses of nitrogen and phosphorus result from the farm's production activity. The excess of N and P, which become accumulated on a small area, seeps into water bodies creating a serious threat to their quality. The following farmstead's "hot spots" are particularly important sources of contamination: manure storage areas, livestock pens, stock buildings, silage piles. Among them, the most serious source of pollution are manure storage areas, especially when they are located directly on the ground. Soil from these storage areas is strongly enriched in nitrogen and phosphorus compounds. Soil tests performed on samples of soil (sandy soil with clay layer at 30-65 cm), taken from the area of regular manure storage for the period of approx. 20 years, revealed a significant enrichment of the soil in nitrate and ammonium (Pietrzak and Nawalany, 2008; Fig. 5.4). The average content of mineral nitrogen in the whole soil profile in these samples was almost seven times higher than that observed in arable soils monitoring tests (see to

Chapter 4). The 0-30 cm soil layer was particularly rich in nitrogen. Concentrations of nitrogen in soil samples taken from under manure heaps were more than eleven times higher in comparison with the average content of mineral nitrogen in soils of comparable arable land. In one of the soil sampling points the mineral nitrogen content  $- N-min (NO_3-N +NH_4-N)$  exceeded 1900 kg · ha<sup>-1</sup>.

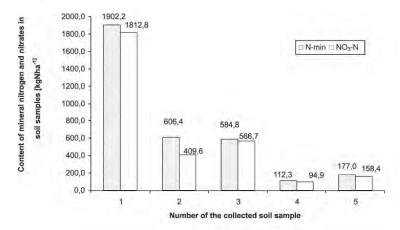


Fig. 5.4 The content of mineral nitrogen (N-min) and nitrates in soil samples from 0-90 cm layer taken at different points from the place of long-term manure storage (source: Pietrzak and Nawalany, 2008)

The average plant available phosphorus content in 0-20 cm soil layer from under manure heaps exceeded more than 3.5 times the limit - 89 mg P kg<sup>-1</sup>, established for mineral soils very rich in this component (Obojski and Strączyński, 1995) (Fig. 5.5).

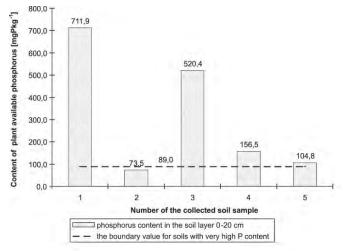


Fig. 5.5 The content of phosphorus (as determined by the Egner-Riehm method) in 0-20 cm soil layer samples taken from places of manure storage (source: Pietrzak, own data)

Also in groundwater, just as in the case of soil, high levels of N and P were found in areas of regular manure storage and near the sites. The eight-month' average content of  $NO_3$ -N in water from the well located directly at the site of manure storage exceeded 118 mg  $\cdot$  dm<sup>-3</sup>, whereas the average content of  $NH_4$ -N almost reached the level of 18 mg  $\cdot$  dm<sup>-3</sup>. Water from the well located near this dunghill was characterized by a relatively low content of nitrates, but it was highly polluted with ammonium - containing approx. 9 mg of  $NH_4$ -N  $\cdot$  dm<sup>-3</sup>, and with phosphates - containing about 11 mg  $PO_4$ - P  $\cdot$  dm<sup>-3</sup>.

The wider range of threats posed to the quality of water and soil by manure storage sites, including also other sources of pollution located at the farmstead, was documented by Sapek and Sapek (2007). Based on their studies, involving 28 farms with different levels of intensity of agricultural production and differently equipped with natural fertilizers storage facilities, the authors found that in the upper 20 cm layers of soil near the "hot spots" much greater amounts of mineral nitrogen and phosphorus compounds are deposited than in the similar layers of soil, which are not exposed to the direct effect of pollutants located in their vicinity (Table 5.3). In the case of NO<sub>3</sub>-N and PO<sub>4</sub>-P these interrelationships were statistically significant.

Table 5.3 Average content of mineral nitrogen compounds and soluble phosphorus<sup>1)</sup> found on 26 farms in 0-20 cm layer of soil taken from pollution affected points and reference points (source: Sapek and Sapek, 2007).

Nutrient	Concentration [mg · dm <sup>-3</sup> ] <sup>1)</sup>				
	Pollution affected points		Reference points		
	Average	Standard deviation	Average	Standard deviation	
NH <sub>4</sub> -N	5.22	16.1	2.95	5.29	
NO <sub>3</sub> -N	46.9	61.4	25.7	36.8	
PO <sub>4</sub> -P	18.4	28.2	7.79	14.3	

<sup>&</sup>lt;sup>1)</sup> the content of mineral forms of nitrogen -  $NO_3$ -N and  $NH_4$ -N and phosphorus -  $PO_4$ -P in the soil samples was determined after their extraction with 1%  $K_2SO_4$ ; the determination was performed in fresh soil material.

The above-mentioned authors also showed a negative effect of the farmstead pollution sources on the quality of groundwater. On the basis of the results of monitoring carried out in 36 livestock farms located in KUJ, PDL and MAZ voivodeships they found particularly high accumulation of N and P in water collected from wells located near manure storage sites. The multi-year average concentrations of nitrates, ammonium, and phosphorus in the water samples amounted to: 7-37 mg NO<sub>3</sub>-N·dm<sup>-3</sup>, 5.2-53 mg NH<sub>4</sub>-N·dm<sup>-3</sup>, and 1.2-11.5 mg PO<sub>4</sub>-P·dm<sup>-3</sup>, respectively (Table 5.4). In most cases, the concentrations of these compounds (analysed over two to seven-year periods), exceeded, sometimes substantially, limits for Class V

(poor quality) groundwater (classification of water quality following EU Water Framework Directive – see to: Czaban, 2008; Kania et al., 2011).

Table 5.4 Average concentrations of nitrogen and phosphorus in groundwater samples taken from sites located in the vicinity of farm manure pits (source: Sapek and Sapek, 2007)

	Period of	Number	Concentration [mg·dm <sup>-3</sup> ]		
Location of farms	study	of samples	PO <sub>4</sub> -P	NO <sub>3</sub> -N	NH <sub>4</sub> -N
The region of Ostrołęka	1993-1995	313	3.6	29	6.8
The region of Ostrołęka	2004-2006	193	4	28	23.2
The community of Ciechocin	1997-2006	102	7.2	20	5.2
The community of Stara Biała	1999-2006	116	10.5	7	23.7
The community of Papowo Biskupie	2004-2006	66	11.5	37	35.6
Falenty	2004-2006	44	1.2	25	53
The community of Klukowo	1999-2003	101	6.9	12	35.34

Also in other places within the farmstead where cattle yards, silos, cattle yard gates, being a passage for cattle to pasture land, the concentrations of mineral forms of nitrogen and phosphorus may reach very high levels (Table 5.5).

Table 5.5 Average concentration of mineral components in groundwater samples taken from different locations on the four dairy farms in the borough of Klukowo (PDL voivodeship) in 1999-2004 (source: Pietrzak, 2005)

Water monitoring location	Number of	Concentration [mg·dm <sup>-3</sup> ]			
water monitoring location	samples	PO <sub>4</sub> -P	NO <sub>3</sub> -N	NH <sub>4</sub> -N	
Young cattle yard	25	3.23	19.19	31.11	
At the farmstead's gate	25	3.38	2.61	5.54	
At the horizontal silo	23	1.22	14.32	14.74	

Groundwater in the farmstead is contaminated not only in areas directly exposed to the individual sources of pollution, but also at a certain, sometimes considerable, distance from these places, such as homestead wells. In the early 1990s, the nitrate concentrations in the water from approx. 50% of rural dug wells exceeded 10 mg  $NO_3$ -N · dm<sup>-3</sup>, and in almost 16% of the wells the concentration was higher than 40 mg  $NO_3$ -N · dm<sup>-3</sup> (Sapek, 1996; Fig. 5.6). The Ministry of Agriculture and Rural Development, based on the data of the Ministry of Health, reported that 44.8%

of homestead wells had poor water quality in the year 2000; non-potable water contained more than 50 mg of NO<sub>3</sub>- · dm<sup>-3</sup> (11.3 mg of NO<sub>3</sub>-N · dm<sup>-3</sup> (Program ..., 2006). Inappropriate ways of manure storage are considered to be the main cause of nitrate pollution of water in the wells (Program ..., 2006). On the basis of various studies Velthof et al. (2007) estimated that during storage for a period of more than 200 days up to 4% of the initial amount of nitrogen is washed out from manure piles which are stored directly on the ground.

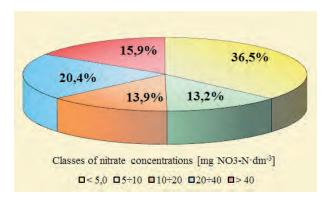


Fig. 5.6 Share of water samples from farmhouse wells in different classes of  $NO_3$ -N concentrations (n = 1324); data from the 1990s (source: Sapek, 1996).

In addition to polluting of groundwater, farming activities conducted within the farmstead can also negatively affect the quality of surface waters. In the case of phosphorus, there is a positive correlation between the content of its mobile forms in the upper soil layer and the content of these forms in the water from surface runoff (Fig. 5.7). So, extensive concentrations of phosphorus species in the upper soil have a great impact on P emission into surface waters. Therefore the direct sources of these excessive P concentrations must be reduced or eliminated. In this respect, it is particularly important to introduce manure storage methods that eliminate runoffs or leakage into the environment (Photos 5.1, 5.2.).

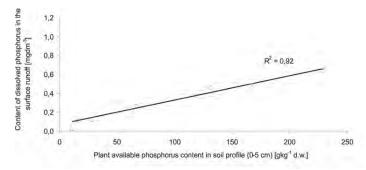


Fig. 5.7 The relationship between plant available phosphorus content in 0-5 cm soil profile and concentrations of dissolved forms of phosphorus in the surface runoff (as determined by the Olsen method); measured in the surface outflow (source: Report..., 2002)



Photo 5.1 Improper manure storage (photo by P. Nawalany)



Photo 5.2 Proper manure storage (photo by P. Nawalany)

Calculations made with the application of MITERRA-Europe model revealed that nitrogen leaching from the livestock buildings and manure piles represent about 40% of the total losses from farming sources in Poland (Assessment..., 2007). The problem of the correct methods of storage of natural fertilizers has not been fully resolved from the legal point of view. Following the Article 25, item 2 of the Act of July 10, 2007 on fertilizers and fertilization, it is clear that an obligation to store manure on impermeable storage plates is limited only to IPPC (Integrated Pollution Prevention and Control) farms (industrial farms). This regulation calls for a change and the restrictive regulations concerning storage of manure and dung should be extended to all farms raising animals in Poland.

## 5.3. Ammonia emission from natural and mineral fertilizers and its significance for water quality

Agricultural production, especially livestock production, is the main source of ammonia (NH<sub>3</sub>) emissions into the atmosphere. It is estimated that the share of agriculture in total emissions of ammonia to the atmosphere in Europe amounts to 80-90%. The remainder of this emission comes from industry, households and natural ecosystems. What concerns the agricultural sector, it is estimated that over 80% of the emissions of this gas comes from animal manure, and the rest mainly originates from nitrogen fertilizers applied to agricultural land (Atmospheric ..., 2000). The emission of ammonia is a major source of nitrogen losses in agriculture and it constitutes a threat to the environment by contributing to soil and water acidification and eutrophication of aquatic and terrestrial ecosystems. Ammonia accelerates the corrosion of metal structures and buildings and has a detrimental effect to the human body.

Emissions of ammonia from manure occur as a result of microbial decomposition of the nitrogen compounds that are contained in manure. The easiest to decompose is urea, which is present in large quantities in animal urine. Urea is rapidly converted to ammonia under the influence of the urease enzyme, which is produced by microorganisms present in faeces:

$$CO(NH_2)_2 + H_2O \xrightarrow{urease} 2 NH_3 + CO_2$$

Decomposition of complex organic nitrogen compounds in natural fertilizers is slower and may take months or even years. The overall losses of ammonia from livestock production consist of ammonia emission from manure in livestock buildings, from storage areas, during the period of its use on agricultural land, and from animal faeces and urine left on the pasture land (Cowell and Webb, 1997; Fig. 5.8).

Emissions of ammonia from livestock buildings depend on the system of animal husbandry and the type of livestock. The highest emissions are present in pig and poultry farms reaching up to 25% of nitrogen excreted in faeces (Hutchings et al., 2001).

The amount of NH<sub>3</sub> escaping from livestock quarters is affected by a number of factors:

- surface covered with faeces (emission increases with increase in the surface area),
- temperature of the manure (the lower the temperature, the lower the emissions),
- pH (lower emission at low pH),
- ammonia content in manure (higher emission at higher content),
- wind speed over the surface of manure (the higher wind speed leads the higher the emission).

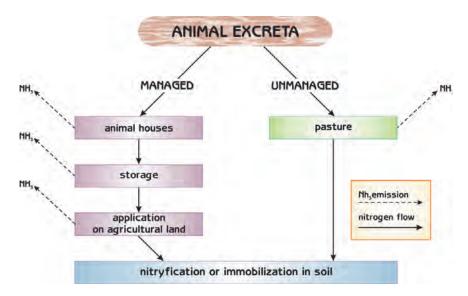


Fig. 5.8 Nitrogen flow and ammonia emission from animal excrements (source: Cowell and Webb, 1997)

Ammonia losses during manure storage depend on the type and composition of manure, time of storage, the meteorological conditions (temperature, precipitation, and wind speed), and the size of the tank. The average losses of ammonia from manure and slurry tanks are rather small, amounting to 2% and 2-9% respectively, and are significantly smaller than those from traditionally stored manure where the average losses reach 15% for cattle manure and 30% in the case of pig manure (Hutchings et al., 2001). However, the losses may be substantially higher, especially in the case of negligent manure storage. Marcinkowski (2002) found that losses of ammonia from manure stored in manure pits on a pig farm in Żuławy amounted to 39% of the initial nitrogen content, whereas on cattle farms the losses from dunghills reached 26% N.

Losses of ammonia occurring during the use of natural fertilizers depend on the type and doses of fertilizer, weather conditions, season, crop type, methods of application (splashing, banding, injecting - in the case of liquid manure). It is assumed that losses from liquid manure may reach 30%, while from manure - 15% (Hutchings et al., 2001). In practice diverse amounts of losses are found.

Measurements of ammonia emissions 3-4 days after natural fertilizer application on arable land on farms in PDL voivodeship amounted to 2.3% - 7.4% from manure, 22.2% - 41.7% from liquid manure, and 24.2% from slurry; the percentage is referred to the initial content of total nitrogen in these fertilizers (Figs. 5.9 and 5.10). Application of manure was done with the use of a spreader (Photo 5.3) while application of slurry with the use of a slurry spreader with splash plates (Photo 5.4).



6,3 Ammonia losses [% of N total] 6 5,0 5 4 3,5 3,3 3 2,3 1,8 2 1 0 1 subsequent day after application ----well-decomposed manure stored for 1 year in the field heap manure stored for 0.5 year in the dunghill fresh manure stored on the manure plate for 1-2 weeks -manure stored in the field heap which was not properly formed

Fig. 5.9 Cumulative emission of ammonia from cattle manure after application on arable land (source: Pietrzak, 2005)

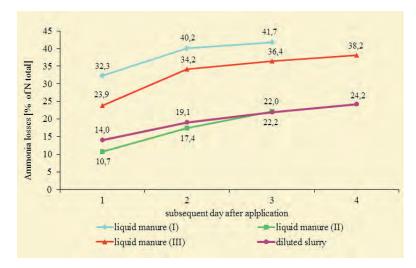


Fig. 5.10 Cumulative emission of ammonia from cattle liquid manure and slurry after application on grassland (source: Pietrzak, 2005)

Losses of ammonia from manure (faeces and urine) left by animals on pastures on average amount to 3.1% of the nitrogen contained in them at the level of mineral fertilization of  $250 \text{ kg N} \cdot \text{ha}^{-1}$  (Bussink, 1996).

Using the rolling costs method, the loss of ammonia from manure can be expressed in the form of coefficients determining amounts of this compound emitted from faeces excreted by various types of livestock throughout the year. These coefficients determine ammonia emissions generated by individual animals, depending on their age and the performance of the breeding system (Table 5.6). They are useful for carrying out the assessment of ammonia emissions in the micro scale (e.g. for individual farms).

Table 5.6 Ammonia emission coefficients for different categories of animals, depending on breeding system (source: Pietrzak, 2006)

	Ammonia emission coefficients for different categories of animals per breeding system [kg NH <sub>3</sub> -N · yr <sup>1</sup> · animal unit <sup>1</sup> ]			
Animal category	Bed	beddingless		
	on deep dung	on the floor with little bedding	(liquid manure)	
Calves 0-3 months of age <sup>1)</sup>	0.48	1.30	_	
Calves 3-6 months of age <sup>1)</sup>	1.01	2.74	_	
Heifers 6-12 months of age <sup>1)</sup>	2.59	6.98	7.33	
Heifers 12-24 months of age <sup>1)</sup>	4.95	13.26	14.00	

	Ammonia emission coefficients for different categories of animals per breeding system [kg NH <sub>3</sub> -N·yr <sup>1</sup> ·animal unit <sup>1</sup> ]			
Animal category	Bed	Bedding		
	on deep dung	on the floor with little bedding	(liquid manure)	
Cows with milk production capacity of 3.5 thousand kg	6.40	15.72	16.90	
Cows with milk production capacity of 4 thousand kg	6.91	16.98	18.25	
Cows with milk production capacity of 4 - 6 thousand kg	7.89	19.40	20.85	
Cows with milk production capacity above 6 thousand kg	10.86	26.70	28.69	
Sows + 18 weaners <sup>1)</sup>	9.75	16.98		
Sows	4.19	7.07		
20 – 30 kg weaners <sup>1)</sup>	1.23	3.28	2.41	
30 – 70 kg piglets <sup>1)</sup>	2.72	6.54	5.33	
70 – 100 kg fattening pigs <sup>1)</sup>	2.72	6.54	5.33	
600 kg horses	8.62	_	_	
400 kg horses	6.55	_	_	
Ewes	1.45	_	_	
Sheep over 12 months of age	1.31	_	_	
Lambs 6-12 months of age <sup>1)</sup>	0.66	_	_	
Laying hens <sup>1)</sup>		0.239	_	
Chickens <sup>1)</sup>		0.014	_	
Turkeys <sup>1)</sup>	_	0.194	_	
Ducks <sup>1)</sup>	_	0.057	_	
Geese <sup>1)</sup>	_	0.112	_	

<sup>&</sup>lt;sup>1)</sup> Computational animal units per year - for which the ammonia emissions were estimated per one stand in farm building assuming that it was occupied by an animal of that category for a year.

Losses of ammonia from mineral nitrogen fertilizers constitute from 1% to 15% of nitrogen by weight in the fertilizer applied (Table 5.7). The largest losses of ammonia occur from urea.

Table 5.7 Coefficients of ammonia	emission from	farmlands	after	application	of
mineral nitrogen fertilizers, (source:	Atmospheric	, 2000)			

Type of fertilizer	Ammonia emission coefficient <sup>1)</sup> , [kg NH <sub>3</sub> -N · (kg N applied in fertilizer) <sup>-1</sup> ]		
Ammonium sulphate	0.05		
Ammonium nitrate	0.01		
Calcium ammonium nitrate	0.01		
Anhydrous ammonia	0.04		
Urea	0.15		
Ammonium phosphate	0.05		
Another fertilizer complex NK, NPK	0.01		
Nitrogen solutions (mixture of urea and ammonium nitrate)	0.08		

<sup>1)</sup> Coefficients elaborated for countries of moderate or cool climate with substantial share of acidic soils

Ammonia emitted to the atmosphere is rapidly removed from it; within the period ranging from several hours to several days it returns to the surface in the form of dry or wet precipitation (Fig. 5.11). Dry deposition of ammonia is usually found near sources of its emission (within the area of about 1 km), while wet deposition can take place even at a distance of hundreds of kilometres from these sources.

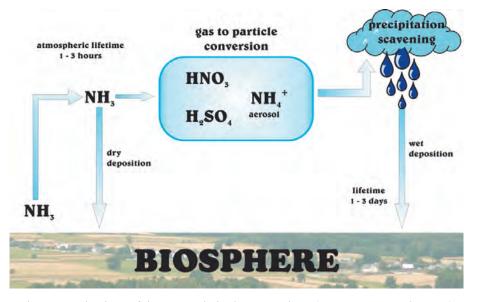


Fig. 5.11 Behaviour of the ammonia in the atmosphere (source: Tang et al., 2005)

The main mechanism for removing ammonia from the air is the reaction with sulphuric acid and nitric acid. These acids reacting with ammonia form ammonium salts, ammonium sulphate (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>, and ammonium nitrate NH<sub>4</sub>NO<sub>3</sub>. As less volatile they form molecules and reach the soil in the form of either dry or wet deposition. This deposition constitutes a serious threat to natural ecosystems, including water reservoirs, as it contributes to their eutrophication. It has been estimated that in 2005 approximately 208,000 tons of nitrogen was deposited into the Baltic Sea from the atmosphere (Bartnicki et al., 2007), which represents about 25% of the total nitrogen getting into the Baltic from different sources. Within the overall atmospheric N deposition, ammonia constituted 92,000 tons (approx 44%), and the remaining was represented by nitrogen oxides (based on Bartnicki et al., 2007). In the Baltic Sea region Poland belongs to the countries emitting the largest amounts of ammonia (Fig. 5.12), thus is responsible for substantial deposition of ammonia to the Baltic Sea (Fig. 5.13).

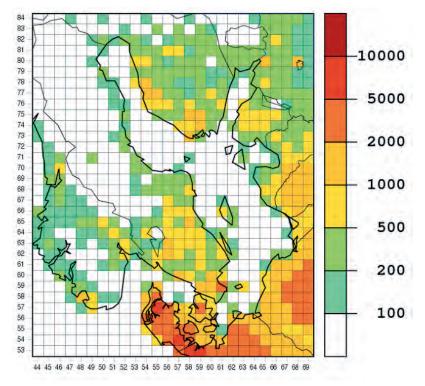


Fig. 5.12 Spatial distribution of annual emissions of ammonia in the Baltic Sea region in 2008. Units: tons of NH<sub>3</sub> per year and per 50 km×50 km grid cell (source: Bartnicki et al., 2008)

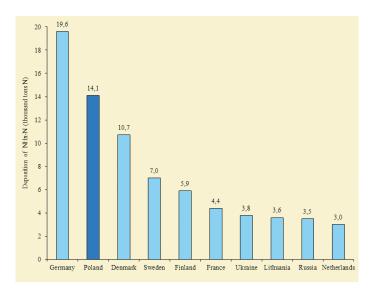


Fig. 5.13 Countries with the greatest contribution to deposition of atmospheric nitrogen in the form of ammonia and ammonium ( $NH_3+NH_4^+$ ) to the Baltic Sea in 2005 (source: Bartnicki et al., 2007)

Emissions of ammonia from agricultural sources cause a number of adverse consequences. For this reason in order to reduce the consequences it is necessary to apply appropriate agricultural practices. Reduction of ammonia emissions from manure can be achieved primarily through (i) reducing the amount of nitrogen excreted in faeces per animal unit and per unit of livestock production, (ii) improving manure handling practices in livestock buildings, and (iii) improving methods of manure storage and use.

Reduction of the amount of nitrogen excreted with animal faeces, (which not only helps to reduce ammonia emission, but also reduces the loss of nitrogen oxides and phosphorus oxides), can be achieved through the use of high quality feed, balanced animal feed rations tailored to the needs of each animal category, and through animal unit productivity increase (Table 5.8).

Table 5.8 Amount of nitrogen excreted by dairy cows per animal and per production unit in relation to their productivity (source: Flachowsky, 1994)

Description	Milk production capacity per cow [kg · cow <sup>-1</sup> · yr <sup>-1</sup> ]			
Description	4000	6000	8000	
The amount of excreted nitrogen:				
kg · cow-1 · yr-1	80	96	120	
g · dm <sup>-3</sup> of milk	20	16	15	

The reduction in ammonia emission can be achieved through different actions. In particular, in ruminant feeding it is recommended (i) to reduce green fodder in favour of bulky feed with lower protein content (corn silage, hay, straw), (ii) to feed ruminants with meadow sward in later stages of growth, or (iii) to reduce the amount of meadow green fodder and at the same time increase portions of high-energy nutritive fodders. In the feeding of pigs and poultry the phase feeding is recommended, as well as the use of growth stimulants and enzymes, e.g. phytase to improve feeding efficiency and the use of synthetic amino acids to improve protein amino acid composition of the feed.

Loss of ammonia in livestock buildings can be prevented by both the reduction of the surface deposition of manure and the reduction of the time of the manure's exposure to open air. In cowsheds and pigsties with bedding it is recommended to use a larger amount of straw for bedding and to ensure rapid drainage of urine into the tank as well as to keep drinkers and troughs in good condition to avoid water leakage. In the beddingless buildings, proper design of floor grates for quick runoff of manure and reduction of the exposed surface of slurry in channels draining faeces to tanks, contribute to the reduction of ammonia losses.

It is very important to reduce ammonia losses during manure storage. The largest losses of ammonia during storage of organic fertilizers occur from manure and slurry because liquid manure is usually stored in closed tanks.



Photo 5.5 Impermeable manure plate (photo by P. Nawalany)

Manure removed from the livestock buildings should be stored on an impermeable manure plates with side walls, drainage channels and drainage tanks (Photo 5.5). It

is recommended to place manure in layers compressing each layer, and to minimize the surface of the pile by higher storage, and to maintain the temperature in the pile below 50°C, or to expand the C:N ratio in the manure to >25 by increasing the amount of bedding material.

Slurry is usually stored in concrete or metal tanks, and less often in lagoons. The latter method is characterized by a relatively large surface area per slurry volume unit, and such storage leads to a greater loss of ammonia. Reduction in ammonia emissions during manure storage is achieved by reducing its contact with the open space. This can be achieved by means of roofs over tanks, natural insulation layer (surface scum) formed spontaneously of organic material on the surface of the slurry, artificial protective layers made of straw, leca (light expanded clay aggregate), peat, oil or other natural floating materials. Ammonia emission is 80% lower from the slurry tanks equipped with roof or floating film covers as compared to emission from open tanks (Sommer and Hutchings, 1995).

Large ammonia losses may occur during application of manure on agricultural land. These losses are much greater from liquid manure and slurry, than from manure.



Photo 5.6 The modern slurry tank with applicator to shallow injection of liquid manure (photo by P. Nawalany)

The most effective way to reduce them is to use modern slurry tanks equipped with attachments for subsurface liquid manure application (Photo 5.6) or with band-spreading devices. According to Rotz (2004) ammonia losses during slurry application using deep soil injectors are on average 90% lower in comparison with the losses of ammonia generated during slurry application with the use of traditional slurry spreaders with splash plates. The use of applicators for shallow

injection and attachments with dragged hoses reduce ammonia losses by 60% and 10%, respectively. The effective way to reduce NH, emissions from manure is the selection of an appropriate period of its application (preferably on cold, windless days with high air humidity) and then ploughing up the manure as soon as possible after its application.

The sources of the largest ammonia emissions from agriculture are natural fertilizers, but approximately 10% of the emissions come also from nitrogen mineral fertilizers. Losses of ammonia from the ammonium nitrate used are usually small, often less than 1% of the nitrogen contained therein. Losses from other fertilizers such as ammonium sulphate or urea can be much larger. In the case of urea the losses may range from 5% to 30%, and for this reason, special attention is paid to the reduction of ammonia emissions from this fertilizer. In order to reduce emissions of NH3 from urea it is recommended to mix the fertilizer with the soil as soon as possible after application, to apply it just before heavy rain, and if possible, to use inhibitors of the ammonification process.

## 5.4. Nitrogen and phosphorus management on farms in the light of water quality protection

In order to meet the requirements of water protection, and the economics of agricultural production, it is desirable that excessive amounts of different forms of nitrogen and phosphorus compounds which are produced on farms are small, while use of N and P is adequately intensive. Obtaining of such results, to a large extent, depends on the decisions made by the farmer. The farmer should consciously control the flow of nutrients on the farm, modelling it as expected e.g. via nutrient management. Plants and animals should be supplied with proper quantities of appropriate nutrients at the right time and place during agricultural production process.

The effectiveness of fertilizer components management is assessed with the help of coefficients based on environmental and production criteria. Nitrogen and phosphorus surplus (environmental criterion), and effectiveness of their use (production-environmental criterion), are the most commonly used synthetic indicators of the management quality. A good tool to assess the quality of fertilizer components management is an application of the equation of efficiency of their use proposed by Schröder et al. (2003) in the following form:

$$\frac{O}{I} = \frac{FP + \frac{EX \cdot (1 - IM)}{HF \cdot (1 - EX)}}{IM + \frac{(1 - IM)}{HF \cdot (1 - EX) \cdot SH} - (1 - FP) \cdot MS}$$

where:

*O* - nutrients output from the farm [kg ·ha<sup>-1</sup>·yr<sup>-1</sup>],

I - nutrients input to the farm [kg ·ha<sup>-1</sup>·yr<sup>-1</sup>],

O/I - nutrients efficiency on the farm,

SH - share of nutrients in harvested crops in the amount delivered to agricultural land,

**HF** - share of nutrients in livestock feed and bedding supplied to animals in the total quantity, of harvested crops not intended for sale,

**FP** - share of nutrients contained in animal products in the amount supplied to animals in feed and bedding,

**MS** - share of nutrients in natural fertilizers introduced into soil in the total amount of faeces excreted by animals,

*IM* - share of nutrients in purchased feed in the total amount of animal feed available, *EX* - share of nutrients contained in plant products sold in the total amount contained in harvested crops.

SH, HF, FP and MS parameters, also called conversion coefficients, express the efficiency (productivity) of the nutrient flow process within the farm, while IM and EX parameters, in direct numbers, characterize amounts of these components - imported to the farms in purchased feed, and exported from the farms in sold plant products, respectively. These parameters reflect the nutrients flow process on the farm (Fig. 5.14). The subjected parameters are determined on the basis of the quantities of elements:

- in harvested crops H, kg·ha<sup>-1</sup>,
- supplied to animals in feed and bedding F, kg·ha<sup>-1</sup>,
- in sold animal products P, kg·ha<sup>-1</sup>,
- in excreted animal faeces M, kg⋅ha<sup>-1</sup>,
- introduced to agricultural land S, kg·ha<sup>-1</sup>.

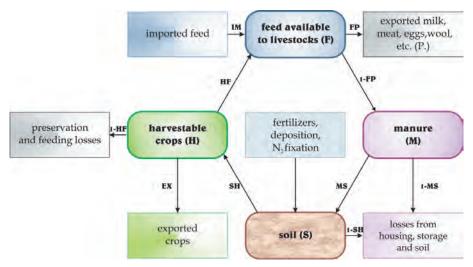


Fig. 5.14 The diagram of nutrients flow in the mixed farms (source: Schröder et al., 2003)

Natural fertilizer management on farms focused on livestock production is much more complicated than on plant production farms. The management is particularly difficult on farms specializing in milk and beef production due to long and complex N and P flow paths and transformations during the production process. On such farms the use of nitrogen and phosphorus is generally low. The results of studies conducted in 2003-2004 in three average farms specializing in milk production in PDL voivodeship showed that the respective nitrogen and phosphorus utilization in this type of agricultural production amounts only to 18.5% and to 26.7%, at the calculated N, P surplus on the level 131.3 kg N · ha<sup>-1</sup> i 16.0 kg P · ha<sup>-1</sup> (Pietrzak, 2008). On these farms the efficiency of N and P flow between various elements of the cycle - expressed with conversion coefficients SH, FP, HF and MS (which ultimately determined the efficiency of N and P use on these farms), was in most cases, much smaller than maximum obtainable limit values (Table 5.9).

Table 5.9 Values of conversion coefficients for nitrogen and phosphorus, obtained in dairy farms in PDL voivedeship, and obtainable maximum limit values for these coefficients

Conversion coefficient	The direction of flow of component	Average v dairy farm voivod	ns in PDL	Obtainable maximum limit values	
		N	P	N	P
FP	from feed and bedding to milk and meat	0.26	0.31	0.30	0.40
MS	from excreted faeces to natural fertilizers applied to soil	0.70	1.00	0.90	1.00
SH	from soil to crops	0.66	0.62	0.90	1.00
HF	from harvested crops to livestock feed	0.712)	$0.75^{3)}$	0.90	1.00

Sources of data: 1) Pietrzak, 2008; 2) Schröder et al., 2005; 3) Jarvis and Aarts, 2000

In order to achieve an effective management of fertilizer components it is essential that the management is carried out in the scale of the whole farm and that it has a system approach. It means that the circulation of components in agricultural production has to be comprehensively analyzed taking into account fertilization of plants, animal nutrition and fodder, and manure management. Selective actions i.e. focused on the optimal use of nutrients only in selected segments of agricultural production will never bring about as good results as the combined actions covering the whole system. An analysis of this issue, which was carried out with application of the model developed by Schröder et al. (2003), has proven that by maximising only one of the SH, HF or FP coefficients to its upper maximum limit, and by keeping values of the other coefficients unchanged, an increase in efficiency of nitrogen utilization on diary farms in PDL may reach 27.6%, 24.9%, and 21.2%; an increase in efficiency of phosphorus utilization on diary farms in PDL may reach 56.0%; 40.4% and 32.2% (Figs. 5.15a and 5.15b). The increase in the *MS* coefficient value for nitrogen to its maximum limit would result in an increase in N utilization on these farms to 20.8%. The *MS* coefficient value for phosphorus is equal to 1; hence it has no influence on further increase in phosphorus utilization on the farm. However, in the case of maximisation of all the conversion coefficients it would be possible to achieve the nitrogen efficiency of approximately 54%, and the phosphorus efficiency of 100% (Fig. 5.15c).

In practice, the fertilizer components management is effected by means of the selection and implementation of specific production practices. It requires understanding of the essence of nutrient circulation, competence, decisiveness, precision, and appropriate technologies. Good fertilizer components management, in particular management of nitrogen and phosphorus, is very beneficial not only with respect to environmental protection, but also as referred to water protection and production economics (reduced expenditures for the purchase of production means, such as fertilizers and fodders). An increase in N and P utilization to values that are considered to be technically obtainable (Jarvis and Aarts, 2000), i.e. to 36% and 100%, respectively, would reduce the surpluses of nitrogen and phosphorus by 77.8 kg N  $\cdot$  ha<sup>-1</sup> i 16.0 kg P  $\cdot$  ha<sup>-1</sup>, respectively (Pietrzak, 2008), and thus would reduce the pressure exerted by these components on the environment. At the same time the demand for purchased fertilizers and fodders on the subjected farms would decrease accordingly. The conclusion is that principles of proper fertilizer components management should be widely implemented in farming practices.

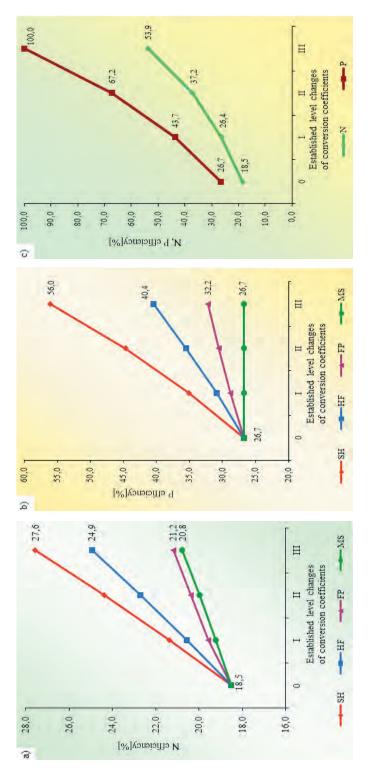


Fig. 5.15 Simulated use a) of nitrogen depending on change of one of the conversion coefficients, b) of phosphorus depending on change of one of the conversion coefficients, c) of nitrogen and phosphorus depending on change of all conversion coefficients source: Pietrzak, 2008).

0 - values of conversion coefficients set for the farms; I - set conversion coefficients values increased by 1/3 of the difference between limit Explanation: the assumed levels of conversion factors SH, HF, FP and MS were adopted for the simulation, and they correspond to: values and set values; II - set conversion coefficients values increased by 2/3 of the difference between limit values and set values; III - upper limit conversion coefficients values from the Table 5.9.

#### References

- Atmospheric emission inventory guidebook, 2000. Ed. 2. Tech. Report No. 30 Vol. 3. Luxembourg: Office for Official Publ. Eur. Comm. 450 pp.
- Assessment of the designation of Nitrate Vulnerable Zones in Poland, 2007. Alterra Environmental Sciences Wageningen University & Research Centre, Wageningen http://www.kzgw.gov.pl/636.html 108 pp. [Accessed in June 2009].
- Bartnicki, J., Gusev A., Aas, W., Fagerli, H., 2007. Atmospheric Supply of Nitrogen, Lead, Cadmium, Mercury and Dioxins/Furans to the Baltic Sea in 2005. EMEP Centres Joint Report for HELCOM EMEP/MSC-W, Oslo, Technical Report 3/2007. http://www.emep.int/publ/helcom/2007/ 170 pp. [Accessed in June 2009].
- Bartnicki, J., Gusev, A., Aas, W., Fagerli, H., Valiyaveetil, S., 2008. Atmospheric supply of nitrogen, lead, cadmium, mercury and dioxins/furans to the Baltic Sea in 2006. EMEP report to HELCOM. 178 pp. Available at: http://www.helcom.fi/environment2/hazsubs/EMEP/en GB/emep2006/
- Bussink, D.W., 1996. Ammonia volatilization from intensively managed dairy pastures. PhD thesis, Landbouwuniversiteit Wageningen, 177 pp.
- Cowell, D., Webb, J., 1997. A review of process-based methodologies for modelling ammonia emissions from agricultural livestock. Meeting of UNECE Technical Group on agricultural emission and ammonia abatement, Reggio Emilia (Italy), 3-7 March 1997, 13 pp.
- Czaban, S., 2008. Klasyfikacja jakości wód powierzchniowych w Polsce Classification of surface water quality in Poland. Infrastruktura i Ekologia Terenów Wiejskich Infrastructure and Ecology of Rural Areas. Polska Akademia Nauk, Oddz. w Krakowie, No. 9, pp. 259-269.
- Flachowsky, G., 1994. Sind unsere Milchkühe 'Umweltsünder'?. Das Milchrind 3, pp.12-15.
- GUS (Central Statistical Office) 2009-2011. Użytkowanie gruntów, powierzchnia zasiewów i pogłowie zwierząt gospodarskich; Annual issued in 2009, 2010, and 2011. Warszawa, Poland.
- Hutchings, N.J., Sommer, S.G., Andersen, J.M., Asman, W.A.H., 2001. A detailed ammonia emission inventory for Denmark, Atmos. Environ., No 35, pp. 1959-1968.
- Jarviss, C., Aarts, H.F.M., 2000. Nutrient management from a farming system perspective. Proc. 18th General Meeting of the European Grassland Federation (EFG). Grassland farming, balancing environmental and economic demands, Aalborg (Denmark) 22-25 May, pp. 363-373.
- Kania, J., Witczak, S., Różański, K., 2011. Classification of groundwater quality based on variability of hydrochemical environment [in:] Baba, A., Tayfur,

References 223

- G., Gűndűz, O.J., Howard, K.W.F., Friedel, M.J.W.F., Chambel, A. (eds.), Climate Change and its effects on water resources. NATO Science for Peace and Security Series C: Environmental Security, Vol. 3, doi:10.1007/978-94-007-1143-3.
- Marcinkowski, T., 2002. Identyfikacja strat azotu w towarowych gospodarstwach rolnych Żuław Wiślanych. Woda Środowisko Obszary Wiejskie Rozprawy naukowe i monografie nr 1, Falenty, pp. 1-79.
- Obojski, J., Strączyński, S., 1995. Odczyn i zasobność gleb Polski w makro i mikroelementy. IUNG, Puławy 1995, pp. 1-40.
- Oenema, O., 1999. Nitrogen cycling and losses in agricultural systems; identification of sustainability indicators. [in:] Sapek A. (ed.), Nitrogen cycle and balance in Polish agriculture. Wydawnictwo IMUZ, Falenty, pp. 25-43.
- Pietrzak, S., 2002. Metoda bilansowania azotu, fosforu i potasu w skali gospodarstwa rolnego. [in:] Zagadnienia doradztwa rolniczego Krajowe Centrum Doradztwa Rozwoju Rolnictwa i Obszarów Wiejskich Odział w Poznaniu, Poznań No 1/2002:54-71.
- Pietrzak, S., 2005. Optymalizacja wykorzystania azotu i fosforu w gospodarstwach prowadzących chów bydła mlecznego na Podlasiu. Woda Środowisko Obszary Wiejskie. Rozprawy naukowe i monografie nr 13, Falenty, pp. 1-129.
- Pietrzak, S., 2006. Metoda inwentaryzacji emisji amoniaku ze źródeł rolniczych w Polsce i jej praktyczne zastosowanie. [in:] Woda Środowisko Obszary Wiejskie, Falenty, Vol. 6 No. 1 (16):319-334.
- Pietrzak, S., 2008. Efektywność wykorzystania azotu i fosforu w gospodarstwach ukierunkowanych na produkcję mleka oraz analiza możliwości jej maksymalizacji za pomocą modelu matematycznego. [in:] Problemy Inżynierii Rolniczej, Instytut Budownictwa, Mechanizacji i Elektryfikacji Rolnictwa, Warszawa 1(59):133-142.
- Pietrzak, S., Nawalany P., 2008. Wpływ długo- i krótkotrwałego składowania obornika na gruncie na zanieczyszczenie gleby i wody związkami azotu. [in:] Woda Środowisko Obszary Wiejskie, Falenty, Vol. 8, No. 2b (24):117-126.
- Program Rozwoju Obszarów Wiejskich na lata 2007 2013 (PROW 2007-2013). 2006. Ministerstwo Rolnictwa i Rozwoju Wsi, Warszawa, 400 pp. http://www.gci.nadbugiem.pl/pliki/prow.pdf [ Accessed in June 2009].
- Report for 2002SD4B. 2002. Establishing a Relationship Between Soil Test P and Runoff P for a South Dakota Soil Using Simulated Rainfall. http://wri.sdstate.edu/pdf/2002\_projects/2002\_Soil\_Test\_P\_Completion.pdf [Accessed on 3 June 2009].
- Rotz, A., 2004. Management to reduce losses in animal production. Journal of Animal Science, No 82 Suppl. E, pp. 119-137.
- Rude, S., Frederiksen, B., 1995. Regulacje dotyczące azotanów we Wspólnocie

- Europejskiej oraz państwach członkowskich. Centrum Doradztwa i Edukacji w Rolnictwie Oddział w Poznaniu, Poznań, pp. 1-97.
- Sapek, A., 1996. Udział rolnictwa w zanieczyszczaniu wody składnikami nawozowymi. [in:] Zeszyty Edukacyjne 1/96. Wydawnictwo IMUZ, Falenty, pp. 9-33.
- Sapek, A., Sapek, B., 2007. Zmiany jakości wody i gleby w zagrodzie i jej otoczeniu w zależności od sposobu składowania nawozów naturalnych. [in:] Zeszyty Edukacyjne 11/2007. Wydawnictwo IMUZ, Falenty, pp. 1-114.
- Schröder, J.J., Aarts, H.F.M., Ten Berge, H.F.M., Van Keulen, H., Neeteson, J.J., 2003. An evaluation of whole-farm nitrogen balances and related indices for efficient nitrogen use. Eur. J. Agron., Vol. 20, No. 1, pp. 33-44.
- Schröder, J.J., Bannik, A., Kohn, R., 2005. Improving the efficiency of nutrient use on cattle operations. [in:] Pfeffer, E., Hristov, Cabi, A.N. (eds.), Nitrogen and phosphorus nutrition of cattle, CABI, Wallingford UK, pp. 255-279.
- Simon, J. C., Le Corre, L., 1992. Le bilan apparent de l'azote á l'échelle du l'exploitation agricole: méthodologie, exemples de résultats. Fourrages, No. 129:79-94.
- Sommer, S.G., Hutchings, N., 1995. Techniques and strategies for the reduction of ammonia emission from agriculture. Water Air Soil Poll., No. 85:237-248.
- Tang, S., Sutton, M., Van Dijk, N., Bealey, B., Theobald, M., Fowler, D., Baker, S., 2005. Monitoring of ammonia concentrations in the United Kingdom. protocol: www.cara.ceh.ac.uk/documents/PresentationSummaries\_NAMN\_Mar05.doc [Accessed in June 2009].
- Velthof, G.L., Oudendag, D.A., Oenema, O., 2007. Development and application of the integrated nitrogen model MITERRA-EUROPE. Task 1 Service contract "Integrated measures in agriculture to reduce ammonia emissions" Alterra, Wageningen. Alterra-rapport 1663.1. 99 pp.

THE PRESENT STATE AND
SIGNIFICANCE OF
TECHNICAL WATER
INFRASTRUCTURE IN RURAL
AREAS

WOJCIECH LIPIŃSKI

# 6. THE PRESENT STATE AND SIGNIFICANCE OF TECHNICAL WATER INFRASTRUCTURE IN RURAL AREAS

### Wojciech Lipiński

#### 6.1. Classification of Waters

Poland faces short water supply, in terms of resources of surface water, ground water or rainwater. In comparison with other European countries, including those from the southern Europe, water resources per capita in Poland are the smallest (Fig. 6.1). This imposes a need for particularly efficient use of these resources and their protection both in terms of water supply and its quality. Issues concerning rainwater and surface water are discussed in Chapter 2, whereas this Chapter focuses on the quality of groundwater, the most vulnerable waters to pollution by nutrients leached from agriculture.

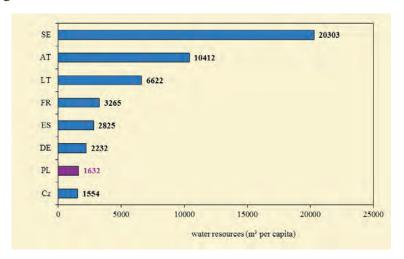


Fig. 6.1 Water resources in selected European countries; abbreviations used for countries - see to Chapter 12 (source: Eurostat http://epp.eurostat.ec.europa.eu/tgm; graph modified)

Classification of water types is not uniform and it depends on science branch or discipline that uses the classification. Considering the scope of this monograph, the most important are two classifications i.e. the hydrological and the one serving the needs of agricultural science and environmental protection. Taking into account these two approaches, waters can be classified into two groups: surface waters, which receive various pollutants originating from e.g. agriculture, and subsurface waters, which are carriers of pollutants and which supply the surface waters (river network); the riverine outflow ultimately feeds the Baltic Sea. Hydrological

classification divides subsurface water into shallow groundwater (soil groundwater) and groundwater of deeper levels. The latter can be divided into subterranean water and deep subterranean water, neither of which is a subject to anthropogenic impact or the actual impact is very small (Figs. 6.2, 6.3).

Shallow groundwater is the domain of interest in agriculture and environmental sciences. Shallow groundwater occurs on agricultural land to a depth of about 3 m and it remains in balance with both the rain water and water of deeper levels. In turn, within this groundwater one can distinguish soil groundwater that is near the surface in the soil profile (to a depth of about 1 m) in the vadose zone, and the typical groundwater occurring in the saturation zone. Groundwater is usually separated from deeper level water by impermeable soil layers. The soil groundwater is directly supplied with rain and it is subject to free vertical and horizontal movements within the soil profile as free and capillary water. Groundwater has a free water table and its position is regulated by gravitational forces. Sometimes the water table is very shallow in the ground (soil) and then it is called subsoil water (Figs. 6.2, 6.3).

Subterranean and deep subterranean water occur in the form of aquifers separated by partially permeable and impermeable layers. Aquifers may be unconfined, i.e. staying in contact with groundwater or surface of the ground, and confined, with both sides separated by impermeable layers of soil. Water in confined aquifers remains in the state of balance with open water which is established extremely slowly, therefore it is resistant to anthropomorphic pollution (Figs. 6.2, 6.3).

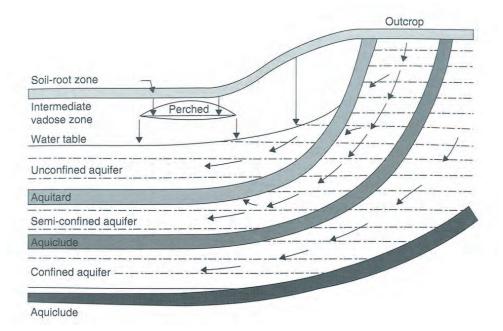


Fig. 6.2 Flow of water in aquifers (source: Hatfield and Follet, 2008)

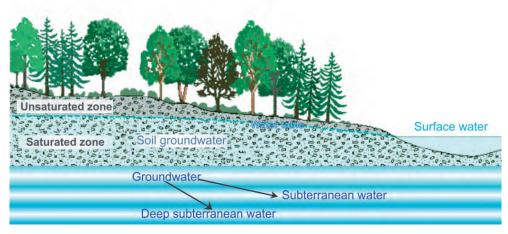


Fig. 6.3 Schematic distribution of groundwater (source: European Environment Agency http://www.eea.europa.eu/themes/water/reports; graph modified)

Drainage systems, dug and drilled wells, and sewage systems constitute an important water engineering infrastructure in rural areas. Drainage systems are installed on the border of the soil groundwater and the typical groundwater, and are designed to discharge excess of water from the unsaturated zone, or from the saturated zone of soil, if the latter is too close to the ground surface. In 2009, 6.4 million hectares out of the total area of approximately 16 million hectares of agricultural land (39.8%) were reclaimed through the range of open and underground drainage systems (GUS, 2010a). The reclaimed area, as well as percentage contribution of reclaimed area to total agricultural area show considerable regional difference (Fig. 6.4).

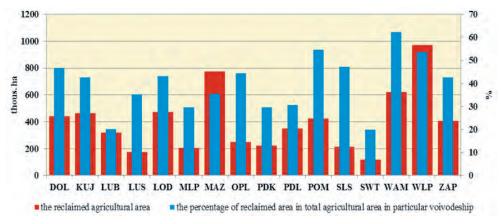


Fig. 6.4 The reclaimed agricultural area and the percentage of reclaimed area to total agricultural area in particular voivodeships; abbreviations used for voivodeships - see to Chapter 12 (source: GUS, 2010a, b)

Monitoring of nutrient concentrations in drainage water is conducted by Agricultural Chemical Stations, which cooperate with the Institute of Soil Science and Plant Cultivation – State Research Institute (IUNG-PIB) in Puławy (for details – see to Chapters 3, 4).

Dug wells are charged with water from the saturated soil zone and they still remain a source of drinking water for a significant percentage of farms in Poland. These wells are not subject to regular monitoring of water quality, but the content of nutrients in water from these wells is thoroughly monitored thanks to the research programmes undertaken by Agricultural Institutes.

Drilled wells are charged with subterranean water and deep subterranean water from different aquifers, and they are a source of water for water supply systems which become more and more common also in rural areas. Quality of deeper levels of water is regularly monitored by the Polish Geological Institute-National Research Institute. Water samples are taken from special wellbores or from drilled wells.

Surface water in rivers and lakes is a subject to the most extensive monitoring with respect to the network of stations and frequency of sampling. Monitoring is conducted by a network of laboratories of Voivodeship Inspectorates of Environmental Protection and the whole undertaking is supervised by the Chief Inspector for Environmental Protection. The measurements of water flows in rivers are conducted by the Institute of Meteorology and Water Management – National Research Institute.

### 6.2. Water supply in rural areas

Most of the recorded water consumption in Poland is in industry and for municipal purposes (Table 6.1), and the share of agriculture is relatively low, with a slight upward trend over the last years (for long term trends see to Fig. 8.10 in Chapter 8).

Table 6.1 The structure of	water consumption in	n 1998 and 2009	(source: Michna,
1998; GUS, 2010a)			

	199	2009	
Section	Poland [%]	Europe [%]	Poland [%]
Industry, including power industry	69.0	53.0	73.8
Municipal services	20.0	19.0	15.0
Agriculture and Forestry	11.0	26.0	11.2

Although agriculture consumes large amounts of water for crop production, it is mostly precipitation water or groundwater mainly from unsaturated layer. Evapotranspiration plays an important role in the water cycle, but for obvious reasons is not included in the recorded water consumption by agriculture. Evapotranspiration is a term used to describe the sum of transport of water into the atmosphere from surfaces, including soil (soil evaporation), and from vegetation (transpiration). Transpiration accounts for the movement of water within a plant and the subsequent loss of water as vapor through stomata in its leaves. However, the records of water consumption by agriculture include water consumed for field crops irrigation with the use of sprinkling machines, and water supplied to fish ponds (Table 6.2). But these quantities are very small due to the reduction of irrigated land area.

Table 6.2 Water withdrawal for irrigation in agriculture and forestry, as well as water for filling up fish ponds (source: GUS, 2010a)

Year	Irrigated land [thous. ha of agricultural land]	Water withdrawal for irrigation [km³]	Water withdrawal for fish ponds [km³]
1990	301.5	51.9 (5.3)	122.8
2000	99.1	11.3 (0.2)	95.0
2009	78.7	9.6 (0.16)	106.3

The recorded amount of water consumed by agriculture refers to drinking water for humans and farm animals, and to water used for hygiene in residential buildings and farming premises. It should be emphasized here that only water from water supply systems is registered, and not the water from farm wells. The statistical data (GUS, 2011b,c) show that most tap water (about 82 km³, i.e. 68%) is consumed in cities, and significantly less (37.8 km³, i.e. 32%) in rural areas inhabited by 39% of total population of our country. In Poland, water consumption per capita in the 1990s was on the level of 310 m³ · yr¹, but the volume varied in urban and rural areas. It reached approx. 368 m³ · yr¹ in urban and ca. 247 m³ · yr¹ in rural areas. It is worth emphasizing that the average water consumption per 1 inhabitant in Western Europe amounts to approx. 700 m³ · yr¹, therefore it is more than two times higher than the average consumption in Poland. This difference is mainly due to the large share of rural population in Poland, and smaller consumption of water by individual farms.

As mentioned earlier, farms get potable water and water for hygienic purposes partly from their own wells, mostly dug wells, and partly from water-pipe networks. In recent years, there has been a very significant expansion of water supply network in rural areas. At the end of 2010 the length of distribution pipe network (without connections to the buildings) in these areas was approximately 212,000 km, and in all voivodeships the increase in distribution pipe network's length was recorded; in some of them the increase reached 30% over the time period 2003-2010 (GUS,

2010a, 2011b). In 2010, more than 3 million buildings were connected to water supply networks. In rural areas, the length of pipe networks, with connections to 736,700 buildings increased by 50,000 km over the period 2000-2010 (GUS, 2010a, 2011b). At present, of the total number of 41,233 villages, constituting separate village administrative units, approx. 86% villages are equipped with water supply systems and almost 16% with sewage systems. In both cases a permanent upward trend has been noted, but in the years 2001-2008 the number of villages equipped with sewage systems doubled (see to the Table 6.6). However, not all the farms in areas covered by water supply systems were connected to them and these farms still use their own wells, mostly dug wells. The quality of tap water in rural areas is a subject to regular inspection and is not any worse than the tap water from municipal water supply systems. However, the quality of water from dug wells leaves a lot to be desired. According to monitoring studies conducted by IUNG-PIB in 2000, 44.8% of homestead wells had water of poor quality that was not suitable for drinking as nitrate content was over 50 mg of NO<sub>3</sub><sup>-</sup>· dm<sup>-3</sup> (11.3 mg NO<sub>3</sub><sup>-</sup>N·dm<sup>-3</sup>) (Igras, 2000). It should be noted, however, that although the majority of farms still have homestead wells, mostly dug wells, they are increasingly used for farming purposes, rather than for consumption (Antoszek, 2002). Water from these wells is primarily used for watering of gardens, washing machines, and for watering livestock. A new problem has appeared, and that is the use of these wells as a kind of septic tanks collecting wastewater discharged from rural households.

Water supply fundamentally affects the quality of life and standards of civilization, but has no direct impact on the emissions of nutrients from agriculture to groundwater and surface water. Environmental standards in this area are critically contingent on the operation of sewer systems, including sewage treatment plants. In an ideal situation one water supply connection should be accompanied by one sewerage connection. In rural areas, however, the situation deviates very much from such an ideal state.

### 6.3. Sewage systems in rural areas

The level of development of sewage systems in rural areas is much lower than the development of water supply systems, and it is far from complying with the rule of "one litre in - one litre out". Prior to 2008, 2,500 collective sewage treatment plants and approximately 35,000 individual sewage treatment plants operated in rural areas. In 2008, of the total number of 41,233 villages, constituting separate village administrative units, 6,661 were equipped with full water supply and sewage systems (approx. 15.7%), whereas 2,331 villages were equipped with partial sewage systems (GUS, 2009). In 2010, the overall length of sewerage network reached 55,500 km. Most of individual sewage treatment plants are located in the MLP, PDK, KUJ, and LUB voivodeships (shortenings – see to Chapter 12). Also the longest overall

sewerage has MLP, PDK, WLP and POM voivodeships (shortenings – see to Chapter 12). Over the last decade, a great progress has been made in this area; in the years 1995-2000, the length of sewerage network in rural areas increased almost 3 times and since 2000 it has grown further 2.5 times to reach the present length of 55,500 km. Most of this kind of development took place in KUJ and LUB voivodeships. Also the structure of population served by sewage treatment plants reveals a clear disparity between urban and rural population. Presently approximately 88.1% of urban population and only about 26.9% of the rural population use wastewater treatment plants (GUS, 2009, 2010a, b; Chapter 8). Construction of sewage treatment plants in rural areas, however, is progressing faster than in cities (Table 6.3). In the years 1995-2006, rural population's access to sewage treatment plants increased by 500%, including the plants with increased removal of nutrients and biological sewage treatment plants. In urban areas, the number of sewage treatment plants increased by about 25%, while in rural areas by nearly 40%. In addition, there were significant improvements in the quality of equipment used for sewage treatment. During the last 6 years the number of biological sewage treatment plants in rural areas has increased by 35%, and the number of sewage treatment plants with increased nutrients removal has doubled and got closer to the number of such plants in cities.

Table 6.3 Quantitative and qualitative changes of sewage treatment facilities (source: GUS, 2010a)

	Urban areas			Rural areas		
Year	Mechanical	Biological	With increased nutrient removal	Mechanical	Biological	With increased nutrient removal
2000	53	656	256	86	1254	170
2009	11	487	411	54	1826	407

The amount of sewage which is treated in municipal sewage treatment plants is nearly 10-fold higher compared with that in rural areas, but it results from a much larger number of urban population in cities and larger water consumption per capita (GUS, 2010 a, b) (see to Chapter 8). Nevertheless, of the total number of 2,171 boroughs, 1,598 are equipped with sewage treatment plants, including more than 500 boroughs with sewage treatment plants with increased nutrient removal. To sum up, we can state that huge progress in the hygienization of rural areas has taken place over the last 10 years (Tables 6.4, 6.5).

Table 6.4 The development of sewerage network and sewage treatment plants in 1995-2009 (source: GUS, 2011b)

Year	Sewerage network in [km]	Number of sewage treatment plants	Number of biological sewage treatment plants and with increased nutrient removal
1995	5359	433	407
2000	16222	1452	1353
2009	50454	2287	2233

Table 6.5 Rural population using sewerage network and sewage treatment plants in 1995-2009 (source: GUS, 2011b)

Year	Total rural population	Sewerage network	Sewage treatment plants	Sewage treatment plants with increased nutrient removal		
		Percentage contribution				
1995	14721	5.9	3.1	2.8		
2000	14584	11.5	10.8	10.6		
2009	14889	23.5	26.9	26.7		

It should be noted that rural areas cover about 93% of the total area of Poland, but they are occupied by only 39% of the total population of our country (GUS, 2011a). The population density in these areas is approximately 50 persons per 1 km², and statistically 277 inhabitants live in one village. Approximately 15% of villages have less than 100 inhabitants, whereas in 66% of villages the number of inhabitants is within the range from 100 to 500. This indicates a very large dispersion of households in rural areas and the dispersion affects the cost of infrastructure development in these areas.

Table 6.6 summarizes the status of supply of tap water and collective sewerage systems in rural areas. As highlighted earlier, there is still a big gap between water supply and wastewater disposal in these areas. Of course the situation is improving by further expansion of individual sewage treatment plants serving single or multiple adjacent households in rural areas. Such plants are practically not found in cities, especially in large ones.

Year	Overall number of	Villages equipped with sewerage network		Villages equipped with water supply systems	
	villages	Total number	[%]	Total number	[%]
2001	42364	3320	7.8	32405	76.5
2005	41137	5584	13.6	35036	85.2
2008	42364	6661	15.7	36464	86.1

Table 6.6 Water supply and sewerage in rural areas in 2001 - 2008 (source: Kaca, 2010)

### 6.4. Infrastructure in animal production

Although hygienization state in rural areas still leaves a lot to be desired, farm animals living in these areas play a much greater role in the generation of nutrient pollutants than the rural population. It should be noted, that a Livestock Unit (LU) (corresponding to a dairy cow weighing 500 kg) annually releases approximately 63 kg of N and about 15 kg of P in the form of manure and liquid manure. Similarly a Human Unit (HU) (10 people with an average individual weight of 50 kg) is the source of about 15 kg of N and approx. 8.5 kg of P (Sapek and Sapek, 2002). Currently about 14.6 million people live in rural areas representing 1.45 million of HU and they breed 7.1 million of LU. Therefore, the total emission of nitrogen and phosphorus by the rural population amounts to approximately 21.7 million kg of and N, and about 12.3 million kg of P, and by the farm animals about 450 million kg of N and approximately 106 million kg of P. Whereas majority of the nitrogen and phosphorus emitted by humans ends up (or should end up) in treatment plants, the entire bulk of nitrogen and phosphorus of animal origin should go to the soil as natural fertilizer. Taking these numbers into account, it is obvious that the role of sanitary infrastructure in animal production is very high.

The management of manure produced on the farm is one of the most serious problems of rural infrastructure. The first regulations in this regard were introduced in Poland in 2000 in the form of the Act on Fertilizers and Fertilization (Dz. U. No. 89, item. 991, 2000). This Act imposes an obligation on farmers to store manure in a solid form in livestock buildings or on impermeable storage plates, which are protected against infiltration of leachate into the ground, and which have adequate systems for leachate drainage to leak proof containers. Natural fertilizers in liquid form should be stored in sealed containers with a capacity allowing collecting of at least 4-month production of fertilizers (Photo 6.1).



Photo 6.1 Tanks for liquid manure and slurry (photo by P. Nawalany)

The regulations were to come into force after 8 years from the announcement of the Act. Regulations under the Act of July 10, 2007 on Fertilizers and Fertilizing (Dz. U. No. 147, item. 1033, 2007) in order to provide the extra time to adapt facilities to store manure; the deadline for storage of solid fertilizers was on 1 January 2009, while for storage liquid fertilizers on 1 January 2011. Entities that carry out farming or animal husbandry on a scale exceeding 40,000 units of poultry, 2,000 pigs weighing over 30 kg, and 750 sows were obliged to have stored manure and slurry in leak proof, sealed containers by 31 December 2010. After that date, the Minister of Environment may lay down specific conditions for storage of liquid manure by these entities, taking into account environmental protection. At the same time, in areas particularly exposed to nitrogen runoff from agricultural sources, farmers are obliged to keep fertilizers in accordance with the principles stipulated in the Code of Good Agricultural Practice, and therefore the capacity of plates and containers must be calculated for a 6-month period of storage of natural fertilizers.

Production of natural fertilizers obviously depends on the density of livestock. Currently livestock density expressed in LU is slightly higher than 44 LU per 100 ha of agricultural land, and in recent years it has shown a slight downward trend (Fig. 6.5). Livestock density is significantly diversified regionally and ranges from about 17 LU in DLN and ZAP voivodeships, to nearly 70 LU per 100 ha in PDL and WLP voivodeships. To a large extent livestock density depends also on the size of the farm. On farms with an area of 5 - 50 hectares, over 75% of the total number of cattle and nearly 70% of the total number of pigs are bred. But such farms occupy only ca. 43% of the total area of agricultural land.

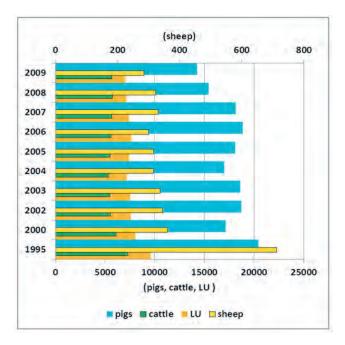


Fig. 6.5 Number of animals in thousands and Livestock Density (LU) (source: GUS, 2010b)

This indicates that apart from livestock density the concentration of livestock production, measured with a number of herds of specified size, is very important. In recent years, there has been a clear tendency towards an increase in the size of herds of cattle and pigs, and poultry in particular, but livestock density remained relatively stable. The number and size of herds of cattle, as well as livestock density show big regional differences (Table 6.7). As indicated in Chapter 4, large herds of cattle are kept on about 13% of the total number of farms, and large herds of pigs (over 50 head) on approximately 15% of farms (with an area of over 1 ha). In the total number of approximately 1.8 million farms (with an area of over 1 ha) there is about 1 million herds of animals (Anonymous, 2008). It means that only approx. 55% of farms deal with livestock production. High concentration of cattle production (over > 10 head) occurs only on 148,725 farms out of the total number of 735,265 farms (23%), while high concentration of pigs (over >31 head) occurs on 94,367 farms out of the total number of 313,332 farms (30%) (Table 6.7).

Table 6.7 Number of herds of cattle and pigs per voivodeships; abbreviations used for voivodeships - see to Chapter 12; (source: Anonymous, 2008)

	Nui	mber of cattle	herds	Nu	mber of pig	herds
Voivodeship	Total	>10 head	Share in total number of herds [%]	Total	>31 head	Share in total number of herds [%]
DLN	14749	2209	15.0	8515	1954	22.9
KUJ	34227	12264	36.4	29296	13904	47.5
LUB	87629	8978	10.2	36786	4832	13.1
LUS	5403	1542	28.5	4152	862	20.8
LOD	66561	13389	20.1	30514	7598	24.9
MLP	85492	2970	3.5	16799	2399	14.3
MAZ	123212	32478	26.3	36028	8578	23.8
OPL	9832	2522	25.7	10178	4217	41.4
PDK	67059	1403	2.1	18938	1925	10.2
PDL	54709	25030	46.3	11864	3133	26.4
POM	19245	5114	26.6	11616	4900	42.2
SLS	22925	2999	13.1	9306	2862	30.8
SWT	54144	3841	7.1	15611	2559	16.4
WAM	26077	11859	45.5	8367	3671	43.9
WLP	55848	20171	36.1	58708	28407	48.4
ZAP	8153	1956	24.0	6654	2566	38.6
Total	735 265	148 725	22.9	313 332	94 367	29.1

In fact, the number of farms with a high concentration of livestock production is much smaller, since many of them breed cattle and pigs at the same time. The estimate of the share of such farms gives the number of 20%. The issue of concentration of livestock production is very important because only large herds of animals pose measurable environmental problems. The degree of concentration of livestock production shows considerable territorial differentiation as indeed it is largely associated with the distribution of farms with a larger area. The highest concentration of production of dairy cattle and pigs is in KUJ, WAM, and WLP voivodeships. In addition to the above-mentioned voivodeships, PDL voivodeship clearly specializes in the production of cattle, whereas OPL voivodeship specializes in the production of pigs (for details see to Chapter 4).

The total production of manure in Poland amounts to approximately 80.7 million tons. Production of liquid manure amounts to about 18.2 million m<sup>3</sup>, and slurry to about 7.5 million tons (Chapter 5). One ton of "mature" manure (after a period of composting in a compost pile) occupies a volume of approximately 1.40 m<sup>3</sup>, and with

the pile height of 2 m it requires the storage space of about 0.70 m<sup>2</sup> in a manure pit. This applies to "mature" manure, and the manure removed from the shallow barn; the latter has much smaller bulk density and requires more storage space. Assuming the twice a year rotation of manure in manure pits, (capacity of the manure pit plate should allow for storage of 6-month production of manure), the proper storage of the whole manure production in Poland calls for at least 28 million m<sup>2</sup> of manure plates, with the addition of about 35 million m<sup>2</sup> surface for "fresh" manure. In 2002, the total surface of manure storage was about 22 million m<sup>2</sup> and the capacity of tanks for liquid manure has reached about 36 million m³ (Romaniuk and Wardal, 2006). In the years 2002-2007, the surface of manure pits increased by almost 4 million m<sup>2</sup> and the capacity of tanks for liquid manure by about 3 million m<sup>3</sup>. This allows the storage of manure on the surface of approximately 25 million m<sup>2</sup>. These data, which may be encumbered with errors, show that the current surface of manure pits ensures proper storage of approximately 70% of manure. The estimate is probably too optimistic, since much of the old manure plates is in poor technical condition and requires complete reconstruction or major renovation. Recently built manure plates, with a capacity of about 4 million m<sup>2</sup>, allow completely proper storage of approximately 8 million tons of manure (at double rotation), i.e. about 10% of the total production of natural fertilizers. Probably about 20% of the total mass of manure is produced on farms with a high concentration of animals. However, only half of these farms is equipped with modern manure plates.

Total production of liquid animal faeces, which consists of liquid manure and slurry is about 26 million m³ (Chapter 3). By analogy with manure, it can be assumed that probably about 20%, i.e. approximately 5 million m³ of liquid manure is produced on farms with a high concentration of animals. Modern tanks, which were built in recent years, allow storage of about 3.2 million m³ of these fertilizers. In this case, needs are also far greater than possibilities, but to a lesser extent, than in the case of manure plates.

Enormous progress that was made over the last 10 years in developing of technical infrastructure for livestock production results from both the domestic and the European Union (EU) funding aimed specifically at that purpose (Anonymous, 2008). As many as 408 projects, producing in total 827 investments which involved construction of manure plates and tanks for liquid manure or slurry, were carried out in Poland in 2002-2006 in the framework of the pre-accession aid programme (SAPARD). That resulted in construction of manure pits with the total volume of 55,000 m³, and tanks for liquid manure with the total capacity of approx. 52,000 m³. The Sectoral Operational Programme "Restructuring and modernization of food sector and rural development 2004-2006" provided funding for 562 infrastructure projects to increase the surface of manure plates by about 38,000 m³ and capacity of tanks for liquid manure and slurry by about 29,000 m³. However, the most important for the development of infrastructure in the field of animal production in the years 2004-2006 was the Rural Development Plan (RDP). Part of this plan

was related to farm adjustments to the requirements for manure storage under the Act on Fertilizers and Fertilization, and the action programmes aimed at reducing the outflow of nitrogen from agricultural sources. As a result, the investments were made on over 71,000 farms, including 3,467 farms located in areas at particular risk to nitrate pollution. The total number of realized investment projects, involving the construction or expansion of existing manure plates and tanks for liquid manure and slurry amounted to more than 143,000. As a result of these projects, manure pits area has increased by approximately 3.7 million m<sup>2</sup> and the capacity of tanks for liquid manure by about 3.1 million m<sup>3</sup> (Table 6.8). The total value of these investments reached PLN 2.4 billion.

Table 6.8 Investments in the field of storage of natural fertilizers implemented under RDP (2004-2006) in a regional context; abbreviations used for voivodeship - see to Chapter 12 (source: Anonymous, 2008)

Voivodeship	Manure	e plates	Tanks for liquid manure		
voivodesiiip	Number	Surface [m <sup>2</sup> ]	Number	Capacity [m³]	
DLN	663	35526	635	25992	
KUJ	13287	702407	13256	551728	
LUB	2988	125567	3418	100077	
LUS	561	43414	531	29438	
LOD	5615	230623	5738	211992	
MLP	858	29487	855	22181	
MAZ	12958	583917	13830	592036	
OPL	614	47238	609	35565	
PDK	638	19364	642	15949	
PDL	5347	251525	6120	317920	
POM	4615	231419	4470	160282	
SLS	621	32561	622	24258	
SWT	1462	49523	1473	39293	
WAM	4344	290772	4404	243577	
WLP	15038	963360	15019	699484	
ZAP	1268	76241	1244	54338	
Total	70 877	3 712 944	72 866	3 124 140	

Majority of investment projects (construction of manure plates and tanks for liquid manure) were carried out in KUJ, WLP, MAZ, and PDL voivodeships (Table 6.8). A comparison of these data with data on the distribution of the largest herds in the voivodeships (Table 6.7) proves that the investments were made in the areas of concentration of animal production.

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#### References

- Anonymous, 2008. Data concerning implementation of 6 RDP (PROW) 2004-2006 "Dostosowanie gospodarstw rolnych do standardów Unii Europejskiej oraz rejestru zwierząt gospodarskich". Agencja Restrukturyzacji i Modernizacji Rolnictwa. Unpublished materials.
- Antoszek, J., 2002. Koncepcja zrównoważonego rozwoju i szanse jej realizacji na obszarach wiejskich Lubelszczyzny (w świetle badań ankietowych). Annales UMCS, Sec. B, , LVII, 11: L, pp. 193-210.
- Dz. U Nr 89, poz. 991, 2000. Ustawa z dnia 26 lipca 2000 r. o nawozach i nawożeniu.
- Dz. U Nr 147, poz. 1033, 2007. Ustawa z dnia 10 lipca 2007 r. o nawozach i nawożeniu.
- GUS (Central Statistical Office), 2009. Ochrona środowiska. Informacje i opracowania statystyczne. Warszawa, Poland.
- GUS (Central Statistical Office), 2010a. Ochrona środowiska. Informacje i opracowania statystyczne. Warszawa, Poland.
- GUS (Central Statistical Office), 2010b. Rocznik statystyczny rolnictwa. Warszawa, Poland.
- GUS (Central Statistical Office), 2011a. Powierzchnia i ludność w przekroju terytorialnym w 2011 r. Warszawa, Poland.
- GUS (Central Statistical Office), 2011b. Infrastruktura komunalna w 2010 r. Warszawa, Poland.
- GUS (Central Statistical Office), 2011c. Obszary wiejskie w Polsce. Warszawa, Olsztyn, Poland.
- Hatfield, J. L., Follet, R.F., 2008. Nitrogen in the Environment. Second Edition. Academic Press. pp. 702.
- European Environment Agency. http://www.eea.europa.eu/themes/ water/reports [Accessed in August 2008].
- Eurostat. http://epp.eurostat.ec.europa.eu/tgm [Accessed in July 2008].
- Igras, J., 2000. Skład chemiczny wód glebowo-gruntowych w Polsce. Nawozy i Nawożenie, IUNG, Puławy, 3a. pp. 38-49.
- Kaca, E., 2010. Zagrożenia wynikające ze stanu sanitacyjnego wsi. Problemy Inżynierii Rolniczej, No. 3, pp. 5-15.
- Michna, W., 1998. Program proekologicznego rozwoju wsi, rolnictwa i gospodarki żywnościowej do 2015 roku. IERiGŻ, Warszawa. pp. 1-285.
- Romaniuk, W., Wardal, W.J., 2006. Techniczne uwarunkowania przechowywania i uzdatniania nawozów naturalnych. Nawozy i Nawożenie IUNG-PIB, Puławy, 4 (29):61-79.
- Sapek, A., Sapek, B., 2002. Obieg i bilans fosforu w łańcuchu pokarmowym człowieka w Polsce. Nawoży i Nawożenie Fertilizer and Fertilization, IUNG, Puławy, 2002, 4(13):105-123.

THE ROLE OF REGULATIONS
IN THE PROTECTION
OF WATER RESOURCES

TAMARA JADCZYSZYN AGNIESZKA RUTKOWSKA

# 7. THE ROLE OF REGULATIONS IN THE PROTECTION OF WATER RESOURCES

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### 7.1. Water quality protection in the light of the Act on Water Law

Agriculture is one of those sectors of the economy that significantly affect the quality of water. In the countries around the Baltic Sea many activities and initiatives are undertaken to reduce the amount of nutrients introduced into surface and underground waters that supply the Baltic Sea.

Poland is a party to the Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea Area, from April, 9 1992 (Dz. Urz. WE, 16.3.1992). The Convention was ratified by Poland in 1999 (Dz. U. No. 28, item. 347, 2000).

Parties to the Convention have agreed to prevent pollution of the Baltic Sea area. Pollution is the direct or indirect introduction of substances or energy (that may pose a threat to human health, living resources, and marine ecosystems) into river estuaries and the sea; pollution may impair the quality of sea water that is being used, and may lead to a reduction of recreational attractiveness.

The Annexes to the Convention set out the procedures and measures to achieve the goals. The parties declared their cooperation in the preparation, adoption, and use of specific programmes, guidelines, standards or regulations on emissions and discharges into water and air; the regulations cover also environmental quality, and products containing harmful substances and materials.

The group of pollutants that should be given priority in taking remedial measures includes, inter alia, compounds of nitrogen and phosphorus.

The basic legal act regulating all water management issues in Poland, and thus directly related to the implementation of the Convention, is the Act on Water Law of July 18, 2001 (Dz. U., No, 115, item 1229, 2001), as amended. The Law regulates the issues of water management in accordance with the principle of sustainable development, taking into account the need for development and protection of water resources. The key issues relevant to the protection of water regulated by the Law are as follows:

- Principles of management and use of water,
- Ownership of water,
- Obligations of water owners,
- Principles of water protection,
- Basis for water monitoring and control,
- Economic instruments for water management.

### Water management and principles of water use

Water management meets the needs of the population and economy, and it is realized through the provision of adequate quantity and quality of water, protecting water resources from pollution, maintaining and improving the state of aquatic and water-dependent ecosystems. It is implemented with the use of the following instruments: water management planning and control, permits and fees required under the Water Law.

The bodies competent for water management are:

- The Minister responsible for water management,
- The President of the National Water Management Authority supervised by the Minister responsible for water management,
- Regional Water Management Boards with operational areas corresponding to water regions,
- The Director of the Regional Water Management Board subordinate to the President of the National Water Management Authority,
- The Voivode.
- Local government bodies.

Every two years, the Minister responsible for water management submits a report on water management to the Sejm (Parliament) of the Republic of Poland.

### Ownership of water and obligations of owners of water

Water in Poland is owned by the State Treasury and other legal entities. Their responsibilities include care for the maintenance of good condition of waters and participation in restoring ecosystems degraded by improper use. The use of water cannot cause a deterioration of the condition of waters and water dependent ecosystems. All waters are protected irrespective of who owns them. The aim of the protection is to maintain or improve water quality. It is achieved by avoiding, eliminating and restricting the introduction of substances that are harmful to the aquatic environment.

## Water protection

For the purpose of water protection the Minister responsible for water management in consultation with the Minister responsible for environmental matters by regulation determine:

- Elements of water status evaluation (chemical, physicochemical, biological, etc.),
- Water status classification,
- Frequency of evaluation of individual elements and presentation of results.
   Water Act specifies a number of principles of the use of water so as to preserve its quality, inter alia:
- Prohibits introduction of liquid manure to the water,

- Requires entities discharging sewage to water or soil to provide protection against pollution, in particular by the construction and operation of appropriate equipment to protect and, where appropriate, reuse treated wastewater,
- Obliges sewage discharging entities to obtain water supply and sewage disposal permit,
- Requires all urban agglomerations with a population equivalent of more than 2000 to be equipped with collective municipal sewerage systems, including sewage treatment plants, in accordance with the national programme for municipal wastewater treatment.

The national programme for municipal wastewater treatment developed by the Ministry of the Environment contains a list of urban agglomerations and the necessary activities for the construction and modernization of the sewage system, and is published in the Official Gazette of the Republic of Poland, "Monitor Polski". Every two years, the Minister of the Environment makes his report to the Council of Ministers on implementation of the programme.

According to the Act on Water Law the Minister of Environment in consultation with the Minister responsible for water management determines by means of regulations:

- Substances that are particularly harmful to the aquatic environment causing water pollution which should be eliminated, and particularly harmful substances that cause water pollution which should be reduced;
- Substances being particularly harmful to the aquatic environment that require sewage disposal permit when introduced with industrial wastewater into sewage systems.

The Water Law permits the treatment of domestic, municipal or industrial sewage of the composition similar to the domestic sewage through their agricultural use, which is understood as: the use of wastewater for irrigation and fertilization of agricultural land or fish ponds. Appropriate regulations of the Minister of Environment stipulate conditions to be fulfilled for the introduction of sewage into water or soil, including the maximum values for contaminants, as well as conditions to be met in order to use sewage for agricultural purposes, the place and minimum frequency of sewage sampling, and reference methods of sewage analysis and assessment. The use of sewage for agricultural purposes is prohibited on land where underground water table is shallower than 1.5 m from the ground level and in areas with slope greater than 10% for arable land, and greater than 20% for meadows, pastures and forest plantations. Plants that discharge sewage for agricultural use are required to carry out measurements of sewage quality and quantity.

The purpose of this regulation is to reduce by 75% the total load of nitrogen and phosphorus in municipal wastewater discharged into the Baltic Sea from the whole territory of Poland.

Regulations aimed at reducing the emission of nutrients from agriculture to water are discussed in the next subsection.

### Water supply and sewage disposal permits

Obtaining a water supply and sewage disposal permit is a prerequisite for any entity to use sewage for agricultural purposes or to discharge industrial wastewater into sewage systems. Water supply and sewage disposal permits for discharging sewage into water or soil are issued for a period not longer than 10 years, and in the case of discharging industrial wastewater containing substances that are particularly harmful to the rural environment to water or sewage systems - for a period not longer than 4 years.

- The permit specifies:
- Quantity, condition and composition of wastewater used for agriculture,
- Quantity, condition and composition of sewage discharged into water, soil or sewage systems, minimum percentage of pollutants reduction in the wastewater treatment process, and in the case of industrial wastewater, if reasonable, allowable emissions of contaminants, especially substances that are particularly harmful to the aquatic environment, expressed in units of mass per unit of used raw materials, materials, fuel, or the resulting product.
- The manner and scope of measurements of quantity and quality of sewage. Additionally, in some cases the permit requires an entity to measure the quality of water upstream and downstream of the place of sewage discharge.

The water supply and sewage disposal permit may be revoked or restricted without compensation, if:

- An entity changes the purpose and scope of water use,
- Water devices are built contrary to the conditions established in the water supply and sewage disposal permit or are not properly maintained,
- An entity does not perform actions to reduce negative environmental impacts.

### Water monitoring and control

The purpose of water monitoring is to collect information on water status for planning and evaluation of the degree of achievement of environmental goals. In Poland, the quality of surface, subterranean water and deep subterranean water is subject to regular inspections carried out under the responsibility of the State Environmental Monitoring. The scope and methods of the monitoring, including water quality criteria, are clearly defined and regulated.

Monitoring of surface waters encompassing rivers, lakes, reservoirs and the Baltic Sea shelf, is carried out by the Inspection of Environmental Protection in cooperation with the Institute of Meteorology and Water Management-National Research Institute and Environmental Protection Institute-National Research Institute.

River water samples are taken at fixed checkpoints located on major rivers and their tributaries. Water flow volume is determined at the same checkpoints, which allows calculating the size of the load of the analyzed substances. Water quality in lakes and reservoirs is analysed under separate research programmes, as they are specific, closed ecosystems, therefore being sensitive to anthropogenic impacts. The Baltic Sea water quality monitoring programme covers deep-water zone and coastal zone with bays. Surface water quality is assessed according to quantitative criteria that include all analyzed mineral and organic components. Based on these criteria five classes of surface water quality are distinguished. The main factors that determine the classification of water are its suitability for consumption and recreation, and susceptibility to eutrophication. Surface water monitoring results are published annually in a series of reports "Library of Environmental Monitoring", Voivodeship reports, and also in the Yearbooks of Environmental Protection issued by GUS (Central Statistical Office).

The monitoring of subterranean water and deep subterranean water, and to a very limited extend groundwater, is performed by the Inspectorate of Environmental Protection under substantive supervision of the Polish Geological Institute-National Research Institute. Sampling network includes 700 control points which are drilled and dug wells, well-heads and piezometers. The quality of the water is assessed primarily in terms of suitability for drinking purposes. The results of groundwater quality monitoring are published by GUS in environmental reports and in regional reports. The scope and methods of surface water and groundwater monitoring conducted in Poland meet the requirements of the Water Framework Directive of the European Parliament from 2000 (Dz. Urz., WE L, No. 327/1, 2000).

- Competent ministers determine by means of regulations:
- Requirements to be met by surface water used for public supply of water for consumption;
- Requirements to be met by inland waters that constitute the habitat of fish in natural conditions and internal sea waters and coastal waters that constitute the habitat for crustaceans and molluscs;
- Requirements to be met by bathing waters.

Water management control concerns, inter alia:

- Protection of waters against pollution;
- Concentrations of nitrates in waters susceptible to pollution with nitrogen compounds from agricultural sources.

# Implementing regulations to the Act on Water Law and other regulations related to the management of water resources

General principles of water management, contained in the Act on Water Law are executed based on the number of implementing regulations:

- 1) Regulation of the Minister of Environment of October 4, 2002 (Dz. U. No. 176, item 1455) on requirements to be met by inland waters that constitute the habitat of fish in natural conditions,
- 2) Regulation of the Council of Ministers of April 27, 2004 (Dz. U. No. 72, item 747) on detailed conditions for granting public aid for investments to protect groundwater from contamination provides for granting public aid for the adaptation to the requirements of environment protection installations, equipment and operating conditions that are subject to the provisions of the Act on Water Law.
- 3) Regulation of the Council of Ministers of December 20, 2005 (Dz. U. No. 260, item 2177) on the individual rates of penalties for exceeding the limits of wastewater discharges into water or soil provides for penalties for, inter alia, exceeding the concentrations of total nitrogen, ammonium, nitrates, nitrites, and total phosphorus,
- 4) Regulation of the Minister of Environment of July 8, 2004 (Dz. U. No. 168, item 1763) on the conditions which should be fulfilled when the wastewater is introduced into water bodies or into the soil, and on substances especially harmful for water environment,
- 5) Regulation of the Minister of Environment of November 10, 2005 (Dz. U. No. 233, item 1988) on substances being particularly harmful to the aquatic environment that require sewage disposal permit when discharged with industrial wastewater into sewage systems, and in the list of substances it specifies, inter alia, substances such as: phosphorus and phosphorus compounds determined as total phosphorus, ammonium nitrogen, and nitrite nitrogen,
- 6) Regulation of the Minister of Environment of February 11, 2004 (Dz. U. No. 32, item 284) on the classification for presentation of the status of surface waters and groundwater, on monitoring methods, and methods of the interpretation of results and presentation of the status of waters distinguishes five classes of water quality, depending on the values of the various quality parameters and defines the rules for monitoring water quality,
- 7) Regulation of the Minister of Environment of July 24, 2006 (Dz. U. No. 137, item 984) on conditions to be met for the introduction of sewage into water or soil, and on substances particularly harmful to the aquatic environment; in Annex 11 it gives a list of substances that are particularly harmful, causing water pollution, to be eliminated (List I), and a list of particularly dangerous substances, which cause water pollution, to be reduced (List II). List II includes, inter alia, inorganic compounds of phosphorus and unbound phosphorus, and

- substances that negatively affect the balance of oxygen in the water, especially ammonium and nitrites. The Regulation defines the principles of quality control of discharged sewage and the principles of sewage discharge into water and soil, and conditions of agricultural use of sewage,
- 8) Regulation of the Minister of Construction of July 14, 2006 (Dz. U. No. 136, item 964) on the methods of meeting requirements by suppliers of industrial wastewater and conditions of sewage discharge to sewage systems determines the acceptable concentration of ammonium in wastewater depending on the size of the urban agglomeration at the level of 100 or 200 mg·dm<sup>-3</sup> (77.77 mg·dm<sup>-3</sup> or 155.55 mg·dm<sup>-3</sup> NH<sub>4</sub>-N) of nitrite nitrogen at the level of 10 mg·dm<sup>3</sup> (3.04 mg·dm<sup>-3</sup> NO<sub>2</sub>-N),
- 9) Regulation of the Minister of Health from March 29, 2007 (Dz. U. No. 61, item 417) on the quality of water intended for human consumption determines the permissible content of substances in water intended for human consumption: including nitrates 50 mg · dm³ (11.29 mg·dm⁻³ NO₃-N) ammonium 0.5 mg · dm³ (0.39 mg·dm⁻³ NH₄-N).

The legal act that significantly contributes to the management of water resources is also the Act of June 7, 2001 (Dz. U. No.72, item 747) on collective water supply and collective sewage disposal, as amended. The Act sets out the rules of collective use of water and sewage disposal taking into account the principles of environmental protection. It prohibits discharge of environmentally hazardous substances into the sewage system, including ammonium solutions, strong acids and bases, as well as wastewater from animal husbandry, particularly slurry, manure, silage effluent. It obligates the water supply and sewage companies to conduct regular monitoring of quality and quantity of the domestic and the industrial sewage, and to control and comply with the requirements for discharging wastewater into sewage systems.

# 7.2. Other regulations restricting the emission of nutrients from agriculture to water - the current state of their implementation

On the Polish accession to the European Union the formal and legal implementation of Council Directive 91/676/EEC (see to: Dz. Urz. UE 68 PL, 15/t.2, L375/1, 31.12.1991; Ministerstwo..., 2003) concerning the protection of waters against pollution caused by nitrates from agricultural sources, known as the Nitrates Directive was completed. The introduction of the Nitrates Directive was due, inter alia, to the increase in consumption of mineral nitrogen fertilizers and manure, and thus to the increase of nitrate content in water intended for human consumption in some areas of Member States exceeding the standards defined by directives relating to the quality of water for the public supply of drinking water (in the light of Directive 75/440/EEC, as amended by Directives 79/869/EEC and 80/778/EEC). It was also concluded that excessive use of fertilizers promotes the growth of concentration of nitrates, which points to the needs of the protection of human health and the protection

of aquatic ecosystems through proper storage of fertilizers and their rational use in agriculture.

The provisions of the Nitrates Directive have been transposed into Polish law by regulations contained in the following acts:

- Act of July 26, 2000 on fertilizers and fertilizing (Dz. U. No. 89, item 991) as amended.
- Act of April 27, 2001 on Environmental Protection Law (Dz. U. No. 62, item 627 as amended),
- Act of July 18, 2001 on Water Law (Dz. U. No. 115, item 1229 as amended),
- Act of July 10, 2007 on fertilizers and fertilizing (Dz. U. No. 147, item 1033), and by appropriate implementing legislation to the above mentioned laws, including:
  - Regulation of the Minister of Agriculture and Rural Development of June 1, 2001 on detailed methods of fertilizer application and training in their use (Dz. U. No. 60, item 616),
  - Regulation of the Minister of Environment of December 23, 2002 on the criteria for designation of waters vulnerable to pollution from nitrogen compounds from agricultural sources (Dz. U. No. 241, item 2093),
  - Regulation of the Minister of Environment of December 10, 2003 on detailed requirements for action programmes aimed at reducing the outflow of nitrogen from agricultural sources (Dz. U. No. 4, item 44).

#### **Nitrates Directive**

In accordance with the Nitrates Directive the Member States are required to designate areas vulnerable to water pollution by nitrates (Nitrate Vulnerable Zones - NVZs), called danger zones. In these zones action programmes to reduce nitrogen emissions from agriculture are implemented. Water status is monitored, and the range of coverage of NVZs must be verified in 4-year cycles. The initial work on the designation of areas particularly vulnerable to nitrogen runoff from agricultural sources began in 2000. At that time, to the order of the Ministry of Environment, departmental research institutes (Institute of Water Management – National Research Institute, Institute of Soil Science and Plant Cultivation – State Research Institute), made the necessary expert appraisals, and based on that the risk of nitrate pollution of water at the moment of implementation of the Directive was assessed.

In accordance with the provisions of the Act on Water Law directors of the Regional Water Management Boards are responsible for designation of groundwaters and surface waters vulnerable to pollution from nitrogen compounds from agricultural sources, and of particularly vulnerable areas where nitrogen runoff from agricultural sources into the waters should be limited. These issues are specifically regulated by

the Regulation of the Minister of Environment of December 23, 2002 on the criteria for designation of waters vulnerable to pollution from nitrogen compounds from agricultural sources. According to this regulation the areas particularly vulnerable to pollution from nitrogen compounds from agricultural sources are those with already polluted waters and with water pollution risk.

**Polluted waters** are defined as groundwater and fresh surface waters, especially used for obtaining drinkable water, where nitrates amount to 50 mg·dm<sup>-3</sup> (NO<sub>3</sub>-N – 11.29 mg·dm<sup>-3</sup>). Also estuarine waters, coastal and marine waters, as well as fresh surface waters are considered polluted when showing eutrophication, which can be effectively combated by limiting doses of nitrogen.

The above mentioned types of waters are considered to be at risk of pollution when their nitrates content amount to 25 mg·dm<sup>-3</sup> (NO<sub>3</sub>-N - 5.65 mg·dm<sup>-3</sup>) and shows an upward trend. In determining waters vulnerable to pollution from nitrogen compounds from agricultural sources the specificity of particular Polish regions must be taken into account. According to cited Act on Water Law the above mentioned waters and areas shall be verified every 4 years to reflect changes in factors unforeseen at the time of their designation. In addition, the designation and verification of waters and areas shall be based on measurements made under the State Environmental Monitoring. Every 4 years, the Regional Inspector of Environmental Protection makes an assessment of the degree of eutrophication of surface waters, internal waters and coastal waters. For each of the affected areas, within 2 years from its designation, the Director of Regional Water Management Board is required to develop an action programme aimed at reducing the outflow of nitrogen from agricultural sources. The essence of the action programmes is stipulated in Article 84 of the Act on Environmental Protection Law, whereas the requirements to be met by the action programmes are contained in the Regulation of the Minister of Environment of December 23, 2002 on detailed requirements for action programmes aimed at reducing the outflow of nitrogen from agricultural sources. Remedies that should be included in the programmes were collected in a set of principles of good agricultural practice, developed by the Minister of Agriculture and Rural Development in consultation with the Minister of Environment under Article 47.2 of the Act of 18 July 2001 on Water Law.

Within the frame of preparation for the implementation of the Nitrates Directive, between August 2002 and September 2004, there was realized a twin project which was funded by the European Union under the "Phare" programme. On the Polish side the Ministry of Environment was responsible for its implementation, while on the European Union side the UK government provided support. The project assumed achieving so-called "Guaranteed Results" involving, inter alia:

- development of recommendations for strengthening the system of water quality monitoring in areas vulnerable to pollution from agricultural sources,
- development of recommendations for harmonization/coordination of activities undertaken in the field of water protection,

- development of guidelines for monitoring and control of agricultural sources of water pollution,
- delivery of training courses for personnel responsible for monitoring water quality, bodies of state administration, and agricultural advisory units,
- development of procedures for implementing the guidelines,
- preparation of technical specifications for the purchase of equipment for water quality monitoring and computer hardware,
- preliminary environmental impact assessment of agricultural activity.

At the first stage of implementation of the Nitrates Directive in Poland, 21 areas vulnerable to nitrates from agricultural sources were designated and they were legally established by virtue of 11 Regulations issued by Directors of Regional Water Management Boards. The Regulations were published in Voivodeship Official Gazettes. The total area of designated areas amounted to 6,263.25 km², representing about 2% of the area of Poland (Fig. 7.1; Table 7.1).



Fig. 7.1 The map of nitrate vulnerable zones (Novas) in the years 2008-2012 (source: Krajowy Zarząd Gospodarki Wodnej, 2008; http://www.kzgw.gov.pl/index.php?id=636)

For all of these areas action programmes have been developed to improve the quality of surface waters and groundwater. All programmes included mandatory measures for use in agriculture, which mainly concerned the elimination of errors in the storage and handling of fertilizers.

The recommendations concerned mainly:

- 1. Periods when the application of fertilizers should be prohibited;
- 2. Fertilization on soils located on steep slopes;
- 3. Fertilization on waterlogged, flooded, frozen or snow covered soil;
- 4. Fertilization near watercourses and surface water;
- 5. Storage of natural fertilizers;
- 6. Dosing and methods of fertilization;
- 7. Land management and organization of farmland production;
- 8. Compilation of nitrogen balance, fertilization plans and documentary cards.

The action programmes, aiming at reducing the outflow of nitrogen from agricultural sources, covered training for farmers on good agricultural practices for the protection of water, and the development of special information and educational materials for farmers (Duer et al., 2002). In all the programs, the role of advising on the implementation of remedial measures for mandatory use on farms was taken into account. Permanent diagnostics of water pollution sources, control and monitoring of the implementation of the programmes were provided for. Continuous water monitoring was also planned.

At the beginning of 2008, new limits of NVZs were delimited taking into account the 19 zones. The total areas of NVZs in individual Regional Water Management Boards are presented in Table 7.1. Currently the area of designated NVZs amounts to 4623.14 km², representing about 1.49% of the area of Poland, being reduced by 0.5% compared to that in 2004. The reason for NVZs area reduction in 2008 was, inter alia, their designation in river basins on the basis of geodesic precincts and not boundaries of boroughs, which was the case in 2004.

Table 7.1 The area of Nitrate Vulnerable Zones (NVZs) in consecutive cycle periods (source: Krajowy Zarząd Gospodarki Wodnej, http://www.kzgw.gov.pl)

Regional Water Management Boards		NVZs area				
Davian	Total area	May 2004 - April 2008		May 2008 - April 2012		
Region	[km <sup>2</sup> ]	[km <sup>2</sup> ]	3 2	[km <sup>2</sup> ]	[% of area]	
Gdańsk	33100	721.00	2.18	613.23	1.87	
Gliwice	8390	317.14	3.78	0.00	0.00	
Kraków	43767	0.00	0.00	0.00	0.00	
Poznań	55098	728.70	1.32	911.05	1.65	
Szczecin	20402	1098.70	5.38	925.42	4.53	

Regional Water Management Boards		NVZs area				
Region	Total area [km²]	May 2004 - April 2008		May 2008 - April 2012		
		[km <sup>2</sup> ]	[% of area]	[km <sup>2</sup> ]	[% of area]	
Warszawa	111160	575.50	0.50	573.24	0.50	
Wrocław	39212	2823.31	7.20	1600.20	4.08	
Poland	311129	6264.35	2.00	4623.14	1.49	

Small area of NVZs in Poland was reluctantly accepted by EU experts and they expressed major reservations about it. Currently the process of reviewing and designating the ranges of new Nitrate Vulnerable Zones comes to an end and that will be in force from 2012 onwards. The study prepared by the Institute of Soil Science and Plant Cultivation – State Research Institute in Puławy indicates that the surface of areas vulnerable to pollution by nitrates from agricultural sources may amount to 16-17% of agricultural land in Poland.

### **Cross-compliance requirements**

Since 2009, the rule of so-called cross-compliance has been implemented in Poland. It has introduced the dependence of direct subsidies obtained by farmers on meeting certain requirements. In the case of farms in NVZs areas, these requirements are related to the protection of waters against pollution caused by nitrates from agricultural sources. Failure to observe the requirements results in a reduction of the subsidies proportionate to the violation found by the inspection. Inspections are conducted by the Agency for Restructuring and Modernisation of Agriculture.

Requirements for the protection of waters against pollution by nitrates are consistent with national regulations on fertilizers and fertilization in force in Poland:

- ✓ Allowable load of nitrogen carried in natural fertilizers may not exceed 170 kg N ha<sup>-1</sup>;
- ✓ Surplus manure may be disposed of a farm under a written agreement, which shall be retained for a period of 8 years from the date of its conclusion:
- ✓ Natural fertilizers may be applied in the period from 1 March to 30 November;
- ✓ Fertilizers shall be applied uniformly over the entire surface of the field in a way preventing fertilization of the fields and crops not intended for that:
- ✓ Manure in liquid form and nitrogen fertilizers shall not be applied to soil without plant cover on slopes greater than 10%;

- ✓ Fertilizers shall not be applied to flooded soils or soils covered with snow or frozen to a depth of 30 cm (not applicable to fishponds);
- ✓ Liquid manure shall not be applied during the growing season of plants intended for direct consumption;
- ✓ Natural fertilizers in liquid form may be used when the groundwater level is below 1.2 m and outside the areas where slotted rocks occur;
- ✓ Natural fertilizers applied to arable land should be covered or mixed with soil, not later than the day following their application;
- ✓ Natural fertilizers shall not be applied closer than 20 meters from water sources and intakes protection zones, banks of water reservoirs and watercourses, bathing areas and marine coastal areas;
- When determining doses of fertilizers the nutritional needs of plants and soil richness in nutrients shall be taken into account, and in the case of applying waste, plant conditioners and soil improvers also doses of nutrients entering the soil in these substances.

Specific requirements of individual action programmes (in different NVZs) may differ. Therefore farmers are required to get acquainted with current action programmes in force in a given NVZ.

#### Act on fertilizers and fertilization

The major provisions of the Act on fertilizers and fertilization take into account the provisions of the Nitrate Directive by means of the following regulations:

- Only fertilizers and plant growth enhancers that have been admitted to trading under the law and natural fertilizers may be applied;
- Fertilizers should be applied in a manner that does not cause risks to human and animal health and the environment;
- The amount of natural fertilizer applied during the year, may not contain more than 170 kg of nitrogen in the pure component per 1 ha of agricultural land.

# It is prohibited to apply:

- Fertilizers to flooded, snow covered soil or soil frozen to a depth of 30 cm;
- Natural fertilizers in liquid form and nitrogen fertilizers to soil without plant cover on slopes greater than 10%;
- Natural fertilizers in liquid form during the growing season of plants intended for direct human consumption.

Natural fertilizers in solid form should be kept in livestock buildings or on impermeable storage plates, protected against infiltration of leachate into the ground and having adequate systems for leachate drainage to leakproof containers, whereas natural fertilizers in liquid form should be stored in sealed containers with a capacity allowing to collect at least 6-month production of fertilizers.

On the basis of the law in force the monitoring of mineral nitrogen and nitrate nitrogen in water to a depth of 90 cm below the surface of the land is carried out in Poland (Fotyma et al., 2005). The task was assigned to chemical and agricultural stations. Monitoring of mineral nitrogen was conducted in Poland since 1998 and its results provided a general background for the status of  $N_{\text{min}}$  in the soil at the stage of preparations for designation of NVZs.

### **Rural Development Programme (RDP)**

Rural Development Programme (RDP), co-funded by the European Agricultural Fund for Rural Development and the national resources, is being implemented throughout the country. RDP for 2007-2013, in its strategic part defines priority areas of support and characterizes in detail various activities planned for rural development in the four issues.

One of them is the improvement of the environment and the countryside and it is a concept model taking into account not only the production function of agriculture, but also the role of the countryside in environmental protection, including water resources. Under these measures the following activities are implemented:

- 1. Support for farming in mountainous areas and other Less Favoured Areas (LFA). This task is intended to prevent depopulation, and thus to maintain the agricultural character of the above mentioned areas taking into account the social, economic and environmental impacts. LFA payments are intended to provide compensation for costs incurred and revenue lost as a result of farming in these areas;
- 3. Agri-environmental program (Agri-environmental payments); the aim of the programme is to promote agricultural production based on the methods compliant with the requirements of environmental protection and nature conservation e.g. through the appropriate use of soil and water conservation. The programme contains 9 packages. Package 8 Protection of Soil and Water comprises three options: supplementary aftercrops, winter intercrops, and stubble intercrops which are intended to prevent, inter alia, water pollution by nitrates;
- 5. Afforestation of agricultural land and non-agricultural land; the programme focuses on afforestation of the land of low valuation class, which is to (i) strengthen the ecological stability of forest areas, (ii) increase the share of forests in global carbon balance, and (iii) reduce climate change;
- 6. Restoring forestry production potential damaged by natural disasters and introducing prevention instruments. The aim is to renew the forest stands damaged by biotic and abiotic factors and to introduce the mechanisms allowing prevention of natural disasters.

Rural Development Programme for 2007-2013 requires that farmers comply

with farming rules contained in the Code of Good Agricultural Practice, including proper use and storage of natural fertilizers, which helps to reduce emissions of nitrogen from agricultural sources into waters.

#### 7.3. Summary

- Polish legislation has created appropriate conditions for protection of waters, including waters feeding the Baltic Sea. The basic legal act regulating water management is the Act on Water Law with a number of implementing acts. Water management throughout the country is conducted by the National Water Management Authority operating through Regional Water Management Boards. The National Water Management Authority is supervised by the Minister responsible for water management.
- Water management includes all aspects of environmental protection, especially
  protection of water resources, which is reflected, inter alia, in close cooperation
  of ministers responsible for water management and environmental protection,
  especially in the creation of interrelated and complementary legislation.
- Relevant legislation clarifies the criteria of evaluation and classification of waters, defining acceptable levels of nitrogen and phosphorus in water and wastewater, depending on their usage.
- In Poland, water quality is regularly monitored in the State Monitoring System.
- Every two years the Minister responsible for water management submits a report on water management to the Sejm of the Republic of Poland.
- In the case of low or deteriorating water quality, the action programmes are
  developed to improve water status. Entities that do not respect the rules of
  sustainable use of water and that do not implement specific actions to protect
  or improve water quality are subject to sanctions provided for by regulations in
  force.
- Public aid is granted to entities developing systems, equipment or taking up other
  activities to improve water status or protection on terms specified in the relevant
  regulation of the Council of Ministers.

#### References

- Duer, I., Fotyma, M., Madej, A., 2002. Ministerstwo Rolnictwa i Rozwoju Wsi, Ministerstwo Środowiska: Kodeks Dobrej Praktyki Rolniczej, Fundacja Programów Pomocy dla Rolnictwa, Warszawa, pp. 1-96.
- Dz. U. Nr 28, poz. 347, 2000: Oświadczenie Rządowe z dnia 29 grudnia 1999 r. w sprawie ratyfikacji przez Rzeczpospolita Polską Konwencji o ochronie środowiska morskiego obszaru Morza Bałtyckiego, sporządzonej w Helsinkach dnia 9 kwietnia.
- Dz. U. Nr 89, poz. 991, 2000 z późn. zm.: Ustawa z dnia 26 lipca 2000 r. o nawozach i nawożeniu.
- Dz. U. Nr 60, poz. 616, 2001: Rozporządzenie Ministra Rolnictwa i Rozwoju Wsi z dnia 1 czerwca 2001 r. w sprawie szczegółowego sposobu stosowania nawozów oraz prowadzenia szkoleń z zakresu ich stosowania.
- Dz. U. Nr 62, poz. 627, 2001 z późn. zm.: Ustawa z dnia 27 kwietnia 2001 r. Prawo ochrony środowiska.
- Dz. U. Nr 72, poz. 747, 2001: Ustawa z dnia 7 czerwca 2001 r. o zbiorowym zaopatrzeniu w wodę i zbiorowym odprowadzaniu ścieków.
- Dz. U. Nr 115, poz. 1229, 2001 z późn. zm.: Ustawa z dnia 18 lipca 2001 r. Prawo wodne.
- Dz. U. Nr 176, poz. 1455, 2002: Rozporządzenie Ministra Środowiska z dnia 4 października 2002 r. w sprawie wymagań, jakim powinny odpowiadać wody śródlądowe będące środowiskiem życia ryb w warunkach naturalnych.
- Dz. U. Nr 241, poz. 2093, 2002: Rozporządzenie Ministra Środowiska z dnia 23 grudnia 2002 r. w sprawie kryteriów wyznaczania wód wrażliwych na zanieczyszczenie związkami azotu ze źródeł rolniczych.
- Dz. U. Nr 4, poz. 44, 2003: Rozporzadzenie Ministra Środowiska z dnia 10 grudnia 2003 r. w sprawie szczegółowych wymagań, jakim powinny odpowiadać programy działań majacych na celu ograniczenie odpływu azotu ze źródeł rolniczych.
- Dz. U. Nr 32, poz. 284, 2004: Rozporządzenie Ministra Środowiska z dnia 11 lutego 2004 r. w sprawie klasyfikacji dla prezentowania stanu wód powierzchniowych i podziemnych, sposobu prowadzenia monitoringu oraz sposobu interpretacji wyników i prezentacji stanu tych wód.
- Dz .U. Nr 72, poz. 747, 2004: Rozporządzenie Rady Ministrów z dnia 27 kwietnia 2004 r. w sprawie szczegółowych warunków udzielania pomocy publicznej na inwestycje służące ochronie wód przez zanieczyszczeniem.
- Dz. U. Nr 168, poz. 1763, 2004: Rozporządzenie Ministra Środowiska z dnia 8 lipca 2004 r. w sprawie warunków, jakie należy spełnić przy wprowadzaniu ścieków do wód lub do ziemi, oraz w sprawie substancji szczególnie szkodliwych dla środowiska wodnego.

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- Dz. U. Nr 233, poz. 1988, 2005: Rozporządzenie Ministra Środowiska z dnia 10 listopada 2005 r. w sprawie substancji szczególnie szkodliwych dla środowiska wodnego, których wprowadzenie w ściekach przemysłowych do urządzeń kanalizacyjnych wymaga uzyskania pozwolenia wodnoprawnego.
- Dz. U. Nr 260, poz. 2177, 2005: Rozporządzenie Rady Ministrów z dnia 20 grudnia 2005 r. w sprawie jednostkowych stawek kar za przekroczenia warunków wprowadzania ścieków do wód lub do ziemi.
- Dz. U. Nr 136, poz. 964, 2006: Rozporządzenie Ministra Budownictwa z dnia 14 lipca 2006 r. w sprawie sposobu realizacji obowiązków dostawców ścieków przemysłowych oraz warunków wprowadzania ścieków do urządzeń kanalizacyjnych.
- Dz. U. Nr 137, poz. 984, 2006: Rozporządzenie Ministra Środowiska z dnia 24 lipca 2006 r. w sprawie warunków, jakie należy spełnić przy wprowadzaniu ścieków do wód lub do ziemi, oraz w sprawie substancji szczególnie szkodliwych dla środowiska wodnego.
- Dz. U. Nr 61 poz. 417, 2007: Rozporządzenie Ministra Zdrowia z dnia 29 marca 2007 r. w sprawie jakości wody przeznaczonej do spożycia przez ludzi.
- Dz. U. Nr 147, poz. 1033, 2007: Ustawa z dnia 10 lipca 2007 r. o nawozach i nawożeniu.
- Dz. Urz. UE 68 PL, 15/t.2, L375/1, 31.12.1991: Dyrektywa Rady z dnia 12 grudnia 1991 r. dotycząca ochrony wód przed zanieczyszczeniami powodowanymi przez azotany pochodzenia rolniczego (91/676/EWG).
- Dz. Urz. WE 16.3.1992: Konwencja o ochronie środowiska morskiego Morza Bałtyckiego.
- Dz. Urz. WE L. 327/1, 22.12.2000: Dyrektywa 2000/60/WE Parlamentu Europejskiego i Rady z dnia 23 października 2000 r. ustanawiająca ramy wspólnotowego działania w dziedzinie polityki wodnej.
- Fotyma, E., Fotyma, M., Igras, I., Kopiński, J., 2005. Sustainable nitrogen management in Poland principles and legislation. Nawozy i Nawożenie, No 1(22), pp. 152-171.
- Krajowy Zarząd Gospodarki Wodnej, 2008. http://www.kzgw.gov.pl/index.php?id=636 [Accessed in December 2008].
- Ministerstwo Środowiska, Departament Zasobów Wodnych, 2003. Informacja o źródłach i zasadach pozyskiwania środków na realizację programów działań na obszarach szczególnie narażonych na azotany pochodzenia rolniczego (wdrażanie dyrektywy 91/676/EWG); http://www.mos.gov.pl/2materialy\_informacyjne/raporty\_opracowania/obszar\_azotan.pdf [Accessed in December 2008].

8

NITROGEN AND PHOSPHORUS EMISSION INTO THE VISTULA AND ODER BASINS - MODELING STUDIES (MONERIS)

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# 8. NITROGEN AND PHOSPHORUS EMISSION INTO THE VISTULA AND ODER BASINS – MODELING STUDIES (MONERIS)

Marianna Pastuszak, Tomasz Kowalkowski, Janusz Igras

#### 8.1. Conceptual scheme of MONERIS model

The GIS (Geographical Information System) oriented model MONERIS (MOdeling Nutrient Emissions in RIver Systems) (Behrendt et al., 2000, 2005 a,b; Fig. 8.1) was adopted by Kowalkowski and Buszewski (2006) and Kowalkowski et al. (2012) to estimate nitrogen and phosphorus emission into the Vistula and Oder basins in various time intervals.

As nutrient concentrations, constituting runoff components in the model, are greatly affected by biogeochemical processes which are different in various ecosystem components, a distinction between the inputs from various nutrient sources is necessary. Therefore, MONERIS takes into account the following seven nutrient pathways (Fig. 8. 1):

- discharges from point sources,
- inputs into surface waters via:
  - atmospheric deposition,
  - groundwater,
  - tile drainage,
  - paved urban areas,
  - surface runoff (only dissolved nutrients),
  - erosion.

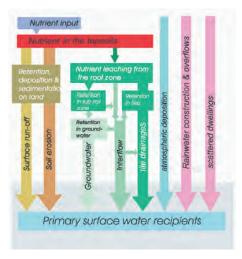


Fig. 8.1 Conceptual scheme of MONERIS model (source: HELCOM, 2004)

In any modeling studies the model validation is indispensible. Model validation is an important step in application of the model and it consists in comparing the obtained results with independent data sets. The model validation in the studies by Kowalkowski et al. (2012) was based on the comparison between the calculated with MONERIS and the monitored (Fig. 8.2) total nitrogen (TN) and total phosphorus (TP) loads (IMWM, 1990-2002; 2003-2009) for all consecutive years of the investigation period (1995-2008). For nitrogen and phosphorus species, the mean relative error amounted to 13% and 19% for the Vistula and the Oder, respectively. It indicates a good accuracy of the calculated emission values (Fig. 8.3). The observed slight underestimation of TN and TP loads (Fig. 8.3) arises from the fact that only Polish parts of Vistula and Oder basins (Fig. 8.2) were investigated.

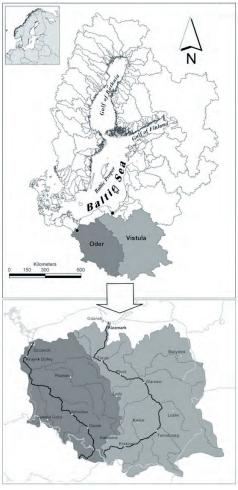
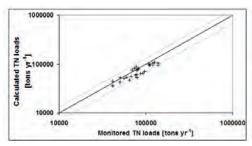


Fig. 8.2 The Baltic Sea catchment and the location of investigated Vistula and Oder basins; two dots in the upper map indicate the lowermost Oder (Krajnik Dolny) and Vistula (Kiezmark) monitoring stations (source: the upper part of the combined map was produced and kindly made available by dr. Erik Smedberg from BNI, Stockholm University, Sweden)



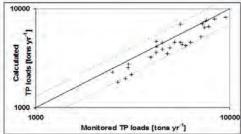


Fig. 8.3 Comparison between TN and TP loads, calculated with MONERIS, and TN and TP mean annual loads monitored at the lowermost Vistula (Kiezmark) and Oder (Krajnik Dolny) stations; doted lines indicate 20% deviation (source: Kowalkowski et al., 2012)

## 8.2. Modeling studies – an useful tool in estimating nutrient losses into inland surface waters

It is a well known fact that mitigation of nitrogen (N) and phosphorus (P) losses from waste water treatment plants (WWTPs) is relatively easy and affordable, but decreases in N and P losses from agriculture into surface waters require drastic improvement in agricultural management and structure, some of which can only be achieved at high costs (Neumann and Schernewski, 2005). The quantification of nitrogen and phosphorus loads entering nutrient-enriched rivers from point and diffuse sources provides critical information to catchment managers, allowing them to select the most suitable nutrient mitigation options to reduce N and P concentrations and eutrophication risk (Johnes et al., 2007; Withers and Sharpley, 2008; HELCOM, 2009b).

Though the recent studies (Pastuszak et al., 2012; Chapter 9) prove that the discharges of all the nitrogen and phosphorus compounds by the Vistula and Oder Rivers significantly declined during the transition period there is still a need for new, effective, but also economically justified programs aiming at further reduction in nutrient concentrations in Polish riverine systems, and consequently declines in nutrient loads discharged into the Baltic Sea. Predicting of the impact of nutrient mitigation measures in the watershed on quality of inland and coastal waters remains, however, a very difficult issue due to a complexity of the physical, chemical, and biological processes involved, which interact non-linearly. The use of correctly validated numerical models, integrating the complex interacting processes, is therefore the best way to tackle the problem (Billen et al., 2001; Alexander et al., 2002; Whitehead et al., 2002; Kersebaum et al., 2003; Behrendt et al., 2005 a,b; Garnier et al., 2002, 2005; Arheimer et al., 2005; Gömann et al., 2005).

Modeling studies allow to define the past and present situation with respect to N and P emission into inland surface waters via specified pathways, but they also allow to estimate the future emission at certain assumed scenarios e.g. intensification of production in agricultural sector e.g. increase in livestock density, higher application

of fertilizers, and/or implementation of mitigation measures e.g. focus on good agricultural practices, establishing of buffer zones, construction of plates and tanks for proper dung and manure storage (e.g. Kowalkowski, 2009).

## 8.3. Nitrogen and phosphorus sources in riverine outflow

In the Baltic catchment (Fig. 8.2) over 60% of nitrogen and ca. 50% of phosphorus in the riverine outflow originates from losses from diffuse sources, with agricultural activity playing a key role in nutrient emission (HELCOM, 2004). The source apportionment of nitrogen and phosphorus losses into inland surface waters, made for all the Baltic countries (HELCOM, 2004), shows that the respective contribution of nitrogen from diffuse sources, point sources, and natural background constituted 62%, 18%, and 20% in Poland in 2000; the respective contribution of phosphorus from diffuse sources, point sources, and natural background constituted 54%, 29%, and 17% (Fig. 8.4). Within the discharges of nutrients from point sources, contribution of WWTPs was in Poland of uppermost importance as it constituted ca. 92% of both N and P loads; contribution of industrial discharges accounted for ca. 8% of both N and P loads.

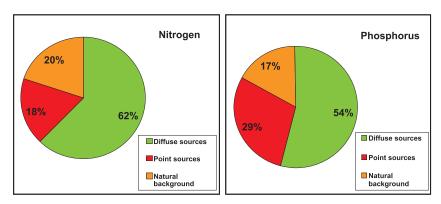


Fig. 8.4 Source apportionment of nitrogen and phosphorus losses into inland surface waters in Poland in 2000 (source: HELCOM, 2004)

Over the last decades there have been observed changes in techniques of soil cultivation and a considerable increase in global consumption of mineral and natural fertilizers (Smil, 2002; Güler, 2006; Heffer and Prud'homme, 2007). Nausch et al. (1999) report 17-fold and 8-fold increases in the consumption of mineral nitrogen and phosphorus fertilizers in the Baltic Sea drainage basin in 1950-1988, with some decreasing tendency in the years that followed. Recent studies indicate that less than half of the total nitrogen input *via* fertilizers and animal manure in crop production is effectively utilized, while the remainder is dissipated into the wider environment, where it contributes to a range of ecological and human health effects (Galloway and Cowling, 2002; Galloway et al., 2003, 2008; Erisman et al., 2007; Howarth, 2008).

Howarth et al. (1996) argue that there is strong statistically significant linear positive correlation between river fluxes of total nitrogen and the sum of anthropogenically-derived nitrogen inputs (fertilizer application, human-induced increases in atmospheric deposition of oxidized forms of nitrogen, fixation by leguminous crops, and the import/export of nitrogen in agricultural products) to the temperate regions of the North Atlantic basin.

Agricultural systems leak N and P *via* three major routes: (i) upward, *via* crop uptake and *via* transfer of gaseous nitrogen compounds (NH<sub>3</sub>, N<sub>2</sub>, N<sub>2</sub>O, NO<sub>x</sub>) and phosphorus as atmospheric aerosols to the atmosphere (minor flux of P), (ii) laterally, *via* surface runoff, subsurface flow and tile drainage, and (iii) downwards, *via* leaching. The balance between these three different routes depends on farming system, nitrogen and phosphorus fertilizing history, climate, topography, soil type, and hydrology (Haycock et al., 1993; Oenema and Roest, 1998; Oenema, 1999; Nixon, 1999; Hooda et al., 2000; Honisch et al., 2002; Oenema et al., 2003; Salo and Turtola, 2006). Surface waters receive agricultural nitrogen *via*: (i) atmospheric deposition, (ii) surface runoff and erosion, (iii) subsurface flow and tile drainage, (iv) seepage of nitrate containing groundwater from agricultural land (Oenema and Roest, 1998). The pool of nutrients that enters the surface waters depends very much on N and P pathways from the soil surface and root zone to the surface recipient of water (Behrendt et al., 2005a,b; Grizetti et al., 2005; Kowalkowski et al., 2012).

Nitrate is the primary form of N leached into surface waters and groundwater; it is totally soluble at concentrations found in soil, and moves freely throughout most soils. The widespread appearance of NO3-N in groundwater is a consequence of its high solubility, mobility, and easy displacement by water. In addition, it is well documented that nitrate leaching rates will be affected by rain, irrigation, tile drainage, and water table fluctuations during the growing season. Movement of nitrates with percolating water, through the unsaturated zone can be very slow, therefore there is significant time span between the enhanced emission and recorded elevated concentrations of N species in groundwater (from a year to 20 years, depending on situation) (Nixon, 1999; Hatfield and Follett, 2008; Haag and Kaupenjohann, 2001). Increased nitrate leaching takes place on farmland with relatively thin soil layer, on fields with low buffering capacity of nutrients, and on fields without vegetation. Great losses of nitrates from agricultural land take place when intensive dosage of fertilizers is not balanced by requirement and consumption by plants in agricultural plant production, and also at heavy rain (Oenema and Roest, 1998; Nixon, 1999; Oenema et al., 2003; Hatfield and Follett, 2008).

There are distinguished fast-flow and slow-flow systems. In the former systems, surface, whereas in the latter subsurface outflows of water play a key role. In the fast-flow systems large loads of N and P can be expected to reach the surface waters, while in the slow-flow systems considerable reduction of nutrient loads through biogeochemical processes, e.g. denitrification can be expected. Predominance of

either fast or slow-flow system depends on land slope, on land cover/use, soil type and its permeability, climate i.e. hydrological and meteorological factors (Sharpley, 1995; Sims et al., 1998; Arheimer and Lidén, 2000; Vagstad et al., 2004; Banaszuk et al., 2005).

Slow-flow systems predominate in Poland; therefore Poland has the highest natural N and P retention in the entire Baltic catchment (HELCOM, 2004; Chapter 1). High retention capacity arises from the fact that Poland is largely a lowland country; 75% of Polish territory has an elevation below 200 m above the sea level. As much as 91.3% of its area lies in the lowland zone; upland and typically mountainous areas account for 7.7% and 1% of its territory, respectively. Nearly 84% of the entire Polish area has a land slope below 3° (GUS, 2007; Chapter 2). Moreover, Polish rivers are the least regulated in the entire Baltic region, and in majority they have grass/bush overgrown river banks. Impact of river regulation on N retention has been shown by Ilnicki (2002), who carried out studies in a large catchment of Warta, one of the largest tributaries of the Oder River. The studies were conducted in Warta tributaries, which have regulated and unregulated river courses. The outcome showed that due much longer water residence time, N retention was incomparably higher in rivers with unregulated river reaches. As shown for various systems, a long residence time favors effective nutrient removal from the system on the way of biogeochemical processes e.g. through denitrification (Nixon et al., 1996; Behrendt et al., 1999, 2005 a, b; Kronvang et al., 1999; Mander et al., 2000; Dannowski et al., 2002; Stålnacke et al., 2003; Vagstad et al., 2004; Grizetti et al., 2005; Pastuszak et al., 2005; Lepistö et al., 2006) (Chapter 10).

Mass balance studies of Caracao and Cole (1999), Howarth et al. (1996), and Jaworski et al. (1992) demonstrate that in partially forested watersheds with substantial agricultural activity some 75-80% of net anthropogenic nitrogen inputs are stored within the watershed or denitrified and only 20-25% exported in rivers. However, the variability in nitrogen losses can be great, ranging from a low of 3% of the rate of nitrogen fertilization on grassland with clay-loam soils to a high of 80% of the rate of nitrogen fertilization for row-crop agriculture on sandy soils (Howarth et al., 2002). Much higher N losses from both arable land and meadows on sandy soils than from the same type of crop on clay or loess, is documented in numerous studies carried out in Poland, and extensively commented by Ilnicki (2004). There are large uncertainties regarding the rates of N accumulation in various reservoirs and they arise from a sequence of transfers, transformations, and environmental effects called "nitrogen cascade" (Galloway and Cowling, 2002).

Unlike nitrogen, the major proportion of phosphorus transported from agricultural soils is generally in sediment-bound form, the remaining percentage constitutes dissolved (molybdate reactive P) (Probst, 1985; Misumura, 1989; Oenema and Roest, 1998; Sharpley, 2006). In most watersheds, P export occurs mainly in surface runoff rather than in subsurface flow. Generally, the concentrations of P in water

percolating through the soil profile are small due to fixation of P by P-deficient subsoils. Exceptions occur in sandy, acid organic, or peaty soils with low P fixation or holding capacities, and in soils where the preferential flow of water can occur rapidly through macro-pores and earthworm holes (Sharpley, 2006).

The sediment-bound phosphorus includes P associated with soil particles and organic material eroded during flow events and constitutes 60% to 90% of P transported in surface runoff from most cultivated land (Sharpley, 2006). Phosphorus in soil exists in inorganic and organic forms. Overall, soil pH is the main property controlling inorganic P forms, although Al, Fe, and Ca content determine the amounts of these forms. In acid soils, Al and Fe dominate fixation of P, while Ca compounds fix P in alkaline soils. As a result, P availability for crops is greatest at soil pH between 6 and 7 (for details - see to Chapter 9). Also unlike nitrogen, only a fraction of the phosphorus transported from agricultural land is directly bioavailable to aquatic biota. However, a substantial portion of particulate P may also be released into an algal-available form, especially when the particles have entered anoxic sediment surface.

In agro-ecosystems, land use changes affect pathways and quantities of nutrient transport, but in general, these effects do not become immediately visible. The lag time depends on the average duration required for water to travel from the location of infiltration to the groundwater or surface water. Additionally, the transport velocity of solutes depends on sorption and desorption, as well as on turnover processes in the soil (Honisch et al., 2002; Haag and Kupenjohann, 2001). According to Vagstad et al. (2004), processes such as mineralization, immobilization and denitrification affect nutrient transportation from the root zone to surface water and it is unlikely that there will be a strong correlation between N balance surpluses and N losses at the catchment outlet in the short term (≤5 years). The studies of Kowalkowski et al. (2012), Pastuszak et al. (2012), and the authors of Chapter 9 cover the period of 14-24 years, so there is no risk that the authors were not able to notice the impact of nutrient mitigation measures in agricultural system in Poland during the transition period.

# 8.4. Source and pathway apportionment of nitrogen and phosphorus emission into the Vistula and Oder basins

#### N and P emission in 1960-2000

Although in this Chapter of the monograph we have mainly concentrated on the transition period in Poland, it is worth mentioning the long-term (1960-2000) modeling studies (MONERIS model) (Behrendt et al., 2005a) which cover also the impact of the former economic system on natural environment in the Oder basin. Between 1960s and 1980s the nitrogen emission from diffuse sources into the Oder basin increased by a factor of 2.7, and in the 1980 N emission exhibited its maximum

(ca. 118,000 tons). In the 1960s nitrogen emission *via* groundwater (40%) was a dominant pathway and that was followed by point sources (23%) and urban areas (16%). During the maximum N emission in 1980s (overlapping with maximum of fertilizer application; Chapter 3), the contribution of tile drainage reached 25%, while groundwater 30%; the share of point sources was reduced down to ca. 20%. In the year 2000, the overall N emission reached 98,000 tons and ca. 35% of the emission took place *via* tile drainage and ca. 28% - *via* groundwater; emission from point sources constituted 23%. The contribution of N emission from atmospheric deposition, surface runoff, and the erosion were of minor importance during the period of these studies.

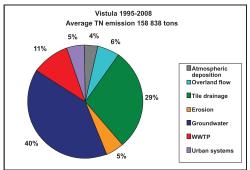
Modeling studies (MODEST), carried out by Dannowski et al. (2002) in the Oder sub-catchments in the 1980s (intensive fertilization) and in the 1990s (after a dramatic decrease in fertilizer application), indicate that in the 1980s no more than 3.5 kg ha<sup>-1</sup> yr<sup>-1</sup> of nitrogen (of the related N input ≤30 kg ha<sup>-1</sup> yr<sup>-1</sup>) was charged into the rivers *via* groundwater flow. About 10 years later, as state these authors, the specific groundwater N load decreased to the level of 1.8 kg ha<sup>-1</sup> yr<sup>-1</sup>. The response of the system to reduced pressure (reduced application of fertilizers after the late 1980s) varied from 5 to 15 years, depending on the Oder sub-catchment. It is further concluded that N maximum that could have supplied groundwater passed in the late 1990s and no threat was expected in the years that followed, provided N surplus in Polish agriculture remained on a reasonably low level.

The maximum of N emission into the Oder basin did not overlap with maximum of P emission which appeared in 1990 and amounted to ca. 15,600 tons (Behrendt et al., 2005a). As to phosphorus, the dominant pathway in the 1960s was the point source discharge (30%), followed by erosion (21%) and by the emission from urban areas (20%). In the 1990s, the total P emission was greatly predominated by point sources (ca. 60%), while relative share of erosion and urban areas dropped down to 12% and 17%, respectively. In the year 2000, total P emission was on the level of 8,800 tons, and point sources remained a major source (37%); due to a visible reduction in nutrient discharges from WWTPs the relative contribution of erosion increased up to 24%.

A source and pathway apportionment of N emission into the Vistula basin in 1991-1995 and 1996-2000, estimated by Kowalkowski and Buszewski (2006) in their modeling studies (MONERIS), indicates that ca. 65% of N emissions were caused by diffuse sources, mainly groundwater and tile drainage; for P, 22-24% contribution of WWTPs, and 26-38% contribution of urban systems was found. The same apportionment for the Oder basin indicates that in 1993-1997 as much as 61%, while in 1998-2002, 56% of N emissions were caused by diffuse sources, mainly groundwater and tile drainage; for P, the contribution of point sources reached ca. 63% in 1993-1997 and 51% in 1998-2002 (the latter percentage represents the sum of point sources and diffuse sources from settlements) (Behrendt et al., 2005b).

#### N and P emission in 1995-2008

Recent modeling (MONERIS) studies, performed for the Vistula and Oder basins for the years 1995-2008, have shown that ca. 70% of **TN** emission into both river basins was *via* groundwater and tile drainage (Kowalkowski et al., 2012; Fig. 8.5). Though three pathways of N emission i.e. groundwater, tile drainage, and WWTPs, showed the highest average contribution in the Vistula and Oder basins in 1995-2008, the average percentage **contribution of groundwater** was much higher in the Vistula (40%) than in the Oder (24%) basin, while the average percentage **contribution of tile drainage** was considerably higher in the Oder (48%) than in the Vistula (29%) basin. N emission (expressed in tons) caused by groundwater in the Vistula basin was by factor of 2.6 higher than in the Oder basin.



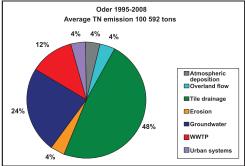


Fig. 8.5 Average (1995-2008) percentage contribution of various pathways of nitrogen emission into the entire Vistula and Oder basins (source: Kowalkowski et al., 2012)

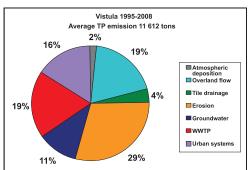
The earlier studies also prove that groundwater was an important pathway of N emission into the two studied rivers in Poland. In 1998-2002, 26.6% of N load reached the Oder basin through the groundwater (Behrendt et al., 2005b); in 1996-2000, 35.3% of N load reached the Vistula basin through this pathway (Kowalkowski and Buszewski, 2006) (see to sub-chapter 8.5).

The percentage **contribution of tile drained** area is by 13% higher in the Oder than in the Vistula basin (Kowalkowski et al., 2012) and that fact explains much higher N and P (P sediment-bound forms) transit *via* this pathway in the Oder basin. In 1990-2011, the average percentage contribution of PO<sub>4</sub>-P concentrations to TP concentrations amounted to 28% in the Oder River and to 51% in the Vistula River (Chapter 9). The controversial role of the tile drainage in N and P export from agricultural land is discussed by Dils and Heathwaite (1999) and Billen and Garnier (2000), who studied mixed agricultural catchments in the UK and France. Tile drainage was considered by these authors an evidently effective conduit for N and P export from agricultural catchments. Many studies have also reported greater P leaching *via* artificial drainage systems from manured and fertilized soils compared

to that from unfertilized and unmanured soils (e.g. Hooda et al., 2000, 2001). Phosphorus loss from agricultural non-point sources depends on the coincidence of source factors (functions of soil, crop, and management; soil P concentration, soil texture, structure, and permeability are of importance) and transport factors (surface and subsurface runoff, erosion, tile drainage, and channel processes) (Sharpley et al., 1999; Sharpley, 2006).

The average **percentage contribution of WWTPs** in TN emission was slightly higher in the Oder (12%) than in the Vistula basin (11%) (Kowalkowski et al., 2012; Fig. 8.5).

In 1995-2008, the percentage contribution of particular **TP** pathways did not show as great difference between the Vistula and Oder basins as in the case of nitrogen. There were four main pathways of P emission into the Vistula and Oder basins i.e. urban systems, WWTPs, overland flow, and erosion (Fig. 8.6). The average (1995-2008) percentage **contribution of overland flow** reached 19% in the Vistula and 15% in the Oder basin, while the percentage **contribution of WWTPs** amounted to 19% in the Vistula and to 24% in the Oder basin; the percentage contribution of urban systems (16-17%) and erosion (28-29%) were comparable in the subjected basins (Kowalkowski et al., 2012; Fig. 8.6). WWTPs were the second largest contributor to TP emission into the river basins (19%-24%) (Fig. 8.6) but their role has been diminishing thanks to investment in WWTPs infrastructure during the transition period (see to next sub-chapters). Erosion was and still is a great contributor to overall P emission and this pathway should be given attention in mitigation measures in agricultural sector in Poland (see to sub-chapter 8.5). Light and very light soils cover almost 60%, while very acid and acid soils cover almost 50% of the agricultural land in Poland. As much as 21% of agricultural land, mainly arable land, and 8% of forested areas are imperiled with soil erosion (Chapter 2).



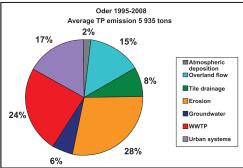
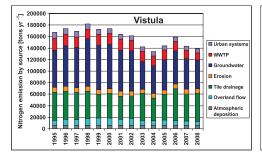


Fig. 8.6 Average (1995-2008) percentage contribution of various pathways of phosphorus emission into the entire Vistula and Oder basins (source: Kowalkowski et al., 2012)

Annual nitrogen and phosphorus loads as well as contribution of various pathways to N and P emission into the Vistula and Oder basins give a more detailed picture with respect to different temporary development of N and P emission patterns (Figs. 8.7, 8.8). Over the years 1988-2008, N emission reached 180,000 tons in the Vistula basin and it was by ca. 60,000 tons higher than in the Oder basin (Fig. 8.7). The average P emission reached ca. 11,600 tons in the Vistula basin and it was about two times higher than in the Oder basin (Fig. 8.8). Nutrient emission into the Vistula basin can be expected to be higher for the following reasons: (i) population figure is by over 8 million higher in the Vistula than in the Oder basin (Kowalkowski et al., 2012), (ii) the Vistula drainage area is by 39% larger than the Oder one (Chapter 1), (iii) the annual water outflow by the Vistula is ca. two times higher than in the case of the Oder River (Fal et al., 2000; Chapters 1 and 9).



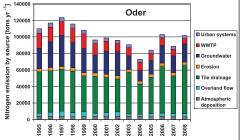
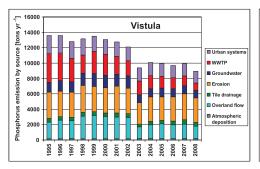


Fig. 8.7 Annual source apportioned nitrogen emission into the Vistula and Oder basins in 1995-2008 (please note different scales) (source: Kowalkowski et al., 2012)

The pattern of the source apportioned nitrogen emission (Fig. 8.7) was slightly different in the Vistula than in the Oder basin, showing nearly no change in N discharges in the Vistula basin in 1995-2000, and a decline in N emission into the Oder basin practically up to the year 2004 (Kowalkowski et al., 2012). In both basins the very dry year 2004 was characterized by the lowest N emissions and those minima were followed by higher, though fluctuating emissions in the Vistula and Oder basins. The most pronounced increase in N emissions was observed in 2006, and that coincided with extremely high water outflow in spring of that year, and with the highest N surplus in the entire period 1995-2008 (Kowalkowski et al., 2012). That very high N surplus did not result only from an increasing application of fertilizers (Pastuszak et al., 2012), but also, if not mainly, from weather conditioned poor yields in 2006, thus low N uptake by plants (Pikuła, 2010).

The pattern of the source apportioned phosphorus emission (Fig. 8.8) showed some differences when comparing the Vistula and Oder basins. An abrupt drop in P emission was observed not earlier than in 2003 in the Vistula basin (from 12,000 down to 9,800 tons), while in the Oder basin there appeared two abrupt changes: the first drop, from ca. 7,300 in the 1990s down to ca. 6,300 tons in 2000-2002, and the second decline, from ca. 6,300 in 2000-2002 down to 4,500-5,000 in 2003

and onwards. That difference must be related to spatially different (i) dynamics in nutrient mitigation from WWTPs, and (ii) restructuring process in agriculture (see to next sub-chapters).



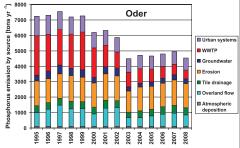


Fig. 8.8 Annual source apportioned phosphorus emission into the Vistula and Oder basins in 1995-2008 (please note different scales) (source: Kowalkowski et al., 2012)

Nitrogen and phosphorus loads carried by the Oder River originate also from the neighboring countries, Czech Republic and Germany. TN emission into the entire Oder basin, estimated in the modeling studies carried out for the years 1993-1997 (Behrendt et al., 2005b), amounted to 124,300 tons N yr<sup>1</sup>. Of that load 85% was ascribed to Poland, 11.3% to Czech Republic, and 3.7% to Germany. In the case of phosphorus the total emission in the subjected period amounted to 12,800 tons P yr<sup>1</sup>. Of that load 89.4% was ascribed to Poland, 8% to Czech Republic, and 2.6% to Germany. In this Chapter of the monograph, we concentrate on the changes that have occurred in the Polish part of the drainage basin.

## N and P emission in two sub-periods: 1995-2002 and 2003-2008

There were two reasons for which Kowalkowski et al. (2012) decided to divide their period of studies (1995-2008) into two sub-periods (Fig. 8.9): (i) changes in N and P emission into the Vistula and Oder basins in 1995-2008 exhibited a step-like character (Figs. 8.7, 8.8), and (ii) such a division provided better visual illustration of changes in contribution of particular N and P sources to their emission into the subjected basins during the transition period.

The drop in N emission between two sub-periods i.e. 1995-2002 and 2003-2008, was comparable in both basins and it amounted to 16-17%, while the decline in P emission reached 26% in the Vistula basin and 32% in Oder basin (Kowalkowski et al., 2012). The decrease in N and P emission can also be expressed in tons, and between the sub-periods 1995-2002 and 2003-2008, total N and P emission into the Vistula basin dropped by ca. 26,900 tons and by ca. 3,400 tons, respectively, while the total N and P emission into the Oder basin dropped by ca. 18,000 tons and by ca. 2,200 tons, respectively (Kowalkowski et al., 2012).

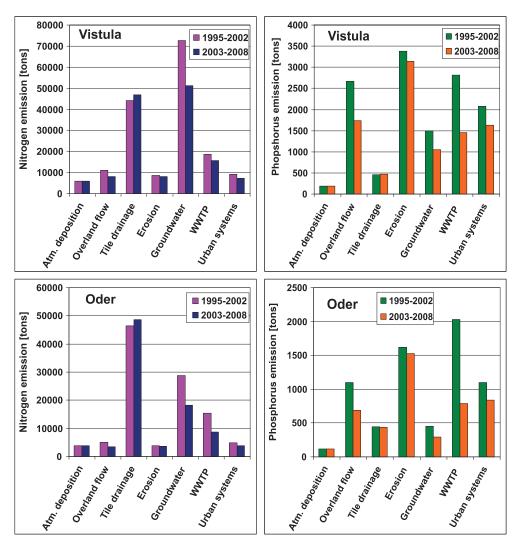


Fig. 8.9 Annual source apportioned nitrogen and phosphorus emission into the Vistula and Oder basins in 1995-2002 and 2003-2008 (*please note different scales*) (source: Kowalkowski et al., 2012)

In both basins the tile drainage and groundwater were the main pathways of N, while overland flow, erosion, WWTPs, and urban systems played a key role in P emission. Between 1995-2002 and 2003-2008 sub-periods N emission *via* groundwater dropped by 30% and 37%, while N emission from WWTPs dropped by 15% and 40% in the Vistula and Oder basin (Fig. 8.9). A significant decline in N and P emission *via* groundwater is an indication of reduced nutrient leaching which in turn could have been connected with reduced pressure in agricultural sector (see to sub-chapter 8.5). More effective N removal from WWTPs in the Oder basin is a result of more advanced measures in nutrient mitigation from point sources in that

basin (see to next sub-chapters). Tile drainage pathway showed a slight increase in N emission (Fig. 8.9) but that was compensated by a decrease in other pathways e.g. overland flow or urban systems. The most spectacular decrease in P emission was observed in the case of WWTPs pathway and the decline reached 48% in the Vistula and 61% in the Oder basin between the two sub-periods i.e. 1995-2002 and 2003-2008 (Fig. 8.9). The decreasing trends in P emission into the Vistula and Oder basins were also noted in the case of overland flow (by 34-37%), erosion (by 5-7%), and urban systems (by 21-23%) (Kowalkowski et al., 2012).

As the same model (MONERIS) was applied in studies carried out in the Oder basin by Behrendt et al. (2005a) and Kowalkowski et al. (2012), comparison of the long-term data is not risky. Between 1980 and the sub-period 2003-2008 the N emission into the Oder basin dropped by 23%, while between 1990 and the sub-period 2003-2008, a 3.3-fold decline in P emission was observed. The presented percentage declines in N and P emission in the given comparisons could have been slightly different if we had carried our studies in the entire Oder basin, covering the German and Czechoslovakian parts, but that was not the case.

# 8.5. Spatially and temporarily diversified pressures on natural environment in Poland – impact of anthropogenic and natural factors

Since 1989 Poland's economy has undergone a profound transformation from a centrally planned to a market economy. This transition has led to major institutional and economic structural changes over the last years. Reforms initiated in the early 1990s provided opportunities to revise and implement environmental management and legislation, and to achieve greater integration of environmental concerns into other policies (Chapter 7). Since the early 1990s Poland has made remarkable environmental progress, meeting most of its environmental targets and decoupling a number of environmental pressures from economic growth. Together with economic structural changes, these efforts have contributed to progress on a number of fronts e.g. reductions in air pollutants emissions (Błaś et al., 2008; GUS, 1991-2010), declines in water withdrawal (Fig. 8.10), declines in nutrient emission into riverine systems (Kowalkowski et al., 2012; Figs. 8.7-8.9), and declines in N and P discharges into the Baltic Sea (Pastuszak et al., 2012; Chapter 9).

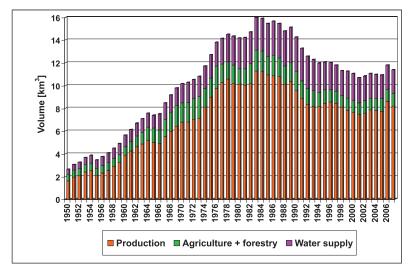


Fig. 8.10 Water withdrawal in Poland for production, agriculture and water supply for people in 1950-2008 (source: GUS, 1960-2003;1981-1989;1991-2010)

The transition period in Poland has been characterized by numerous proecological decisions of the State authorities, partly imposed by the European Union (EU) regulations after accession of Poland to the EU in 2004, and by the Helsinki Commission (HELCOM) actions and declarations (HELCOM, 2007, 2010a; Chapters 1 and 7). Polish legislative acts, also those aiming at mitigation of nutrient emission into Polish rivers, had to be harmonized with the EU Directives e.g. the Framework Water Directive, the Urban Waste Water Treatment Directive, the Nitrates Directive (Chapter 7). The Nitrates Directive, introduced in 1991, is the most important EU regulation concerning mitigation of nitrogen losses from agriculture. The regulations of this Directive were transposed into Polish legislative acts such as: Law on Fertilizers and Fertilization (Dz. U. Nr 89, 2000), Water Law (Dz. U. Nr 115, 2001), Law on Environment Protection (Dz. U. Nr 62, 2001).

# Agricultural sector

Polish agriculture, in contrast to that in other Central and Eastern European countries, to a great extent remained in private hands throughout the communistic era. Therefore, the changes in this sector during the transition period were limited in comparison with those in other European countries in transition (Bański, 2008). The privatization process in Poland first and foremost concerned the State-owned farms (ca. 20% of the agricultural land), whose assets were taken over either by individually-owned farms or commercial-law companies, with the intermediation of the State Treasury Fund for Land Ownership Agency established to serve the purpose (Milczarek, 2000; Syryczyński, 2003; Kiryluk-Dryjska, 2007; Bański, 2008,

2011). A major element of the assets undergoing privatization was agricultural land. However, the extent of the ownership change varied spatially. In the western and northern Poland (mainly the Oder basin), where more than half of the farmland area had been in hands of the State-owned Farms up to 1989, a significant increase in the share of land under private ownership was observed. In central and eastern Poland (mainly the Vistula basin), the changes were very limited and concerned only the transfer of land between private farms. The ownership changes deepened spatial polarization, as an increase in farm size took place in the regions where a large average farm area has long been a typical feature (western Poland – Oder basin) (Bański, 2011).

Following the restructuring and privatization of the State-owned Farms, local overloads of organic fertilizers decreased, thus environmental threats from this source were diminished or eliminated entirely. Good agricultural practices on those farms were not respected, or were rather unknown prior to the transition time (Jankowiak et al., 2003).

Economic reforms in the transition economies of Central and Eastern Europe and the Newly Independent States of the former USSR has transformed the volume and mix of these countries' agricultural production, consumption, and trade. The main development has been the drop in output, ranging in most countries from 25 to 50 percent, the livestock sector being hit particularly hard (Liefert and Swinnen, 2002). The beginning of the transition period in Poland, marked by a severe recession at the beginning of the 1990s, was characterized by drastic cuts in governmental subsidies, in both the industrial and the public agricultural sectors (Kurowski, 1998; Mulas-Granados et al., 2008). The early transition period was characterized by a significant drop in application of mineral fertilizers and a decline in number of animals on Polish farms (Pastuszak et al., 2012; Chapters 2, 3, and 4). The total stocks of pigs and cattle in Poland, calculated in equivalent units (Livestock Units = LU), decreased by 20.6% (Jankowiak et al., 2003).

Polish agriculture has benefited from the financial assistance from the EU funds, and the major aims of direct agricultural assistance from public sources included e.g. modernization of farms, complying with environmental protection regulations, as well as standards of good agricultural practice (Kata and Miś, 2006). The period covered by those studies (1999-2005) to a great extent preceded Poland's accession to the EU, but Common Agricultural Policy was already in function in Poland. There are also other studies (Kiryluk-Dryjska, 2007) and those aimed at defining farmers' interest in the measures of Polish Rural Development Program (2004-2006), co-financed by the EU. The objectives of this program covered several aspects, with agro-environmental measures and meeting the EU standards in agricultural production, included. In these two independent studies the authors identified four overlapping macro-regions and have proven that macro-regions characterized by a greater agricultural economic potential and favorable agrarian system (mainly

north-western and western Poland i.e. the Oder basin) benefited more from public assistance than macro-regions with economically weaker agriculture and fragmented farming systems (mainly south-eastern and eastern Poland i.e. the Vistula basin). That may point to more efficient measures in nutrient mitigation in nutrient leaching from agricultural sector in the Oder basin during the transition period.

There are 1.8 million farms and 0.6 million of small settlements (possessing less than 1 ha of agricultural land) in Poland and all of them contribute to emission from so called dispersed point sources in agriculture. Farmyards and stables are the main sources of nutrient emission on farms. The production of dung, liquid manure, and slurry amounts to about 80.7 million tons, 18.2 million m<sup>3</sup>, and 7.5 million tons, respectively. As many as 408 projects, directly related to 827 investments which involved construction of manure plates and tanks for liquid manure or slurry, were carried out in Poland in 2002-2006 in the framework of the pre-accession aid programme (SAPARD). That resulted in construction of manure pits with the total volume of 55,000 m<sup>3</sup>, and tanks for liquid manure with the total capacity of approx. 52,000 m<sup>3</sup>. The most important for the development of infrastructure in the field of animal production in the years 2004-2006 was the Rural Development Plan (PROW). Within this plan, the investments were made in over 71,000 farms, including 3,467 farms located in areas at particular risk to nitrate pollution; the manure pits area has increased by approximately 3.7 million m<sup>2</sup> and the capacity of tanks for liquid manure by about 3.1 million m<sup>3</sup>. The current surface of manure pits ensures proper storage of approximately 70% of manure (Chapter 6).

The development of the sanitary infrastructure on farms is in the focus of the Program of Rural Area Development and there is steadily growing percentage of rural population connected to sewage system (see to the text below and Fig. 8.15; Chapter 5).

All actions aiming at nutrient mitigation call for adequate environmental monitoring. The State Monitoring of the Environment is responsible for monitoring of the water level and quality, while monitoring of soils and shallow groundwater is carried out by 17 agrochemical laboratories supervised directly by the Ministry of Agriculture and Rural Development. A broad educational program provided for farmers and aiming at environment protection in rural areas is being implemented by Advisory Centers in Agriculture in each voivodeship. Farmers are taught how to handle obligations resulting from the "polluter-pays-principle" and the "providergets-principle". The first principle concerns all farmers profiting from the common area payments and from the less favored area payments (cross-compliance rule). The second principle concerns farmers who voluntarily declare improvement of the natural environment in the frame of cross-compliance rules (Chapters 6 and 7) (Duer, 2009).

Some of the above described changes as well as drastic drop in fertilizer consumption on the turn of the 1980s and 1990s resulted in (i) a pronounced drop in N surplus in agriculture, reaching 40 kg N ha<sup>-1</sup> in the Oder basin and 17 kg N ha<sup>-1</sup> in the Vistula basin between the years 1990 and 2002 (Fig. 8.11), (ii) a considerable decrease in P surplus in agriculture, from 17-18 kg P ha<sup>-1</sup> in the 1980s to values 3-4 kg P ha<sup>-1</sup> in 1993-2001 and below 5 kg P ha<sup>-1</sup> in 2009-2010 (Chapter 4). There was an increase in N and P surplus in 2006 (wet spring; Chapter 9) but that seems to be conditioned by poor yields in that year, thus low nutrient uptake by plants (Pikuła, 2010). This is explained by the gradually reduced pressure on natural environment due to (i) restructuring process that occurred in the agricultural sector (Bański, 2011), (ii) investment in environmental protection in agricultural sector thanks to financial assistance of the EU; that encompassed also education of farmers (Kata and Miś, 2006; Kiryluk-Dryjska, 2007), and (iii) increase in nitrogen efficiency (defined as the ratio of the crop nitrogen uptake, to the total input of nitrogen fertilizer) in the late 1990s and onwards (OECD, 2001; Fotyma at al., 2009).

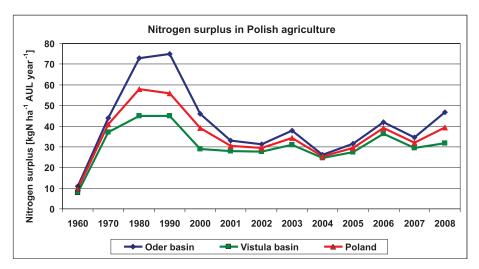


Fig. 8.11 Nitrogen surplus in Polish agriculture calculated for the catchment areas of the Oder River, the Vistula River, and Poland over the years 1960-2008; AUL – Agriculturally Utilized Land (source: data for the years 1960-2000 are from Eriksson et al., 2007; N surpluses on the level of voivodeships in 2001-2008 were provided by IUNG-PIB, Puławy; recalculations for the river basins were performed by T. Kowalkowski).

The reduced pressure on natural environment may explain a considerable decline in percentage contribution of groundwater in N and P emission in both basins during the transition period. Between the two sub-periods (1995-2002 and 2003-2008) N emission *via* groundwater dropped by 30% and 37% in the Vistula and Oder basin, while P emission dropped by 30% and 36% in the Vistula and Oder basin (Fig. 8.9). Owing to deeper changes in agricultural sector in the Oder basin during the transition period, more pronounced declines in groundwater emission were observed in that catchment. Studies of Oenema et al. (2005) show that nitrate leaching to

groundwater and N and P discharges to surface waters are related to N and P surpluses, hydrological conditions, land use and soil type. As further stated by these authors, on a national scale (Denmark), decreasing N surplus by 1 kg ha<sup>-1</sup>, decreased nitrate leaching to groundwater on average by 0.08 kg ha<sup>-1</sup> and leaching to surface waters on average by 0.12 kg ha<sup>-1</sup>.

Polish agriculture is not geared toward intensive commercial production and it is not uniform countrywide. In contrast to the Vistula basin, the Oder basin is characterized by larger farms (Bański, 2011). Larger farms with higher income

- (i) use modern machinery, thus, different ways of soil cultivation (Ilnicki, 2004),
- (ii) are characterized by larger tile drainage area (the drainage area is by 13% larger in the Oder than in the Vistula basin; Kowalkowski et al., 2012; Chapter 5),
- (iii) apply higher doses of mineral fertilizers, thus have higher N and P surplus in agriculture (Chapters 3 and 4; Fig. 8.11),
- (iv) are characterized by greater congestion of concentrated pig farms, thus higher risk of environment polluting with excessive application or improper storage of manure (GUS, 2009a; Pastuszak et al., 2012; Chapter 6; Fig. 8.12),
- (v) have lower percentage of grassland in agricultural land (by 40%; GUS, 2009b; Fig. 8.12).

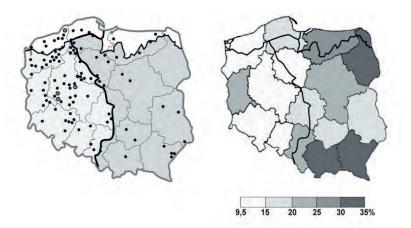


Fig. 8.12 Location of large-scale pig farms in Poland in 2007 (left) (graph was produced and kindly made available by M.Sc. Jakub Skorupski from the Department of Genetic and Animal Breeding, West Pomeranian University of Technology, Poland), and share of grassland in agricultural land in 2008 (right); borderlines indicate main river catchments, including the Vistula and the Oder catchment (source: GUS, 2009b)

All the listed anthropogenic factors enhance N and P leaching from agricultural sector, particularly in the Oder basin. Moreover, the impact of anthropogenic factors is strengthened in the Oder basin by natural factors. In comparison with the Vistula basin the Oder basin is characterized by lower percentage of high porosity bedrock (by 11%) and lower lake area (by 18%) (Kowalkowski et al., 2012). These two factors are responsible for lower natural nutrient retention, thus they favor higher nutrient emission into the Oder than into the Vistula basin. On the other hand larger farms achieve higher yields and are more efficient in absorbing EU money provided for their modernization and for environmental protection (Kata and Miś, 2006; Kiryluk-Dryjska, 2007).

#### Point sources

In connection with the accession of Poland to the EU, the EU has been an actively influential agent in the Polish transition through a variety of mechanisms. Foremost amongst these has been a variety of multilateral and bilateral aid and loans programs implemented since 1990 (Steves, 2001; Ners, 1996). Starting from the beginning of the 1990s, more and more money has been invested in environment protection in Poland, and for example in 2007 the outlays in this sector reached 1.9 billion Euro (7.5 billion PLN), whereof 1.2 billion Euro was spent on fixed assets in sewage treatment and water protection (GUS, 1991-2010). In 2009 the outlays on fixed assets have increased by 40% in comparison with those in the year 2007 (Fig. 8.13; GUS, 2010a).

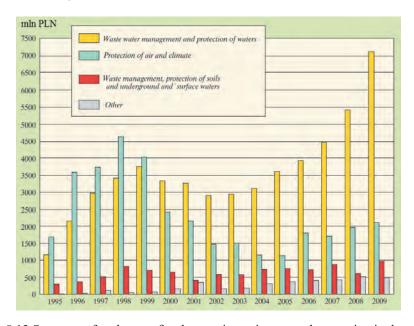


Fig. 8.13 Structure of outlays on fixed assets in environmental protection in the years 1995-2009 (source: GUS, 2010a)

The maintenance of good quality river water and the clean-up of polluted water are of major European concern. A major impetus for improving the riverine environment has been introduction of the Waste Water Directive (91/271/EEC; adopted on 21 May 1991) that demands new approaches for managing and improving surface and groundwater quality across the European Union, with emphasis shifting from chemical towards ecological water quality standards. It addresses all compounds that affect the ecological status of surface waters, including N and P from agriculture. On 16 December 2003, the Council of Ministers of the Republic of Poland approved the National Program for Municipal Waste Water Treatment (NPMWWT) which has been introduced into Polish national legal framework. The program is to serve the implementation of the Directive 91/271/EEC with regard to the relevant four transition periods i.e. by 31 December of the following years: 2005, 2010, 2013, 2015 (Krajowy Program..., 2003). The NPMWWT is the largest investment and most costly from among all tasks resulting from the implementation of the EU Directives in the field of environmental protection in Poland. The NPMWWT investment will require over 8 billion Euros in the period until 2015, and the money is planned for construction of 30 thousand km of sewage collection system, construction of 177 treatment plants, modernization and expansion of 569 waster water treatment plants, amongst them:

- "Czajka" WWTP in Warsaw which is one of the largest investments in Europe with a value of 650 million Euros. It will handle over 1.5 million residents in 2012 and ensure a high level of purification in accordance with EU standards.
- "Pomorzany" WWTP in Szczecin with the cost of 282 million Euros, handling about 340 thousand residents, reducing pollutants loads in waste water by 84.6% for nitrogen and 90% for phosphorus and enabling the deletion of Szczecin from hot spots list. This WWTP is in operation now,
- "Płaszów" WWTP in Cracow, handling now about 560 thousand residents, reducing pollutant loads in waste water by 88.8% of nitrogen and 96.1% of phosphorus including the scheduled thermal utilization of sewage sludge station allowing nearly 9-fold reduction in the amount of waste generated in the process of waste water treatment. This WWTP is in operation now (HELCOM, 2010b).

These three WWTPs have been listed here because they are largest in the country and are/will be serving over 6% of the entire Polish population, and because none of these WWTPs was in operation in 2008, the last year covered by studies of Pastuszak et al. (2012) (the WWTP in Szczecin is below the lowermost monitoring station on the Oder River – so the reduced nutrient discharges will have positive impact on the Szczecin Lagoon as well as the Pomeranian Bay ecosystem functioning). "Czajka"

and "Płaszów" fall within the Vistula basin. These WWTPs will inevitably contribute to further reduction in N and P loads carried in riverine outflow to the Baltic Sea.

Between the years 1995 and 2008, the number of municipal WWTPs increased from 1226 to 3090; in the same time period there was 2-3 fold increase in number of tertiary treatment plants, as well as in their capacity and the percentage of population served (the latter increased by 10% between 2002 and 2010) (GUS, 2000a, 2009b; Pastuszak et al., 2012; Fig. 8.14). Implementation of water conservation measures, and economizing in water consumption (Fig. 8.10) resulted in two-fold reduction in the volume of industrial and municipal waste waters, ten-fold reduction in the volume of untreated waters discharged into rivers and soil, a steadily growing volume of sewage treated by very efficient tertiary treatment systems (GUS, 1981-1989; 1991-2010; 2010b; Przepióra, 2007; Figs. 8.14, 8.15). With the observed radical decrease in the total volume of untreated sewage discharge, the relative contribution of municipal sources remained essentially unchanged, at about 70% between 1990 and 2005 (Przepióra, 2007). Very fast growing number of WWTPs is directly connected with realization of NPMWWT program as an action to fulfill the goals of the EC Urban Waste Water Treatment Directive (91/271/EEC) adopted on 21 May 1991.

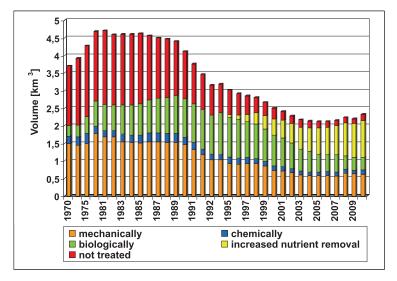
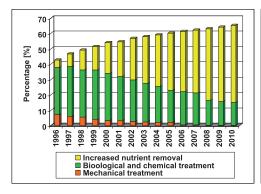


Fig. 8.14 Volume of industrial and municipal waste water (requiring treatment and treated) discharged to the surface waters or ground over the years 1970-2010 (source: GUS, 1981-1989; 1991-2010)

In 2010, waste water treatment plants serviced 65.2% of the population (89% in urban areas and 28.8% in rural areas), and these numbers, as well as percentage of population connected to tertiary treatment systems are steadily growing (GUS, 1991-2010; Fig. 8.15). The construction of sewage infrastructure during the transition period has not had the same dynamics in the urban and rural areas. Between the years 1990

and 2010 the percentage of population that was served by WWTPs in urban and rural areas increased from 54% to 89% and from 3% to 28.8%, respectively (Fig. 8.15). In 2010, 95.3% of urban population was using a water-line system, while 86.1% of this population was using a sewerage system, and 88.6% was using WWTPs; in the same year, 24.8% of rural population was using sewerage system, whereas 28.8% was using WWTPs (GUS, 1991-2010). However, it has to be remembered that there is an expansion of individual sewage treatment plants serving single or multiple adjacent households in rural areas, and these facilities are not covered by the official statistics. Such plants are practically not found in cities, especially in large ones.

The Vistula and Oder basins within the Polish territory are inhabited by 21.3 million and 13.2 million people, respectively (GUS, 2010b). Rural (14.8 million) and urban (23.3 million) population account for 38.8% and 61.2% of the total Polish population. Rural population is dispersed across the country and people live in 41 thousand villages, of which about 15% have less than 100 inhabitants, while 66% have from 100 to 500 inhabitants. This dispersion partly explains poor infrastructure in rural areas (Chapter 6).



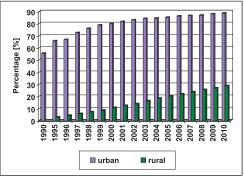


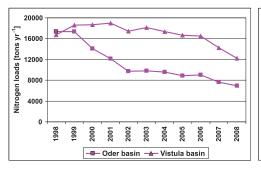
Fig. 8.15 Percentage of population in Poland connected to various types of municipal sewage treatment in 1996-2010 (left graph) and percentage of population in urban and rural areas that was connected to sewage treatment systems in 1990-2010 (right graph) (source: GUS, 1991-2010)

Diversified nutrient mitigation measures during the transition period, concerned the construction of WWTPs, closure of obsolete factories and modernization of the remaining ones, and introduction of clean technologies. The measureable effect of the Baltic Sea Joint Comprehensive Action Program (HELCOM, 2009a,b), aiming at facilitation of the implementation of pollution reduction measures at the most polluted sites in the Baltic Sea catchment area, was elimination of 29 hot spots in Poland. Majority of these hot spots were located in western Poland (Oder basin) (Chapter 1).

The actions aiming at reducing nutrient loads from point sources in the Vistula and Oder basins have not had the same legislative and financial support, thus, comparable dynamics in mitigation of nutrient emission (Dubicki, 1999, 2000; Anonymous, 2000; Program..., 2006). The expenditures on WWTPs in the Vistula basin during the transition period were covered only by local authorities (Anonymous, 2000), while two centrally-financed programs were realized in 1997-2002 and undertaken in 2002-2016 in the Oder basin (Dubicki, 1999, 2000; Program..., 2006). Between 1998 and 2008, the reduction in N loads, discharged from municipal WWTPs into surface waters or soil in the Vistula and Oder basin, reached 4,540 tons and 10,400 tons, respectively (Table 8.1; Fig 8.16). That explains a more pronounced decline in N emission from WWTPs in the Oder basin (by 43%) than in the Vistula basin (by 15%) (Kowalkowski et al., 2012).

Table 8.1 Population connected to sewage systems in the Vistula and Oder basins in 1998 and 2008, and the reduction of N and P loads discharged from municipal WWTPs into these basins over the period 1998-2008 (source: GUS, 2010b)

Specification	1998		2008		Reduction of	Reduction of
		plation Population cotted to		N load from municipal WWPTs	P load from municipal WWPTs	
		VTPs	connected to WWTPs		between 1998 and 2008	between 1998 and 2008
	[%]	[mil.]	[%]	[mil.]	[tons N]	[tons P]
Vistula basin	35	7.5	58	12.4	4,540	1,430
Oder basin	45	5.9	66	8.7	10,400	1,650



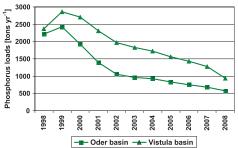


Fig. 8.16 Nitrogen and phosphorus loads discharged from municipal WWTPs into surface waters or soil in the Vistula and Oder basins in 1998-2008 (source of data: GUS, 2010b)

## Natural factors

Fotyma et al. (Chapter 3) calculated nitrate leaching directly from a difference in the nitrate content determined in the soil profile (0-90 cm) in early spring and late autumn. The input data were gathered from the soil monitoring program carried out in Poland since 1997 at 5000 monitoring sites representing the whole area of the country. The losses of nitrate (leaching in winter below 90 cm of soil depth) depended mainly on the texture of the soil; on average they reached 19 kg N·ha<sup>-1</sup> yr<sup>-1</sup>, 13 kg N·ha<sup>-1</sup> yr<sup>-1</sup>, 8 kg N·ha<sup>-1</sup> yr<sup>-1</sup> and 4 kg N·ha<sup>-1</sup> yr<sup>-1</sup> in the case of sandy soil (very light soil), sandy loam soil and loamy sand (light soil), loam soil (medium soil), and clay soil (heavy soil), respectively. The area with sandy soils is by ca. 13% larger in the Oder basin (Kowalkowski et al., 2012); this, highly permeable type of soil, in combination with higher application of natural and mineral fertilizers in western Poland (Chapters 3 and 4) may have added to much higher N emission via larger drainage network (by 19%) in the Oder than in the Vistula basin (Kowalkowski et al., 2012).

Erosion is a great contributor to overall P emission, but it has to be pointed out that there is a great spatial diversity in P emission via this pathway (Fig. 8.17). Foothill regions are characterized by an order of magnitude higher P emission by erosion than the flat areas, as shown for the Vistula basin.

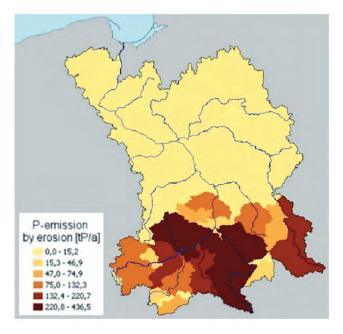


Fig. 8.17 Phosphorus emission by erosion in the Vistula basin (source: Kowalkowski and Buszewski, 2003)

The high percentage of unconsolidated bedrock in the Vistula (59.3% of the area) and Oder (70.2% of the area) basins (Kowalkowski et al., 2012) explains the high percentage contribution of groundwater pathway to nitrogen emission in these basins (Fig. 8.5). However, the higher percentage of high porosity bedrock in the Vistula than in the Oder basin seems to be responsible for much higher percentage contribution of emission *via* groundwater in the Vistula catchment. In the case of deep soils and permeable bedrock, percolation to groundwater rather than channeling of flow laterally occur (Heathwaite et al., 2005). That pathway considerably prologs the transit time of water and that is of high importance with respect to enhanced N retention (Nixon et al., 1996). Therefore, the enhanced N and P leaching driven by anthropogenic factors can be even strengthened in the Oder basin by these natural factors.

Though the portion of regions with unconsolidated rock in the total catchment area of the Oder is lower than in the Vistula basin, it is still higher than in other riverine systems in Central Europe. Behrendt et al. (2005b) estimated that areaspecific diffuse emissions (expressed in kg ha<sup>-1</sup> yr<sup>-1</sup>) and loads of nitrogen in the Oder basin in the period 1993-1997 were low in comparison to other systems in Central Europe.

In comparison with Vistula basin, the Oder basin has lower lake area (by 18%; Kowalkowski et al., 2012). Studies of Lepistö et al. (2006) showed that of the total N input to Finnish river-systems, 0% to 68% was retained in surface waters and/ or peatlands, with a mean retention of 22%. The highest retention of N (36-61%) was observed in the basins with the highest lake percentages. The lowest retention (0-10%) was in the coastal basins with practically no lakes. In the national mass balance, the lake retention in Finland was estimated on the level of 32%. Lake retention of ca. 30-35% for both N and P is also reported by Vassiljev and Stålnacke (2005) in the Lake Peipsi drainage basin (situated between Estonia and Russia).

# 8.6. Measures that may result in further reduction of nitrogen and phosphorus emissions into Polish rivers

The flow normalization method applied by the authors of Chapter 9 made it possible to remove the natural fluctuations in nutrient loads and concentrations caused by variability in water discharge, and thus helped to clarify the impact of human activities on riverine loads of nutrients discharged into the Baltic Sea by the Vistula and Oder Rivers in 1988-2011. This information is important for the HELCOM, the EU, and Polish decision makers, all these bodies being involved in mitigation of nutrient emission to the internal waters, as well as to the Baltic Sea. The HELCOM Baltic Sea Action Plan (HELCOM, 2010b) presents a series of actions to be taken by the Baltic States not later than in 2016 in order to restore good ecological status of the Baltic marine environment by 2021 (eutrophication-related

targets on water transparency, primary production and nutrient concentrations). The maximum overall allowable nutrient inputs to the Baltic Sea are planned to reach ca. 600,000 tons of total nitrogen (TN) and 21,000 tons of total phosphorus (TP). Poland is expected to reduce its annual TN and TP loads by 62,400 tons and 8,760 tons, respectively.

Behrendt et al. (2005b) calculated the reduction of N and P emissions under different scenarios. Their results show that with the implementation of phosphorus-free detergents in Czech Republic and Poland, and the implementation of the EU Urban Waste Water Treatment Directive, a reduction of P input by point sources to 20-25% of the value for the period 1993-1997 would be possible. If additional measures to reduce P emissions by erosion and from urban areas are implemented, a total reduction of P emissions and load of the Oder River into the Baltic Sea up to 62% can be expected within next 10-20 years. The reduction of TP flow normalized loads in the Oder River reached ca. 80% over the years 1988-2011, and this percentage covers the reduction of loads from both, the point sources and the diffuse sources (Chapter 9).

As to nitrogen, Behrendt et al. (2005b) estimated that at full implementation of the EU Urban Waste Water Treatment Directive, a decrease in point sources discharge by 65% can be reached. A possible further reduction of the average N surplus in the agricultural area would lead to a decrease of the diffuse N inputs into the Oder River system by 17% within next 20 years. Together with the point sources reduction, a decrease by 34%, compared to the level in the period 1993-1997, seems to be possible. The study of the authors of Chapter 9 shows that the Oder TN loads decreased by ca. 28%, which is somewhat lower than the percentage given by Behrendt et al. (2005b) in their scenarios.

### 8.6.1. Scenarios in N and P emission into the Vistula basin

Substantial regional diversity in total N and P emission (expressed in kg ha<sup>-1</sup>yr<sup>-1</sup>) from the Oder sub-catchments has been documented by Behrendt et al. (2005b). The maximum emissions values were noted in the areas situated in a foothill locations, where the thin soil layer above bedrock prevails, and in the central part of the Warta catchment (tributary of Oder) characterized by high percentage of drained soils. Water residence time is short in such systems, therefore the process of denitrification very limited. All these findings point to the fact that, firstly, the river basin approach is essential in undertakings focused on mitigation of N and P emission into the river basins, and secondly, it is advisable to continue modeling studies in the Vistula and Oder sub-catchments in order to provide more specific advice for the decision makers. Hereafter, we present the outcome of scenarios already accomplished for the Vistula basin.

## Emission from point sources – combined outcome for the entire Vistula River basin

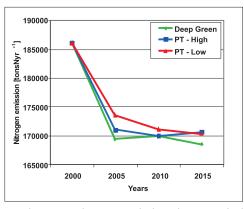
The future trends of N and P emission into the Vistula catchment were calculated for the period of 2005-2015 with the MONERIS model, and the calculations were based on the three socioeconomic scenarios (Table 8.2), which take into account different levels of economy growth defined by gross domestic product value (GDP). Apart from growth in GDP, many other elements that influence the state of the environment in Poland e.g. changes in transportation, ecological awareness, changes in population number, development of the sewage systems (Bartczak et al., 2003), have been taken into consideration in the scenarios. Such an approach falls within the scope of actions taken by the National Program of Municipal Wastewater Treatment and aiming the reduction of nutrients from point sources. It has to be pointed out, that all the presented scenarios are related mostly to the reduction of emission from point sources. In all scenarios, the most important agricultural factor i.e. N and P surplus in agriculture was kept at a constant level, and such an assumption turned out to be close to the outcome of calculations of N surplus shown in Fig. 8.11; slight increases in 2006 could have been caused by exceptionally wet spring (Chapter 9). The year 2000 was considered to be a reference year in the studies and the outcome of calculations is presented in Fig. 8.18.

Table 8.2 Short characteristics of socio-economic scenarios (source: Kowalkowski and Buszewski, 2006)

Scenario elements	Policy Targets - High	Policy Targets – Low	Deep Green
GDP growth	5 – 6%	2 – 4%	5 – 6%
Realization of WWTP program <sup>1)</sup>	Full	5 years delay	Full
Changes of NO <sub>x</sub> atmospheric emission (2005-2015)	- 13%	- 13%	- 16.6%
Other features	None	None	- use of detergents without phosphates - increase in ecological awareness of Polish society
Projection of changes of Polish population <sup>2)</sup>	Implemented	Implemented	Implemented

<sup>1) -</sup> The National Program of Municipal Wastewater Treatment (according to Directive 91/271/EEC)

<sup>&</sup>lt;sup>2)</sup> - according to GUS (2000b)



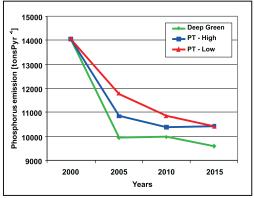


Fig. 8.18 Nitrogen and phosphorus emission from point sources into the Vistula basin; adopted scenarios (DG-Deep Green, PTH - Policy Targets High, PTL- Policy Targets Low) (source: Kowalkowski and Buszewski, 2006)

Depending on the scenario, the reduction of nitrogen emission ranges from 8.4%, for Policy Targets Low and High, to 9.7% - for Deep Green scenario (Fig. 8.18). The reduction of TN emission in all scenarios is rather small, but that is what could be expected as contribution of point sources to overall nitrogen emission was within the range 10-12% in the Oder and Vistula basin in 1995-2008 (see to sub-chapter 8.4); the differences in projections of nitrogen discharge among scenarios is very small and it can be neglected. The only way to achieve a substantial reduction of overall TN emission is through further modernization of WWTPs in rural areas, but first of all through introducing ecologically friendly technologies in agricultural sector. The impact of changes in agriculture on nutrient emission was studied at regional level and it is described in the last section of this Chapter.

The phosphorus reduction from point sources is much larger and ranges from 23.9% for the Policy Targets Low scenario through 43.5% for Deep Green scenario to almost 50% for Deep Green scenario (Fig. 8.18). The difference between low and high Policy Targets scenarios in 2015 is very small.

The N and P loads simulated by the MONERIS model can be compared with the monitoring data at the lowermost monitoring station (Kiezmark). In 2009, TN and TP loads reached the values of 92,100 and 6,440 tons, respectively (GUS, 2010b). The MONERIS calculations for Deep Green scenario indicated the loads about 104,000 and 3,670 tones for TN and TP in 2010. The difference between the monitoring values and the simulated ones is rather small (~10%) in the case of nitrogen, but it is substantial in the case of phosphorus; the simulated TP load is smaller by factor of 2. The explanation of this significant difference is probably connected with: (i) reported huge delays in realization of WWTPs program related to increased costs of such actions (Ekopartner, 2009), and (ii) lack of restrictions on use of phosphate detergents and that was in contrast to the assumptions.

## Emission from point sources - outcome for the Vistula sub-catchments

Simulations made for the Vistula sub-catchments point to very large spatial variations of nutrient emission (Kowalkowski and Buszewski, 2003; Kowalkowski, 2010; Fig. 8.19). The prognoses were done for 38 sub-catchments and were based on model validated in previous studies (Kowalkowski and Buszewski, 2006). The relative error between measured and estimated loads was ranging from a few percent to nearly 30%, depending on location of regions, but the mean value of error for the entire Vistula catchment was about 20% for both NT and TP. Therefore, specific ranges of reduction were indicated in Fig 8.19 and they are as follows:

- (i) the range between -20 and 20% is equal to the precision of modeling and shows the fluctuations of emission comparable with error of the model,
- (ii) the range between 20 and 50% of reduction indicates moderate reduction,
- (iii) the range above 50% of reduction indicates the biggest reduction of TN or TP emission,
- (iv) the range below -20% is actually showing the increase in emission.

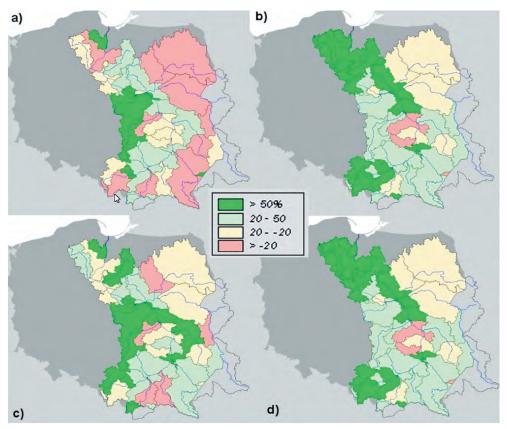


Fig. 8.19 Changes in TN and TP emission estimated by MONERIS based on Deep Green scenario: a) TN emission from WWTPs; b) TN emission from urban areas; c) TP emission from WWTPs; d) TP emission from urban areas (source: Kowalkowski, 2010)

A close look into the Fig. 8.19 allows to distinguish great difference between the left-bank and right-bank Vistula tributaries, with much more effective mitigation of N and P emission in the former parts of the Vistula catchment. Undoubtedly, it is related to considerably higher number of agglomerations with biggest population equivalent in the left-bank catchments, and these agglomerations were given priority in the National Program of Municipal Wastewater Treatment. Higher nutrient loads in sewage in the easternmost part of the country can be explained by much lower percentage of population connected to WWTPs. The easternmost part of Poland is characterized by a predominating role of agricultural activity, which in turn means a high dispersion of population inhabiting these region and high costs connected with construction of sewage systems (Fig. 8.20).

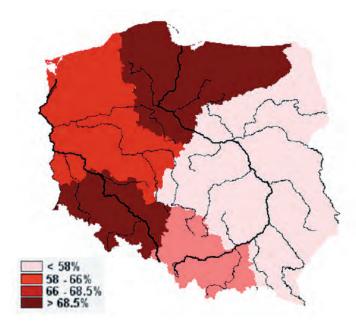


Fig. 8.20 Percentage of population connected to WWTPs by regions in 2010 [source: own calculations based on GUS (2011) data]

## Emission from all sources – outcome of statistical analysis performed for the Vistula sub-catchments

Seeing great spatial diversity in nutrient emission, and taking into account the fact that there are numerous other catchment properties which affect the level of N and P emission (such as population density, urbanization, average slope of catchment etc.), Kowalkowski (2009) applied the multivariate classification methods which is an alternative way to find regions sharing similar pattern of nutrient emission. In order to serve the purpose, the author created a dataset which contained nitrogen and phosphorus emission values (calculated with MONERIS) for seven different

pathways (see the list in the sub-chapter 8.1) and for 17 sub-catchments within the Vistula basin (Fig. 8.21).

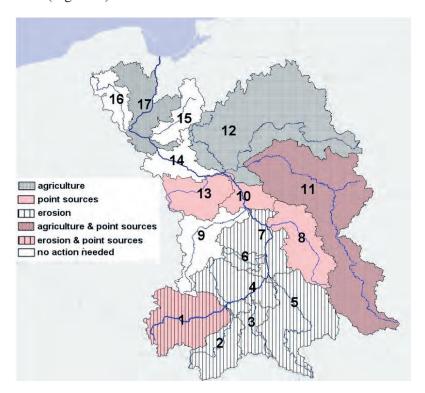


Fig. 8.21 Identification of predominating pathways of nutrient emission in the Vistula River sub-catchments that require actions of the decision makers focused on mitigation of nutrient emission into the river basin; the numbers indicate Vistula sub-catchments which are referred to in the text (source: Kowalkowski, 2009)

Prior to multidimensional statistical analysis the normality of all variables (nitrogen and phosphorus emission *via* different pathways) was checked by analyzing the histograms and skewness index and by applying the Shapiro-Wilk test (Kowalkowski et al., 2006). In majority of cases (catchments), the variable distribution was far from normality (skewness index >2, and p<0.05). Hence, the transformation function was applied to all pollution parameters (variables) in the

form 
$$x_{norm} = \frac{x - x}{SD}$$
. Factor analysis (FA) was performed on the prepared data set.

Calculations of factors in FA were based on principal component analysis. Number of PCs has been limited to three with minimal eigenvalue criterion of 1. Computed factors were finally rotated using normalized Varimax method. The new factors explained 95% of cumulative variance, meaning that almost all variability of dataset was explained by derived factors. The factors loadings are presented in Table 8.3,

the highlighted loading values are bigger than 0.7. All the highlights have the positive values indicating the positive correlation between emission caused by particular source and the factor. In other words, the higher the factor score the bigger emission *via* a particular source. Factor 1 is mainly related to parameters describing diffuse emission sources of N and P *via* atmospheric deposition, emission through groundwater and emission *via* drainage network. The deposition from atmosphere is rather small as compared to other two sources, therefore Factor 1 can be named *impact of agriculture*. Factor 2 explains influence of *erosion* and finally, Factor 3 covers the parameters related to *point sources*.

Table 8.3 Factor loadings structure; in bold are the numbers indicting loading values bigger than 0.7 (source: Kowalkowski, 2009)

<u> </u>			
Emission source	Factor 1	Factor 2	Factor 3
N – atmospheric deposition	0.97	0.00	0.20
N - overland flow	0.66	0.62	0.31
N - drained areas	0.91	-0.29	0.16
N – erosion	-0.08	0.96	0.23
N – groundwater	0.71	0.48	0.30
N - wastewater treatment plants	0.07	0.20	0.97
N – urban areas	0.54	0.32	0.75
P - atmospheric deposition	0.97	-0.02	0.13
P - overland flow	0.62	0.65	0.35
P - drained areas	0.97	-0.01	0.18
P – erosion	-0.10	0.95	0.25
P – groundwater	0.90	0.35	0.18
P - wastewater treatment plants	0.17	0.23	0.94
P – urban areas	0.56	0.32	0.74
Eigenvalue	6.45	3.37	3.51
Explained variance [%]	46.00	24.00	25.00

The FA scores for evaluated catchments show the groups of the catchments with similar pollution character (Fig. 8.21). Factor 1 has the biggest values for the catchments 11 and 12 located in the eastern part of Vistula basin, and for catchment 17 in the northernmost part of the Vistula catchment (Żuławy Wiślane). These are the regions with high influence of agriculture on nutrient emission (Factor 2). The influence of Factor 2 is decreasing with the increasing distance from the mountainous regions; it has the highest values for catchments 4 and 5 and those correspond to erosion figures calculated by the model (Fig. 8.17). The influence of erosion sources

remains also important for the catchments 1, 2, and 3. The strongest influence of point sources, represented by means of Factor 3, has been found in the biggest rural region of Silesia (catchment 1), and other industry burdened catchments located in the central part of the Vistula catchment (8, 10, 11, and 13).

The applied statistical approach made it possible to aggregate the data and the outcome clearly indicates which pollution sources should be given attention in particular regions in Poland (Fig. 8.22). The Silesia region (catchment 1) is particularly exposed to the influence of municipal and industrial point sources, but it is also affected by the emission of nutrients *via* erosion. In this case, 30% reduction of phosphorus emission *via* point sources results in 20% reduction of total P emission from this area (Kowalkowski and Buszewski, 2006). Such decrease is significant even in the entire Vistula basin scale and can be achieved efficiently by improving WWTPs technology and by applying non-phosphate detergents policy. The first problem is being slowly solved as the town of Cracow has got very efficient and modern WWTP (see to sub-chapter 8.5). The nutrient load from point sources can be reduced within a short period of time and the required financial expenditure is lower as compared with expenses related to N and P mitigation from diffuse sources (Neumann and Schernewski, 2005).

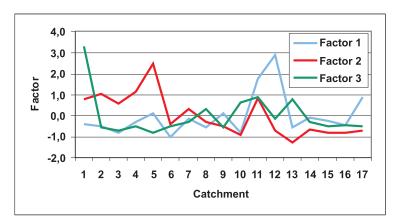


Fig. 8.22 Results of factor analysis: principal component scores for investigated catchments: A) factor 1 associated with agriculture; B) factor 2 associated with erosion; C) factor 3 associated with point sources (source: Kowalkowski, 2009)

The second "hot spot" is the Bug River region (catchment 11), followed by the Narew catchment (12) where agriculture have the biggest influence on water quality. The crucial parameter in these cases is the surplus of phosphorus and nitrogen in agricultural soils. Research done by Behrendt et al. (2002) shows that reduction of N, P surplus to 70% by 2020 can lead to a significant decrease in nitrogen emitted to groundwater and tile drainage (both by 8% in 2020). Such a reduction of nutrient surplus can be realized by increasing the effectiveness of fertilizer application and its proper dosage in both catchments.

The simple mathematical calculations indicate that 23% of total N reduction and 30% of total P reduction in entire Vistula basin can be achieved by 50% decrease of emission from one particular pathway (point sources or erosion in agriculture) in the selected regions indicated in Fig. 8.21. The presented here results of statistical analysis show the key areas where emission of nutrients is related to particular pathways. The idea of such differentiation can be applied to evaluate new, "pathway-oriented" scenarios for nutrient reduction. The combination of both, regional and pathway oriented reduction policies seems to be a good alternative in the light of the assumptions adopted in the Baltic Sea Action Plan (HELCOM, 2009b).

# Emission from agriculture – outcome for the two local Vistula subcatchments: Drwęca and Brda

The prognoses of nutrient emission from agriculture is a complex task, therefore precise studies were carried out at regional level for only two sub-catchments: Drwęca and Brda (catchments 15 and 17 in Fig. 8.21) (Kowalkowski and Buszewski, 2008). Both regions have similar area and population, both are located in the northern part of the Vistula basin, however they substantially differ in land utilization. This difference is particularly connected with the percentage of forest and agricultural area (Fig. 8.23). In the case of Drwęca catchment more than 70% of total area is covered by agricultural land while in the case of Brda catchment this value is 20% smaller. The differences in land use are directly reflected in nutrient emission pattern.

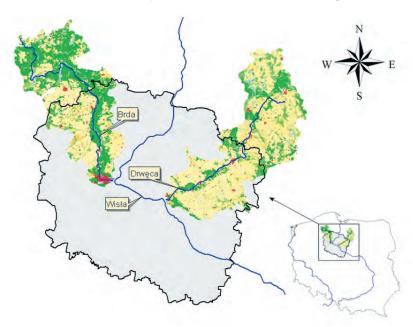


Fig. 8.23 Land utilization in investigated catchments; yellow color indicates agricultural land and green – forest areas (source: Kowalkowski and Buszewski, 2008)

The prognosis of N and P emission was based on N and P surpluses being equal to 43 kg N ha<sup>-1</sup> and 7 kg P ha<sup>-1</sup> (Pietrzak, 2000) and the year 2000 was assumed a reference year. Two scenarios were taken into consideration: (i) AGRI HIGH - assuming a continuous decline in N and P surplus to 15 kg N ha<sup>-1</sup> yr<sup>-1</sup> and 1 kg P ha<sup>-1</sup> yr<sup>-1</sup> in 2015; this scenario assumed a decrease in tillage drainage area (by 10% every 5 years) and an increase in forested areas by (5% every 5 years) at the expense of agricultural land (meadows and pastures), and (ii) AGRI LOW – assuming intensification of agricultural production with subsequent increase in drainage area, and at N and surpluses on the level of 55 kg N ha<sup>-1</sup> and 18 kg P ha<sup>-1</sup> in 2015. The modeling outcome indicates great differences in nutrient emission (Table 8.4).

Table 8.4 Relative reduction of nutrient emission in Brda and Drwęca catchments in 2015 (data referred to emission in 2000); negative values indicate increase in emission

River	Reduction of ni	trogen emission 6]	Reduction of phosphorus emission [%]	
	AGRI HIGH	AGRI LOW	AGRI HIGH	AGRI LOW
Brda	31	-23	-1	-7
Drwęca	45	-40	-2.1	0.5

The Drwęca catchment is characterized by substantial variability in N emission. The estimated total emission of nitrogen was achieved exclusively through N leaching from agricultural land to surface waters. Increase in fertilization considerably increases N emission within 15 years taken into consideration in the studies. However, the same parameters are by 15% lower in the Brda catchment which is characterized by lower contribution of agricultural land (by 20%). Though changes in N emission from agricultural land are strongly connected with land use, this simple dependence cannot be expanded to the entire Vistula catchment. The outcome of these studies calls for the same type of studies in other Vistula sub-catchments. Impact of agricultural activity on P emission is insignificant in the two catchments studied, and it can be explained by a dominating point sources emission and low P surplus in agriculture.

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#### References

- Alexander, R.B., Johnes, P.J., Boyer, E.W., Smith, R.A., 2002. A comparison of models for estimating the riverine export of nitrogen from large watersheds. Biogeochemistry, 57/58:295-339.
- Anonymous, 2000. Program dla Wisły i jej dorzecza 2000-2020. Związek Miast Nadwiślańskich. http://www.zmn.org.pl/download/polski.pdf. [Accessed on 5 May 2010].
- Arheimer, B., Lidén, R., 2000. Nitrogen and phosphorus concentrations from agricultural catchments influence of spatial and temporal variable. J. Hydrol., 227:140-159.
- Arheimer, B., Löwgren, M., Pers, B.C., Rosberg, J., 2005. Integrated catchment modelling for nutrient reduction: scenarios showing impacts, potential, and cost of measures. AMBIO, 34(7):513-520.
- Banaszuk, P., Wysocka-Czubaszek, A., Kondratiuk, P., 2005. Spatial and temporal patterns of groundwater chemistry in the river riparian zone. Agr. Ecosyst. Environ., 107:167-179.
- Bański, J., 2008. Agriculture of Central Europe in the period of economic transformation. [in:] Bański, J. Bednarek, M. (eds.), Contemporary changes of agriculture in East-Central Europe. Stanislaw Leszczynski Institute of Geography and Spatial Organization, Polish Academy of Sciences, Rural Studies, Warsaw, Vol. 15, pp. 8-20.
- Bański, J., 2011. Changes in agricultural land ownership in Poland in the period of the market economy. Agric. Econ.-Czech, 57(2):93-101.
- Bartczak, A., Giergiczny, M., Kaniewska, M., Panasiuk, D., Śleszynski, J., Żylicz T., 2003. Report on the redefiniton of scenarios, VisCat Raport, Warszawa.
- Behrendt, H., Kornmilch, M., Korol, R., Strońska, M, Pagenkopf, W.-G., 1999. Point and diffuse nutrient emissions and transport in the Odra basin and its main tributaries. Acta Hydrochim. Hydrobiol., 27:274-281.
- Behrendt, H., Huber, P., Kornmilch, M, Opitz, D., Schmoll, O., Scholz, G., and Uebe, R., 2000. Nutrient emissions into river basins of Germany. Berlin: UBAText 23/00, Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany p. 45-144.
- Behrendt, H., Dannowski, R., Deumlich, D., Dolezal, F., Kajewski, I., Kornmilch, M., Korol, R., Mioduszewski, W., Opitz, D., Steidl, J., Strońska, M., 2002. Investigation on the quantity of diffuse entries in the rivers of the catchment area of the Odra and the Pomeranian Bay to develop decision facilities for an integrated approach on waters protection. Research Report on the joint international project (FKZ: 298 28 299).
- Behrendt, H., Opitz, D., Korol, R., Strońska, M., 2005a. Changes of the nutrient loads of the Odra River during the last century their causes and consequences. ICID 21<sup>st</sup> European Regional Conference, 15-19 May 2005, Frankfurt (Oder) and Słubice Germany and Poland. 9 pp.

- Behrendt, H., Dannowski, R., Deumlich, D., Doležal, F., Kajewski, I., Klir, J., Kornmilch, M., Korol, R., Łabędzki, L., Makom, E., Mioduszewski, W., Opitz, D., Steidl, J., Strońska, M., Tippl, M., Zdanowicz, A., 2005b. Nutrient and heavy metals in the Odra River system. Emissions from point and diffuse sources, their loads, and scenario calculations on possible changes. Weiβensee Verlag ökologie, 353 pp.
- Billen, G., Garnier, J., 2000. Nitrogen transfers through the Seine drainage network: a budget based on the application of the "Riverstrahler" model. Hydrobiology, 410:139-150.
- Billen, G., Garnier, J., Ficht, A., Cun, C., 2001. Modelling response of water quality in the Seine River estuary to human activity in its watershed over the last 50 years. Estuaries, 24(6B):977-993.
- Błaś, M., Sobik, M., Twarowski, R., 2008. Changes of Cloud water chemical composition in the Western Mountains, Poland. Atmos. Res., 87:224-231.
- Caracao, N.F., Cole, J.J., 1999. Human impact on nitrate export: an analysis using major world rivers. Ambio, 28 (2):67:70.
- Dannowski, R., Steidl, J., Mioduszewski, W., Kajewski, I., 2002. GIS-based distributed analysis of subsurface nitrogen flow in the Odra basin. J. Water Land Develop., 6:91-104.
- Dils, R.M., Heathwaite, A.L., 1999. The controversial role of tile drainage in phosphorus export from agricultural land. Wat. Sci. Tech., Vol. 39, No. 12, pp. 55-61.
- Dubicki, A., 1999. Program szybkiego działania dla ochrony rzeki przed zanieczyszczeniem 1007-2002. KORAB, Wrocław, 111 pp.
- Dubicki, A., 2000. Ocena stanu realizacji inwestycji objętych programem szybkiego działania dla ochrony rzeki Odry przed zanieczyszczeniem 1997-2002. KORAB, Wrocław, 38 pp.
- Duer, I., 2009, Zasada Wzajemnej Zgodności nowym elementem Wspólnej Polityki Rolnej. IUNG-PIB Puławy, pp.193-205.
- Dz. U. Nr 89, poz. 991, 2000 z późn. zm.: Ustawa z dnia 26 lipca 2000 r. o nawozach i nawożeniu.
- Dz. U. Nr 60, poz. 616, 2001: Rozporządzenie Ministra Rolnictwa i Rozwoju Wsi z dnia 1 czerwca 2001 r. w sprawie szczegółowego sposobu stosowania nawozów oraz ochrony środowiska.
- Dz. U. Nr 115, poz. 1229, 2000 z późn. zm.: Ustawa z dnia 18 lipca 2001 r. Prawo wodne.
- Ekopartner, 2009. Oczyszczanie ścieków komunalnych zagrożone. No. 5 (210), 10 ISSN 1230-2961.
- Eriksson, H., Pastuszak, M., Löfgren, S., Mörth, C-M., Humborg, C., 2007. Nitrogen budgets of the Polish agriculture 1960-2000 Implications for riverine nitrogen loads to the Baltic Sea. Biogeochemistry, 85:153-168.
- Erisman, J.W., Bleeker, A., Galloway, J., Sutton, M.S., 2007. Reduced nitrogen in ecology and the environment. Environ. Pollut., 150:140-149.
- Fal, B., Bogdanowicz, E., Czernuszenko, W., Dobrzyńska, I., Koczyńska, A., 2000.

- Przepływy charakterystyczne głównych rzek polskich w latach 1951-1995. Materiały Badawcze, Seria: Hydrologia i Oceanologia, Instytut Meteorologii i Gospodarki Wodnej, Warszawa. No. 26, 137 pp.
- Fotyma, M., Igras, J., Kopiński, J., 2009. Produkcyjne i środowiskowe uwarunkowania gospodarki nawozowej w Polsce. Studia i Raporty IUNG-PIB, Puławy, 14: 187-206.
- Galloway, J.N., Cowling, E.B., 2002. Reactive Nitrogen and The World: 200 Years of Change. AMBIO, Vol. 31, Issue 2, pp 64-71.
- Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howarth, R.W., Bowling, E.B., Cosby, B.J., 2003. The nitrogen cascade. Bioscience, 53:341-356.
- Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A., 2008. Transformation of the nitrogen cycle: recent trends, Questions and potential solutions. Science, 320:889-892.
- Garnier, J., Billen, G., Hannon, E., Fonbonne, S., Videnina, Y., Soulie, M., 2002. Modelling the transfer and retention of nutrients in the drainage network of the Danube River. Estuar. Coast. Shelf Sci., 54(3):285-308.
- Garnier, J., Némery, J., Billen, G., Théry, S., 2005. Nutrient dynamics and control of eutrophication in the Marne River system: modeling the role of exchangeable phosphorus. J. Hydrol., 304:397-412.
- Gömann, H., Kreins, P., Kunkel, R., Wendland, F., 2005. Model based impact analysis of policy options aiming at reducing diffuse pollution by agriculture a case study for the river Ems and a sub-catchment of the Rhine. Environ. Modell. Softw., 20:261-171.
- Grizetti, B., Bouraoui, F., De Marsily, G., Bidoglio, G., 2005 A statistical method for source apportionment of riverine nitrogen loads. J. Hydrol. 304:302-315.
- GUS (Central Statistical Office), Rocznik Statystyczny. Annuals issued in 1960-2003. Waszawa, Poland.
- GUS (Central Statistical Office), Statystyka Polski, Ochrona Środowiska, Gospodarka Wodna. Annuals issued in 1981-1989, Warszawa, Poland.
- GUS (Central Statistical Office), 2000a. Mały Rocznik Statystyczny, Warszawa, Poland.
- GUS (Central Statistical Office), 2000b. Prognoza ludności Polski według województw na lata 1999-2030, Warszawa, Poland.
- GUS (Central Statistical Office), 2007. Mały Rocznik Statystyczny Polski, Warszawa, Poland.
- GUS (Central Statistical Office), Ochrona Środowiska. Annuals issued in 1991-2010, Warszawa, Poland.
- GUS (Central Statistical Office), 2009a. Użytkowanie gruntów, powierzchnia zasiewów i pogłowie zwierząt gospodarskich w 2009 r. Informacje i Opracowania Statystyczne, Warszawa, Poland.
- GUS (Central Statistical Office), 2009b. Rocznik Statystyczny Rolnictwa, Warszawa, Poland.
- GUS (Central Statistical Office), 2010a. Ochrona Środowiska, Environment.

- Warszawa, Poland.
- GUS (Central Statistical Office) Bank Danych Regionalnych., 2010b. http://www.stat.gov.pl/bdr\_n/app/dane\_podgrup.wymiary?p\_kate=9&p\_grup=220&p\_pgru=1670&p\_dane=0. [Accessed on 13 January 2010].
- GUS (Central Statistical Office) Bank Danych Lokalnych., 2011. www.stat.gov.pl/bdl/index.html. [Accessed on 6 December 2011].
- Güler, S., 2006. Developments of fertilizer consumption of the world and Turkey, J. of Fac. of Agric., OMU, 21(2):243-248.
- Haag, D., Kaupenjohann, M., 2001. Landscape fate of nitrate fluxes and emissions in Central Europe A critical review of concepts, data, and models for transport and retention. Agriculture, Ecosys. Environ., 86:1-21.
- Hatfield, J.L., Follett, R.F., (eds.), 2008. Nitrogen in the Environment (second edition): Sources, Problems and Management. Academic Press, 702 pp.
- Haycock, N.E., Pinay, G., Walker, C., 1993. Nitrogen retention in river corridors: European perspective. Ambio, 22(6):340-346.
- Heathwaite, A.L., Quinn, P.F., Hewett, C.J.M., 2005. Modelling and managing critical source areas of diffuse pollution from agricultural land using flow connectivity simulation. J. Hydrol., 304:446-461.
- Heffer, P., Prud'homme, M., 2007. World agriculture and fertilizer demand, global fertilizer supply and trade 2007-2008, Summary Report. International Fertilizer Industry Association (IFA), 33<sup>rd</sup> IFA Enlarged Council Meeting, Doha (Qatar), 27-29, Nov. 2007, 6 pp.
- HELCOM, 2004. The Fourth Baltic Sea Pollution Load Compilation (PLC-4). Baltic Marine Environ. Protection Com. Proc., No. 93.
- HELCOM, 2007. Towards a Baltic Unaffected by eutrophication, HELCOM Overview 2007, HELCOM Ministerial Meeting, Kraków, Poland.
- HELCOM, 2009a. HELCOM JCP pollution Hot Spots as for March 2008. (http://www.helcom.fi/projects/jcp/hotspots/en\_GB/hotspots/) [Accessed on 07 Oct. 2011].
- HELCOM, 2009b. Eutrophication in the Baltic Sea An integrated thematic assessment of the effects of nutrient enrichment in the Baltic Sea region. Baltic Sea Environ. Proc. No. 115B.
- HELCOM, 2010a. Ecosystem Health of the Baltic Sea. HELCOM Initial Holistic Assessment. Baltic Sea Environ. Proc. No. 122.
- HELCOM, 2010b. HELCOM Ministerial Declaration on the implementation of the HELCOM Baltic Action Plan, 20 May 2010, Moscow, 18 pp.
- Honisch, M., Hellmeier, C., Weiss, K., 2002. Response of surface and subsurface water quality to land use changes. Geoderma, 105:277-298.
- Hooda, P.S., Edwards, A.C., Anderson, H.A., Miller, A., 2000. A review of water quality concerns in livestock farming areas. Sci. Total Environ., 250:143-167.
- Hooda, P.S., Truesdale, V.W., Edwards, A.C., Withers, P.J.A., Aitken, M.N., Miller, A., Rendell, A.R., 2001. Manuring and fertilization effects on phosphorus accumulation in soil and potential environmental implications. Adv. Environ. Res., 5:13-21.

References 305

- Howarth, R. W., 2008. Coastal nitrogen pollution: A review of sources and trends globally and regionally. Harmful Algae, 8:14-20.
- Howarth, R.W., Billen, G., Swaney, D., Townsend, A., Jaworski, N., Lajtha, K., Downing, J.A., Elmgren, R., Caraco, N., Jordan, T., Berendse, F., Freney, J., Kundeyarov, V., Murdoch, P., Zhao-Liang, Z., 1996. Regional nitrogen budgets and riverine N P fluxes for the drainages to the North Atlantic Ocean: Natural and human influence. Biogeochemistry, 35:75-139.
- Howarth, R. W., Boyer, E.W., Pabich, W.J., Galloway, J.N., 2002. Nitrogen use in the United States from 1961 to 2000 and potential future trends. Ambio, 31:88-96.
- Ilnicki, P., 2002. Przyczyny źródła i przebieg eutrofizacji wód powierzchniowych. Przegląd Komunalny Dodatek. 2(125):35-49.
- Ilnicki, P., 2004. Polskie Rolnictwo a Ochrona Środowiska. Wydawnictwo Akademii Rolniczej im. Augusta Cieszkowskiego w Poznaniu, Poznań, 485 pp.
- IMWM (Institute of Meteorology and Water Management) in Warsaw, 1990-2002. Monthly Bulletins "Zasoby Wodne Kraju" ("Water Resources in Poland") (in Polish).
- IMWM (Institute of Meteorology and Water Management) in Warsaw, 2003-2009. "Miesięczne Biuletyny Państwowej Służby Hydrologiczno-Meteorologicznej", Warszawa ("Monthly Bulletins of the National Hydrological and Meteorological Service") (in Polish).
- Jankowiak, J., Szpakowska, B., Bienkowski, J., 2003. Ecological aspects of transformation in Poland's agriculture based on the Wielkopolska region. Ambio, Vol. 32, No. 6, pp. 418-423.
- Jaworski, N.A., Groffman, P.M., Keller, A.A., Prager, J.C., 1992. A watershed nitrogen and phosphorus balance: The upper Potomac River basin. Estuaries, 15:83-95.
- Johnes, P.J., Foy, R., Butterfield, D., Haygarth, P.M., 2007. Land use scenarios for England and Wales: evaluation of management options to support "good ecological status" in surface freshwater. Soil Use Manage., 23:176-194.
- Kata, R., Miś, T., 2006. Regional disparities of Poland's agriculture in aspect of its financing from the European Union funds. [in:] New Members New Challenges for he European Regional Development Policy, Technical University of Košice, University of Economics in Bratislava, German Section in ERSA, Novy Smokovec, pp. 164-170.
- Kersebaum, K.C., Steidl, J., Bauer, O., Piorr, H-P., 2003. Modelling scenarios to assess the effects of different agricultural management and land use options to reduce diffuse nitrogen pollution into the river Elbe. Phys. Chem. Earth, 28:537-545.
- Kiryluk-Dryjska, E., 2007. Macro-regional differentiation of farmers;' interest in Polish rural development program measures in Poland. Roczniki Akademii Rolniczej w Poznaniu. CCCLXXXV, p.68-75.
- Kowalkowski, T., 2009. Classification of Nutrient Emission Sources in the Vistula River System. Environ. Pollut., 157:1867-1872.

- Kowalkowski, T., 2010. Ocena jakości wód śródlądowych oraz prognoza redukcji zanieczyszczenia substancjami pożywkowymi w rzece Wiśle i jej dorzeczu. Komentarz do rozprawy habilitacyjnej. Toruń.
- Kowalkowski, T., Buszewski, B., 2003. Modeling of past, present and future state of nutrient emission into the Vistula river system. Implementation of MONERIS model to the Vistula river catchment. WP4 VisCat raport, Toruń. pp. 44.
- Kowalkowski, T., Buszewski, B., 2006. Emission of nitrogen and phosphorus in Polish rivers: past, present, and future in the Vistula River catchment. Environ. Eng. Sci., 23(4):615-622.
- Kowalkowski, T., Buszewski, B., 2008. Zagrożenia eutrofizacji wód w dorzeczach rzek Drwęcy i Bdry. Ekologia i Technika 3(94):124-128.
- Kowalkowski, T., Pastuszak, M., Igras, J., Buszewski, B. 2012. Differences in emission of nitrogen and phosphorus into the Oder and Vistula basins in 1995-2008 natural and anthropogenic causes (MONERIS model). J. Mar. Syst., 89:48-60.
- Kowalkowski, T., Zbytniewski, R., Szpejna, J., Buszewski, B., 2006. Application of chemometrics in river water classification. Water Res., 40 (4):744–752.
- Krajowy Program Oczyszczania Ścieków Komunalnych. 2003. (http://www.kzgw.gov.pl/files/file/Materialy\_i\_Informacje/Programy/KPOSK/kposk.pdf). [Accessed on 18 Oct. 2011].
- Kronvang, B., Hoffmann, C.C., Svendsen, L.M., Windolf, J., Jensen, P., Dørge, J., 1999. Retention of nutrients in river basins. Aquat. Ecol., 33:29-40.
- Kurowski, P., 1998. Scope and Forms of State Support to Enterprises in Poland in Period of Transition, [in:] Petersen H-G. (ed.), Special Series: Industrial and Social Policies in Countries in Transition. University of Potsdam, faculty of Economics and Social Sciences, 18 pp.
- Liefert, W., Swinnen, J., 2002. Changes in agricultural markets in transition economies. Economic Research Service/USDA. Agricultural Economic Report. Katholieke Universiteit Leuven, Washington, DC 20036-5831. No. AER- 806, 15 pp.
- Lepistö, A., Granlund, K., Kortelainen, P., Räike, A., 2006. Nitrogen in river basin: Sources, retention in the surface waters and peatlands, and fluxes to estuaries in Finland. Sci. Total Environ., 365:238-259.
- Mander, Ű., Kull, A., Kuusemets, V., Tamm, T., 2000. Nutrient runoff dynamics in a rural catchment: Influence of land-use changes, climatic fluctuations and ecotechnological measures. Ecol. Eng., 14:405-417.
- Milczarek, D., 2000. Privatization of State farms in Poland a new institutional approach. Paper presented at the KATO Symposium, Berlin, Germany, Nov. 2-4. 2000. 29 pp. http://paradies.agrar.hu-berlin.de/wisola/ipw/KATO/KATOsymDominika.pdf [Accessed on 6 Oct. 2011].
- Misumura, K., 1989. Hydrologic approach to prediction of sediment yield. J. Hydraul. Eng., 115(4):529-535.
- Mulas-Granados, C., Korenchelian, T., Segura-Ubiergo, A., 2008. Reforming Government Subsidies in the New Member States of the European Union.

References 307

- International Monetary Fund Working Paper. WP/08/165, 39 pp.
- Nausch, G., Nehring, D., Aertebjerg, G., 1999. Anthropogenic nutrient load of the Baltic Sea. Limnologica, 29:233-241.
- Ners, K., 1996. Foreign assistance to transition in Central and Eastern Europe, six years of experience. Polish Quarterly of International Affairs, 5(3-4):59-80.
- Neumann, T., Schernewski, G., 2005. An ecological model evaluation of two nutrient abatement strategies for the Baltic Sea. J. Mar. Syst., 56:195-206.
- Nixon, S., (ed.), 1999. Groundwater quality and quantity in Europe. European Environment Agency, Copenhagen, Denmark, 123 pp.
- Nixon, S.W., Ammerman, J.W., Atkinson, L.P., Berounsky, V.M., Billen, G., Boicourt, W.C., Boynton, W.R., Church, T.W., Diroto, D.M., Elmgren, R., Garber, J.H., Giblin, A.E., Jahnke, R.A., Owens, N.J.P., Pilson, W.E.Q., Seitzinger, S.P., 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. Biogeochemistry, 35:141-180.
- OECD (Organization for Economic Cooperation and Development), 2001. Environmental Indicators for Agriculture. Methods and Results. Agriculture and Food. Paris, France, Volume 3, 409 pp.
- Oenema, O., 1999. Nitrogen cycling and losses in agricultural systems; identification of sustainability indicators [in:] Sapek, A., (ed.), Poland Agriculture and Water Quality Protection, Nitrogen Cycle and Balance in Polish Agriculture, Conference Proceedings, Institute for Land Reclamation and Grassland Farming (IMUZ), Falenty pp. 25-43.
- Oenema, O., Roest, C.W., 1998. Nitrogen and phosphorus losses from agriculture into surface waters; the effects of policies and measures in the Netherlands. Wat. Sci. Tech., Vol. 37, No. 2, pp. 19-30.
- Oenema, O., Kros, H., De Vries, W., 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Europ. J. Agronomy, 20:3-16.
- Oenema, O., Van Liere, L., Schoumans, O., 2005. Effects of lowering nitrogen and phosphorus surpluses in agriculture on the quality of groundwater and surface water in the Netherlands. J. Hydrol., 304:289-301.
- Pastuszak, M., Witek Z., Nagel, K., Wielgat, M., Grelowski, A., 2005. Role of the Oder estuary (southern Baltic) in transformation of the riverine material. J. Mar. Syst., 57:30-54.
- Pastuszak, M., Stålnacke, P., Pawlikowski, K., Witek, Z., 2012. Response of Polish rivers (Vistula, Oder) to reduced pressure from point sources and agriculture during the transition period (1988-2008). J. Mar. Syst., 94:157-173.
- Pietrzak, S., 2000. Dobre praktyki w rolnictwie. Sposoby ograniczania emisji zanieczyszczeń wód. Przysiek, pp.7-13.
- Pikuła, D., 2010. The yield of winter wheat depending on weather and nitrogen supply. Fertilizers and Fertilization. 41/2010: 187-198.
- Program dla Odry 2006 aktualizacja (2009) Wrocław; http://www.programodra. pl/aktualizacjaPdO2006/PdO\_2006\_AKTUALIZACJA\_24\_07\_09.pdf [Accessed on 6 May 2010].

- Probst, J.L., 1985. Nitrogen and phosphorus exportation in the Garonne basin (France). J. Hydrol., 76:281-305.
- Przepióra, A., 2007. Poland's progress A case for cautious environmental optimism 18 years after communism. Water & Wastewater News, June 01, 2007, http://wwn-online.com/articles/2007/06/01/polands-progress.aspx . [Accessed on 22 Oct. 2009].
- Salo, T., Turtola, E., 2006. Nitrogen balance as an indicator of nitrogen leaching in Finland. Agr. Ecosyst. Environ., 113:98-108.
- Sharpley, A.N., 1995. Soil phosphorus dynamics: agronomic and environmental impacts. Ecological Engineering, 5:261-279.
- Sharpley, A.N., 2006. Agricultural Phosphorus management: Protecting Production and Water Quality. Lesson 34. Agricultural Research Service. Mid West Plan Service. Iowa State University, Ames, Iowa 50011-3080; http://www.lpes.org/Lessons/Lesson34/34\_Phosphorus\_Management.html. [Accessed: on 22 Oct. 2009].
- Sharpley, A.N., Gburek, W.J., Folmar, G., Pionke, H.B., 1999. Sources of phosphorus exported from an agricultural watershed in Pennsylvania. Agr. Water Manage., 41:77-89.
- Sims, J.T., Simard, R.R., Joern, B.C., 1998. Phosphorus loss in agricultural drainage: historical perspective and current research. J. Environ. Qual., 27:277-293.
- Smil, V., 2002. Phosphorus: global transfers causes and consequences of global environmental change, [in:] Munn, T. (ed.), Encyclopedia of Global Environmental Change, John Wiley& Sons, LTD, Chichester, Vol. 3, pp. 1-7.
- Stålnacke, P., Grimvall, A., Libiseller, C., Laznik, M., Kokorite, I., 2003. Trends in nutrient concentrations in Latvian rivers and the response to the dramatic change in agriculture. J. Hydrol., 283:184-205.
- Steves, T., 2001. Poland and the international system: external influences on democratic consolidation. Communist and Post-Communist Studies, 34:339-352.
- Syryczyński, P., 2003. Privatisation programmes in Poland and Romania: who should pay for site restoration?. Land Contamination & Reclamation 11(1):59-67.
- Vagstad, N., Stålnacke, P., Andersen, H-E., Deelstra, J., Jansons, V., Kyllmar, K., Loigu, E., Rekolainen, S., Tumas, R., 2004. Regional variations in diffuse nitrogen losses from agriculture in the Nordic and Baltic regions. Hydrol. Earth Syst. Sci., 8(4):651-662.
- Vassiljev, A., Stålnacke, P., 2005. Source apportionment of nutrients in the Lake Peipsi drainage basin experiences from a statistical model. Water Sci. Technol., 51:309-317.
- Whitehead, P.G., Johnes, P.J., Butterfield, D., 2002. Steady state and dynamic modeling of nitrogen in the River Kennet: impacts of land use change since the 1930's. Sci. Total Environ., 282-283:417-434.
- Withers, P.J.A., Sharpley, A.N., 2008. Characterization an apportionment of nutrient and sediment sources in catchments. J. Hydrol., 350:127-130.

DISCHARGES OF WATER
AND NUTRIENTS BY THE
VISTULA AND ODER RIVERS
DRAINING POLISH

MARIANNA PASTUSZAK ZBIGNIEW WITEK

**TERRITORY** 

# 9. DISCHARGES OF WATER AND NUTRIENTS BY THE VISTULA AND ODER RIVERS DRAINING POLISH TERRITORY

Marianna Pastuszak, Zbigniew Witek

## 9.1. Water outflow from Polish territory

Almost all of Poland (99.7%) lies within the Baltic Sea drainage basin. Most of Polish land belongs to the large drainage basins of the Vistula River (194,424 km², with 168,699 km² within Polish borders, constituting ca. 54% of Polish territory) and the Oder River (118,861 km², with 106,056 km² within Polish borders, constituting ca. 34% of Polish territory) (Fig. 9.1). Small rivers, carrying their waters directly to the Baltic Sea, drain the remaining area (>11%) (HELCOM, 2004). The length of the Vistula River equals to 1,047 km and the river flows entirely through the territory of Poland; the length of the Oder River equals to 854 km, with 742 km spreading in Poland. The Vistula and Oder Rivers belong to the seven largest rivers in the Baltic catchment (Chapter 1) and they carry about 82% of water from Polish territory to the Baltic Sea. About 17% of riverine water is discharged by the remaining Polish rivers either directly inflowing to the Baltic Sea or *via* the riverine systems of Pregel and Nemunas. The water outflow from Polish territory to other seas is marginal and it constitutes only 1% of the entire water volume drained from Polish territory (Fal et al., 2000; Bogdanowicz, 2004).

Precipitation as well as overall water outflow from Polish territory to the Baltic Sea show substantial inter-annual variability, with the lowest precipitation reaching 500 mm in 2003 and the highest amounting to ca. 750 mm in 1980 and 2001 (Fig. 9.2). When water outflow is taken into consideration, three wet periods can be distinguished over the years 1975-2009, the first occurring on the turn of the 1970s and the 1980s, the second in the late 1980s, and the third in 1997-2002. Although all called wet, they greatly differed in water outflow and the difference reached ca. 20 km³. Very dry periods were observed in 1983-1985, in 1989-1993, and in 2003-2009, with water outflow dropping to 45-50 km³. The difference between the water outflow in dry and wet periods is substantial as it reaches ca. 40 km³ and that figure is close to overall outflow in the dry period 1989-1993 (GUS, 1991-2010).

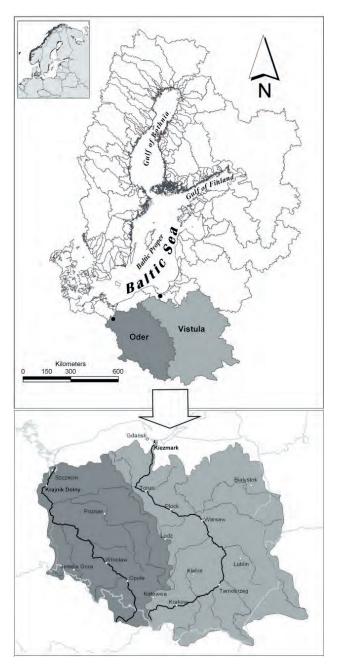


Fig. 9.1 The Baltic Sea catchment and the location of investigated Vistula and Oder basins; two dots in the upper map indicate the lowermost Oder (Krajnik Dolny) and Vistula (Kiezmark) monitoring stations (source: the upper part of the combined map was produced and kindly made available by dr. Erik Smedberg from BNI, Stockholm University, Sweden)

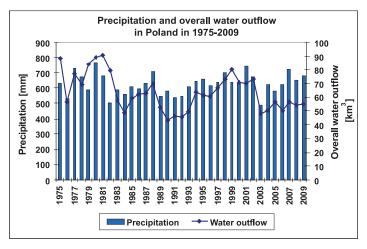


Fig. 9.2 Precipitation and water outflow from Polish territory in 1975-2009 (source: GUS, 1991-2010)

In 1951-2011 the annual water outflows with the Vistula and the Oder River ranged from 20.5 km³ to 56.04 km³ and from 9.5 km³ to 25.4 km³, respectively. The average water flows in the Vistula and Oder Rivers, estimated for the period 1951-1990, reached 1081 m³s⁻¹ and 574 m³s⁻¹ (GUS, 1981-1989; 1991-2010; Fal et al., 2000; IMWM, 2003-2011; HELCOM, 2004). It is worth noticing that the frequency of alternating dry and wet periods has changed over the last 20-25 years. The wet and dry periods have been much longer over the last two decades, most probably owing to climate changes (Fig. 9.3).

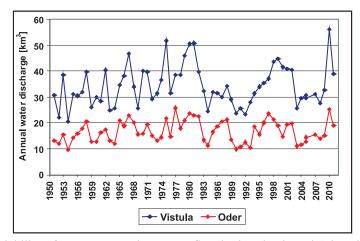
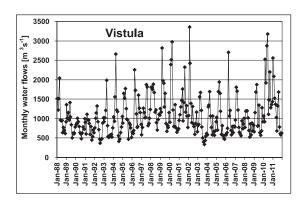


Fig. 9.3 Variability of average annual water outflow in the Vistula and Oder River over the years 1951-2008 (source of data: Fal et al., 2000; IMWM, 2003-2011)

The historical data indicate that annual cycles of water flows in the Vistula and Oder River showed similar character, with maxima in spring, during freshets and minima in summer (Majewski, 1974, 1980; Fal et al., 2000; Bogdanowicz, 2004; Figs. 9.4, 9.5). There are, however, exceptions to this general rule. In 2002 and 2007, the maxima of water flow, though considerably differing in their heights, were observed as early as in February. Very unusual was the pattern of water outflow in 2010, with an average spring maximum but extremely high outflow in June in both rivers (in the case of Oder – a record high flow amounting to ca. 1600 m<sup>3</sup>s<sup>-1</sup>). Those maxima were followed, by a sudden and short-lasting drop (noted only in July 2010), and then a much higher than average, though fluctuating flows throughout the rest of 2010. A continuation of the very wet 2010 was found in January 2011, which was characterized by a maximum in water outflow in both rivers, a phenomenon not observed in other years (Figs. 9.4, 9.5). Summers 2001 and 2010 were exceptionally wet in both river basins and water flows were nearly three times as high as the seasonal average (maximum 2200-2300 m<sup>3</sup>s<sup>-1</sup> in the Vistula and 900-950 m<sup>3</sup>s<sup>-1</sup> in Oder). The duration of seasonal high water flows can be different in the Vistula and the Oder River, e.g. the wet period in summer in 2001 and 2010 was much longer in the Oder than in the Vistula River (Fig. 9.5).



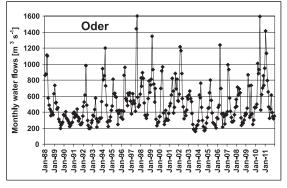


Fig. 9.4 Average monthly water flows in the Vistula and Oder River in 1988-2011 (source of data: IMWM, 1989-2001, 1990-2002, 2003-2011)

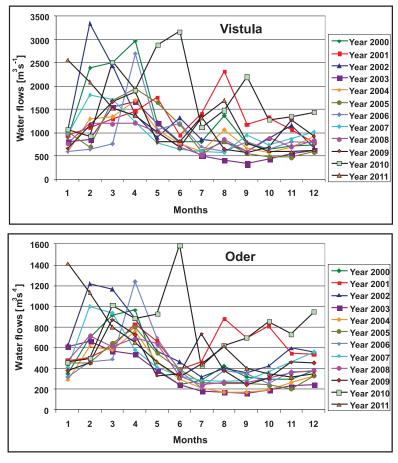


Fig. 9.5 Seasonal variability of water flow in the Vistula and Oder River in the years 2000-2011 (source of data: IMWM, 1990-2002; 2003-2011)

# 9.2. Nutrient concentrations in the Vistula and Oder waters directed to the Baltic Sea

Nutrient concentrations in surface waters show seasonal cycles as well as long-term changes. This variability is different in the case of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP =  $PO_4$ -P - mainly orthophosphates), which can readily be taken up by phytoplankton and macrophytes, and different in the case of organic or particle-bound P forms.

## Short-term variability of concentrations

Seasonal patterns of nitrogen species concentrations in the Vistula (lowermost monitoring station in Kiezmark, ca. 32 km upstream from the river outlet to the sea) and in the Oder (lowermost monitoring station in Krajnik Dolny, ca. 106 km upstream

from the Świna outlet to the sea), showed in 2001-2005: (i) very well developed seasonality, with concentrations maxima found in winter, and their minima observed in summer, (ii) considerable predominance of DIN ( $NO_3$ -N+ $NO_2$ -N+ $NH_4$ -N) over organic nitrogen ( $N_{org.}$ = TN - DIN) in all seasons but summer, when DIN can become exhausted and only organic forms of nitrogen are present, and (iii) higher nutrient concentrations in the Oder than in the Vistula waters, particularly in winter time (Fig. 9.6).

In the case of phosphorus, a predominating role of organic and particle-bound P forms over PO<sub>4</sub>-P was well observed in the Vistula and Oder waters in spring/summer time, particularly in 2003-2005 (Fig. 9.6). The seasonal pattern of phosphorus species concentrations, though showing slight maxima in winter and minima in spring, is not as evident as in the case of nitrogen species. Phosphorus species concentrations were slightly higher in the Oder than in the Vistula waters in 2000-2005.

The observed, well developed seasonality in nitrogen species in the Vistula and Oder can be related to both, the seasonally variable N emission from agricultural land and seasonally variable biological activity in the river waters. The emission from agricultural land remains in close connection with the seasonally variable N amount in soil (Chapter 3) and seasonally variable precipitation and water outflow (Fig. 9.5). In spring, the amount of N in soil rapidly increases due to the process of mineralization and seasonal fertilization, while in summer it declines due to N uptake by crops, and in autumn, it increases again due to intensified processes of mineralization and nitrification. Autumn and spring, which are characterized by both lacking plant cover in agricultural systems and by increased precipitation, become critical periods with respect to N leaching. Process of leaching concerns first of all the nitrate ions (NO<sub>3</sub><sup>-</sup>), which do not undergo sorption in the soil; leaching of ammonium ions (NH<sub>4</sub><sup>+</sup>) is very little as ammonium ions, released during the mineralization process of organic matter or introduced to soil in fertilizers, are sorbed to soil colloids and undergo nitrification (Hatfield and Follett, 2008; Chapter 3). Even at low N contents in soil in summer, the N leaching may take place at torrential rains and significant surface water outflow from fields. Such a situation was observed in summer 2001, when nitrates in the Vistula and Oder peaked to values much higher than those observed prior to and after the event (Figs. 9.5, 9.6). Arheimer and Lidén (2000), studying nutrient leaching from arable land in Sweden, also found that nutrient concentrations were elevated during flow increase at low-flow conditions.

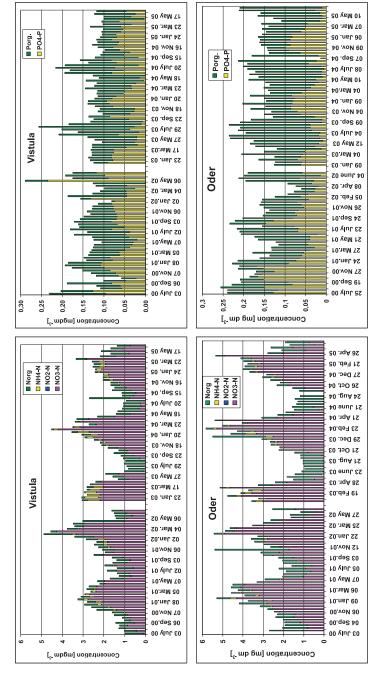


Fig. 9.6 Variability of nitrogen and phosphorus concentrations in the Vistula (Kiezmark) and Oder (Krajnik Dolny) over the period July 2000 – June 2005 (own data; the measurements made in the frame of the European Union (EU) projects: SIGNAL and SIBER)

## Variability of nutrient concentrations in the Vistula and Oder waters in 1988-2011

All the river monitoring data presented in this Chapter are from the official sources and the monthly data, including river nutrient concentrations and water flows, are reported in monthly bulletins of the Institute of Meteorology and Water Management in Gdynia and Warsaw (IMWM, 1989-2001; 1990-2002; 2003-2011). Data on aggregated annual nutrient concentrations and loads are submitted to international organizations such as Helsinki Commission (HELCOM). River monitoring at the lowermost monitoring stations on the Vistula (Kiezmark) and Oder (Krajnik Dolny) Rivers (Fig. 9.1) is conducted by the laboratories of the Inspectorate of Environmental Protection (IEP) in Gdańsk and Szczecin, under auspices of the National Environment Monitoring Program. Both laboratories conducting the river monitoring have Accreditation Certificates (No. AB 177 issued by Polish Accreditation Center) which meet the requirements of the PN-EN ISO/IEC 17025 standard. The scope, the frequency of sampling (at least once a month), and the analytical methods are regulated by the Water Law, which is also rooted in the EU Water Framework Directive 2000/60/EC (Chapter 7).

A comparison of average monthly nutrient concentrations in the Vistula (Kiezmark) and Oder (Krajnik Dolny) (Figs. 9.7, 9.8) allows to draw the following conclusions: (i) the initial concentrations of all the nutrients were higher in the Oder than in the Vistula waters; the difference is particularly well pronounced in the case of DIN (constituting a main pool in total nitrogen), total nitrogen (TN), and total phosphorus (TP), (ii) a decrease in nutrient concentrations is visible in both rivers in 1988-2011, but the decreasing trends are stronger in the Oder River.

The average TN and TP concentrations in the Vistula waters showed a decreasing tendency starting from the year 2000, reaching the lowest values in the last years of the study period (ca. 2.1 mg N dm<sup>-3</sup>; 0.17 mg P dm<sup>-3</sup>). In the 1990s, DIN concentrations were on the level of ca. 2 mg N dm<sup>-3</sup>, and starting from 1998 they showed a distinct declining trend which continued till the year 2011, which was characterized by an average value of ca. 1.1 mg N dm<sup>-3</sup>. Average DIP concentrations in the Vistula waters were ranging from 0.16 mg P dm<sup>-3</sup> in the 1990s to 0.07 mg P dm<sup>-3</sup> over the last years of the study (Fig. 9.7).

The average TN concentrations in the Oder exhibited the highest values in the 1980s (max. ca. 4.7 mg N dm<sup>-3</sup>) and then were gradually dropping to reach the value of ca. 3 mg N dm<sup>-3</sup> in the last 2 years of the study period. TP showed the highest average concentrations (ca. 0.55 mg P dm<sup>-3</sup>) in the 1990s, followed by a declining trend and then leveling off at 0.18 mg P dm<sup>-3</sup> over the last 5 years of the study period. Average DIN concentrations in the Oder were declining from ca. 2.7 mg N dm<sup>-3</sup> in the 1990s to ca. 2 mg N dm<sup>-3</sup> over the last 5 years. Average DIP concentrations in the Oder were steadily dropping from max. of ca. 0.2 mg P dm<sup>-3</sup> in the 1990s to 0.04 mg P dm<sup>-3</sup> over the last 7 years of study (Fig. 9.8).

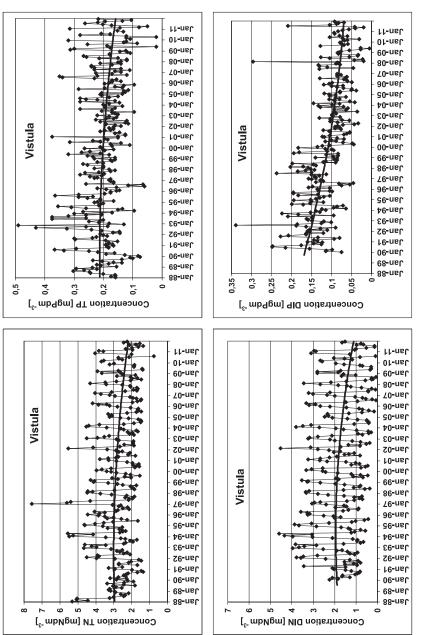
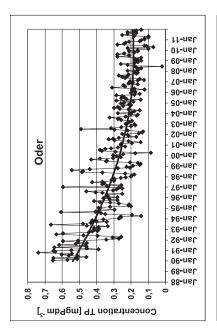
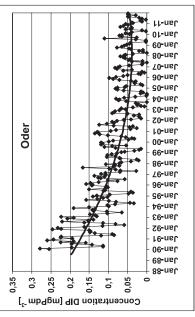
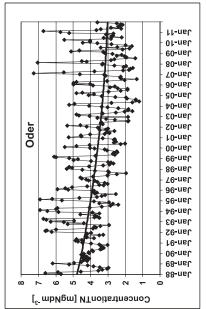
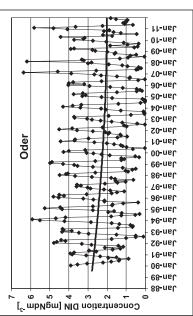


Fig. 9.7 Average monthly concentrations of total nitrogen (TN), total phosphorus (TP), dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphorus (DIP) in the Vistula (Kiezmark) over the period 1988-2011 (DIP in the years 1988-1989 - data are lacking) (source of data: IMWM, 1989-2001; 1990-2002; 2003-2009; data for the years 2009-2011 – provided by IEP, Gdańsk on our request)









DIP in the years 1988-1989 – data are lacking) (source of data: IMWM, 1989-2001; 1990-2002; 2003-2009; data for Fig. 9.8 Average monthly concentrations of total nitrogen (TN), total phosphorus (TP), dissolved inorganic nitrogen (DIN), and dissolved inorganic phosphorus (DIP) in the Oder (Krajnik Dolny) over the period 1988-2011 (DIN and the years 2009-2011 – provided by IEP, Szczecin on our request)

# 9.3. Riverine nutrient loads directed from Polish territory to the Baltic Sea in 1988-2011

### 9.3.1. Actual nutrient loads based on river monitoring data

Monthly riverine nutrient loads are obtained by multiplying monthly concentration of a given nutrient by monthly riverine water outflow. Monthly values are then used to calculate annual N and P loads by a particular river. The diffuse sources (from manure and fertilizer, soil erosion) are principally flow dependent, and studies in basins dominated by such sources have shown that the nutrient load increases with increasing flow (Arheimer and Lidén, 2000; Wood et al., 2005; Bowes et al., 2009). Scatter-plots for nitrates vs. water discharge (Fig. 9.9) showed a positive relationship which indicates a significant input of nitrogen from diffuse sources in the Vistula and Oder basin, and this finding was confirmed in both the outcome of parallel modeling studies carried out by Kowalkowski et al. (2012) (see to Chapter 8) and the outcome of studies focused on source identification of nitrate by means of isotopic tracers in the Baltic Sea catchment, the Vistula and Oder catchments included (Voss et al., 2006). Nitrates were the main components in DIN pool, but they also greatly contributed to the TN pool. In 1990-2008, the percentage contribution of  $NO_3$ -N concentrations to TN concentrations varied from 20 to 80% (the average 51%) in the Oder River and from 20 to 70% (the average 45%) in the Vistula River.

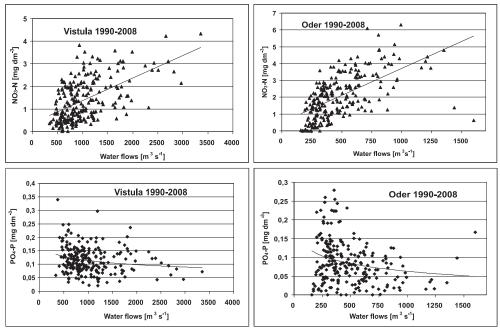
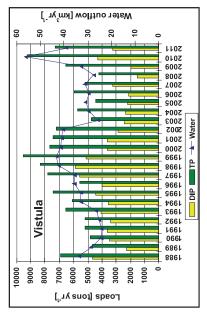
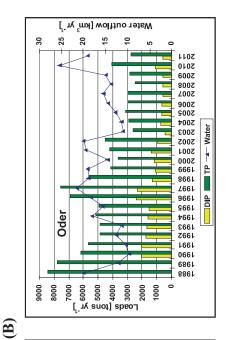


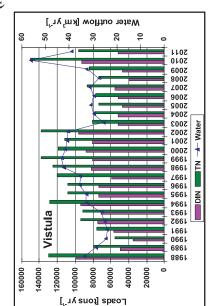
Fig. 9.9 Average monthly concentrations of nitrates (NO<sub>3</sub>-N) and phosphates (PO<sub>4</sub>-P) versus average monthly water flows in the Vistula (Kiezmark) and Oder River (Krajnik Dolny) in 1988-2008 (source of data: IMWM, 1989-2001; 1999-2002; 2003-2011)

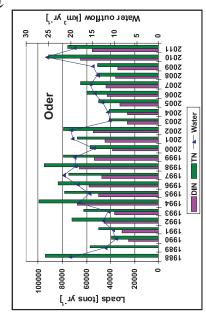
Point sources (from WWTPs and industry) provide a relatively constant input of P to the river throughout the year. Therefore, rivers that are point-source dominated will have P concentrations that are highest at low river flows, and these concentrations will decrease reciprocally with increasing flow rates, due to dilution. Scatter-plots for phosphates in the Vistula and Oder River exhibited a weak and negative correlation which indicates an important role of non-agricultural sources (point sources, urban systems) in PO<sub>4</sub>-P emissions (Fig. 9.9). This may also explain why the highest PO<sub>4</sub>-P concentrations always occur in the Vistula and Oder waters during the July to October period, when flows in these rivers are at their lowest (Figs. 9.5, 9.6). In 1990-2011, the percentage contribution of PO<sub>4</sub>-P concentrations to TP concentrations varied from 0 to 59% (the average 28%) in the Oder River and from 12 to 95% (the average 51%) in the Vistula River. That visible difference must be the result of (i) higher P removal from WWTPs in the Oder basin during the transition period, and (ii) higher sediment-bound P emission from agriculture e.g. *via* larger drainage network in the Oder basin (Kowalkowski et al., 2012; see to Chapter 8).

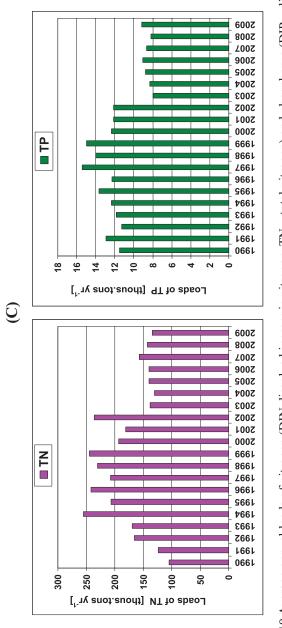
TN and TP loads discharged by the Vistula River demonstrated substantial temporary variability, with the maximum TN values observed in 1988, 1994, 1999, 2002, and 2010, and the maximum TP values recorded in 1999 and 2010 (Fig. 9.10A). Of these five years, 1994, 1999, and 2002 were characterized by very high spring water outflow, while 2010 was characterized not only by a record high annual water outflow but also by very unusual annual pattern of water outflow (IMWM, 1989-2001; 1990-2002; 2003-2011; Figs. 9.3, 9.4, 9.5). A dramatic decrease in TN and DIN loads was observed over the years 2003-2009, and that decrease in loads was accompanied by much lower water outflow. The water outflow with the Vistula River was highest (over 40 km<sup>3</sup> yr<sup>-1</sup>) in 1998-2002 and record high in 2010 (56.04 km<sup>3</sup> yr<sup>-1</sup>), and much lower (ca. 25-30 km<sup>3</sup> yr<sup>-1</sup>) in the early 1990s and then again in 2003-2009 (Figs. 9.3-9.5). As to discharges of phosphates by the Vistula, their loads were systematically declining from a maximum of 6,000 tons in 1998 to a minimum of 1,500 tons in 2008 with the exception of the year 2007. Very high water outflow in 2010 and 2011 was followed by a sudden increase in DIP loads (Fig. 9.10A). Over the years 1988-2011, the percentage contribution of DIN to TN loads in the Vistula River was changing from 54% to 80%, while the percentage contribution of DIP to TP loads was varying from 36% to 72%.











inorganic phosphorus, TP – total phosphorus) introduced to the Baltic Sea with the Vistula (Kiezmark) (A) and Oder River (Krajnik Dolny) over the years 1988-2011 (B), and overall loads of nitrogen and phosphorus discharged to the Baltic Sea over the years 1990-2009 by the Fig. 9.10 Average annual loads of nitrogen (DIN dissolved inorganic nitrogen, TN – total nitrogen) and phosphorus (DIP – dissolved Vistula, Oder, and Pomeranian rivers (C); the right Y axis - water outflow to the Baltic Sea (sources of data: IMWM, 1989-2001;

1990-2002; 2003-2011; GUS, 1991-2010)

TN and TP loads discharged by the Oder River showed more pronounced temporal variability than in the case of the Vistula River (Fig. 9.10B). Also annual water outflows were more variable in the Oder than in the Vistula. Notwithstanding, a huge decline in DIN and TN can be observed in the Oder River in 2003 and that minimum was followed by a slight increase in loads in 2004-2007, then a decrease in 2008-2008, and again a substantial increase in 2010-2011. The loads in 2010-2011 were at comparable level as those in the 1990s. Similarly to the Vistula River, patterns of loads strongly followed the patterns of water outflow which showed a maximum in the 1990s, then a drop in 2003-2009, and again a substantial increase to reach the record high value in 2010 (25.4 km<sup>3</sup>). A decrease in TP and DIP loads is much more evident, their values dropping from max. of 8,300 tons to 2,400 tons (TP) and from ca. 2,000 tons to 480 tons (DIP) over the years of studies (Fig. 9.10B). Slightly exceptional was the year 1996 (for unknown reason), then 1997 with its huge flood in the Oder basin causing substantial washing out of nutrient from fields and households (Mohrholz et al., 1998), and the year 2010 with record high water outflow. The temporary development of Oder DIP loads was much more flattened in comparison with the pattern in the Vistula basin (Fig. 9.10A, B). The percentage contribution of DIN to TN loads in the Oder River ranged from 58% to 73%, therefore it remained in a similar range as in the Vistula River, whereas the percentage contribution of DIP to TP loads was by ca. 50% lower in the Oder than in the Vistula waters and it was changing from 18% to 39% (see to Chapter 8).

The overall TN and TP loads discharged into the Baltic Sea by the Vistula, the Oder, and the Pomeranian rivers (Fig. 9.10C) exhibited temporal variability, with an increasing trend in 1990-1998 and a decreasing tendency in the years that followed. The year 2002 diverged from an overall declining trend in TN loads, and so did the water outflow, which was record high in January 2002 (ca. 3400 m³s⁻¹; Fig. 9.5). The declining tendency in TN and TP loads occurred 10 years after a drastic drop in mineral fertilizers application (Pastuszak et al., 2012; Chapters 3 and 4), and practically at the same time when the volume of untreated sewage started to decrease, while volume of treated sewage with new efficient technologies started to increase (Chapter 8).

#### 9.3.2. Flow normalized loads discharged by the Vistula and Oder Rivers

Keeping in mind that environmental data, such as nutrient concentrations and loads in rivers, often exhibit substantial natural variability caused by the weather conditions (e.g. shown by the temporal variability in water discharge) on, or prior to the sampling occasion, Pastuszak et al. (2012), as well as authors of this Chapter, have applied the flow-normalization method of N and P loads discharged by the Vistula and Oder Rivers in 1988-2011. The normalization method aims at removing the natural fluctuations in loads and concentrations caused by variability in water discharge or other weather-dependent variables. Simply speaking, the aim of flow-

normalization is to estimate the load at the 'normal' water discharge. Such removal or reduction of irrelevant variation in the collected data can help to clarify the impact of human pressures on the environment (in our case, the impact on riverine loads of nutrients). It is clear from the data presented in sections that follow, that substantial fractions of the inter-annual variation in TN and TP loads were removed in both rivers when the load data were flow normalized, especially in the years with very high or low flows (fluctuating dry and wet periods are seen in Fig. 9.4). Flow normalizing methodology facilitates drawing of reliable conclusions from the evaluated trend lines, provided certain conditions are fulfilled: (i) it requires a river basin approach, (ii) flow normalization must be based on monthly nutrient concentrations and monthly water flows (such data constitute a reliable base for calculation of monthly and then annual flow normalized nutrient loads), (iii) long-term data are indispensable for mathematical evaluation of trend lines in N and P loads, and the longer the time series the more reliable the outcome; this statement is particularly crucial in the case of Polish slow-flow systems which greatly predominate in the country, (iv) any segmenting of a long period and calculation of short-term trends must lead to doubtful and highly speculative conclusions. These conditions are specified in methodology described by Libiseller and Grimvall (2002) and they were met in elaboration of the Polish data (Pastuszak et al., 2012; this Chapter).

The Partial Mann-Kendall test (Libiseller and Grimvall, 2002) was used to statistically test long-term changes in solute concentrations and flow-normalized loads. The test has its methodological basis in the seasonal Mann-Kendall-test (Hirsch and Slack, 1984), which has been the major method used to detect temporal trends in environmental data, with the difference that water discharge is included as explanatory variable. It has also been shown that semiparametric normalization models were almost invariably better than ordinary regression models (Hussian et al., 2004). Moreover, a trend line, given as a smoother, was obtained by statistical cross-validation that minimizes the residuals in the statistical modeling determined according to the newly-developed method by Wahlin and Grimvall (2009).

#### Trends in nutrient loads in the Vistula and Oder River in 1988-2011

#### Nitrogen species

Over the years 1988-2011, the flow normalized TN loads declined from a maximum 118,000 tons N yr $^{-1}$  to around 78,000 tons N yr $^{-1}$  in the Vistula River, and from ca. 75,000 tons N yr $^{-1}$  to ca. 54,000 tons N yr $^{-1}$  in the Oder River. The load patterns of TN and NO $_3$ -N in the Vistula River showed a pronounced variability, with minimum values in 1990, then increasing trends up to 1994, followed by decreasing trends till 2000-2001, and again slight increase up to 2004, and the latter increase was followed by very well pronounced decrease expressed by these parameters (Fig. 9.11). The leveling-off of TN and NO $_3$ -N loads in the Oder River is characteristic

starting from the year 2000.  $NH_4$ -N loads showed a strong declining tendency in both rivers, dropping from 18,000 tons N yr<sup>-1</sup> to 4,700 tons N yr<sup>-1</sup> in the Vistula, and from 5,200 tons N yr<sup>-1</sup> to 1,900 tons N yr<sup>-1</sup> in the Oder River. It is very likely that the observed substantial decrease in  $NH_4$ -N loads was caused by the decrease in loading of organic matter from point sources and the implementation of nitrification in WWTPs. Similar dramatic decreases in  $NH_4$ -N concentrations and loads were also observed in numerous Finnish rivers (Räike et al., 2003) and that was also related to the investments in wastewater purification. The decline in TN loads primarily seems to be related to a significant drop in  $NH_4$ -N concentrations and loads (Fig. 9.11) in both rivers, and secondarily to a tendency of decline in  $NO_3$ -N.

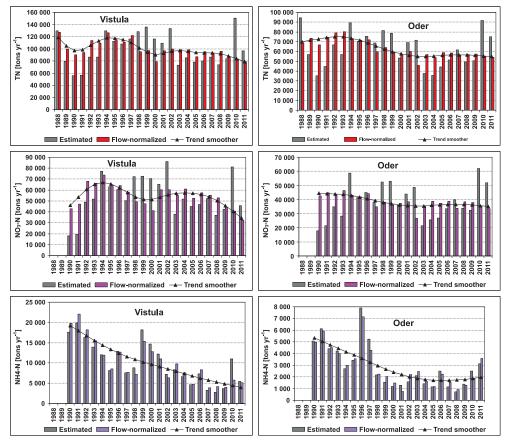


Fig. 9.11 Flow normalized loads of total nitrogen, nitrates, and ammonium directed to the Baltic Sea by the Vistula and Oder Rivers in 1988-2011 (sources of data: IMWM, 1989-2001; 1990-2002; 2003-2009; data for the years 2009-2011 – provided by IEP, Gdańsk and Szczecin on our request; calculations were made by dr. Per Stålnacke and dr. Paul Andreas Aakerøy, Bioforsk, Norway)

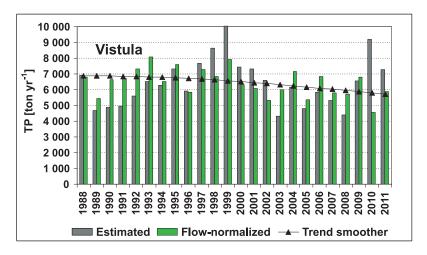
The difference between the maximal and minimal loads of NO<sub>3</sub>-N in both rivers, reached ca. 33,000 tons in the Vistula River and ca. 8,000 tons in the Oder River over the entire period of studies. This reduction is likely to have resulted from the positive changes in agricultural sector. As Poland is largely a lowland country (75% of its area lies in lowland zone i.e. <200 m above the sea level) (Chapter 2), groundwater is a great contributor to overall N emission into Polish rivers, with greater role observed in the Vistula basin. Between 1995-2002 and 2003-2008 sub-periods the decline in N emission *via* this pathway reached 30% in the Vistula and 37% in the Oder (Kowalkowski et al., 2012). More pronounced decline in groundwater emission in the Oder basin can be explained by deeper changes taking place in agricultural sector in western Poland during the transition period (Kata and Miś, 2006; Kiryluk-Dryjska, 2007; Bański, 2011; Chapter 8).

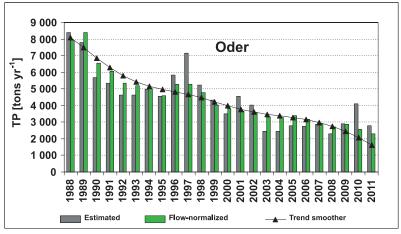
There was a significant difference between TN, NO<sub>3</sub>-N, Norg. concentrations and loads in the Vistula and Oder Rivers in the early 1990s, which also affected the final overall trend patterns (Pastuszak et al., 2012; Fig. 9.11). The Vistula basin experienced a very dry period in 1990-1993, undoubtedly affecting nitrate emission, which is strongly correlated with water discharge (Hooda et al., 1997, 2000). A considerably reduced nitrate leakage, thus low NO<sub>3</sub>-N concentrations, may not have fully been compensated by the calculated TN and NO<sub>3</sub>-N flow-normalized concentrations and loads. In 1990-1991, NO<sub>3</sub>-N concentrations in the Vistula were extremely low, reaching only ca. 0.6-0.8 mg dm<sup>-3</sup>. The dry period seems to have affected not only TN, NO<sub>3</sub>-N loads, but also N-org. loads in the Vistula basin, which were low in the early 1990s (Pastuszak et al., 2012; present studies).

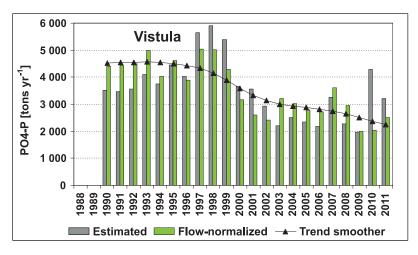
### Phosphorus species

TP loads generally showed a large inter-annual variability, and prior to flow normalization they dropped in the Vistula River from a maximum 10,000 tons yr<sup>-1</sup> (1999) to 4,200-4,400 tons yr<sup>-1</sup> (2003 and 2008), while in the Oder River they dropped from a maximum 8,400 tons  $yr^{1}(1988)$  to 2,300 tons  $yr^{1}(2003)$  and 2008). Likewise nitrogen, a substantial fraction of the inter-annual variation in TP loads was removed in both rivers when the load data were flow normalized, especially in years with very high or low flows, like in an extremely wet year 2010 (Fig. 9.12). The flow normalized TP loads declined from ca. 6,900 tons P yr<sup>1</sup> in 1988-1998 to 5,700 tons P yr<sup>-1</sup> in 2011 in the Vistula River and from ca. 8,000 tons P yr<sup>-1</sup> in 1988 to 1,500 tons P yr<sup>1</sup> in 2011 in the Oder River. The TP load time-trends were statistically significant in both rivers, but stronger statistically significant downward trends (p<0.0001) were detected for both the concentrations and the loads in the Oder River. The PO<sub>4</sub>-P load patterns were quite different in the rivers studied, with a decreasing tendency appearing not earlier than in 1998 in the Vistula River and a steep decline in loads in the Oder River during the whole period studied. The PO<sub>4</sub>-P flow normalized loads declined from 4,500 tons P yr<sup>1</sup> in the 1990s to 2,200 tons P yr<sup>1</sup> in 2011 (by ca. 50%) in the Vistula River and from 2,200 tons P yr<sup>1</sup> in 1990 to 400 tons P yr<sup>1</sup> in 2011 (by ca. 80%) in the Oder River. The decreasing trends in  $PO_4$ -P loads and concentrations were statistically significant in both rivers.

The actions aiming at reducing nutrient loads from point sources in the Vistula and Oder basins have not had the same financial support, thus, comparable dynamics in mitigation of nutrient emission (Dubicki, 1999, 2000; Anonymous, 2000; Program..., 2006). Modeling studies evidently show spatial difference in temporal patterns as well as in the extent of decline in P emission *via* WWTPs. Between the two sub-periods i.e. 1995-2002 and 2003-2008 the decline in P emission *via* this pathway reached 48% in the Vistula and 61% in the Oder basin. The decreasing trends in P emission into the Vistula and Oder basins were also noted in the case of overland flow (by 34-37%), erosion (by 5-7%), and urban systems (by 21-23%) (Kowalkowski et al., 2012; Chapter 8).







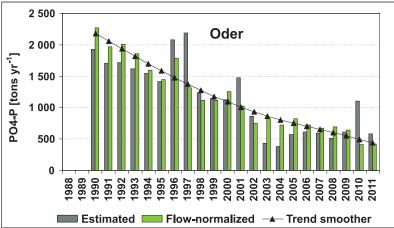


Fig. 9.12 Flow normalized loads of total phosphorus and phosphates directed to the Baltic Sea by the Vistula and Oder Rivers in 1988-2011 (sources of data: IMWM, 1989-2001; 1990-2002; 2003-2009; data for the years 2009-2011 – provided by IEP, Gdańsk and Szczecin on our request; calculations were made by dr. Per Stålnacke and dr. Paul Andreas Aakerøy, Bioforsk, Norway)

The presented data show that flow normalized loads of TN decreased by ca. 34% (40,000 tons) and 28% (21,000 tons) in the Vistula and Oder; the TP loads dropped by ca. 18% (1,200 tons) and 80% (6,500 tons) in the Vistula and Oder waters directed to the Baltic Sea over the years 1988-2011. Flow normalization covering a shorter period (1988-2008) (Pastuszak et al., 2012) gave the following numbers: TN decreased by ca. 20% (20,000 tons) and 25% (20,000 tons) in the Vistula and Oder; the TP loads dropped by ca. 15% (900 tons) and 65% (5,400 tons) the Vistula and Oder water directed to the Baltic Sea. It is clear from the comparison of the above numbers that over the last few years we have experienced further decrease in TN and TP loads in both rivers, with the most pronounced decrease in the case of TN loads in the Vistula River and TP loads

in the Oder River. This is an evident proof that (i) the two largest Polish rivers still respond to positive changes in Polish economy, and it further points to the fact that, (ii) long-term data are indispensible for mathematical evaluation of trend lines in N and P loads; the longer the time series the more reliable the outcome, (iii) any segmenting of a long period and calculation of short term trends must lead to doubtful and highly speculative conclusions.

The modeling studies (Kowalkowski et al., 2012) have proven that between the sub-periods 1995-2002 and 2003-2008, overall N emission into the Vistula and Oder basins decreased by 16-17%, while P emission declined by 23% in the Vistula and by 32% in the Oder River. Though there is an evident indication that pressure onto natural environment has decreased in Poland during the transition period, one should be cautious with any direct comparisons of the specified declines in N and P loads, estimated at the lowermost river monitoring stations (Kiezmak and Krajnik Dolny), with the modeled emission into the Vistula and Oder basins. Such a limitation is caused by the fact that the subjected river monitoring data represent the net N and P loads, i.e. fluxes after reworking of the material in the riverine systems. The retention in the river network is estimated on the level of 20% for N (Howarth et al., 1996), and on the level of ca. 15% for P (House, 2003; Vassiljev and Stålnacke, 2005). Despite the shortcoming, it is obvious that major improvement in water quality in Polish rivers is a fact, both in terms of annual nutrient loads reduction, but also reductions in PO<sub>4</sub>-P concentrations during ecologically sensitive plant and algae growing period (Pastuszak et al., 2012).

## 9.4. Factors affecting nutrient concentrations and loads in waters of the Vistula and Oder Rivers

Studies, carried out by numerous researchers over the last decades have shown that nutrient concentrations in water discharge from river basins are a result of several interacting processes, including exchange between cycles in the terrestrial, aquatic, geological, and atmospheric environment (Haycock et al., 1993; Nixon et al., 1996; Behrendt et al., 1999, 2005 a,b; Arheimer and Lidén, 2000; Mander et al., 1995, 2000; Mc Lenaghen et al., 1996; Kronvang et al., 1999; Dannowski et al., 2002; Bogdanowicz, 2004; Stålnacke et al., 2003; Ilnicki, 2004; Vagstad et al., 2004; Grizetti et al., 2005; Pastuszak et al., 2005; Lepistö et al., 2006; Salo and Turtola, 2006; Voss et al., 2005, 2006, 2010; Moreno et al., 2007). These processes can be categorized into:

(i) nutrient release e.g. through mineralization, weathering, fertilization, atmospheric deposition, sewage effluents; the release must be referred to type of crops, techniques of soil cultivation, intensity of fertilization (related to increased N and P surplus, and possible P accumulation in soil), types of soils and their permeability,

- (ii) water transport (transit time and flow paths, with geomorphology playing a very important role),
- (iii) transformation and immobilization e.g. denitrification, sedimentation and adsorption taking place in riverine systems, estuaries, and lakes.

The influence of different catchment processes varies spatially and temporarily, because they may be more or less favored by conditions in basins such as: land use, land cover, physiography, management, meteorology, and hydrology.

There are some obvious reasons for which the difference in nutrient loads, discharged by the Vistula and Oder River into the Baltic Sea, can be expected. The Vistula drainage area (within Polish borders) is by 38% larger than the Oder one, the number of people inhabiting the Vistula basin is by 8 million higher, and the Vistula annual water outflow is nearly twice as high as that of the Oder River (Fig. 9.3). Apart from these three undisputable factors, there are two complex groups of spatially diversified anthropogenic factors, generally encompassing agriculture and point sources, and a complex group of natural factors. All of them greatly affect nutrient emission into Polish large river basins and then into the Baltic Sea (Voss et al., 2006; Kowalkowski et al., 2012).

The studies on nutrient emissions into the river basins (Kowalkowski et al., 2012; Chapter 8) evidenced that not only loads of N and P emitted into the river basins but also the contribution of N and P pathways, particularly overland flow, tile drainage, groundwater, and WWTPs, showed differences between the Vistula and Oder basins. It is obvious that various pathways are characterized by different transit time which is vital for N and P retention within systems, therefore it is vital for the net fluxes of N and P into the river systems and then into the marine coastal zones (e.g. Nixon at al., 1996). The differences in contribution of various N and P pathways in the Vistula and Oder River are explained by:

- (i) spatially diversified restructuring process in agricultural sector during the transition period (Kata and Miś, 2006; Kiryluk-Dryjska, 2007); the ownership changes deepened spatial polarization, as an increase in farm size took place in the regions where a large average farm area has long been a typical feature (western Poland – Oder basin) (Bański, 2011),
- (ii) spatially diversified farm size, with much larger farms, thus higher income in western Poland (Oder basin); larger farms:
  - o use modern machinery, thus, apply different ways of soil cultivation (Ilnicki, 2004),
  - o are characterized by larger tile drainage area (in 2005, the contribution of tile drainage area in the Oder basin was by 13% larger than that in the Vistula basin; Kowalkowski et al., 2012; Chapter 5),
  - o apply higher doses of mineral fertilizers, thus have higher N and P surpluses in agriculture (Chapters 3, 4, and 8),
  - o are characterized by greater livestock density (Chapter 5),
  - o are characterized by greater congestion of concentrated pig farms,

thus higher risk of environment polluting with excessive application or improper storage of manure (GUS, 2009a; Pastuszak et al., 2012; Chapters 5 and 8),

o have lower percentage of grassland in agricultural land (by 40%; GUS, 2009b; Chapter 8).

All the above listed factors contribute to higher diffuse N and P emission into the Oder basin, as evidenced by Kowalkowski et al. (2012). Contribution of tile drainage pathway to overall N emission into the Oder basin was by 19% higher than that in the Vistula basin. Larger tillage system in the Oder basin turned out to enhance transport of particle-bound P forms, whose contribution to TP was by 23% higher than that in the Vistula basin (Fig. 9.6). However, the problem must be looked into also from a different angle. The extent of the land ownership change during the transition period varied spatially. In the western and northern Poland (mainly the Oder basin) more than half of the farmland area was in hands of the State-owned Farms up to 1989 (Bański, 2011), so, obviously the restructuring process was deeper in that part of the country. Following the restructuring and privatization of the State-owned Farms, local overloads of fertilizers decreased, thus environmental threats from this source were diminished or eliminated entirely (Jankowiak et al., 2003). The other positive aspect is that larger farms achieve higher yields and are more efficient in absorbing EU money provided for their modernization and for environmental protection (Kata and Miś, 2006; Kiryluk-Dryjska, 2007), both contributing to lower diffuse nutrient emission. All these findings corroborate well with the outcome of other studies. A pronounced drop in N surplus in agriculture reached 40 kg N ha<sup>-1</sup> in the Oder basin and 17 kg N ha<sup>-1</sup> in the Vistula basin between the years 1990 and 2002 (Fig.8.11 in Chapter 8). Between the sub-periods 1995-2002 and 2003-2008 the relative decline in emission via groundwater was by 7% higher in the Oder basin (Kowalkowski et al., 2012).

Concentrations of TN, nitrate (NO<sub>3</sub>-N), and TP were higher in the Oder than in the Vistula waters throughout the 24-year-period covered by the researchers (Figs. 9.7, 9.8). In the case of NO<sub>3</sub>-N the difference reached ca. 0.6 mg dm<sup>-3</sup> and it remained unchanged over the entire study period. This finding may be an indication that though nutrient mitigation (agriculture and point sources) was more advanced in the Oder basin, it may not have overbalanced still higher emission from much more intensive agricultural sector in this basin. This statement finds confirmation in the studies of stable isotope signatures of nitrogen ( $\delta^{15}$ N-NO<sub>3</sub>-) and oxygen ( $\delta^{18}$ O-NO<sub>3</sub>-) in 12 Baltic rivers, the Vistula and Oder included (Voss et al., 2006). The subjected studies focused on attributing nitrate in river water to specific sources (farmland/sewage, atmosphere deposition and from runoff of pristine soils). As these authors state, the highest  $\delta^{18}$ O values are found in nitrate from atmospheric deposition while the highest  $\delta^{15}$ N values are measured in manure and septic tanks, where <sup>14</sup>N is preferentially lost via ammonia volatilization. The ranges of isotope values for different sources tend to overlap, but even then measurements of both

stable isotope pairs can often give a unique characterization of nitrate from different sources. The proportion of nitrate originating from agricultural runoff, which was calculated using two isotope mixing models, showed higher values of  $\delta^{15}$ N-NO<sub>3</sub><sup>-</sup>(‰) in the Oder River than in the Vistula River in 2000-2002. Also the load weighted monthly  $\delta^{15}$ N-NO<sub>3</sub><sup>-</sup> values showed different annual patterns, with the Vistula pattern being less pronounced (Voss et al., 2006). The more flattened annual pattern showed also NO<sub>3</sub>-N concentrations in the Vistula River (Fig. 9.6).

As to point sources, it has been evidenced that the investment in mitigation of N and P from this sources has been spatially diversified, with much more dynamic and efficient actions taking place in western Poland (Dubicki, 1999, 2000; Anonymous, 2000; Program..., 2006). Between 1998 and 2008, the reduction in N loads, discharged from municipal WWTPs into surface waters or soil in the Vistula and Oder basin, reached 4,540 tons and 10,400 tons, respectively. That explains a more pronounced decline in N emission from WWTPs in the Oder basin (by 40%) than in the Vistula basin (by 15%) between 1995-2002 and 2003-2008. The most spectacular decrease in P emission was observed in the case of WWTPs pathway and the decline reached 48% in the Vistula and 61% in the Oder basin between the two sub-periods i.e. 1995-2002 and 2003-2008 (Kowalkowski et al., 2012; Chapter 8).

Natural factors constitute the third group of factors affecting spatially diversified nutrient emission in Poland. The high percentage of unconsolidated bedrock in the Vistula (59.3% of the area) and Oder (70.2% of the area) basins explains the high percentage contribution of groundwater pathway to nitrogen emission into the Vistula (40%) and the Oder basin (24%). However, the higher percentage of high porosity bedrock in the Vistula than in the Oder basin seems to be responsible for much higher percentage contribution of emission *via* groundwater in the Vistula catchment (Kowalkowski et al., 2012; Chapter 8). In the case of deep soils and permeable bedrock, percolation to groundwater rather than channeling of flow laterally occur (Heathwaite et al., 2005). That pathway considerably prologs the transit time of water and that is of high importance with respect to enhanced N retention (Nixon et al., 1996). Therefore, the enhanced N and P leaching driven by anthropogenic factors can be even strengthened in the Oder basin by these natural factors.

# 9.5. Nitrogen and phosphorus outflow in the light of agricultural practices in various European countries

In many Eastern and Central European countries huge changes in agricultural practices have taken place over the last two decades. These changes encompassed a decrease in animal stocking, a decline in application of mineral fertilizers, and investment in efficient sewage treatment. There are few river basins for which impact of reduced pressures, imposed by farming and point sources (waste water treatment plants – WWTPs), on riverine nutrient discharges, has been specified (Dannowski et al., 2002; Iital et al., 2003, 2005; Stålnacke et al., 2003, 2004; Hussian et al., 2004;

Kronvang et al., 2005; Oenema et al., 2005; Povilaitis, 2006; Pastuszak et al., 2012). Not all the changes which took place in agricultural sector in the countries under transition in Eastern and Central European countries have had the same dynamics (Bański, 2008). Despite political turbulence in the history of Poland, 80% Polish agricultural land remained in private hands and that contrasted very much with the situation in other countries of the former communistic block. Such a situation had further consequences, as it automatically meant much smoother switching from the central to market economy in Polish agricultural sector (Kurowski, 1998; Bański, 2008, 2011).

The appearance of strongly elevated concentrations of nitrogen and phosphorus in major European rivers was found to be primarily a post-war phenomenon (Grimvall et al., 2000). However, as stated by the authors, the relatively rapid water quality response to increased point source emissions and intensified agriculture does not imply that the watershed reaction to decreased emissions will be equally rapid. Long-term fertilization experiments have shown that important processes in the large-scale turnover of nitrogen operate on a time scale of decades up to at least a century, and in several major Eastern European rivers there is a remarkable lack of response to the dramatic decrease in the use of commercial fertilizers that started in the late 1980s. As to phosphorus, studies carried out in Western Europe and focused on decreased phosphorus emissions, have revealed that riverine loads of this element can be rapidly reduced from high to moderate levels, whereas a further reduction, if achieved at all, may take decades (Grimvall et al., 2000).

The number of variables affecting the diffuse nutrient emission, in combination with complexity of biogeochemical processes taking place in soil, cause that the river response to changing pressures may be slow and limited in the case of numerous rivers (Grimvall et al., 2000; Oenema et al., 2005). Considerable decline in N concentration was observed in large catchments where the fertilizer application, thus the calculated N surplus was much higher than in Poland:

- In the basin of German Elbe River, with similar catchment size and geographical setting as the catchments of the Vistula and Oder, the N surplus dropped from about 140 to 20 kg ha<sup>-1</sup> and that led to a significant decline in riverine TN concentrations (from 7 to 5 mg dm<sup>-3</sup>; Hussian et al., 2004).
- In the basin of Hungarian Tisza River the consumption of mineral fertilizers dropped from 617,000 to 124,000 tons yr1 (Oláh and Oláh, 1996) and that resulted in a significant drop in NO<sub>3</sub>-N concentrations (from 3 to 1.5 mg dm<sup>-3</sup>).
- A national program focusing on nitrogen and phosphorus mitigation from agriculture (by 50% N and by 80% P) was implemented in Denmark in 1987. Fundamental changes in agricultural practices resulted in significant drop in N and P surplus (Kronvang et al., 2005). The N surplus dropped from about 136 to 88 kg N ha<sup>-1</sup> and the P surplus dropped from 19 to 11 kg P ha<sup>-1</sup> during the period 1985-2002. A non-parametric statistical trend analysis (similar

to the method applied by Pastuszak et al., 2012 and by the authors of this Chapter) of TN concentrations in streams draining agricultural catchments showed a significant downward trend in 48 streams, with downward trend being stronger in loamy compared to sandy catchments, and more pronounced with increasing dominance of agricultural exploitation of the catchment. In contrast, a statistical trend analysis of TP concentrations did not reveal any significant trends (Kronvang et al., 2005).

- The mineral fertilizer use within the catchments of many small Estonian rivers reached 300 kg ha<sup>-1</sup> prior to the transition period and it dropped to less than 100 kg ha<sup>-1</sup> (63 kg N ha<sup>-1</sup> and 13 kg P<sub>2</sub>O<sub>5</sub> kg ha<sup>-1</sup>) in 2001, thus obviously changing the N and P surpluses in the agriculture in these catchments (Iital et al., 2003, 2005). Dramatic decline in mineral and natural fertilizer application in Estonia was accompanied by (i) a decrease in livestock, (ii) increased proportions of grassland and abandoned land at the expense of arable land, and (iii) better farm management practices. Out of 22 river sites studied in Estonia, 20 showed statistically significant downward trends in TN concentrations (from 6 mg dm<sup>-3</sup> to 1 mg dm<sup>-3</sup>). TP concentrations showed significant downward trends only at 2 sites, and upward trends at two sites; different behavior of TP was explained by changes in P emission from municipalities (Iital et al., 2003, 2005).
- However, studies of Stålnacke et al. (2003) have shown that the reaction of Latvian rivers to changes in agricultural practices was slow and limited. Despite an unprecedented decrease in application of mineral fertilizers (127 kg N ha<sup>-1</sup> in 1987 and 8 kg N ha<sup>-1</sup> in 1996; 30 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> in 1987 and 1.5 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> in 1996) only 3 out of 12 sampling sites showed downward trend in nitrate, and 6 out of 12 sites downward trend in phosphate concentrations. Slow river response the authors attribute to (i) long water-transit times in soil water and groundwater causing a time lag in response, (ii) mineralization of large pools of organic N that had been accumulated in previous years.

We also wish to present here a very well pronounced response of an exemplary small Polish river (Słupia River), discharging its water directly to the Baltic Sea. Application of mineral fertilizers (NPK) in this catchment dropped from 245 kg yr<sup>-1</sup> in the 1980s to 45.5 kg yr<sup>-1</sup> in 1991, and then it increased, to stabilize at ca. 90 kg yr<sup>-1</sup> over the last few years. At the same time, (i) restructuring of the State farms, (ii) a significant drop in livestock, (iii) significant investment in construction of WWTPs, were observed. All these changes resulted in declines in NO<sub>3</sub>-N (from 1.22 to 0.9 mg dm<sup>-3</sup>), NH<sub>4</sub>-N (from 0.75 to 0.02 mg dm<sup>-3</sup>), TN (from 4.3 to 2 mg dm<sup>-3</sup>), PO<sub>4</sub>-P (from 0.26 to 0.06 mg dm<sup>-3</sup>), and TP (from 0.49 to 0.15 mg dm<sup>-3</sup>) concentrations (Jarosiewicz, 2009).

It should be emphasized here that even before the observed significant decline in nutrient concentrations in the Vistula and Oder waters feeding the Baltic Sea, their values were low in comparison with values detected in other eutrophied European

rivers (5-8 mg N dm<sup>-3</sup> in Thames, Rhine, Elbe or Seine) which drain the catchments characterized by higher fertilization than in Poland (Meybeck, 2001; Neal et al., 2006; Chapter 3). Average nitrate concentrations in the basin of Humber River in north-western England are in the range 3.3-18.8 mg N dm<sup>-3</sup>, while phosphate concentrations vary between 0.023 mg P dm<sup>-3</sup> and 1.96 mg P dm<sup>-3</sup> (Neal et al., 2008). Nitrogen surplus in Polish agriculture in 1960-2000 was up to two times lower than that in other Baltic countries under transition, and it was much lower than in countries of Western Europe, characterized by very intensive agricultural activity (OECD, 2001; Campling et al., 2005; Eriksson et al., 2007; Chapter 3). At the same time the nitrogen efficiency in Poland (defined as the ratio of the crop nitrogen uptake, to the total input of nitrogen fertilizer), was among the highest determined for numerous European and other world countries (OECD, 2001).

## 9.6. Contribution of Poland to polluting the Baltic waters with nitrogen and phosphorus compounds

In 2000, the total riverine nitrogen and phosphorus loads entering the Baltic Sea amounted to 706,000 tones and 31,800 tones, respectively. The bulk (over 80%) of N and P load was discharged by monitored rivers, with about 40% of the N load and 50% of the P load originating from the catchment area of the Baltic Proper. Approximately 75% of the riverine nitrogen and 83% of phosphorus were discharged by the region's three rivers: the Vistula, the Oder, and the Nemunas. In 2000, the Vistula River discharged 117, 000 tons TN and 7,500 tons TP, while the Oder River was responsible for 53,000 tons TN and 3,700 tons TP. Contribution of Poland to overall loads of N and P reaching the Baltic Sea constituted 26% and 37% for total nitrogen and total phosphorus, respectively (HELCOM, 2004; Fig. 9.13).

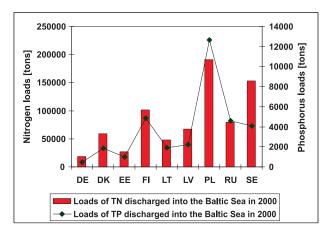


Fig. 9.13 Nitrogen and phosphorus loads discharged into the Baltic Sea in riverine outflow in 2000; abbreviations used for the Baltic countries - see to Chapter 12 (source: HELCOM, 2004)

The source apportionment of nitrogen and phosphorus losses into inland surface waters, made for all the Baltic countries (HELCOM, 2004), shows that the respective contribution of nitrogen from diffuse sources, point sources, and natural background constituted 62%, 18%, and 20% in Poland in 2000; the respective contribution of phosphorus from diffuse sources, point sources, and natural background constituted 54%, 29%, and 17%. Source apportionment of nitrogen and phosphorus as well as N and P pathways in the Vistula and Oder basin are extensively discussed in Chapter 8. It is evident from that Chapter that diffuse sources (mainly N) and point sources (mainly P) play a very important role in nutrient emission into the Vistula and Oder basins.

For the past decades, high contribution of Poland to overall loads of nitrogen and phosphorus reaching the Baltic Sea, has been a subject to severe, not fully justified, criticism on an international level. The high annual loads of N and P have never been denied by Poles, but that truth requires explanation which should be based on scientific findings on complexity of factors responsible for N and P emission from man utilized land to riverine systems and then to the sea (Haycock et al., 1993; Oenema and Roest, 1998; Oenema, 1999; Nixon, 1999; Hooda et al., 2000, 2001; Honisch et al., 2002; Oenema et al., 2003; Salo and Turtola, 2006). Among the main factors one must take into consideration:

- (i) the area of the catchment,
- (ii) the land use/cover, and within this, the area of agricultural land,
- (iii) the geomorphologic features,
- (iv) the geographical setting which is connected with climate, thus type and intensity of precipitation and consequently the volume of water drained from the catchment,
- (v) the population in a particular catchment because that is connected with point sources discharges; besides, higher human population density is connected with accelerated nitrogen cycling through fertilizer use, food movement, atmospheric pollution, and land disturbance, and therefore is responsible for higher diffuse N outflow, as stated by Howarth et al. (1996).

If 62% TN and 54% TP, discharged to surface waters of the Baltic catchment, originates from diffuse sources, it is advisable to show the agricultural land area in all the Baltic countries (Fig. 9.14).

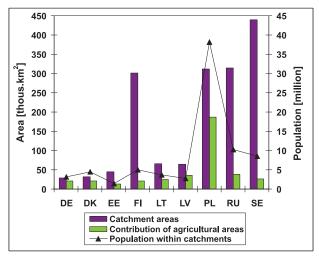


Fig. 9.14 Surface of the catchment areas, contribution of agricultural land, and population in countries in the catchment area of the Baltic Sea; abbreviations used for the Baltic countries - see to Chapter 12 (source of data: HELCOM, 2001, 2004).

As much as 99.7% of Polish territory constitutes the Polish catchment, one of the four largest catchments in the Baltic region. The agricultural land and agriculturally utilized land in Poland account for 61% and 51%, respectively, of the entire Polish territory (Chapters 2 and 8). Majority of Polish territory is drained by the Vistula and Oder, two out of the seven largest rivers feeding the Baltic Sea. Comparison of all the Baltic catchments, in particular the four largest ones (Finnish, Polish, Russian, and Swedish) clearly shows that:

- (i) the four largest catchments considerably differ in land cover/use; contribution of forested areas is ca. two times higher in the Finnish and Swedish, and considerably higher in the Russian catchment than in the Polish one; the forested areas cover ca. 60% of the entire Finnish catchment (Chapter 1),
- (ii) Polish agricultural area constitutes about 50% of the agricultural land in the entire Baltic catchment (Chapter 1; Fig. 9.14),
- (iii) contribution of lake areas is incomparably higher in Russian, Finnish, and Swedish catchment than in Polish one (Chapter 1),
- (iv) Swedish catchment is by 30% larger than the Polish one, but ca. 25% of Swedish catchment is covered by high mountains (Chapter 1),
- (v) urban areas show the greatest share in Polish catchment, and that stems from the highest population, the latter constituting ca. 45% of the entire Baltic catchment population (Chapter 1; Fig. 9.14).

It is well documented in scientific literature that emission of nutrients from the forested areas, or from the regions with high contribution of meadows and pastures is incomparably lower than nutrient export from the agriculturally cultivated land.

Nitrate concentrations are most strongly correlated with arable land and water runoff (Hooda et al., 1997; Sharpley et al., 1999; Arheimer and Lidén, 2000; Vagstad et al., 2004; Salo and Turtola, 2006; Sharpley, 2006; Voss et al., 2006; Kvítek et al., 2009; Hatfield and Follett, 2008). Studies carried out in Finland (Rekolainen et al., 1995) and the US (Hatfield and Follett, 2008), indicate that land management for agricultural purposes results in approximately eight (the US) or tenfold (Finland) higher nitrogen losses per unit area compared to the forest land. Thus, even in areas where agricultural land use is minor, it may have a notable contribution to total nitrogen losses. Very high, statistically significant correlation coefficients between average proportion of total nitrogen and total phosphorus discharges by the Baltic countries and average proportion of arable land and population prove the findings of the above cited authors (Table 9.1).

Table 9.1 Correlation coefficients between average proportion of total nitrogen and total phosphorus inputs by the Baltic countries and average proportion of specific land use and proportion of population; calculations based on data by HELCOM (2009) and data from Baltic GIS (source: Land Cover & Population Statistics.... www.grida.no)

Specification	Catchment	Arable land	Forest area	Open land	Population
	area				
TN	0.77	0.84	0.46	0.77	0.89
TP	0.64	0.91	0.26	0.75	0.95

Of the total N input to Finnish river systems, 0% to 68% was retained in surface waters and/or peatlands, with a mean retention of 22%. The highest retention of N (36-61%) was observed in the basins with the highest lake percentages. The lowest retention (0-10%) was in the coastal basins with practically no lakes. In the national mass balance, the lake retention in Finland was estimated on the level of 32% (Lepistö et al., 2006). Lake retention of ca. 30-35% for both N and P is also reported by Vassiljev and Stålnacke (2005) in the Lake Peipsi drainage basin (situated between Estonia and Russia).

Howarth et al. (1996) and Peierls et al. (1991) noted that on a log-log plot, nitrate and TN fluxes in major rivers of the world are correlated with human population density. However, the slope of the relationship for TN fluxes is less than that for nitrate fluxes in major world rivers by almost a factor of 2. This suggests, as state the authors, that disturbance associated with human population density preferentially mobilizes nitrate over other nitrogen forms. Moreover, these correlations between population density and either nitrate or TN fluxes could reflect (i) the importance of human waste, as one of nitrogen inputs to watersheds, or (ii) could reflect correlations between human population density and accelerated nitrogen cycling through fertilizer use, food movement, atmospheric pollution, and land disturbance. Howarth et al.

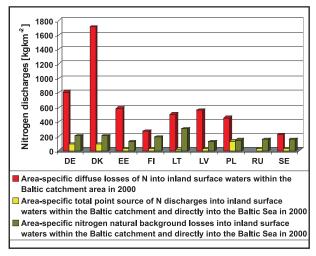
(1996) are of the opinion that the latter explanation is perhaps more likely since non-point sources of nitrogen dominate fluxes of nitrogen in the rivers of the North Atlantic Ocean. These findings are very important when it comes to interpretation of diversified N fluxes by the Baltic countries which differ in agricultural land area, in intensity of agricultural production, but also greatly differ in population number and density (Fig. 9.14; Chapter 1).

#### Comparison of loads and area specific loads of N and P discharged by the Baltic countries

#### Nitrogen

The area specific loads, but not riverine loads of TN and TP, are an indication of potential environment degradation in the catchment. In the HELCOM (2004) report the area specific loads are divided into area specific diffuse losses, area specific point source discharges, and area specific background losses (Fig. 9.15). Overall riverine TN load introduced by Poland to the Baltic Sea in the year 2000, was the highest (Fig. 9.13) but the Polish area specific diffuse loss of N belonged to the low ones in the Baltic region. It was over fourfold and twofold lower than that in Denmark and Germany (Fig. 9.15). Overall area specific N load (the sum of the three sources) was over three times lower in Poland than the same specific N load in Denmark. If the Polish figure approached that in Demark, the country with exceptionally intensive agriculture, Poland would have introduced well over 600,000 tons of N but not the recorded ca. 190,000 tons of N in the year 2000. Interestingly, the agricultural land area and population in Sweden are 7 times and 4.5 times smaller than those in Poland but there was only 20% difference between TN loads discharged into the Baltic Sea by these two countries in the year 2000 (Fig. 9.13).

Problem of environment degradation in Denmark should be a warning signal for the decision makers in Poland, because at the transforming agricultural sector, Poland has already faced conflicts of interest connected with introduction of industrial pig farming based on western capital investment (FoE Europe, 2004; Ilnicki, 2004; Landsberg-Uczciwek et al., 2005; Pastuszak et al., 2012). Danish problem is not rooted in a number of pigs because that was by 5 million lower than in Poland in 2002; problem lies in pigs density expressed in LU (Livestock Units) per 100 ha of agricultural land, which was over four times higher than in Poland (Fernández et al., 1999; Landsberg-Uczciwek et al., 2005). Polish average animal density is not high (in 2009-2011 - on average 45 LU per 100 ha) but regional differences are relatively high, with a minimum within a range 15-29 LU per 100 ha, and a maximum value being equal to 68-78 LU per 100 ha. The highest number of farms with intensive animal raising, is in Wielkopolskie and Kujawsko-Pomorskie voivodeships (western/ central Poland) (mainly pigs), and Podlaskie voivodeship (northeastern Poland) (mainly cattle) (Chapters 2 and 5). That automatically means that environmental pressures must be looked into regionally.



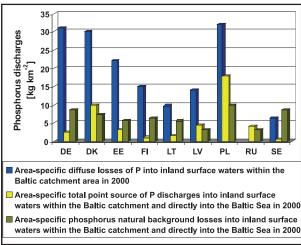


Fig. 9.15 Area-specific loads of total nitrogen and total phosphorus discharged into inland surface waters within the Baltic catchment and directly into the Baltic Sea in 2000; abbreviations used for the Baltic countries – see to Chapter 12 (source of data: HELCOM, 2004)

Concentrated industrial pig production in Denmark resulted in high production of manure, reaching 12.5 million tons in 1995. It contained 104,000 tons of N and 2,500 tons of P and caused a substantial emission of ammonia (16,000 tons) to the atmosphere (Fernández et al., 1999). It has been estimated that as much as 70% ->80% of nitrogen emission and >50% of phosphorus emission into Danish rivers, lakes, and coastal waters originates from agriculture (Van Eerdt and Fong, 1998; Kronvang et al., 2005).

The area specific point source N discharge in the year 2000 was highest in Poland, but at the same time we should be aware of the fact that 45% of overall

Baltic population lives in Poland, and though agriculture is of uppermost importance in N emission to river basins, WWTPs are also a source of N in riverine outflow (Chapter 8). The role of WWTPs in N emission into river basins has been diminishing during the transition period in Poland and that has been demonstrated by a very well pronounced decrease in NH<sub>4</sub>-N loads (Fig. 9.11).

#### **Phosphorus**

An analysis of phosphorus area specific losses into inland surface waters within the Baltic catchment in 2000 is also very educative. Similarly to loads of nitrogen, Poland was also responsible for the highest loads of phosphorus discharged into the Baltic Sea in 2000 (Fig. 9.13). However, the pattern of P loads reaching the Baltic Sea strongly deviates from the pattern of P diffuse area specific loads (Fig. 9.15), with nearly the same highest values in Germany, Denmark, and Poland. Estonia is only slightly below these three highest contributors. If the drainage areas in Germany, Denmark, and Estonia were comparable to that in Poland (Fig. 9.14), the P outflow from the agricultural land would have theoretically been identical, provided the geomorphologic and climatic features, the agricultural land area, the agricultural intensity, the fertilizing history etc. were the same, which is definitely not the case. The Danish and German catchment areas and agricultural land areas are ca. tenfold smaller than the Polish one and this single argument is sufficient to get away from a comparison of P loads discharged into the Baltic Sea by the subjected countries (Fig. 9.13).

The high area specific diffuse P loss in Poland in 2000, may have resulted from P surplus in Polish agriculture in 1984-1994, with particularly high values found in 1984/85 and 1989/1990, reaching 19.1 kg P ha<sup>-1</sup> and 15.5 kg P ha<sup>-1</sup> (Sapek, 1998). Similar high values of P surplus are reported for the years 1985-1990 by the authors of Chapter 4. High P surplus may have led to P accumulation, making it long-term diffuse sources of P loss to water. Phosphorus surplus in 1991-2010 was much lower than in the 1980s and, with a few exceptions, it remained below 5 kg P ha<sup>-1</sup> (Chapter 4). Application of phosphorus fertilizer, though increasing after a drastic drop during the recession on the turn of the 1980s and 1990s, is still two times below the maximum of P application in the 1980s; the present application is on the level of ca. 25 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> (Chapter 4).

Phosphorus has to be added to most soils so that there are adequate levels for optimum crop growth and yield. However, when added to soil in the form of fertilizers, phosphorus can be rapidly fixed (adsorbed) in forms unavailable to plants. Phosphorus content in soil and availability varies with soil parent material, texture, pH, as well as with management factors such as the rate of P applications and tillage practice. The decay of remains of plants, as well as dosage of fertilizers take place in the surface soil layer and that causes that P accumulation occurs in the soil surface layer from a few to a dozen or so centimeters (Heathwaite and Dils, 2000; Sadej, 2000; Steineck et al., 2002; Szara et al., 2004). Although P is relatively immobile in

the soil, it is not non-mobile. It can move, especially where soils have become highly enriched with P (Sharpley, 1995; Carpenter et al., 1998; Moskal et al., 1999; Sądej, 2000; Ruttenberg, 2003).

On average, only 30% of the fertilizer and feed P input to farming system is output in crops and animal produce (Sharpley, 1995). Soil P exists in inorganic and organic forms. In most soils, 50% to 75% of the P is inorganic. Conversion of unavailable to available forms of soil P usually occurs too slowly to meet crop P requirements. Inorganic P is usually associated with Al, Fe, and Ca compounds of varying solubility and availability to plants. However, P can be rapidly fixed (also referred to as sorption) in forms of unavailable to plants, depending on soil pH and type (Al, Fe, and Ca content). Overall, soil pH is the main property controlling inorganic P forms, although Al, Fe, and Ca content determine the amounts of these forms. Soils with fine texture and higher content of Fe and Al have greater potential for P fixation than other soils. In acid soils, Al and Fe dominate fixation of P, while Ca compound fix P in alkaline soils. The rate and the extensiveness of these reactions depend on type of soil cultivation and tillage network (Sharpley, 1995, 2006; Busman et al., 1998; Ruttenberg, 2003; Hyland et al., 2005). P availability in soil is greatest at soil pH between 6 and 7 (Sharpley, 2006; Fig. 9.16).

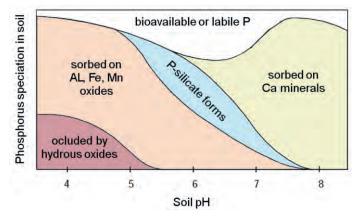


Fig. 9.16 Approximate representation of the fate of P added to soil by sorption and occlusion forms, as a function of soil pH (source: Sharpley, 2006; modified graph)

As much as 21% of agricultural land in Poland, mainly arable land, and 8% of forested area are imperiled with soil erosion (erosion caused by water flow), and as proven by Kowalkowski et al. (2012) (Chapter 8) erosion is one of four the most important pathways in P transport to river basins. Over 50% soils in Poland are acidified, with acidification originating from the type of the bed-rock and anthropogenic factors such as fertilization and "acid rains". It is documented by Mayer (1998) that anthropogenic changes in atmospheric deposition have led to accelerated soil acidification in many sites, especially in soils and/or bedrocks low in

acid neutralizing capacity. Acid rain is caused by emissions of carbon dioxide, sulfur dioxide and nitrogen oxides which react with the water molecules in the atmosphere to produce acids (Błaś et al., 2008; Kelly et al., 2005). Kelly et al. (2005) state that (i) the rate of conversion of NH3 to NH4 is controlled by factors such as relative humidity, temperature, the availability of oxides of nitrogen and sulfur, and that (ii) the regional transport of SO<sub>4</sub><sup>2-</sup> may have greater impact on concentration of NH<sub>4</sub><sup>+</sup> and subsequent deposition than local agricultural emissions of NH<sub>2</sub>. Studies on changing composition of cloud water and precipitation were carried out in the "Black Triangle", where Poland, Germany and the Czech Republic meet in one of Europe's most industrialized regions (Błaś et al., 2008). This region was characterized by highest pollution emission, and as a consequence the highest acid deposition in Europe (exceeding 1500 mol ha-1 yr-1 in the "Black Triangle"). The outcome of the research has shown considerable reduction of sulfur dioxide emissions between the early 1990s and the present times (from 2 million tons to around 0.2 million tons), with a substantial decline of sulfate and hydrogen concentration in cloud water ( $SO_4^{2-}$  - from more than 200 µmol dm<sup>-3</sup> to 70 µmol dm<sup>-3</sup>). The authors state further that this is a result of pollutant abatement policy since the beginning of the nineties; the emission reduction achieved by Poland so far meets the targets of the Gothenburg protocol (Błaś et al., 2008). Poland has spent huge amounts of money on environment protection, the protection of air and climate included (see to Fig. 8.13 in Chapter 8).

The loss of P in agricultural runoff occurs in sediment-bound and dissolved forms (Carpenter et al., 1998; Fig. 9.17). Sediment P includes P associated with soil particles and organic material eroded during flow events and constitutes 60% to 90% of P transported in surface runoff from most cultivated land (Sharpley, 1995, 2006; Ruttenberg, 2003).

Surface runoff from grass, forest, or uncultivated soils carries little sediment, and therefore, is generally dominated by dissolved P. Thus erosion control is of prime importance in minimizing P loss from agricultural land (Sharpley, 1995, 2006). Honisch et al. (2002) have shown that adapted land use practice can reduce groundwater and surface loads of nutrients effectively. Their anti-erosion program (mulching, minimum tillage, fallow strips and others) minimized lateral loads to the surface water and optimized fertilization and intercropping, whereas eco-farming mainly reduced the leakage potential of soils. Additionally, agricultural practices such as intercropping, green borders along surface waters and permanent fallow had stopped the erosion process.

The area specific point source P discharge in the year 2000 was highest in Poland, but at the same time we should keep in mind that 45% of overall Baltic population lives in Poland, and that WWTPs are, or rather were a substantial source of P source in riverine P outflow. A dramatic decrease in TP and PO<sub>4</sub>-P loads in the riverive outflow has been observed over the last two decades in Poland (Fig. 9.12), and that has been attributed to not only restructuring in agricultural sector, but first of all, to a very efficient removal by newly constructed and/or modernized WWTPs (Chapter 8).

Analysis of Fig. 9.15 puts Poland in entirely different light than the outcome arising from analysis of N and P loads discharged by particular Baltic countries (Fig. 9.13). That, however, does not mean that further nutrient mitigation in Poland is not necessary. The transition period in Poland was marked by political and consequently economic changes in the agricultural sector, the industry, and the environmental protection, the latter being also imposed by the EU Directives and the HELCOM declarations aiming at mitigation of nutrient emission into the rivers basins, and consequently to the Baltic Sea (Syryczyński, 2003; HELCOM, 2007; Chapters 2, 7, and 8).

- Anonymous, 2000. Program dla Wisły i jej dorzecza 2000-2020. Związek Miast Nadwiślańskich. http://www.zmn.org.pl/download/polski.pdf. [Accessed in May 2010].
- Arheimer, B., Lidén, R., 2000. Nitrogen and phosphorus concentrations from agricultural catchments influence of spatial and temporal variable. J. Hydrol. 227:140-159.
- Bański, J., 2008. Agriculture of Central Europe in the period of economic transformation. [in:] Bański, J. Bednarek, M. (eds.), Contemporary changes of agriculture in East-Central Europe. Stanislaw Leszczynski Institute of Geography and Spatial Organization, Polish Academy of Sciences, Rural Studies, Warsaw, Vol. 15, p. 8-20.
- Bański, J., 2011. Changes in agricultural land ownership in Poland in the period of the market economy. Agric. Econ.-Czech., 57(2):93-101.
- Behrendt, H., Kornmilch, M., Korol, R., Strońska, M, Pagenkopf, W.-G., 1999. Point and diffuse nutrient emissions and transport in the Odra basin and its main tributaries. Acta Hydrochim. Hydrobiol., 27:274-281.
- Behrendt, H., Opitz, D., Korol, R., Strońska, M., 2005a. Changes of the nutrient loads of the Odra River during the last century their causes and consequences. ICID 21<sup>st</sup> European Regional Conference, 15-19 May 2005, Frankfurt (Oder) and Słubice Germany and Poland. 9 pp.
- Behrendt, H., Dannowski, R., Deumlich, D., Doležal, F., Kajewski, I., Klir, J., Kornmilch, M., Korol, R., Łabędzki, L., Makom, E., Mioduszewski, W., Opitz, D., Steidl, J., Strońska, M., Tippl, M., Zdanowicz, A., 2005b. Nutrient and heavy metals in the Odra River system. Emissions from point and diffuse sources, their loads, and scenario calculations On Possible Changes. Weiβensee Verlag Ökologie, 353 pp.

- Błaś, M., Sobik, M., Twarowski, R., 2008. Changes of Cloud water chemical composition in the Western Mountains, Poland. Atmos. Res., 87:224-231.
- Bowes, M.J., Smith, J.T., Jarvie, H.P., Neal, C., Barden, R., 2009. Changes in point and diffuse source phosphorus inputs to the River Frome (Dorset, UK) from 1966 to 2006. Sci. Tot. Environ. 407:1954-1966.
- Bogdanowicz, R., 2004. Hydrologiczne uwarunkowania transportu wybranych związków azotu i fosforu Odrą i Wisłą oraz rzekami Przymorza do Bałtyku. Wydawnictwo Uniwersytetu Gdańskiego, Gdańsk, 156 pp.
- Busman, L., Lamb, J., Randall, G., Rehm, G., Schmitt, M., 1998. The nature of phosphorus in soils. University of Minnesota. http://www.extension.umn.edu/distribution/cropsystems/DC6795.html [Accessed in June 2009].
- Campling, P., Terres, J.M., Walle, S.V., Van Orshoven, J., Crouzet, P., 2005. Estimation of nitrogen balances from agriculture for EU-15: spatialisation of estimates to river basins using the CORINE Land Cover. Phys. Chem. Earth, 30:25-34.
- Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., Smith, V.H., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol. Appl., Vol. 8, No. 3:559-568.
- Dannowski, R., Steidl, J., Mioduszewski, W., Kajewski, I., 2002. GIS-based distributed analysis of subsurface nitrogen flow in the Odra basin. J. Wat. Land Develop., 6:91-104.
- Dubicki, A., 1999. Program szybkiego działania dla ochrony rzeki przed zanieczyszczeniem 1007-2002. KORAB, Wrocław, 111 pp.
- Dubicki, A., 2000. Ocena stanu realizacji inwestycji objętych programem szybkiego działania dla ochrony rzeki Odry przed zanieczyszczeniem 1997-2002. KORAB, Wrocław, 38 pp.
- Eriksson, H., Pastuszak, M., Löfgren, S., Mörth, C-M., Humborg, C., 2007. Nitrogen budgets of the Polish agriculture 1960-2000 Implications for riverine nitrogen loads to the Baltic Sea. Biogeochemistry, 85:153-168.
- Fal, B., Bogdanowicz, E., Czernuszenko, W., Dobrzyńska, I., Koczyńska, A., 2000. Przepływy charakterystyczne głównych rzek polskich w latach 1951-1995. Materiały Badawcze, Seria: Hydrologia i Oceanologia, Instytut Meteorologii i Gospodarki Wodnej, Warszawa. No. 26, 137 pp.
- Fernández, J. A., Poulsen, H. D., Boisen, S., Rom, H. B., 1999. Nitrogen and phosphorus consumption, utilization and losses in pig production: Denmark. Livestock Production Science, 58:225-242.
- (FoE Europe) Friends of the Earth Europe, maj/czerwiec 2004. Rozszerzenie Unii Europejskiej a rolnictwo szanse i zagrożenia, 73 pp. http://www.foeeurope.org/agriculture/publications/E&A\_national/PKE\_rolnictwo.pdf [Accessed: on 02 June 2009].
- Grimvall, A., Stålnacke, P., Tonderski, A., 2000. Time-scales of nutrient losses from land to sea an European perspective. Ecol. Eng., 14:363-371.
- $Grizetti, B., Bouraoui, F., De\ Marsily, G., Bidoglio, G., 2005.\ A\ statistical\ method\ for$

- source apportionment of riverine nitrogen loads. J. Hydrol., 304:302-315.
- GUS (Central Statistical Office), Statystyka Polski, Ochrona Środowiska, Gospodarka Wodna. Annuals issued in 1981-1989, Warszawa, Poland.
- GUS (Central Statistical Office), Ochrona Środowiska. Annuals issued in 1991-2010, Warszawa, Poland
- GUS (Central Statistical Office), 2009a. Użytkowanie gruntów, powierzchnia zasiewów i pogłowie zwierząt gospodarskich w 2009 r. Informacje i Opracowania Statystyczne, Warszawa, Poland.
- GUS (Central Statistical Office), 2009b. Rocznik Statystyczny Rolnictwa, Warszawa, Poland.
- Hatfield, J.L., Follett, R.F., (eds.), 2008. Nitrogen in the Environment (second edition): Sources, Problems and Management. Academic Press, 702 pp.
- Haycock, N.E., Pinay, G., Walker, C., 1993. Nitrogen retention in river corridors: European perspective. Ambio, 22(6):340-346.
- Heathwaite, A.L., Dils, R.M., 2000. Characterizing phosphorus loss in surface and subsurface hydrological pathways. Sci. Tot. Environ., 251:523-538.
- Heathwaite, A.L., Quinn, P.F., Hewett, C.J.M., 2005. Modelling and managing critical source areas of diffuse pollution from agricultural land using flow connectivity simulation. J. Hydrol., 304:446-461.
- HELCOM, 2001. Environment of the Baltic Sea area 1944-1998. Baltic Sea Environment Proceedings No. 82A.
- HELCOM, 2004. The Fourth Baltic Sea Pollution Load Compilation (PLC-4). Baltic Marine Environ. Protection Com. Proc. No. 93.
- HELCOM, 2007. Towards a Baltic Unaffected by eutrophication, HELCOM Overview 2007, HELCOM Ministerial Meeting, Kraków, Poland.
- HELCOM, 2009. Eutrophication in the Baltic Sea An integrated thematic assessment of the effects of nutrient enrichment and eutrophication in the Baltic Sea region. Baltic Sea Environ. Proc. 155B.
- Hirsch, R.M., Slack, J.R., 1984. A nonparametric trend test for seasonal data with serial dependence. Water Resources Research 20:727–732.
- Honisch, M., Hellmeier, C., Weiss, K., 2002. Response of surface and subsurface water quality to land use changes. Geoderma, 105:277-298.
- Hooda, P.S., Moynagh, M., Svoboda, I.F., Thurlow, M., Stewart, M., Thomson, M., Anderson, H.A., 1997. Stream-water nitrate concentrations in six agricultural catchments in Scotland. Sci. Tot. Environ., 201:63-78.
- Hooda, P.S., Edwards, A.C., Anderson, H.A., Miller, A., 2000. A review of water quality concerns in livestock farming areas. Sci. Total Environ., 250:143-167.
- Hooda, P.S., Truesdale, V.W., Edwards, A.C., Withers, P.J.A., Aitken, M.N., Miller, A., Rendell, A.R., 2001. Manuring and fertilization effects on phosphorus accumulation in soil and potential environmental implications. Adv. Environ., Res. 5:13-21.

- House, W.A., 2003. Geochemical cycling of phosphorus in rivers. Appl. Geochem., 18:739–48.
- Howarth, R.W., Billen, G., Swaney, D., Townsend, A., Jaworski, N., Lajtha, K., Downing, J.A., Elmgren, R., Caraco, N., Jordan, T., Berendse, F., Freney, J., Kundeyarov, V., Murdoch, P., Zhao-Liang, Z., 1996. Regional nitrogen budgets and riverine N P fluxes for the drainages to the North Atlantic Ocean: Natural and human influence. Biogeochemistry, 35:75-139.
- Hussian, M., Grimvall, A., Petersen, W., 2004. Estimation of the human impact on nutrient loads carried by the Elbe River. Environ. Monit. Assess., 96:15-33.
- Hyland, C., Ketterings, Q., Dewing, D., Stockin, K., Czymmek, K., Albrecht, G., Geohring, L., 2005. Nutrient Management Spear Program, Cornell University, Cooperative Extension http://nmsp.css.cornell.edu/publications/factsheets/factsheet12.pdf [Accessed in June 2009].
- Iital, A., Loigu, E., Vagstad, N., 2003. Nutrient losses and N & P balances in small agricultural watersheds in Estonia. Nordic Hydrol., 34:531-542.
- Iital, A., Stålnacke, P., Deelstra, J., Loigu, E., Pihlak, M., 2005. Effects of large-scale changes in emissions on nutrient concentrations in Estonian rivers in the Lake Peipsi drainage basin. J. Hydrol., 304:261-273.
- Ilnicki, P., 2004. Polskie Rolnictwo a Ochrona Środowiska. Wydawnictwo Akademii Rolniczej im. Augusta Cieszkowskiego w Poznaniu, Poznań, 485 pp.
- IMWM (Institute of Meteorology and Water Management) in Gdynia, 1989 2001. Annual Reports "Warunki środowiskowe polskiej strefy południowego Bałtyku" ("Environmental conditions in the Polish zone of the southern Baltic Sea") (in Polish).
- IMWM (Institute of Meteorology and Water Management) in Warsaw, 1990-2002. Monthly Bulletins "Zasoby Wodne Kraju" ("Water Resources in Poland") (in Polish).
- IMWM (Institute of Meteorology and Water Management) in Warsaw, 2003-2011. "Miesięczne Biuletyny Państwowej Służby Hydrologiczno-Meteorologicznej", Warszawa ("Monthly Bulletins of the National Hydrological and Meteorological Service") (in Polish).
- Jankowiak, J., Szpakowska, B., Bienkowski, J., 2003. Ecological aspects of transformation in Poland's agriculture based on the Wielkopolska region. Ambio, Vol. 32 No. 6, pp. 418-423.
- Jarosiewicz, A., 2009. Transformation of the water quality in the Słupia River (Poland) Environment Technology Resources Proceedings of the 7<sup>th</sup> International Scientific and Practical Conference. Vol. II, pp. 64-70.
- Kata, R., Miś, T., 2006. Regional disparities of Poland's agriculture in aspect of its financing from the European Union funds. In: New Members New Challenges for he European Regional Development Policy, Technical University of Košice, University of Economics in Bratislava, German Section in ERSA, Novy Smokoves, pp. 164-170.

- Kelly, V.R., Lovett, G.M., Weathers, K.C., Likens, G., 2005. Trends in atmospheric ammonium concentrations in relation to atmospheric sulfate and local agriculture. Environ. Pollut., 135:363-369.
- Kiryluk-Dryjska, E., 2007. Macro-regional differentiation of farmers' interest in Polish rural development program measures in Poland. Roczniki Akademii Rolniczej w Poznaniu. CCCLXXXV, pp.68-75.
- Kowalkowski, T., Pastuszak, M., Igras, J., Buszewski., B. 2012. Differences in emission of nitrogen and phosphorus into the Vistula and Oder basins in 1995-2008 Natural and anthropogenic causes (MONERIS model). J. Mar. Syst., 89:48-60.
- Kronvang, B., Hoffmann, C.C., Svendsen, L.M., Windolf, J., Jensen, P., Dørge, J., 1999. Retention of nutrients in river basins. Aquatic Ecology, 33:29-40.
- Kronvang, B., Jeppesen, E., Conley, D.J., Søndergaard, M., Larsen, S.E., Ovesen, N.B., Carstensen, J., 2005. Nutrient pressures and ecological responses to nutrient loading reductions in Danish streams, lakes and coastal waters. J. Hydrol., 304:274-288.
- Kurowski, P., 1998. Scope and Forms of State Support to Enterprises in Poland in Period of Transition, [in:] Petersen, H-G. (ed.), Special Series: Industrial and Social Policies in Countries in Transition. University of Potsdam, faculty of Economics and Social Sciences, 18 pp.
- Kvítek, T., Žlábek, P., Bystřicky, V., Fučik, P., Lexa, M., Gergel, J., Novák, P., Ondr, P., 2009. Changes of nitrate concentrations in surface waters influenced by land use in the crystalline complex of the Czech Republic. Phys. Chem. Earth, 34:541-551.
- Land Cover & Population Statistics, Baltic Sea Region GIS, Maps and Statistical database www.grida.no [Accessed on 22 November 2011].
- Landsberg-Uczciwek, M., Mazur, J., Pietruszak, A., Strogonowski, A., Szablewska, J., Wierzchowska, E., Wiśniowski, Z., Złoczowska, I., Zawadzki, T., 2005. Analiza oddziaływania rolnictwa na środowisko wodne w województwie zachodniopomorskim potencjalne zagrożenia w rozwoju produkcji. Inspekcja Ochrony Środowiska, Wojewódzki Inspektorat Ochrony Środowiska, Szczecin, 57 pp.
- Lepistö, A., Granlund, K., Kortelainen, P., Räike, A., 2006. Nitrogen in river basin: Sources, retention in the surface waters and peatlands, and fluxes to estuaries in Finland. Sci. Tot. Environ., 365:238-259.
- Libiseller, C., Grimvall, A., 2002. Performance of Partial Mann Kendall Tests for Trend Detection in the Presence of Covariates, Environmetrics, 13:71-84.
- Majewski, A., 1974. Charakterystyka Hydrologiczna Zatoki Pomorskiej. Wydawnictwo Komunikacji i Łączności, Warszawa. 110 pp.
- Majewski, A. (ed.), 1980. Zalew Szczeciński. Wydawnictwo Komunikacji i Łączności, Warszawa. 339 pp.
- Mander, Ü., Kuusemets, V., Ivask, M., 1995. Nutrient dynamics of riparian ecotones: a case study from the Porijõgi River catchment, Estonia., Landscape Urban Plan, 31:333-348.

- Mander, Ű., Kull, A., Kuusemets, V., Tamm, T., 2000. Nutrient runoff dynamics in a rural catchment: Influence of land-use changes, climatic fluctuations and ecotechnological measures. Ecol. Eng., 14:405-417.
- Mayer, R., 1998. Soil acidification and cycling of metal elements: cause-effect relationship with regard to forestry practices and climatic changes. Agric. Ecosyst. Environ., 67:145-152.
- Mc Lenaghen, R.D., Cameron, K.C., Lampkin, N.H., Daly, M.L., Deo, B., 1996. Nitrate leaching from ploughed pasture and the effectiveness of winter catch crops in reducing leaching losses. New Zealand, J. Agr. Res., 39:413-420.
- Meybeck, M., 2001. River Basin under Anthropocene Conditions. [in:] Bodungen, B.v., Turner, R.K., (eds.), Science and Integrated Coastal Management, Dahlem University Press, pp. 275-294.
- Mohrholz, V., Pastuszak, M., Sitek, S., Nagel, K., Lass, H.U., 1998. The exceptional Oder flood in summer 1997 Riverine mass- and nutrient transport into the Pomeranian Bight. 1998. Dtsch. Hydrogr., Z., Vol. 50, No. 2/3, pp. 129-144.
- Moreno, D., Pedrocchi, C., Comín, F.A., García, M., Cabezas, A., 2007. Creating wetland for the improvement of water quality and landscape restoration in semi-arid zones degraded by intensive agricultural use. Ecol. Eng., 30:103-111.
- Moskal, S., Mercik, S., Turecka, E., Stępień, W., 1999. Bilans fosforu nawozowego w wieloletnich doświadczeniach polowych w Skierniewicach. Zesz. Prob. Post. Nauk. Rol., 465:61-69.
- Neal, C., Jarvie, H.P., Neal, M., Hill, L., Wickham, H., 2006. Nitrate concentrations in river waters of the upper Thames and its tributaries. Sci. Tot. Environ., 365:15-32.
- Neal, C., Davies, H., Neal, M., 2008. Water quality, nutrients and the water framework directive in agricultural region: The lower Humber Rivers, northern England. J. Hydrol., 350:232-245.
- Nixon, S., (ed.), 1999. Groundwater quality and quantity in Europe. European Environment Agency, Copenhagen, Denmark, 123 pp.
- Nixon, S.W., Ammerman, J.W., Atkinson, L.P., Berounsky, V.M., Billen, G., Boicourt, W.C., Boynton, W.R., Church, T.W., Diroto, D.M., Elmgren, R., Garber, J.H., Giblin, A.E., Jahnke, R.A., Owens, N.J.P., Pilson, W.E.Q., Seitzinger, S.P., 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. Biogeochemistry, 35:141-180.
- OECD (Organization for Economic Cooperation and Development), 2001. Environmental Indicators for Agriculture. Methods and Results. Agriculture and Food. Paris, France, Vol. 3, 409 pp.
- Oenema, O., 1999. Nitrogen cycling and losses in agricultural systems; identification of sustainability indicators [in:] Sapek, A., (ed.), Poland Agriculture and Water Quality Protection, Nitrogen Cycle and Balance in Polish Agriculture, Conference Proceedings, Institute for Land Reclamation and Grassland Farming (IMUZ), Falenty pp. 25-43.

- Oenema, O., Roest, C.W., 1998. Nitrogen and phosphorus losses from agriculture into surface waters; the effects of policies and measures in the Netherlands. Wat. Sci. Tech., Vol. 37, No. 2, pp. 19-30.
- Oenema, O., Kros, H., De Vries, W., 2003. Approaches and uncertainties in nutrient budgets: implications for nutrient management and environmental policies. Europ. J. Agronomy, 20:3-16.
- Oenema, O., Van Liere, L., Schoumans, O., 2005. Effects of lowering nitrogen and phosphorus surpluses in agriculture on the quality of groundwater and surface water in the Netherlands. J. Hydrol., 304:289-301.
- Oláh, J., Oláh, M., 1996. Improving landscape nitrogen metabolism in the Hungarian lowlands. Ambio, 25:331-335.
- Pastuszak, M., Witek, Z., Nagel, K., Wielgat, M., Grelowski, A., 2005. Role of the Oder estuary (southern Baltic) in transformation of the riverine material. J. Mar. Syst., 57:30-54.
- Pastuszak, M., Stålnacke, P., Pawlikowski, K., Witek, Z., 2012. Response of Polish rivers (Vistula, Oder) to reduced pressure from point sources and agriculture during the transition period (1988-2008). J. Mar. Syst., 94:157-173.
- Peierls, B., Caraco, N., Pace, M., Cole, J., 1991. Human influence on river nitrogen. Nature, 350:386-387.
- Povilaitis, A., 2006. Impact of agriculture decline on nitrogen and phosphorus loads in Lithuanian rivers. Ekologia, No. 1, pp. 32-39.
- Program dla Odry 2006 aktualizacja (2009) Wrocław; http://www.programodra. pl/aktualizacjaPdO2006/PdO\_2006\_AKTUALIZACJA\_24\_07\_09.pdf [Accessed: on 6 May 2010].
- Räike, A., Pietiläinen, O.-P., Rekolainen, S., Kauppila, P., Pitkänen, H., Niemi, J., Raateland, A., Vuorenmaa, J., 2003. Trends of phosphorus, nitrogen and chlorophyll *a* concentrations in Finnish rivers and lakes in 1975-2000. Sci. Tot. Environ., 310:47-59.
- Rekolainen, S., Pitkänen, H., Bleeker, A., Felix, S., 1995. Nitrogen and phosphorus fluxes from Finnish agricultural areas to the Baltic Sea. Nordic Hydrology, 26:55-72.
- Ruttenberg, K.C., 2003. The Global Phosphorus Cycle. Treatise on Geochemistry, Vol. 8; (Elsevier ISBN: 0-08-043751-6) pp. 585-643.
- Salo, T., Turtola, E., 2006. Nitrogen balance as an indicator of nitrogen leaching in inland. Agr. Ecosyst. Environ.,113:98-108.
- Sapek, A., 1998. Phosphorus cycle in Polish agriculture [in:] Phosphorus in agriculture and water quality protection. Conference Proceedings, Institute for Land Reclamation and Grassland Farming (IMUZ), Falenty pp. 8-18.
- Sądej, W., 2000. Badania nad przemianami fosforu w glebach i jego wykorzystaniem przez rośliny uprawne w warunkach zróżnicowanego nawożenia. Praca Habilitacyjna. UMW Olsztyn, 78 pp.
- Sharpley, A.N., 1995. Dependence of runoff phosphorus on extractable soil

- phosphorus. J. Environ. Qual., 24:920-926.
- Sharpley, A.N., 2006. Agricultural Phosphorus management: Protecting Production and Water Quality. Lesson 34. Agricultural Research Service. Mid West Plan Service. Iowa State University, Ames, Iowa 50011-3080; http://www.lpes.org/Lessons/Lesson34/34\_Phosphorus\_Management.html [Accessed in June 2009].
- Sharpley, A.N., Gburek, W.J., Folmar, G., Pionke, H.B., 1999. Sources of phosphorus exported from an agricultural watershed in Pennsylvania. Agr. Water Manage., 41:77-89.
- Stålnacke, P., Grimvall, A., Libiseller, C., Laznik, M., Kokorite, I., 2003. Trends in nutrient concentrations in Latvian rivers and the response to the dramatic change in agriculture. J. Hydrol., 283:184-205.
- Stålnacke, P., Vandsemb, S.M., Vassiljev, A., Grimvall, A., Jolankai, G., 2004. Changes in nutrient levels in some Eastern European rivers in response to large-scale changes in Agriculture. Water Sci. Techno., 49(3):29-36.
- Steineck, S., Jakobson, Ch., Carlson, G., 2002. Fosfor stosowanie, wykorzystanie przez rośliny uprawne i nagromadzenie w glebach użytków rolnych. Zeszyty Edukacyjne IMUZ, 7, pp. 25-36.
- Szara, E., Mercik, S., Sosulski, T., 2004. Bilans fosforu w trzech systemach nawożenia. Annales Universitas Mariae Curie-Skłodowska, Lublin, Polonia, Vol. LIX, Nr. 2, Sectio E., pp. 599-606.
- Syryczyński, P., 2003. Privatisation programmes in Poland and Romania: who should pay for site restoration?. Land Contamination & Reclamation, 11(1):59-67.
- Vagstad, N., Stålnacke, P., Andersen, H-E., Deelstra, J., Jansons, V., Kyllmar, K., Loigu, E., Rekolainen, S., Tumas, R., 2004. Regional variations in diffuse nitrogen losses from agriculture in the Nordic and Baltic regions. Hydrol. Earth Syst. Sc., 8(4):651-662.
- Van Eerdt, M.M., Fong, P.K.N., 1998. The monitoring of nitrogen surpluses from agriculture. Environ. Poll., 102, S1:227-233.
- Vassiljev, A., Stålnacke, P., 2005. Source apportionment of nutrients in the Lake Peipsi drainage basin experiences from a statistical model. Water Sci. Technol., 51:309-317.
- Voss, M., Deutsch, B., Liskow, I., Pastuszak, M., Schulte, U., Sitek, S., 2010. Nitrogen retention in the Szczecin Lagoon, Baltic Sea. Isotopes in Environmental & Health Studies, Vol. 46, Issue 3, pp. 355-369.
- Voss, M., Deutsch, B., Elmgren, R., Heiskanen, A-S., Kuuppo, P., Liskow, I., Pastuszak, M., Rolff, C., Schulte, U., 2006. Source identification of nitrate by means of isotopic tracers in the Baltic Sea catchments. Biogeosciences, 3:663-676.
- Voss, M., Liskow, I., Pastuszak, M., Rűß, D., Schulte, U., Dippner, J.W., 2005. Riverine discharge into coastal bay: A stable isotope study in the Gulf of Gdańsk, Baltic Sea. J. Mar. Syst., 57:127-145.

- Wahlin, K., Grimvall, A., 2009. Roadmap for assessing regional trends in groundwater quality. Submitted to Environmental Monitoring and Assessment.
- Wood, F.L., Heathwaite, A.L., Haygarth, P.M., 2005. Evaluating diffuse and point phosphorus contribution to river transfers at different scales in the Taw catchment, Devon, UK. J. Hydrol., 304:118-138.

10

ROLE OF THE ODER AND VISTULA ESTUARIES IN RETENTION OF NITROGEN AND PHOSPHORUS LOADS DIRECTED TO THE BALTIC SEA IN RIVERINE OUTFLOW

MARIANNA PASTUSZAK ZBIGNIEW WITEK

# 10. ROLE OF THE ODER AND VISTULA ESTUARIES IN RETENTION OF NITROGEN AND PHOSPHORUS LOADS DIRECTED TO THE BALTIC SEA IN THE RIVERINE OUTFLOW

Marianna Pastuszak, Zbigniew Witek

#### 10.1. Oder estuary, Pomeranian Bay

Following the definition given by Jasińska (1991), the Oder estuary is an area that is delimited by a fork of the Oder River in the south (into the Eastern and Western Oder), and the gradient of physical and chemical parameters in the Pomeranian Bay. In this Chapter, we will use two terms: (i) the inland part of the Oder estuary, which is delimited by the lowermost river monitoring station in the south (this monitoring station was assumed by us as the southern borderline of the estuary), and by the outlets of Świna, Dziwna, and Piana (Peenestrom – on German side) Straits in the north, and (ii) the marine part of the Oder estuary corresponding with the inner Pomeranian Bay (Fig. 10.1). The position of the northern boundary of the marine part of the Oder estuary is variable and it depends on the extent of outflowing riverine waters, and that in turn depends on seasonally variable water outflow and on strength and direction of prevailing winds in this part of the Baltic Sea (Pastuszak et al., 2003).

In order to define the position of the northern boundary of the Oder estuary i.e. the borderline between the inner and the outer Pomeranian Bay in 1993-1998, Pastuszak et al. (2005) calculated the average horizontal salinity distribution and accepted that the isohaline 7.1 PSU, positioned in the steepest part of the salinity gradient, would represent the border line between the subjected parts of the bay (Fig. 10.1). Defining of this borderline, and consequently the sub-areas in the bay, is necessary as it enables budget calculations and makes it possible to compare average values of salinity and average concentrations of nutrients in the neighboring regions. It is crucial that both regions have adequate coverage (in time and space) with oceanographic sampling stations because only extensive data sets assure reliable outcome of budgeting.

The length of the Oder estuary, measured from the lowermost river monitoring station up to the division line between the inner and the outer Pomeranian Bay equals to ca. 140 km, while its area amounts to ca. 2,800 km², and the volume reaches ca. 24.8 km³. North of the river monitoring station (Krajnik Dolny) the Oder River splits into the Eastern and Western Oder, which carry waters over the distance of about 30 km. The Eastern Oder flows then through the Lake Dąbie to converge with the Western Oder in Roztoka Odrzana, and then the waters continue through a large and shallow Szczecin Lagoon to reach the Pomeranian Bay through the three connecting straits. The area between the river branches, called Międzyodrze, is filled with polders and canals connecting the river branches, therefore it plays a very important role in water retention, particularly in seasonal freshets (Buchholz, 1990, 1991).

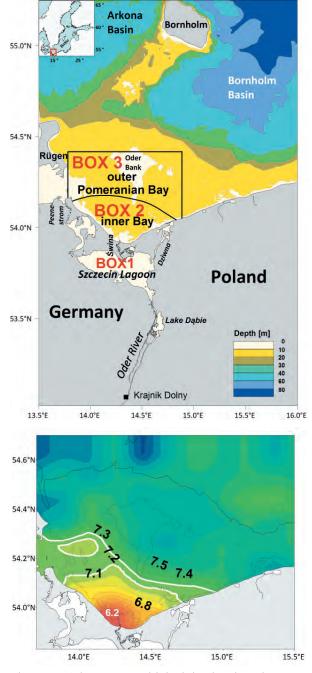


Fig. 10.1 The study area – Oder estuary with its inland and marine parts (the marine part corresponds with the inner Pomeranian Bay); boxes 1, 2 and 3 – indicate N and P budgeting compartments; lower map shows averaged salinity in PSU (Practical Salinity Units) in the Pomeranian Bay (1993-1998) (source: maps prepared and made available by M.Sc. Lena Szymanek, NMFRI, Gdynia)

The Szczecin Lagoon, a very important component of the entire Oder estuary, has a character of a shallow (average depth of about 3.8 m) coastal lake. The area of the lagoon is 687 km<sup>2</sup>, while its volume equals to 2.6 km<sup>3</sup> (Majewski, 1980). There are two major geographical parts of the lagoon – the Kleines Haff on the German side and the Wielki Zalew on the Polish side, both differing considerably in water exchange (Mohrholz and Lass, 1998; Fig. 10.1).

The Pomeranian Bay is bordered by the Polish and German coast in the south, and by the Arkona Basin and the Bornholm Basin in the north (Fig. 10.1). The Arkona and the Bornholm Basin are the first recipients of salt water from the Danish Straits. The northern boundary of the bay stretches approximately along the 20 m isobath. The area of the entire Pomeranian Bay, calculated within this boundary, equals to ca. 6000 km², while its volume reaches 73 km³. The bay is shallow and its depth does not exceed 20 m, dropping even to 6 m on the Oder Bank (Majewski, 1974).

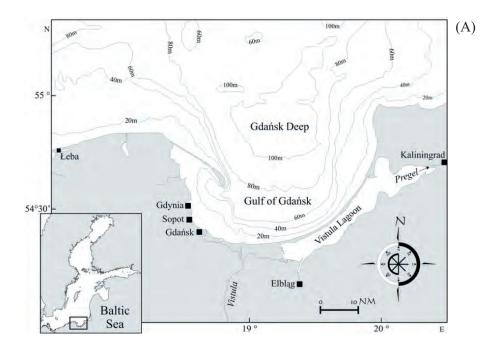
Between the years 1951-1998, the annual volumes of the Oder water, discharged into the Pomeranian Bay, varied from 9.46 km³ to 25.83 km³, with an average value of 16.83±4.24 km³; the average flow rate was of 535 m³s⁻¹ (Fal et al., 2000; IMWM, 1990-2002). The outflow of water transported through the three straits that connect the bay with the Szczecin Lagoon (Świna 75 %, Dziwna 10%, and Peene 15%), has a complex and unsteady nature induced by baroclinic and/or barotropic gradients (Beszczyńska-Möller, 1999; Mohrholz and Lass, 1998; Lass et al., 2001). On a time scale of several days the water exchange is mainly controlled by the sea level difference between the bay and the Szczecin Lagoon and by NE component of the wind-stress over the central Baltic Sea (Mohrholz and Lass, 1998). This results in temporary inflow/outflow events through the straits. The duration of a pulse-like outflow from the upper Oder estuary is about one day. The annual variability in water outflow is characterized not only by variable volumes of water discharged, but also by time of occurrence of spring peak in the outflow (Pastuszak et al., 2001).

## 10.2. Vistula River outlet, Gulf of Gdańsk

The Gulf of Gdańsk (Fig. 10.2 A) is fed by the Vistula River, the second largest river in the Baltic catchment. The average water flows in the Vistula River, estimated for the time period 1951-1990, reached 1081 m³s⁻¹ (Fal et al., 2000) which gives the annual water outflow on the level of 34.09 km³ yr¹, and this volume constitutes 90% of the entire riverine outflow supplying the gulf. The remaining 10% of water discharge comes mainly from the Vistula Lagoon which is fed by the Pregel River and some other rivers discharging their waters with an average water flow rate of 117 m³s⁻¹ (3.7 km³ yr¹) (Lazarienko and Majewski, 1975). At present, the Vistula Lagoon does not have a direct connection with the Vistula River. The surface area of the Gulf of Gdańsk equals to 4940 km², while the volume reaches 291 km³. The maximum depth of the Gulf of Gdańsk is 118 m (Majewski, 1994) and this parameter

distinguishes the gulf from the Pomeranian Bay. The substantial depth causes that the water in the Gulf of Gdańsk is permanently stratified. The Vistula River plume has usually horizontal extension of about 5-15 nautical miles from the river mouth, while the vertical extension is in a range 0.5-12 m (Cyberska and Krzymiński, 1988; Grelowski and Wojewódzki, 1996). Salinity in the Gulf of Gdańsk is uniform (7-8 PSU) down to the depth of 60-70 m, and this upper isohaline layer constitutes 75-84% of the entire gulf volume; the halocline (zone of the strong salinity gradient) and the deep waters constitute the remaining 16-25%. Salinity in the deep layer depends on water inflows from the North Sea, thus it depends on large scale processes (Lass and Matthäus, 2008). The deep waters are occasionally stripped of oxygen, and at anoxic conditions they become rich with phosphates and ammonium.

In order to meet the requirements of the N and P budgeting, similarly to the Pomeranian Bay, the entire Gulf of Gdańsk was horizontally divided into two closed areas (the inner Gulf of Gdańsk and the open waters; Fig. 10.2 B, C). The layering of the water column in the Gulf of Gdańsk imposed necessity of dividing the outer gulf as well as open waters into the upper zone (mixed) and the lower zone (stratified) (Fig. 10.2 C).



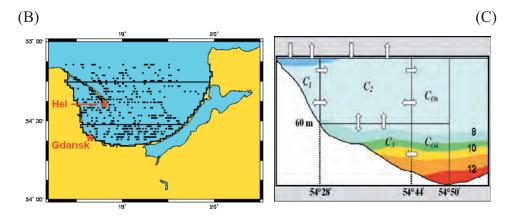


Fig. 10.2 The Gulf of Gdańsk with the lowermost section of the Vistula River (A), coverage with the study stations in 1993-1998 (B), and salinity stratification (average salinity in 1993-1998 in PSU), and simple diagram showing water and nutrient flows between the compartments specified for the budgeting (C); symbols C<sub>1</sub>, C<sub>2</sub>, C<sub>3</sub> indicate salinity and nutrient concentrations in the inner, the outer upper, and the outer lower parts of the gulf; C<sub>0s</sub> and C<sub>0d</sub> – concentrations in the upper and lower layer of the open sea. Line 60 m indicates an average level of halocline upper limit, and it is a borderline between the upper mixed and lower stratified layer of water (source: Witek et al., 2003).

# 10.3. The method of nitrogen and phosphorus mass balance calculations

The papers dealing with N and P balance in the Oder estuary and in the Gulf of Gdańsk have been published by Grelowski et al. (2000), Witek et al. (2003), and Pastuszak et al. (2005), therefore the details concerning the methodology of budgeting have been omitted in this monograph as they can be found in the source materials. It is, however, worth mentioning that N and P mass balance was calculated in accordance with the recommended international LOICZ method (Land-Ocean Interactions in the Coastal Zone) (Gordon et al., 1996), which is rooted in the salt balance (Knudsen, 1900). The basic assumptions of the Knudsen's (1900) salt balance are graphically presented in Fig. 10.3.

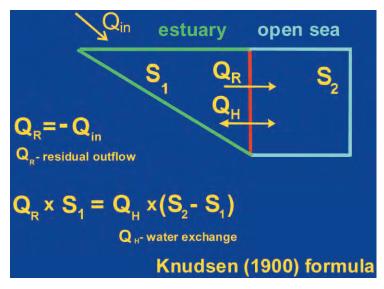


Fig. 10.3 Schematic graph explaining calculations of water exchange intensity ( $Q_H$ ) between two areas with different salinity ( $S_1$  and  $S_2$ ); one of the areas is fed with the riverine outflow ( $Q_{in}$ ).  $Q_R$  is the residual outflow, balancing the riverine outflow, at the assumption that the water volume in the estuary is constant. Value  $Q_H$  is then used in N, P budgeting; equation after: Knudsen (1900). For simplicity precipitation, evaporation, groundwater flow etc. were omitted

There are only two defined areas (boxes) in Fig. 10.3, but it is obvious that the same principle is obligatory for the cascade system which was applied in the case of the Pomeranian Bay and the Gulf of Gdańsk. In order to perform the balance calculations it is essential that we know the volume of the riverine inflow  $(Q_{in})$ , the residual outflow  $(Q_R)$ , and the water exchange between the estuary and the open sea  $(Q_H)$ . The residual outflow, without taking into account precipitation and evaporation, is numerically equal to the riverine inflow. The water exchange between the estuary and the open sea can be calculated based on salt balance. Salt is a conservative parameter, thus salinity is unrelated to biological processes occurring in a given region. Mixing of various water masses is the only process shaping the salinity. The Knudsen's (1900) formula states that in order to maintain salinity on unchanged level the salt inflow must be balanced by the salt outflow:

$$\mathbf{Q}_{\mathrm{in}} \times \mathbf{S}_{\mathrm{r}} + \mathbf{Q}_{\mathrm{H}} \times \mathbf{S}_{\mathrm{2}} = \mathbf{Q}_{\mathrm{R}} \times \mathbf{S}_{\mathrm{1}} + \mathbf{Q}_{\mathrm{H}} \times \mathbf{S}_{\mathrm{1}},$$

where:  $S_r$ ,  $S_1$ , and  $S_2$  indicate mean salinity of riverine, estuarine, and open sea waters, respectively.

Assuming that salinity of riverine waters  $Q_r$  equals 0, we obtain a simplified version of the equation:  $Q_H \times S_2 = Q_R \times S_1 + Q_H \times S_1$ 

This, after rearranging, allows calculation of the volume of water exchange:

$$Q_{H} = Q_{R} \times S_{1} / (S_{2} - S_{1}).$$

Knowing  $Q_{\rm R}$  and  $Q_{\rm H}$ , and knowing from the measurements the average nutrient

concentrations in distinguished areas, we are able to calculate loads of the substances which migrate between these areas. Knowing loads of nitrogen and phosphorus introduced into the system and knowing, from the balance calculations, loads of N and P exported from the system, we are able to calculate the retention i.e. the amounts of N and P that are kept in the system. The reliable budgeting calls for such a number of monitoring data that would assure minimizing of any interferences arising from the temporal (seasonal) as well as spatial variability of parameters studied. In the case of our studies, the input data encompassed (i) N and P loads introduced into the system with riverine outflow (monitoring data from Krajnik Dolny – for the Oder, and from Kiezmark – for the Vistula) and from deposition from the atmosphere (monitoring data on atmospheric deposition at Łeba station), (ii) information on N and P input from point sources, (iii) salinity and nutrient concentrations in the Szczecin Lagoon, in the inner and outer Pomeranian Bay, in the inner and outer Gulf of Gdańsk, in the open gulf waters, and in the open sea waters adjacent to the Gulf of Gdańsk. Sources of these data are given in papers by Pastuszak et al. (2005) and Witek et al. (2003).

## 10.4. Seasonal variability in nutrient concentrations in the Oder River and the Świna Strait

Patterns of nitrogen species concentrations in the Oder (Krajnik Dolny) clearly show: (i) a very well developed seasonality, with maximum concentrations in winter and minimum concentrations in summer, (ii) significant predominance of DIN (dissolved inorganic nitrogen; N-NO $_3$ +N-NO $_2$ +N-NH $_4$ ) over organic nitrogen (N $_{\rm org}$ )  $(N_{org.} = N_{tot.} - DIN)$  in all seasons but summer, when DIN can be exhausted and nitrogen is then present mainly as  $N_{org.}$  (Fig. 10.4). DIN concentrations, greatly predominated by nitrates, only incidentally reached the value of ca. 5 mg dm<sup>-3</sup>, but generally the winter and early spring outflow was characterized by DIN concentrations in a range 3-4 mg dm<sup>-3</sup>.

There are two features that distinguish patterns of phosphorus concentrations: (i) a considerable contribution of organic forms whole year round, and (ii) the fact that seasonality of this element is not as clear as in the case of nitrogen. The seasonal cycle of DIP (dissolved inorganic phosphorus; PO<sub>4</sub>-P) shows maximum concentrations in autumn and winter and minimum in spring (Fig. 10.4).

A direct comparison of nutrient concentrations in the Oder River and Świna Strait (Fig. 10.4) demonstrates that: (i) concentrations in Świna were characterized by much more pronounced short term variability which is a result of a pulsating character of water exchange between the bay and the lagoon, (ii) DIN concentrations in Świna were much lower than in the Oder and that is due the dilution effect, the N uptake by phytoplankton, and the denitrification process, (iii) during summer season, DIP concentrations in the Świna Strait were higher than those in the Oder, and that in turn indicates a predominance of DIP regeneration over its uptake (Pastuszak et al., 1996).

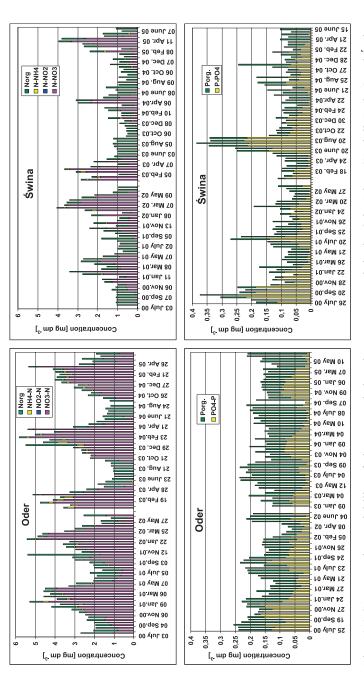


Fig. 10.4 Concentration variability of nitrogen and phosphorus compounds in the Oder River (Krajnik Dolny) and Świna Strait (sampling point at Świna Strait outlet) over the period July 2000 - June 2005 (own data; the measurements made in the frame of EU projects: SIGNAL and SIBER)

## 10.5. Results of mass balance calculations in the Oder estuary

The budgeting of N and P must be preceded by calculation of water balance, because water is a physical carrier of nutrients. The whole process of calculations is described in detail by Pastuszak et al. (2005). In this Chapter we wish to provide the tabular (Table 10.1) and graphic (Fig. 10.5) presentation of the final results of N and P budgeting performed for the described regions; all the input data, indispensable for budget calculations, are in detail presented by Pastuszak et al. (2005). The Table 10.1 contains the loads for Peenestrom, and we need to explain here that Peenestrom was beyond our calculating area; therefore the subjected numbers had to be placed in a separate budgeting column.

Table 10.1 Nutrient budget for: (A) the inland part of the estuary, (B) the marine part of the estuary (inner Pomeranian Bay), and (C) the entire Oder estuary calculated for the years 1993-1998

(A)

Nutrients	$X_{inL}$ [tons yr <sup>-1</sup> ]	X <sub>out-Peene</sub> [tons yr <sup>-1</sup> ]	$X_{\text{NETWZ}} $ [tons yr <sup>1</sup> ]	$\Delta X_L$ [tons yr <sup>-1</sup> ]	RET-F <sub>XL</sub>
DIN	53 411	2 674	31 268	19 469	0.36
TN	80 312	5 316	43 771	31 225	0.39
DIP	2 108	271	1 771	66	0.03
TP	5 878	612	3 703	1 563	0.27

(B)

Nutrients	$X_{inPB1}$	X <sub>NETPB1</sub>	$\Delta X_{_{\mathrm{PB}1}}$	RET-F <sub>XPB1</sub>
	[tons yr <sup>-1</sup> ]	[tons yr <sup>-1</sup> ]	[tons yr <sup>-1</sup> ]	
DIN	31 935	26 051	5 884	0.18 (0.11)
TN	44 438	38 821	5 617	0.13 (0.07)
DIP	1 771	1 888	- 117	-0.07 (0.06)
TP	3 703	3 100	603	0.16 (0.10)

Numbers in brackets indicate the retention factors when referred to  $X_{\text{inL}}$ 

(C)

Nutrients	X <sub>in-est</sub> [tons yr <sup>-1</sup> ]	X <sub>out-Peene</sub> [tons yr <sup>-1</sup> ]	X <sub>NET-PB1</sub> [tons yr <sup>-1</sup> ]	$\Delta X_{EST}$ [tons yr <sup>-1</sup> ]	RET-F <sub>X-est</sub>
	[tons yr ]	[tons yi ]	[tons yr ]	[tons yr ]	
DIN	54 078	2 674	26 051	25 353	0.47
TN	80 979	5 316	38 821	36 842	0.45
DIP	2 108	271	1 888	-51	-0.02
TP	5 878	612	3 100	2 165	0.37

Symbols used:  $X_{inL}$ ,  $X_{inPBI}$ ,  $X_{in-est}$  – respective total loads to the Szczecin Lagoon, the inner Pomeranian Bay, and the entire Oder estuary;  $X_{out\text{-}Peene}$  – nutrient outflows through Peenestrom;  $X_{NETWZ}$  and  $X_{NET\text{-}PBI}$  – nutrient net outflow from the Szczecin Lagoon to the inner Pomeranian Bay, and from the inner to the outer bay;  $\Delta X_L$ ,  $\Delta X_{PBI}$  and  $\Delta X_{est}$  – the amounts of a nutrient retained in the lagoon, in the inner bay, and in the entire estuarine system;  $RET\text{-}F_{XL}$ ,  $RET\text{-}F_{XPBI}$  and  $RET\text{-}F_{X\text{-}est}$  - the retention factors for the inland part of the estuary, the inner Pomeranian Bay, and the entire Oder estuary. Numbers in brackets indicate the retention factors when referred to  $X_{inL}$ ; DIN- dissolved inorganic nitrogen, DIP – dissolved inorganic phosphorus, TN – total nitrogen, TP – total phosphorus (source: Pastuszak et al., 2005).

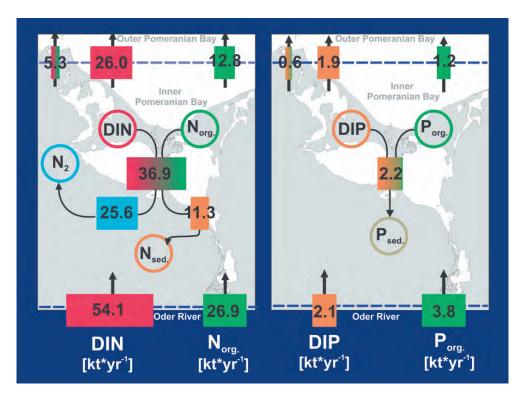


Fig. 10.5 Graphic illustration of mass budget calculations. Symbols used: DIN – dissolved inorganic nitrogen, N<sub>org</sub>.- organic nitrogen, N<sub>sed.</sub> – nitrogen directed to sediments,
 N<sub>2</sub> – nitrogen leaving the system through denitrification process, DIP – dissolved inorganic phosphorus, P<sub>org.</sub> – organic phosphorus, P<sub>sed.</sub> - phosphorus directed to sediments;
 kt - kiloton = 10<sup>3</sup> tons (data from the Table 10.1)

In 1993-1998, the annual net export of nutrients from the inner to the outer Pomeranian Bay, thus to open waters of the Baltic Sea, can be estimated at ca. 39,000 tons TN and ca. 3,100 tons TP. Additional 5,300 tons yr<sup>-1</sup> of nitrogen and 600 tons yr<sup>-1</sup> of phosphorus were outflowing from the Oder estuary to the Greifswalder Bodden

via Peenestrom (Table 10.1; Fig. 10.5). Compared to the inputs it means that about 45% of TN and 37% of TP were retained in the entire estuarine system, the rest was exported to the Baltic Sea. Budget calculations for the sub-areas also show that the inland part of the estuary played a key role in nutrient retention in the system. Almost 85% of TN retention and about 72% of TP retention took place there (Pastuszak et al., 2005).

There was quite substantial modification of percentage contribution of phosphorus compounds (DIP,  $P_{org}$ ) and nearly no change in composition of nitrogen pool (DIN,  $N_{org}$ ) after passing through the entire estuary. The contribution of DIP to TP increased from 36% in the inflowing water to 60% in the outflowing water, while contribution of DIN to TN remained on unchanged level of ca. 66%. Considerable increase in contribution of DIP to TP resulted from the fact that at ca. 30% reduction of TP load in the estuarine system there was practically no reduction of DIP load. Only slightly changed DIP loads at the entrance and at the exit of the estuary indicate that P assimilation during photosynthesis was balanced by its regeneration in the system. As for nitrogen, apart from the uptake and mineralization processes, there are two other processes that affect the net DIN loads, and that is denitrification, leading to N, release to the atmosphere, and N, fixation by blue-green algae. Mass balance calculations, made with application of LOICZ method, make it possible to estimate only the net effect of these two processes. Having uptake by algae balanced by mineralization, the DIN retention in the entire Oder estuary (about 25,000 tons yr<sup>-1</sup>; Table 10.1) may be considered as a net denitrification in excess of nitrogen fixation (Den-Nfix). Most of Den-Nfix took place in the inland part of the estuary (19,000 tons yr<sup>-1</sup>), while only a minor part (less than 6,000 tons yr<sup>-1</sup>) can be attributed to the inner Pomeranian Bay. When recalculated per unit area, it gives about 19 gN m<sup>-2</sup> yr<sup>-1</sup> for the inland estuary, and about 5 gN m<sup>-2</sup> yr<sup>-1</sup> for the marine part of the Oder estuary. Denitrification in the marine part of the Oder estuary was practically the only process causing N retention there (Pastuszak et al., 2005). That statement has been recently supported by findings of Voss et al. (2010) who studied nitrogen retention and transformation in the Szczecin Lagoon. The authors performed their studies by means of budget calculations and stable isotope data of dissolved and particulate matter. The outcome showed that denitrification played a major role in N removal process.

#### 10.6. Results of mass balance calculations in the Gulf of Gdańsk

Similarly to the Pomeranian Bay, we present here only final results of mass balance calculations (Table 10.2); the other data, indispensible in budgeting, can be found in the paper by Witek et al. (2003).

Table 10.2 Nitrogen and ph	nosphorus fluxes in the	he Gulf of Gdańsk in	1993-1998
estimated from budget calcul	lations (source: Witel	k et al., 2003)	

	DIP	DIN	TP	TN
	[tons yr-1]	[tons yr <sup>-1</sup> ]	[tons yr <sup>-1</sup> ]	[tons yr-1]
Discharge <sup>1)</sup>	5647	86 420	8786	130 787
Residual export	-1930	-10 459	-3604	-46 728
Deep inflow	6220	14 369	8196	38 360
Surface exchange	-3405	-21 526	-10 403	-92384
Net exchange	885	-17 617	-5812	-100 752
X retained	6532	68 803	2974	30 035
Retention coefficient	1.16	0.80	0.34	0.23

 <sup>1) -</sup>loads introduced to the system constitute a sum of those: a) carried with the Vistula River,
 b) from the Vistula Lagoon, c) from waste water treatment plants, d) from industry, and e) from atmosphere

The total loss of TN to the open sea (net exchange) exceeded 100,000 tons annually or about 77% of the total inputs from riverine, atmospheric, and point sources, while 23% was retained in the gulf system (Table 10.2). About 66% of the TN load from terrestrial and atmospheric sources was in dissolved inorganic forms, and therefore potentially available for primary producers in the gulf. The DIN contribution to the net export was much smaller and 83% of the exported nitrogen was in organic form. Thus, the net flux of DIN to the Baltic represented only about 20% of the DIN discharges to the gulf, 80% was retained or transformed into organic forms in the gulf. The estimated denitrification (Den-Nfix) in the Gulf of Gdańsk and in the river section between Kiezmark and the river mouth, reached the value of 6.7 gN m<sup>-2</sup> yr<sup>-1</sup>.

The net exchange of TP to the Baltic Sea constituted ca. 66% of the inputs from riverine, atmospheric, and point sources; 34% of the load was retained in the gulf (Table 10.2). Similar to nitrogen, approximately 2/3 of these inputs were in dissolved inorganic form. The deep inflow of DIP appeared to be higher than the combined residual outflow and surface exchange, leading to the net import from the open sea (the retention coefficient above 1) and resulting in a total DIP retention or transformation into P particulate forms, of 6,532 tons yr<sup>1</sup>, thus by 885 tons more than influx from land and atmosphere.

#### 10.7. Nutrient transformation in estuarine and coastal zones

There are numerous processes leading to modification of dissolved/suspended matter brought into any estuary. These processes take place in both water column and sediments, and the most important ones include uptake by algae and bacteria (Lebo, 1990; Magnien et al., 1992), demineralization (Vidal and Morguí, 1995; Malone et al., 1996), nitrification (Pakulski et al., 1995), denitrification (Seitzinger and Giblin, 1996), sorption/desorption (Anschutz et al., 1998), sedimentation and resuspension (Vidal, 1994, Conley and Johnstone, 1995) and burial in sediments (Boynton et al., 1995, Howarth et al. 1995; Nixon et al. 1995, 1996). Processes in sediments play a very important role in shallow coastal estuarine systems, because a substantial part of the nutrients taken up by phytoplankton, sinks down to the bottom, and is recycled there (Boynton and Kemp 1985; Kemp et al., 1990; Van Raaphorst et al., 1992; Baird et al., 1995; Cowan and Boynton 1996; Cowan et al., 1996; Conley et al., 1997; Pastuszak et al., 2001, 2003, 2005, 2008). The above mentioned processes are driven by a number of factors, variable in time and space, such as the quantity and quality of the organic material supplied to the bottom sediments, temperature, salinity, oxygen content, redox status in the sediments, macrofaunal activity, and physical parameters causing resuspension.

Fast flowing, turbid Oder waters reduce their flow when they reach a complex and extensive Oder estuary, with its largest component - the Szczecin Lagoon, playing a very important role. The reduced water flow favors natural process of suspended matter sedimentation, and that in turn increases the light penetration through the water column. Increased light penetration in the Szczecin Lagoon, as compared to the Oder River, creates favorable conditions for freshwater and oligohaline phytoplankton to develop and utilize dissolved nutrients. Long-term studies carried out in the Szczecin Lagoon demonstrate that intensive primary production in the vegetative period results in a significant increase in chlorophyll a concentrations (Landsberg-Uczciwek, 1997), decreased levels of nutrients (first to drop are phosphates in spring, then nitrates in summer) (Poleszczuk et al., 1995; Pastuszak et al., 1998, 1999, 2001). While passing from the Szczecin Lagoon to the Pomeranian Bay, salinity of water changes rapidly from about 1-2 PSU in the lagoon to ca. 7.3-7.6 PSU in the bay (Pastuszak et al., 2003). The rise in salinity imposes a threat to freshwater and oligohaline phytoplankton species, whose fallout proved to be substantial in the vicinity of the lagoon outlets (Gromisz et al., 1999; Wasmund et al., 1999). Despite being partly impoverished, waters inflowing from the Szczecin Lagoon are still richer with inorganic nutrients than less eutrophied marine waters of the Pomeranian Bay. The input of nutrients, together with the regenerative flux from decaying freshwater and oligohaline algae and other allochthonous organic material, stimulate development of the mesohaline phytoplankton community in the bay. Phytoplankton biomass, chlorophyll a concentrations and primary production in inshore waters are several times higher in comparison with the open bay values (Gromisz et al., 1999; Ochocki et al., 1999; Wasmund et al., 1999).

Accumulation and decomposition of the organic matter, in the inland part of the estuary and in the coastal zone of the bay, gives rise to a drop in oxidation potential at high summer temperatures (Burska et al., 1999) and gives impetus for ammonium and phosphate regeneration in the system (Fig. 10.6). Phosphate concentrations in the Szczecin Lagoon, in the Świna Strait and in the inner bay show very pronounced maxima due not only to phosphorus regeneration in the system, but also to nitrogen-limited primary production in that period of the year, which in turn leads to ineffective phosphorus uptake (Kaczewiak and Wolnomiejski, 1977; Pastuszak et al., 2001, 2003). Scarcity of nitrogen in summer, at simultaneous high demand for this element, arise from seasonally lowest N discharges from external sources, namely in riverine outflow.

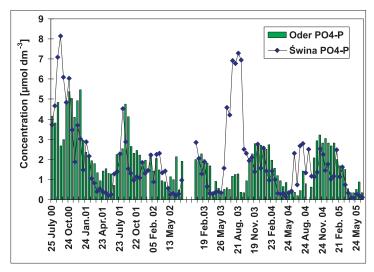


Fig. 10.6 Seasonal variability of phosphate concentrations in the Oder waters (Krajnik Dolny) and Świna Strait (outlet to the Baltic Sea) over the period July 2000 – June 2005 (own data; the measurements made in the frame of EU projects: *SIGNAL* and *SIBER*)

Part of the organic matter that sediments in the system, undergoes the recycling process, and the remaining part becomes retained in the sediments. Burial of organic matter in sediments, apart from denitrification in the case of nitrogen, greatly contributes to internal losses of TN and TP in estuaries as evidenced by (Boynton et al., 1995; Howarth et al., 1996). The N and P retention in the inland part of the Oder estuary due to other than Den-Nfix processes (denitrification reduced by the amount of molecular N taken up by blue-green algae) was estimated at 12,000 tons N yr<sup>-1</sup> and 1,500 tons P yr<sup>-1</sup>. When referred to estimates of the rate of nutrient accumulation in the Szczecin Lagoon (Leipe et al., 1998; Meyer and Lampe, 1999; Humborg et al., 2000), it turns out that only a minor part of these amounts can be attributed to the accumulation in soft bottom sediments of this region (between 500 and 2,600 tons N

yr¹ and between 80 and 700 tons P yr¹). An additional way of nutrient withdrawal in the Szczecin Lagoon was indicated by Minning (2004) who estimated, that about 2,200 tons N and almost 1,000 tons P were annually dredged out from the shipping channel, crossing the Szczecin Lagoon from the Świna outlet up to the Szczecin harbor. The accumulation in the bottom sediments and the dredging may fully explain phosphorus retention; however these processes are insufficient with respect to nitrogen retention. The explanation may lie in the fact that estimation of Den-Nfix made by Pastuszak et al. (2005) was based only on dissolved N forms, therefore it can be underestimated. As proven by Seitzinger and Giblin (1996) and Van Raaphorst et al. (1992) denitrification takes place in estuarine sediments but also in wetlands (Nixon and Lee, 1986; Seitzinger, 1994).

The N loss in the entire Oder estuary via estimated denitrification constituted about 30% of terrestrial plus atmospheric nitrogen inputs to the estuary and that number falls within a range given for tributary estuaries to the Chesapeake Bay (Boynton et al., 1995) but it is lower than in some other aquatic systems (40-55%; Seitzinger, 1988). Denitrification is the major process responsible for removing N in most estuaries, and the fraction of TN input that is denitrified appears to be directly proportional to the log mean water residence time (Nixon et al., 1996). Four times higher denitrification rate in the inland than in the marine part of the Oder estuary (Table 10.1), can be explained by much longer residence time in the inland estuary, but also, as shown by Boynton at al. (1995) for the US estuaries, by lower salinity in the inland parts of estuaries than in mesohaline zone, and by higher upstream loading from terrestrial and atmospheric sources. The estimated denitrification in the marine part of the Oder estuary was very close to that estimated for the Gulf of Gdańsk (Witek et al., 2003), and corresponded to the ranges reported for other regions of the Baltic Sea (Table 10.3; Savchuk and Wulff, 1996; Wulff et al., 1994; Savchuk, 2002) and elsewhere (Dettmann, 2001; Seitzinger and Giblin, 1996; Smith, 2002).

Though the lowermost part of the Vistula River has a completely different geomorphologic character as compared with the extensive Oder estuary, about 50% of nitrates undergo retention or transformation into the organic forms at the Vistula section delimited by the lowermost monitoring station and the river mouth (32 km) (Voss et al., 2005).

Nixon et al. (1996) estimated that estuarine processes at the land-sea margin of the North Atlantic Ocean retain and remove 30-65% of the total N and 10-55% of the total P that otherwise would pass into the coastal ocean. An analysis of annual total N and total P budgets for various estuaries around the Atlantic Ocean revealed that the net fractional transport of these nutrients through estuaries to the continental shelf is inversely correlated with the log mean residence time of water in the system. Studies of Howarth et al. (1996) show that the amount of N retained in an estuary is relatively insensitive to trophic status; in contrast, the percentage accumulation of phosphorus in sediments decreases as an estuary becomes more eutrophic. Referring

these findings to Polish studies, it can be concluded that during the transition period N retention in a large Oder estuary remained at the unchanged level, whereas P retention could have even increased owing to considerably decreasing P emission to the Oder basin (Chapter 8) and consequently significantly decreasing P loads introduced to the estuarine system (Chapter 9).

## 10.8. Comparison of nutrient retention in various systems

Coastal systems are diverse and they may vary widely in size and type, mean depth, water exchange time, and nutrient load rate. These features cause that the estuarine systems may represent a wide range of biogeochemical behavior, from almost a complete transfer of N and P from land to the shelf to almost complete interception of the flux from land (Wulff and Stigebrandt, 1989; Nixon et al., 1996). As shown by numerous authors (Froelich, 1988; Seitzinger, 1988; Caraco et al., 1990; Howarth et al., 1995, Nixon et al., 1996) the behavior of N and P in fresh and salt water, and in lake and marine sediments is quite different.

The Baltic Sea, treated as one water body, is characterized by high retention of TN and TP in the system (Wulff and Stigebrandt, 1989; Nixon et al., 1996), but particular Baltic sub-regions differ very much with respect to TN, TP, DIN, and DIP retention factors (Table 10.3). The highest TP retention factors were found in the Bothnian Sea, the Bothnian Bay, and the Gulf of Finland, with the RET-F above 1 indicating a massive P import from the Baltic Proper (Wulff et al., 1994; Pertilla et al., 1995). The Bothnian Sea was also found an importer of N as shown by Wulff et al. (1994). The lowest TP retention factors were recorded in the Gulf of Riga (Yurkovskis et al., 1993; Savchuk, 2002). The TN and TP retention factors in the Oder estuary, as well as in the part of the Gulf of Gdańsk studied by Witek et al. (2003), belong to the low ones in the entire Baltic region. It is worth pointing out that these regions are characterized by the shortest water exchange time (WET; Table 10.3) which is of crucial importance with respect to nutrient retention. The Oder estuary and the Gulf of Gdańsk are supplied with high annual loads of TN and TP (HELCOM, 1998; Table 10.3), and moreover, these loads when recalculated per regions' areas give yields one order of magnitude higher than in any other Baltic region.

Table 10.3 Loads of nitrogen and phosphorus, retention factors and denitrification rates in the Baltic Sea and its subregions (source: Pastuszak et al., 2005)

Source		Gordon et al., 1996	Wulff and Stigebrandt, 1989	Savchuk and Wulff, 1996	Wulff et al., 1994	Wulff et al., 1994	Pertilla et al., 1995	Yurkovskis et al., 1993	Savchuk, 2002	Witek et al., 2003	Pastuszak et al., 2005
Den- Nfix	$[giN]$ $m^2yr^1$	1.4-4.2		4.8	3.22	0.64	2.2		4.5	6.7	19 (5)*)
)r	DIP	1.06			2.62	1.18		0.57	0.51	1.16	-0.02
n Factc F-F)	NIQ	1.02			0.83	0.59		0.78	0.82	08.0	0.47
Retention Factor (RET-F)	TP		0.92	0.56	2.73	1.13	1.70	0.07	0.02	0.34	0.37
R	IN		0.91	0.99	1.33	09.0	0.59		0.64	0.23	0.45
	DIP	69.5			2.1	1.7		2.2	2.2	5.6	2.1
$\begin{array}{c} \text{Loads} \\ [\text{t-}10^3  \text{yr}^{-1}] \end{array}$	DIN	1241			85	34		92	81	98	54
$\frac{\text{Los}}{[\text{t-}10^3]}$	TP		66.5	32	3.9	3.6	11.8	2.9	3.0	8.8	5.9
	NI		1110	713	112	64	170		135	131	81
WET	[ycars]	18.5	21.8		1.8	4.2		2.5	2.3	0.04	$0.2$ $(0.06)^*$
Vol- ume	$[km^3]$	21721	20706	13500	4485	1440	1100	420	424	159	15.8
Area		416	374.6	255	72	35.7	29.6	19	16.3	3.3	2.1
Region		Baltic Sea	Baltic Sea (Baltic Proper + Bothnian Bay + Bothnian Sea)	Baltic Proper + Gulf of Finland	Bothnian Sea	Bothnian Bay	Gulf of Finland	Gulf of Riga	Gulf of Riga	Gulf of Gdańsk (2/3 of the area)	Oder estuary

\*) Water Exchange Time (WET) and Den-Nfix - for the inland and the marine (in brackets) part of the Oder estuary

The studies carried out in Pomeranian Bay (incorporating marine part of Oder estuary) by Christiansen et al. (2002) and Emeis et al. (2002) give evidence for a limited retention capacity of this region. The open bay system is a receiver of dissolved and suspended matter from the Szczecin Lagoon, and at the same time a producer of new organic material. The short residence time in the water column of Pomeranian Bay and frequent resuspension events provide a fast operating benthic-pelagic coupling. This makes the system very active and characterized by an intensive matter turnover. As further proven by these authors, due to the high-energy input, the shallow water areas, like the Pomeranian Bay, are not depositional on time scales longer than 1-2 weeks; all the material produced in the Pomeranian Bay water column, delivered by rivers, or eroded from the seafloor and cliffs is transported near the seafloor to the depositional areas of the Arkona, Bornholm, and Gdańsk basins. Jost and Pollehne (1998), who state that autotrophic and heterotrophic processes in the pelagic zone of the entire Pomeranian Bay appear balanced over a wide range of salinity gradient, demonstrate similar findings.

- Anschutz, P., Zhong, S., Sundby, B., 1998. Burial efficiency of phosphorus and the geochemistry of iron in continental margin sediments. Limnol. Oceanorg., 43(1):53-64.
- Baird, D., Ulanowicz, R.E., Boynton, W.R., 1995. Seasonal nitrogen dynamics in Chesapeake Bay: a network approach. Estuar., Coast. Shelf Sci., 41:137-162.
- Beszczyńska-Möller, A., 1999. Transport of the Odra waters and circulation patterns in the Pomeranian Bay. Oceanologia, 41(3):279-308.
- Boynton, W. R., Kemp, W. M., 1985. Nutrient regeneration and oxygen consumption by sediment along an estuarine salinity gradient. Mar. Ecol. Prog. Ser., 23:45-55.
- Boynton, W.R., Garber, J.H., Summers, R., Kemp, W.M., 1995. Inputs, transformation, and transport of nitrogen and phosphorus in Chesapeake Bay and selected tributaries. Estuaries, 18:285-314.
- Buchholz, W., 1990. Materiały Do Monografii Dolnej Odry Warunki Hydrologiczno-Hydrodynamiczne. Prace Instytutu Budownictwa Wodnego PAN, Gdańsk No. 22, 117 pp.
- Buchholz, W., 1991. Monografia Dolnej Odry Hydrologia Dynamika. Instytut Budownictwa Wodnego PAN, Gdańsk No. 25, 102 pp.
- Burska, D., Frankowski, L., Bolałek, J., 1999. Temporal variability in the chemical composition of bottom sediments in the Pomeranian Bay (southern Baltic). Oceanologia, 41(3):445-459.
- Caraco, N., Cole, J., Likens, G. E., 1990. A comparison of phosphorus immobilization in sediments of freshwater and coastal marine systems. Biogeochemistry, 9:277-279.

- Christiansen, C., Edelvang, K., Emeis, K., Graf, G., Jähmlich, S., Kozuch, J., Laima, M., Leipe, T., Löffler, A., Lund-Hansen, L.C., Miltner, A., Pazdro, K., Pempkowiak, J., Shimmield, T., Smith, J., Voss, M., Witt, G., 2002. Material transport from the near-shore to the basinal environment in the southern Baltic Sea: I. Processes and mass estimates. J. Mar. Syst., 35(3-4):133-150.
- Conley, D. J., Johnstone, R. W., 1995. Biogeochemistry of N, P and Si in the Baltic Sea sediments: response to a simulated deposition of a spring diatom bloom. Mar. Ecol. Prog. Ser., 122:256-276.
- Conley, D.J., Stockenberg, A., Carman, R., Johnstone, R.W., Rahm, L., Wulff, F., 1997. Sediment-water nutrient fluxes in the Gulf of Finland, Baltic Sea. Estuar., Coast. Shelf Sci., 45:591-598.
- Cowan, J.L.W., Boynton, W.R., 1996. Sediment-water oxygen and nutrient exchanges along longitudinal axis of Chesapeake Bay: Seasonal patterns controlling factors and ecological significance. Estuaries, 19(3):562-580.
- Cowan, J.L.W., Pennock, J.R., Boynton, W.R., 1996. Seasonal and interannual patterns of sediment-water nutrient and oxygen fluxes in Mobile Bay, Alabama (USA): regulating factors and ecological significance. Mar. Ecol. Prog. Ser., 141:229-245.
- Cyberska, B., Krzymiński, W., 1988. Extension of the Vistula River water in the Gulf of Gdańsk. Proceedings of the 16<sup>th</sup> Conference of Baltic Oceanographers. Vol. 1, pp. 290-304. Institute of Marine Research, Kiel University.
- Dettmann, E.H., 2001. Effect of water residence time on annual export and denitrification of nitrogen in estuaries: a model analyses. Estuaries, 24:481-490.
- Emeis, K., Christiansen, C., Edelvang, K., Jähmlich, S., Kozuch, J., Laima, M., Leipe, T., Löffler, A., Lund-Hansen, L. C., Miltner, A., Pazdro, K., Pempkowiak, J., Pollehne, F., Shimmield, T., Voss, M., Witt, G., 2002. Material transport from the near shore to the basinal environment in the southern Baltic Sea, II Synthesis of data on origin and properties of material. J. Mar. Syst., 35(3-4):151-168.
- Fal, B., Bogdanowicz, E., Czernuszenko, W., Dobrzyńska, I., Koczyńska, A., 2000. Przepływy charakterystyczne głównych rzek polskich w latach 1951-1995. Materiały Badawcze, Seria: Hydrologia i Oceanologia, Instytut Meteorologii i Gospodarki Wodnej, Warszawa. No. 26, 137 pp.
- Froelich, P.N., 1988. Kinetic control of dissolved phosphate in natural rivers and estuaries: A primer on the phosphate buffer mechanism. Limnol. Oceanogr., 33(4), Part 2:649-668.
- Gordon, D.C, Jr., Boudreau, P.R., Mann, K.H., Ong, J.-O., Silvert, W.L., Smith, S.V., Wattayakom, G., Wulff, F., Yanagi, T., 1996. LOICZ Biogeochemical Modelling Guidelines. LOICZ/RS/95-5, vi+96 str. LOICZ, Texel, The Netherlands; http://nest.su.se/mnode/in.
- Grelowski, A., Wojewódzki, T., 1996. The impact of the Vistula River on the

- hydrological conditions in the Gulf of Gdańsk in 1994. Bulletin of the Sea Fisheries Institute, 137:23-33.
- Grelowski, A., Pastuszak, M., Sitek, S., Witek, Z., 2000. Budget calculations of nitrogen, phosphorus and BOD<sub>5</sub> passing through the Oder estuary. J. Mar. Syst., 25:221-237.
- Gromisz, S., Witek, Z., Mackiewicz, T., 1999. Impact of the Oder River on phytoplankton composition and biomass in the Pomeranian Bay. Oceanologia, 41(3):403-427.
- HELCOM, 1998. The Third Baltic Sea Pollution Load Compilation. Baltic Sea Environ. Proc. No. 70.
- Howarth, R. W., Jensen, H.S., Marino, R., Postma, H., 1995. Transport to and processing of P in near-shore and oceanic waters. [in:] Tiessen, H. (ed.), Phosphorus in the global environment: transfers, cycles and management. SCOPE. Wiley Sons, Chichester, UK. pp. 323-345.
- Howarth, R.W., Billen, G., Swaney, D., Townsend, A., Jaworski, N., Lajtha, K., Downing, J.A., Elmgren, R., Caraco, N., Jordan, T., Berendse, F., Freney, J., Kundeyarov, V., Murdoch, P., Zhao-Liang, Z., 1996. Regional nitrogen budgets and riverine N, P fluxes for the drainages to the North Atlantic Ocean: Natural and human influence. Biogeochemistry, 35:75-139.
- Humborg, C., Fennel, K., Pastuszak, M., Fennel, W., 2000. A box model approach for a long-term assessment of estuarine eutrophication, Szczecin Lagoon, southern Baltic. J. Mar. Syst., 25:387-403.
- IMWM (Institute of Meteorology and Water Management) in Warsaw, 1990-2002. Monthly Bulletins "Zasoby Wodne Kraju" ("Water Resources in Poland") (in Polish).
- Jasińska, E., 1991. Dynamika słonych wód w estuariach polskich rzek. Polska Akademia Nauk, Instytut Budownictwa Wodnego, Gdańsk, No. 24, 206 pp.
- Jost, G., Pollehne, F., 1998. Coupling of autotrophic and heterotrophic processes in a Baltic estuarine mixing gradient (Pomeranian Bight). Hydrobiologia, 363:107-115
- Kaczewiak, C., Wolnomiejski, N., 1977. Fosforany wód Zalewu Szczecińskiego w aspekcie eutrofizacyjnym (1969-1973). Stud. Mater. MIR, 17(A):33-49.
- Kemp, W. M., Sampou, P., Caffrey, J., Mayer, M., Henriksen, K., Boynton, W. R., 1990. Ammonium recycling versus denitrification in Chesapeake Bay sediments. Limnol. Oceanogr., 35(7):1545-1563.
- Knudsen, M., 1900. Ein hydrographischer Lehrsatz. Annalen der Hydrographie und Maritimen Meteorologie, 28:316-320.
- Landsberg-Uczciwek, M. (ed.), 1997. Raport o Stanie Środowiska w Województwie Szczecińskim w latach 1995-1996. Państwowa Inspekcja Ochrony Środowiska w Szczecinie, Biblioteka Monitoringu Środowiska, pp. 48-59.
- Lass, H.U., Matthäus, W., 2008. General Oceanography of the Baltic Sea, [in: Feistel, R., Nausch, G., Wasmund, N. (eds.), State and Evolution of the Baltic Sea,

- 1952-2005; A detailed 50-year survey of meteorology and climate, physics, chemistry, biology, and marine environment. Wiley Interscience, A. John Wiley & Sons, Inc. Publication, pp. 5-43.
- Lass, H.U., Mohrholz, V., Seifert, T., 2001. On the dynamics of the Pomeranian Bay. Cont. Shelf Res., 21:1237-1261.
- Lazarienko, N., Majewski, A., 1975. Hydrometeorological regime of the Vistula Lagoon. Warsaw: Communication Press in Polish, 516 pp.
- Lebo, M. E., 1990. Phosphate uptake along a coastal plain estuary. Limnol. Oceanogr., 35(6):1279-1289.
- Leipe, T., Eidam, J., Lampe, R., Meyer, H., Neumann, T., Osadczuk, A., Janke, W., Puff, T., Blanz, T., Gingele, F. X., Dannenberger, D., Witt, G., 1998. Das Oder Haff-Beiträge zur Rekonstruktion der holozänen und geologischen Entwicklung und anthropogenen Beeinflussung des Oder Ästuars. Marine Science Reports (28):83 pp.
- Magnien, R.E., Summers, R.M., Seller, K.G., 1992. External nutrient sources, internal nutrient pools, and phytoplankton production in Chesapeake Bay. Estuaries, 15(4):497-516.
- Majewski, A., 1974. Charakterystyka Hydrologiczna Zatoki Pomorskiej. Wydawnictwo Komunikacji i Łączności, Warszawa. 110 pp.
- Majewski, A. (ed.), 1980. Zalew Szczeciński. Wydawnictwo Komunikacji i Łączności, Warszawa. 339 pp.
- Majewski, A., 1994. Natural environmental conditions of the Gulf of Gdańsk and its surroundings. [in:] Blazejowski, J. and Schuller, D. (eds.), Pollution and renewal of the Gulf of Gdańsk, Gdańsk University, pp. 35-42.
- Malone, T.C., Conley, D.J., Fisher, T.R., Glibert, P.M., Harding, L.W., Sellner, K.G., 1996. Scales of nutrient-limited phytoplankton productivity in Chesapeake Bay. Estuaries, 19(2B):371-385.
- Meyer, H., Lampe, R., 1999. The restricted buffer capacity of a south Baltic estuary the Oder estuary. Limnologica, 29:242-248.
- Minning, M., 2004. Der Einfluss des Schifffahrtskanal auf den Stoffhaushalt des Oderhaffs. [in:] Schernewski, G., Dolch, T. (eds.), The Oder Estuary against the background of the European water Framework Directive. Marine Science Reports (57):179-222.
- Mohrholz, V., Lass, H.U., 1998. Transports between Oderhaff and the Pomeranian Bight a simple barotropic box model. Dtsch. Hydrogr., Z. 50(4):371-382.
- Nixon, S.W., Lee, V., 1986. Wetlands and Water Quality. Final Report. Dept. Army. Technical Report Y-86-2. 229 pp.
- Nixon, S.W., Granger, S.L., Nowicki, B.L., 1995. An assessment of the annual mass balance of carbon, nitrogen, and phosphorus in Narragansett Bay. Biogeochemistry, 35:15-61.
- Nixon, S.W., Ammerman, J.W., Atkinson, L.P., Berounsky, V.M., Billen, G., Boicourt, W.C., Boynton, W.R., Church, T.W., Diroto, D.M., Elmgren, R., Garber, J.H.,

- Giblin, A.E., Jahnke, R.A., Owens, N.J.P., Pilson, W.E.Q., Seitzinger, S.P., 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. Biogeochemistry, 35:141-180.
- Ochocki, S., Chmielowski, H., Nakonieczny, J., Zalewski, M., 1999. The impact of Odra River waters on the seasonal and spatial distribution of primary production and chlorophyll <u>a</u> concentrations in the Pomeranian Bay in 1996-1997. Oceanologia, 41(3):373-388.
- Pakulski, J.D., Benner, R., Amon, R., Eadie, B., Whitledge, T., 1995. Community metabolism and nutrient cycling in the Mississippi River plume: evidence for intense nitrification at intermediate salinities. Mar. Ecol. Prog. Ser., 117:207-218.
- Pastuszak, M., Nagel, K., Nausch, G., 1996. Variability in nutrient distribution in the Pomeranian Bay in September 1993. Oceanologia, No. 38(2):195-225.
- Pastuszak, M., Sitek, S., Grelowski, A., 1998. The exceptional Oder flood in summer 1997 Nutrient concentrations in the Świna Strait during the years 1996-1997 with emphasis on the flood event. Dtsch. Hydrogr., Z., 50(2/3):183-202.
- Pastuszak, M., Siegel, H., Sitek, S., Gerth, M., Tschersich, G., Grelowski, A., 1999. Impact of water temperature on nutrient concentrations in the Oder estuary in 1996-1998. Dtsch. Hydrogr., Z., 51(4):423-439.
- Pastuszak, M., Wielgat, M., Sitek, S., 2001. Nutrient status in the Szczecin Lagoon past, present, and future prospects. Oceanological Studies, 30(1-2):59-86.
- Pastuszak, M., Nagel, K., Grelowski, A., Mohrholz, V., Zalewski, M., 2003. Nutrient dynamics in the Pomeranian Bay (southern Baltic): impact of the Oder River outflow. Estuaries, 26(5):1238-1254.
- Pastuszak, M., Witek, Z., Nagel, K., Wielgat, M., Grelowski, A., 2005. Role of the Oder estuary (southern Baltic) in transformation of the riverine material. J. Mar. Syst., 57:30-54.
- Pastuszak, M., Conley, D., Humborg, C., Witek, Z., Sitek, S., 2008. Silicon dynamics in the Oder estuary, Baltic Sea. J. Mar. Syst., 73:250-262.
- Pertillä, M., Niemistö, L., Mäkelä, K., 1995. Distribution, development and total amounts of nutrients in the Gulf of Finland. Estuar., Coast. Shelf Sci., 41:345-360.
- Poleszczuk, G., Garbacik-Wesołowska, A., Sitek, S., Mutko, T., 1995. Status tlenowy wód estuarium Odry. Stud. Mat. Mor. Inst. Ryb., Gdynia, Seria A, No. 33, 101 pp.
- Savchuk, O., 2002. Nutrient biogeochemical cycles in the Gulf of Riga: scaling up field studies with mathematical model. J. Mar. Syst., 32:253-280.
- Savchuk, O., Wulff, F., 1996. Biogeochemical transformations of nitrogen and phosphorus in the marine environment coupling hydrodynamic and biogeochemical processes in models for the Baltic Proper. Contrib. Syst. Ecol., Stockholm Univ., 2, 79 pp.
- Seitzinger, S.P., 1988. Denitrification in freshwater and coastal marine ecosystems:

- Ecological and geochemical significance. Limnol. Oceanogr., 33:703-724.
- Seitzinger, S.P., 1994. Linkages between organic matter mineralization and denitrification in eight riparian wetlands. Biogeochemistry, 25:19-39.
- Seitzinger, S.P., Giblin, A.E., 1996. Estimating denitrification in North Atlantic continental shelf sediments. Biogeochemistry, 35:235-260.
- Smith, S.V., 2002. Carbon-nitrogen-phosphorus fluxes in the coastal zone; the global approach. Global Change Newsletter, 49:7-11.
- Van Raaphorst, W. V., Kloosterhuis, H. T., Berghuis, E. M., Gieles, A. J. M., Malschaert, J. F. P., Noort, G. J. V., 1992. Nitrogen cycling in two types of sediments of the southern North Sea (Frisian Front, Broad Fourteens): Field data and mesocosm results. Neth. J. Sea. Res., 28(4):293-316.
- Vidal, M., 1994. Phosphate dynamics tied to sediment disturbances in Alfact Bay (NW Mediterranean). Mar. Ecol. Prog. Ser., 110:211-221.
- Vidal, M., Morguí, J.A., 1995. Short-term pore water ammonium variability coupled to benthic boundary layer dynamics in Alfacs Bay, Spain (Elbro Delta, N Mediterranean). Mar. Ecol. Prog. Ser., 118:229-236.
- Voss, M., Liskow, I., Pastuszak, M., Rűß, D., Schulte, U., Dippner, J.W., 2005. Riverine discharge into coastal bay: A stable isotope study in the Gulf of Gdańsk, Baltic Sea. J. Mar. Syst., 57:127-145.
- Voss, M., Deutsch, B., Liskow, I., Pastuszak, M., Schulte, U., Sitek, S., 2010. Nitrogen retention in the Szczecin Lagoon, Baltic Sea. Isotopes in Environmental & Health Studies Vol. 46, Issue 3, pp. 355-369.
- Wasmund, N., Zalewski, M., Busch, S., 1999. Phytoplankton in large river plumes in the Baltic Sea. ICES J. Mar. Sci., 56 Supplement: 23-32.
- Witek, Z., Humborg, C., Savchuk, O., Grelowski, A., Łysiak- Pastuszak, E., 2003. Nitrogen and phosphorus budgets of the Gulf of Gdańsk (Baltic Sea). Estuar., Coast. Shelf Sci., 57:239-248.
- Wulff, F., Perttilä, M., Rahm, L., 1994. Mass-balance calculations of nutrients and hydrochemical conditions in the Gulf of Bothnia, 1991. Aqua Fennica, 24(2):121-140.
- Wulff, F., Stigebrandt, A., 1989. A time-dependent budget model for nutrients in the Baltic Sea. Global Biochemical Cycles, 3:63-78.
- Yurkovskis, A., Wulff, F., Rahm, L., Andruzaitis, A., Rodrigues-Medina, M., 1993. A nutrient budget of the Gulf of Riga; Baltic Sea. Estuar., Coast. Shelf Sci., 37:113-127.

EXCESSIVE SILICON
RETENTION - IMPLICATIONS
FOR MARINE ENVIRONMENT

MARIANNA PASTUSZAK

# 11. EXCESSIVE SILICON RETENTION – IMPLICATIONS FOR MARINE ENVIRONMENT

#### Marianna Pastuszak

#### 11.1. Sources and forms of silicon in the environment

Silicon (Si) is the eighth most common element in the universe by mass, but very rarely occurs as the pure free element in nature. It is most widely distributed in dusts, sands, planetoids, and planets as various forms of silicon dioxide (silica) or silicates. Over 90% of the Earth's crust is composed of silicate minerals, making silicon the second most abundant element in the Earth's crust (about 28% by mass) after oxygen (O'Neill, 1998). Unlike nitrogen (N) and phosphorus (P), the silicon is present as H<sub>4</sub>SiO<sub>4</sub> in dissolved form and its source in aquatic systems is dominated by the chemical weathering of silicate minerals.

The natural weathering pathway, derived from reaction of the carbonic acid on minerals to produce dissolved inorganic carbon (mainly HCO<sub>3</sub>), is largely reported in the literature (e.g. Mortatti and Probst, 2003).

$$2CO_{2} + CaSiO_{3} + 3H_{2}O \Rightarrow Ca^{2+} + 2HCO_{3}^{-} + H_{4}SiO_{4}$$

$$2CO_{2} + MgSiO_{3} + 3H_{2}O \Rightarrow Mg^{2+} + 2HCO_{3}^{-} + H_{4}SiO_{4}$$

$$2CO_{2} + 2NaAlSi_{3}O_{8} + 11H_{2}O \Rightarrow Al_{2}Si_{2}O_{5}(OH)_{4} + 2HCO_{3}^{-} + 2Na^{+} + 4H_{4}SiO_{4}$$

$$2CO_{2} + 2KAlSi_{3}O_{8} + 6H_{2}O \Rightarrow Al_{2}Si_{4}O_{10}(OH)_{2} + 2HCO_{3}^{-} + 2K^{+} + 2H_{4}SiO_{4}$$

$$2CO_{2} + CaAl_{3}Si_{2}O_{8} + 3H_{2}O \Rightarrow Al_{5}Si_{2}O_{5}(OH)_{4} + 2HCO_{3}^{-} + Ca^{2+}$$

The dissolved silica, released from these reactions reaches the ocean *via* rivers. Rivers are responsible for almost 80% of the Si entering the global ocean as dissolved silicate (DSi) [DSi=Si(OH)<sub>4</sub>], a product of weathering of continental rock and the continental and oceanic crust (Meybeck, 1982; Tréguer et al., 1995; Gerard and Ranger, 2002; Dűrr et al., 2009). The riverine transport of dissolved and particulate materials to the oceans is generally related to a large number of interactions involving climatic, hydrological, physico-chemical, and biological aspects. Temperature, precipitation, runoff, lithology are the major factors controlling the weathering rate of silicate rocks, and partially control the riverine DSi outflow (Meybeck, 1981, 1994; Tréguer et al., 1995; O'Neill, 1998; Mortatti and Probst, 2003). A large fraction of DSi released by weathering is converted by plants into phytoliths and temporarily stored in soils (Saccone et al., 2008). Rivers also carry Si in various forms of particulate matter that can play a significant role as a source of Si for coastal diatoms (Conley, 1997). Anthropogenic Si input originates from the introduction of small amounts of Na<sub>2</sub>SiO<sub>3</sub> in washing powders (Berner and Berner, 1996), and the urban discharge

can contribute to more that 8% of the total Si inputs in hydrologically dry years, as exemplified in the Seine basin (Sferratore et al., 2006).

The geographic position of coastal waters at the interface between land and ocean implies that diatoms can use Si coming from land via rivers, groundwater, or the atmosphere; these are external sources of Si. There is also an internal source of DSi, a final product of biogenic silica (BSi) recycling in the water column, at the sediment-water interface and deeper in sediments (overview see to: Ragueneau et al., 2006b). Silicon is an essential nutrient for certain groups of organisms such as diatoms, radiolarians, sponges, and chrysophytes, all these constituting amorphous silica, called biogenic silica (BSi) (Simpson and Volcani, 1981). BSi is an amorphous form that dissolves five orders of magnitude faster than silicate minerals (Hurd, 1983). BSi dissolution varies significantly with area and depth; temperature is the most often mentioned parameter strongly affecting Si internal cycling (Conley and Malone, 1992; Cowan and Boynton, 1996; Ragueneau et al., 1994, 2000). The dissolution rate of BSi also depends on pH, the nature and concentration of aqueous salt solutions, and Al content of the surrounding solution (overview in Gallinari et al., 2002). BSi dissolution can constitute an important source of DSi for coastal diatoms.

BSi is also known as biogenic opal or simply opal by geologists, and it may comprise not only the above mentioned components of biological origin but also non-biological forms of amorphous silica which are not as common and widespread as the biogenically formed amorphous silica (Wilding et al., 1977). In aquatic sciences, estimates of BSi are most often used as an index of the amount of siliceous microfossils abundance in sediments, which in most environments are primarily the diatoms (Conley, 1988). Therefore, BSi is extensively used as a paleoindicator of diatom production (Andrén, 1999; Ragueneau et al., 2000; Conley and Schelske, 2001), and used to reconstruct changes in paleoproductivity.

### 11.2. Role of silicon in marine ecosystems

Nitrogen compounds such as nitrate and ammonium, phosphorus compounds such as phosphate, and silicon compounds such as silicate belong to major nutrients taken up by phytoplankton in freshwater and marine ecosystems. The role of N, P, Si is however quite different, with nitrogen and phosphorus compounds being required by almost all marine plankton, while silicon, as DSi, is needed only by certain organisms (diatoms, radiolarians, sponges, and chrysophytes) (Simpson and Volcani, 1981; Ragueneau et al., 2006a). Unlike N and P, which occur in a variety of inorganic and organic forms in the sea, silicon occurs predominantly as undissociated monomeric silicic acid, Si(OH)<sub>4</sub>, and represents the main form under which silicon can be assimilated by organisms (Brzezinski and Nelson, 1989; Del Amo and Brzezinski, 1999).

Diatoms (Bacillariophyceae) are the major component of the spring phytoplankton blooms in both freshwater and marine ecosystems (Fig. 11.1). As proven by Alverson (2007), marine and freshwater diatoms show several important differences in silicon physiology. In addition to containing an order of magnitude more silica in their cell walls, freshwater diatoms appear to have less efficient silicic acid uptake mechanism. Diatoms' nutritional value and limited amount of trophic steps between them and higher trophic levels make these phytoplankton class groups a primary energetic source for estuarine and coastal food chains (Ragueneau et al., 2006a; Struyf et al., 2009). They are responsible for about half the primary production in the world's oceans (Tréguer and Pondaven, 2000). It is estimated that 20% to 25% of all organic carbon fixation on the planet (transformation of carbon dioxide and water into sugars, using light energy) is carried out by diatoms (Goldman, 1993; Dugdale et al., 1995; Smetacek, 1999). Diatoms tend to dominate the 'new primary production' (new primary production is supported by nutrients coming into ecosystem or habitat from other ecosystems or habitats) (Domine et al., 2010) in marine ecosystems. They are preferably grazed upon by the macrozooplankton (copepods), which in turn serve as a direct food source for higher trophic levels such as commercially exploitable fish species (Round et al., 1990; Hansen et al., 1997; Irigoien et al., 2002) (Fig. 11.2). Si is not passed up the food chain to any degree, and its regeneration is not by organic degradation but by dissolution of opaline SiO, (Broecker and Peng, 1982). Diatoms form the basis of the food web that characterizes the most productive regions and sustains the most important fisheries on the planet. The biogeochemical cycling of DSi in aquatic systems is thus of environmental importance in structuring biological communities (Round et al., 1990; Hansen et al., 1997; Irigoien et al., 2002; Ragueneau et al., 2006a).

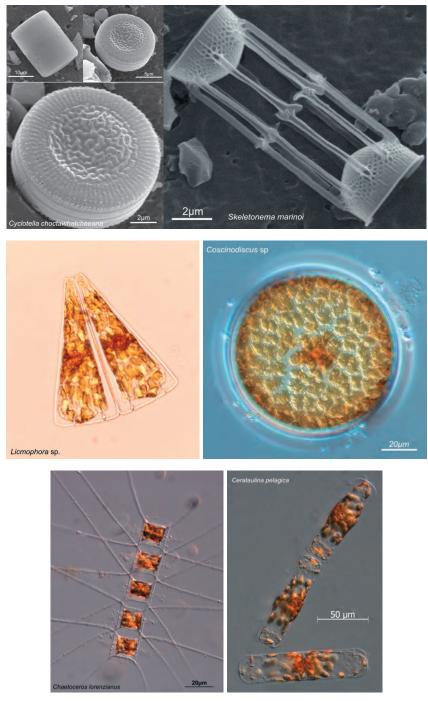


Fig. 11.1 Selected images of diatom species; images obtained with application of SEM and LM techniques and made available by M.Sc. Janina Kownacka (NMFRI, Gdynia)

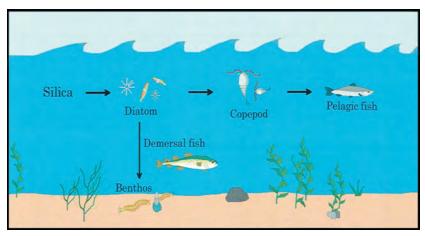


Fig. 11.2 Schematic picture of the silicate transfer in food web (source: graph taken from the brochure prepared within the *SIBER* project)

Part of Si(OH)<sub>4</sub>, which is incorporated into diatoms, is exported to deep water through sinking of phytoplankton particulate silicon (BSi) or Si(OH)<sub>4</sub> – rich fecal pellets (Staresinic et al., 1983). This process is often called in literature "a silicate pump" (Dudgale et al., 1995; Ragueneau et al., 2002a; Fig. 11.3). The essential difference in the behavior between N, P and Si is their rate of regeneration and recycling. Si(OH)<sub>4</sub> is not retained in a recycled pool, as is nitrogen in the ammonium (NH<sub>4</sub><sup>+</sup>) pool, and is continually exported from the system at a higher rate than nitrogen, leading to Si(OH)<sub>4</sub> limitation. Si is released back to the water column *via* the dissolution of biogenic silica (BSi), which is a considerably slower process compared to the remineralisation of N and P (Dudgale et al., 1995). Regeneration of biogenic silica is primarily a chemical phenomenon whereas the regeneration of N and P are biological mediated by grazers and bacteria. In addition, P may be re-mineralized autolytically, whereas N is strictly biologically mediated (Garber, 1984).

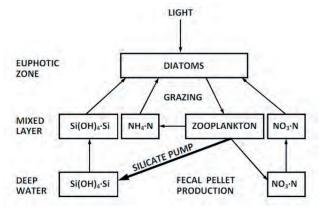


Fig. 11.3 Idealized flow diagram to show the flow of nitrogen and silicon (silicate pump) in a diatom-dominated grazed system (source: Dudgale et al., 1995)

Diatom production is closely linked to the generation of fast sinking particles which play a major role in exporting organic carbon to deep ocean waters and thus in sequestering anthropogenic CO<sub>2</sub>. Dissolved silica available in the global ocean is absorbed by diatoms and incorporated together with CO<sub>2</sub> through photosynthesis taking place in the euphotic zone. A compensation of CO<sub>2</sub> from atmosphere to the ocean is needed in order to establish the equilibrium at the air-water interface, process that occurs on time scales of weeks or months (Michaels and Silver, 1988; Smetacek, 1998, 1999; Furnas, 1990; Broecker and Peng, 1993; Tréguer and Pondaven, 2000; Yool and Tyrrell, 2003).

## 11.3. Disturbed silicon cycling in the Anthropocene era

Limnological investigations by Schelske and Stoeremer (1971) and Schelske et al. (1983) provide a convincing argument for hypothesis that some of the negative impacts of eutrophication are related to Si deficiency. Their studies of Lake Michigan demonstrated that the addition of an external nutrient supply, high in N and P but low in Si, resulted in increased primary productivity, Si depletion, and burial of Si in the sediments. They have hypothesized that the Si depletion might have caused a shift in dominance from diatoms to blue-green and green algae.

## 11.3.1. Impact of eutrophication

The Anthropocene is a recent and informal geologic chronological term that serves to mark the evidence and extent of human activities that have had a significant global impact on the Earth's ecosystems, particularly regarding the climate (Meybeck, 2001a, b; Crutzen and Stoermer, 2000). In the last few decades, human activities (intensive agriculture with excessive use of fertilizers, deforestation, mining, urbanization, industrialization, irrigation, and damming) have caused dramatic changes in riverine geochemistry (Billen et al., 1995; Meybeck 2001a, b, 2002, 2004; Meybeck and Vörösmarty, 2005) which consequently affected the supply of constituents from rivers to the estuarine and coastal ecosystems. The fluxes of phosphorus and nitrogen to the oceans have increased worldwide by more than a factor of three, and by factor of ten to fifty at some regional and local scales (Meybeck, 2001a; Howarth et al., 1996; Nixon et al., 1996; Goudie and Cuff, 2002; Howarth, 2008), but barely that of silicon (Berner and Berner, 1996). There are numerous authors that report the decreasing Si fluxes to coastal ecosystems (Justić et al., 1994, 1995a; Turner and Rabalais, 1994; Rabalais et al., 1996; Conley et al., 1993, 2008; Garnier et al., 1999; Humborg et al., 1997, 2000, 2002, 2006, 2008).

Although nitrogen and phosphorus as such do not pose any direct hazard to marine organisms or people, their excessive inputs may disturb the balance of the ecosystem (Savage et al., 2010). Recent decades have seen a massive increase in coastal eutrophication globally, leading to widespread hypoxia and anoxia, habitat

degradation, alteration of food-web structure, loss of biodiversity, and increased frequency, spatial extent, and duration of harmful algal blooms (Anderson et al., 2008; Håkanson and Bryhn, 2008; Heisler et al., 2008; Howarth, 2008; Smith and Schindler, 2009). Excessive primary production in the Baltic Sea, fueled by high concentrations of phosphorus and nitrogen (HELCOM, 2009; Sandén and Rahm, 1993), has doubled in the last two decades of the XXth century (Wasmund et al., 2001), and has caused:

- an increase in phytoplankton biomass and abundance (Kahru et al., 1994; Niemkiewicz and Wrzołek, 1998; Wasmund et al., 1998; Pliński and Jóźwiak, 1999; Hajdu et al., 2000),
- development of anoxic and hypoxic conditions in deeper waters (HELCOM, 2002), and consequent declines in commercially and recreationally valuable fish species (ICES, 2001).

Nutrient-enhanced phytoplankton growth concerns also diatoms, and the more diatoms that are produced, the more BSi becomes deposited in sediments (DeMaster, 1981), which can eventually deplete the water column reservoir of DSi, as Si recycling remains slower than the recycling of N and P, which are biologically mediated (Schelske and Stoermer, 1971; Officer and Ryther, 1980). Increases in the sedimentation rate of diatoms can result in increasing amounts of diatoms (BSi) stored in the sediments (Fig. 11.4), eventually leading to a reduction in DSi supplies to the water column, especially in the systems with long residence time e.g. the Baltic Sea (Conley et al., 1993, 2008). An increase in BSi accumulation has also been reported for some other regions; the BSi accumulation coefficient in delta of the Mississippi River has increased by 100% over the XX<sup>th</sup> century (Turner and Rabalais, 1994). That increase was particularly well pronounced up to the 1980s, when the riverine loads of nitrogen doubled, while loads of DSi dropped by 50%.

Biogenic silica accumulation in the Baltic Sea varies spatially, with northernmost Gulf of Bothnia, the Gulf of Riga, and Finland showing larger share of biogenic silica accumulation than the Baltic Proper (Burska and Bolałek, 2011). Different hydrographic and hydrochemical features in the Baltic Sea are responsible for spatial diversity in BSi accumulation (Papuch et al., 2009). Dissolution of diatom silica is regulated by pH, temperature, specific surface area, aluminum content and the protective organic coating (Van Cappellen et al., 2002). The rate of BSi dissolution depends also on salinity and it increases by factor of two by changing salinity from 1 to 5 PSU (Practical Salinity Unit) (Hurd, 1983).

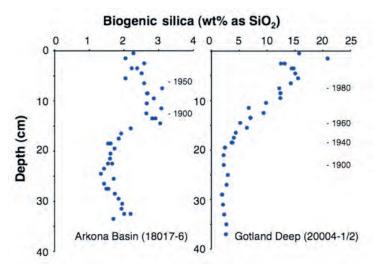


Fig. 11.4 Changes in biogenic silica (BSi) concentration down cores in the Arkona Basin and in the Gotland Deep (Baltic Sea) (numbers next to blue dots indicate years) (source: Conley et al., 2008)

Recent studies on the biogeochemical Si cycle in the Baltic Sea (Conley et al., 2008) have revealed that:

- the present day DSi load to the Baltic Sea is 855,000 tons yr<sup>-1</sup>,
- hydrological regulation and eutrophication of inland waters can account for a DSi reduction of 420,000 tons yr<sup>-1</sup>,
- the BSi accumulation in the sediments of the Baltic Sea is by 36% higher as compared with earlier estimates from the literature,
- the historical DSi concentrations were 2.6 times higher at the turn of the last century (ca. 1900) than at present,
- although the DSi decrease has leveled out and at the present there are only restricted areas of the Baltic Sea with DSi concentrations limiting diatoms growth and abundance, further decline in DSi concentrations will lead to widespread DSi limitation of diatoms growth with severe implications for the food web.

## 11.3.2. Impact of river damming

A series of studies have shown that, apart from eutrophication enhanced by excessive loads of N and P, the hydrological alterations, e.g. through dams and water reservoirs construction (Fig. 11.5), have decreased the DSi loads to the sea with adverse effects on the marine ecosystem (Conley et al., 1993; Garnier et al., 1999; Ittekkot et al., 2000; Humborg et al., 1997, 2000, 2002, 2006, 2008; Vörösmarty et al., 2003).



Fig. 11.5 Dam on the Vistula River in Włocławek (Poland) (source: http://static.panoramio.com/photos/original/51124017.jpg)

Schelske and Stoermer (1971) and Van Bennekom and Salomons (1981) used the term "articial lake effect" and under this term one should understand the fact that dams convert a river into a lake, increasing water residence time and often improving light conditions in the water column, thus providing conditions for enhanced algal growth, including diatoms. Diatoms frustules, consisting of BSi, undergo deposition and burial in the sediments (Fig. 11.3). The process of re-dissolution of the BSi trapped behind dams is probably low, since burial rates in the reservoirs are estimated to be 6-80 times higher than in natural lakes (Dean and Gorham, 1998). Major dams currently harness main rivers on all continents (Dynesius and Nilsson, 1994; Vörösmarty et al., 1997b) and store 90-99% of the incoming sediments (Vörösmarty et al., 1997a).

It has been lately suggested that perturbed surface water-groundwater interactions through hydrological alterations, leading to less contact of river and stream waters with vegetated soils along the riparian zone, are additional causes for the reduced DSi concentrations observed in many ultra-oligotrophic regulated rivers in Northern Sweden (Humborg et al., 2002, 2006).

Modeling studies, conducted by Laruelle et al. (2009) and focused on anthropogenic perturbation of the silicon cycle at the global scale, have shown that global temperature rise will significantly affect the production and recycling of BSi in the coastal zones. Climate variability has become more important as a factor influencing coastal eutrophication in recent decades, explaining 14% of the variance in the algal data in the Baltic Sea since 1975 (Savage et al., 2010).

### Examples of heavily and moderately dammed rivers

A full account on the Danube River damming and on consequences for the riverine ecosystem can be found in publications by Humborg et al. (1997, 2000, 2006). The Danube was dammed in the early 1970s at the Serbian/Romanian border where the Danube passes the so ca-called "Iron Gate". Following the construction of the dam Iron Gate I the sediment discharge decreased by 30-40% at the nearest downstream station and simultaneously the DSi winter concentrations declined sharply along the Romanian coast (Humborg et al., 1997). In 1984, a second dam, the Iron Gate II (located at km 864), was erected and a further drastic decrease in both the sediment discharge (by 60-70%; Panin and Jipa, 2002) and the DSi winter concentrations along the Black Sea coast was observed. The mean DSi concentration in the Danube River decreased from a pre-dam concentration of 140 μmol dm<sup>-3</sup> for the year 1959 and 1960 to a mean post-Iron Gates concentration of 60 μmol dm<sup>-3</sup> (Humborg et al., 1997).

A simultaneous decrease in total suspended solids (TSS) and DSi loads has also been reported for the Changjiang River based on long-term records initiated in 1959; more significant decrease in both TSS and DSi loads is anticipated now, after recent closing of the Three Gorges Dam (Li and Cheng, 2001).

The effect of hydrological alterations on reduced Si land-sea fluxes has been demonstrated by Humborg et al. (2006) in their studies in the northern boreal/subarctic and oligotrophic Swedish rivers Kalixälven and Luleälven. These rivers have steeper catchment slope compared to the rivers draining the southeastern catchments of the Baltic Sea. Damming is much more frequent in the boreal rivers owing to its higher effectiveness in terms of power generation. The DSi yield of the heavily dammed Luleälven (793 kg km<sup>-2</sup> yr<sup>-1</sup>) constituted only 63% of that found in the unregulated Kalixälven (1261 kg km<sup>-2</sup> yr<sup>-1</sup>), despite the specific runoff of the Luleälven being by 19% higher than that of the Kalixälven. Flow normalized DSi yield of Luleälven, regulated watershed, was only half of the DSi yield of Kalixälven, unperturbed watershed (Humborg et al., 2006).

The Vistula River has been moderately dammed in Włocławek since 1970 with a total volume and surface area equal to 0.41 km³ and 70.4 km², respectively. About 1.7 million m³ yr¹ of sediments accumulate in this reservoir (Anonymous, 2001) reducing the TSS concentration by some 50 mg dm⁻³. This estimate is in good accordance with historical measurements indicating TSS concentrations of some 75 mg dm⁻³ in the Vistula River before damming (Miliaman et al., 1975), in contrast to the mean concentrations of 17 mg dm⁻³ found in the 1990s. This gives a sedimentation rate of about 2 cm yr¹, if it is assumed that all material is evenly distributed over the reservoir area with a bulk density of 1,000 kg m⁻³. Water residence time in the Vistula reservoir is about 1 day, thus, massive diatom blooms are not very likely to occur (Humborg et al., 2006).

## Spatial diversity in silicon retention

Changes in dissolved silicate loads to the Baltic Sea with respect to trapping effects of lakes and reservoirs have been studied by Humborg et al. (2008). The authors tested

the hypothesis that DSi yields (kg km<sup>-2</sup> yr<sup>1</sup>) of 82 major watersheds of the Baltic Sea (Fig. 11.6) can be expressed as a function of the hydraulic load (HL) i.e. as a measure of water residence time and the total organic carbon (TOC) concentration, both variables affecting the DSi yield. Most boreal rivers fitted a linear regression model using HL as an independent variable to explain the DSi yield. As the authors further state, rivers with high HL, i.e., shortest residence times, showed highest DSi yields up to 2,300 kg km<sup>-2</sup> yr<sup>-1</sup>, and that is explained by the fact that geochemical sources prevail over biological sinks in the boreal watersheds which provide ca. 40% of the total DSi load to the Baltic Sea. The larger eutrophic watersheds, draining cultivated landscape of the southern catchment of the Baltic Sea and representing ca. 50% of the annual water discharge to the Baltic Sea, showed the yields in the range 60-580 kg km<sup>-2</sup> yr<sup>-1</sup>. The subjected studies have proven that in the southern catchment DSi is retained in the watersheds through BSi production and subsequent sedimentation along the entire river network. The riverine DSi loads to the Baltic Sea might have dropped by 30-40% during the last century (Humborg et al., 2008).

Highest DSi concentrations within the Baltic catchment were found for the northernmost rivers, e.g. the rivers entering the Gulf of Bothnia have medians ca. 100  $\mu$ mol dm<sup>-3</sup>. Compared to these rivers, the rivers discharging into the Gulf of Finland, the Gulf of Riga, the Baltic Proper, and the Kattegat all have medians between 70  $\mu$ mol dm<sup>-3</sup> and 80  $\mu$ mol dm<sup>-3</sup> (Humborg et al., 2006; Fig. 11.6).

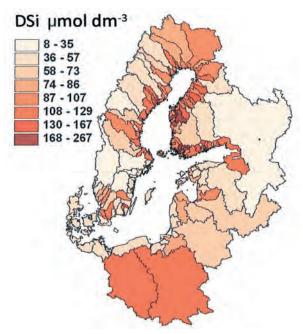


Fig. 11.6 Mean (1980-2000) discharge weighted dissolve silicate (DSi) concentrations of 82 major rivers draining into to the Baltic Sea (source: Humborg et al., 2008)

# 11.4. Seasonal variability in DSi, BSi concentrations in the Vistula, Oder, Daugava, and Danube Rivers

Similarly to DIN (DIN=NO<sub>3</sub>-N+NO<sub>2</sub>-N+NH<sub>4</sub>-N) and dissolved inorganic phosphorus (DIP) (Chapter 9), DSi and BSi in the Vistula and Oder River exhibit well developed annual patters. Maximum DSi concentrations were observed in autumn and winter, up to 250 μmol dm<sup>-3</sup>, whereas minimum values or even depletion were found in spring (as in 2003 and 2004), concomitant with diatom growth; DSi depletion points to possible diatoms growth limitation (Pastuszak et al., 2008; Fig. 11.7). DSi cycles in Oder and Vistula are very similar, with slightly higher DSi concentrations (by ca. 10 μmol dm<sup>-3</sup>) in the Vistula River characterized by higher DSi yields. The differences in DSi yields, at comparable DSi concentrations, of the Oder River (525 kg km<sup>-2</sup> yr<sup>-1</sup>) and the Vistula River (768 kg km<sup>-2</sup> yr<sup>-1</sup>) can be mainly attributed to differences in their specific runoffs; the specific runoff in the watershed of the Vistula River (189 mm m<sup>-2</sup> yr<sup>-1</sup>) was by about 25% higher than in the watershed of the Oder River (141 mm m<sup>-2</sup> yr<sup>-1</sup>) (Humborg et al., 2006).

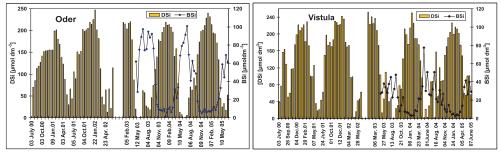


Fig. 11.7 Dissolved (DSi) and biogenic silicate (BSi) in the Oder River (Krajnik Dolny) and the Vistula River (Kiezmark) in 2000-2005 (source: own data gathered within the *SIGNAL* and *SIBER* projects; Pastuszak et al., 2008)

The BSi concentrations pattern showed two differences as compared to DSi annual cycles in the rivers studied: (i) maximum BSi concentrations, reaching ca.  $100 \, \mu \text{mol dm}^{-3}$  in the Oder and ca.  $50 \, \mu \text{mol dm}^{-3}$  in the Vistula River, were observed from spring throughout summer, whereas minima in autumn and winter, (ii) BSi concentrations were by half lower in the Vistula than in the Oder River (effect of Vistula damming). The observed depletion of DSi in April and May is concomitant with the spring diatom growth resulting in seasonal BSi peaks.

Generally, the proportion of BSi in total Si pool (DSi+BSi) is higher in eutrophied rivers (Conley, 1997; Humborg et al., 2006). BSi ranges only from 10 to 20% of the sum of DSi+BSi during non-blooming conditions, whereas during diatom blooms this percentage ranges from 50% to 70% (Conley, 1997). The proportion of BSi in eutrophied rivers entering the Baltic Sea has been shown to be among the highest observed worldwide (Conley, 1997; Humborg et al., 2006). BSi contribution to overall Si pool (DSi+BSi) in the Oder River reached 99.8% in spring/summer and

0.8% in winter (as in January 2003) (Fig. 11.7).

The effect of a single artificial water reservoir and consecutive reservoirs on silica river fluxes is exemplified by the moderately dammed Vistula River and the heavily regulated Daugava River that are compared with the practically undammed (*sensu* Dynesius and Nilsson, 1994) Oder River (Humborg et al., 2006). All these rivers are characterized by a similar eutrophication status and by similar geological and climatic settings. The sum of the discharge weighted annual mean BSi and DSi concentrations in the rivers Oder, Vistula, and Daugava were about 160 μmol dm<sup>-3</sup> (40+120 μmol dm<sup>-3</sup>), 150 μmol dm<sup>-3</sup> (20+130 μmol dm<sup>-3</sup>) and 88 μmol dm<sup>-3</sup> (6+82 μmol dm<sup>-3</sup>), respectively (Humborg et al., 2006; Fig. 11.8). These studies showed that damming considerably affects BSi and DSi dynamics and concentrations in riverine waters; BSi concentrations in the undammed Oder were two times higher than in the Vistula, and as much as 7 times higher than BSi in the Daugava. The authors further conclude that a complete trapping of BSi in heavily dammed Baltic rivers, could have lowered Si fluxes to the Baltic Sea from rivers with cultivated watersheds even by 25%.

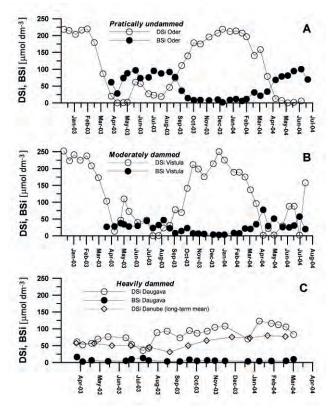


Fig. 11.8 Dissolved silicate (DSi) and biogenic silicate (BSi) concentrations measured at the mouth of the Oder (A), Vistula (B), Daugava, and Danube (C) Rivers (source: Humborg et al., 2006)

#### 11.5. Role of estuaries in DSi⇔BSi transformation

Studies in estuaries of the Amazon, Mississippi, and Danube (Milliman and Boyle, 1975; Nelson and Dortch, 1996; DeMaster et al., 1996; Ragueneau et al., 2002b) have shown that DSi uptake in estuaries can be significant and DSi can even limit estuarine primary production, but dissolution of sedimented diatom frustules is rapid, leading to a significant internal DSi source (Conley and Malone, 1992). The riverine outflow also transports BSi to the estuarine environment where freshwater diatoms die out immediately and re-dissolution of BSi is fast, as observed in many estuaries, including the Danube estuary which is supplied with much lower loads of BSi (Ragueneau et al., 2002b) as compared with those in the Oder estuary (Pastuszak et al., 2008).

#### Oder estuary - modified DSi and BSi fluxes to the Baltic Sea

Similarly to Danube estuary, the Oder estuary proved to be an important component of the Oder River-Baltic Sea continuum where very intensive seasonal DSi uptake during spring and autumn, but also BSi regeneration during summer take place (Pastuszak et al., 2003, 2008) (see to the section below). The complexity of the estuary (flood plains, numerous canals, lake, and lagoon) undoubtedly makes it a natural deposition site for particulate matter. The sedimentation of allochthonous and autochthonous matter in the Oder estuary is favored by physical and biological processes, namely a reduced water flow and a massive phytoplankton development and sedimentation, including fast sedimenting siliceous plankton species. Often, diatoms dominate among the sedimented phytoplankton cells during period of new production in coastal or upwelling areas (Dugdale et al., 1995) and that is the case in the Szczecin Lagoon (Zembrzuska, 1962; Wiktor, 1980). An increased dissolution of diatom frustules at high seasonal temperature has been reported by Ragueneau et al. (1994) and Cowan et al. (1996).

## Alternating phytoplankton in the Oder estuary

Fast flowing, turbid Oder waters reduce their flow rate in the uppermost section of the estuary allowing suspended matter to sediment and biota to gradually adapt to salinity which slowly increases up to 0.3-1.0 PSU in the Szczecin Lagoon (maximum 2.5 PSU observed in 1992; Pastuszak et al., 2001) and to 1.2 – 7.8 PSU at the lagoon outlet (Pastuszak et al., 2003, 2005, 2008). Increased light penetration in the Szczecin Lagoon, as compared to the Oder River, creates favorable conditions for freshwater and oligohaline phytoplankton to develop and utilize dissolved nutrients. Intensive primary production in vegetation period results in high chlorophyll *a* concentrations (Landsberg-Uczciwek, 1997), decreased levels of nutrients (first to drop are phosphates and silicates in spring, followed by nitrates in summer) (Pastuszak et al., 1999, 2001, 2005; Grelowski et al., 2000), and water over-saturation with

oxygen, its values reaching even 160-180% (Wiktor, 1980; Poleszczuk et al., 1995; Poleszczuk, 1998). The estimates made for the period 1964-66 indicated that annual phytoplankton production in the lagoon varied from 612 to 761 g m<sup>-2</sup> dry weight, making the lagoon one of the most productive reservoirs bordering the Baltic Sea (Wiktor, 1971).

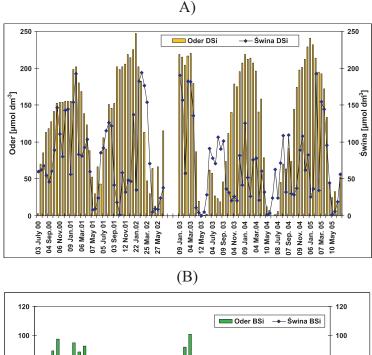
The Szczecin Lagoon is characterized by a succession of phytoplankton species (Zembrzuska, 1962; Wiktor, 1980). In shallow coastal regions of the south-eastern Baltic, the Szczecin Lagoon included, the wind-driven mixing reaches the sediments, enabling seeding and therefore diatom growth. Correspondingly, diatoms are still dominant there in most of spring blooms (Wasmund et al., 2001) and their average biomass may reach 11.411 mg ww. dm<sup>-3</sup>, constituting 84% of the average spring phytoplankton biomass estimated by Wolnomiejski and Witek (in prep.) for the Wielki Zalew (Polish part of the Szczecin Lagoon) for 1999-2005. Phytoplankton in the Szczecin Lagoon is dominated by diatoms which are represented by the highest number of species; however only some of them reach a mass development, therefore this fact is important with respect to seasonal changes in plankton biomass. Diatoms are mainly represented by freshwater genus such as Diatoma (D. elongatum), Melosira (mainly M.granulata, M. varians and M. distans) and Asterionella (mainly A. formosa and A. gracillima). The maximum of their development is observed between May and June when the percentage contribution of Diatoma elongatum may reach even 70% (Zembrzuska, 1962). Massive growth of diatoms leads to depletion of DSi in both the Oder and in the estuary, and to occurrence of BSi maxima (up to 100 µmol dm<sup>-3</sup> in the Oder and 40-60 μmol dm<sup>-3</sup> in the Świna Strait (Fig. 11.9 A, B).

The second peak diatoms show in autumn, but at that period they do not always play a dominant role (Zembrzuska, 1962; Gromisz and Witek, 2001). Though not always dominant, diatoms may contribute in ca. 36% to overall autumn phytoplankton biomass (5.693 mg ww. dm<sup>-3</sup>), as stated by Wolnomiejski and Witek (in prep.) for the Wielki Zalew (see to Fig. 11.10) for 1999-2005; that contribution reaches 40% on an annual basis, or 25% when recalculated into carbon. The demand for DSi in autumn is great and the DSi budget points to that (see the text below). The DSi loads exported from the estuary dropped from its summer maximum of ca. 2.5-4.5 kt month<sup>-1</sup> to ca. 1-2.5 kt month<sup>-1</sup> in autumn 2003-2004. However, in between these two diatom peaks, when the blue green algae (*Aphanizomenon flos aquae* and *Microcystis aeruginosa*) dominate, significant amounts of BSi that were formerly sequestered in the sediments of the lagoon are transformed into DSi and exported to the open Baltic Sea.

## DSi, BSi concentrations in the Oder River and Świna Strait

A direct comparison of DSi concentrations in the Oder River and the Świna Strait, a main outlet of the Oder estuary (Fig. 11.9A), showed that DSi concentrations in the Świna Strait exhibited greater short term variability resulting from (i) the pulsating nature of water exchange between the lagoon and the bay (Pastuszak et al., 2003),

(ii) appearance of additional DSi minima in autumn (October, November) which is a consequence of DSi uptake by diatoms showing the second seasonal maximum in the Szczecin Lagoon (Zembrzuska, 1962; Wiktor, 1980), and (iii) appearance of summer DSi maxima as a result of BSi dissolution in the water column and the water/sediments interface, as proven in the Si budget presented below.



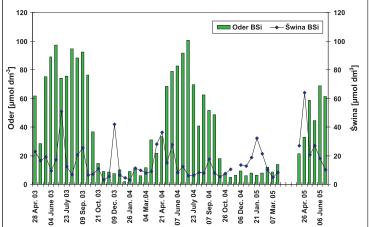


Fig. 11.9 Dissolved silicate (DSi) concentrations in the Oder River (Krajnik Dolny – estuary entrance) and the Świna Strait (estuary exit) in 2000-2005 (A), and biogenic silicate (BSi) concentrations in 2003-2005 (B); for sampling locations - see to Fig. 11.10 (source: own data gathered within the SIGNAL and SIBER projects; Pastuszak et al., 2008)

Apart from inter-annually variable internal DSi cycling there can appear a variable external forcing affecting DSi concentrations in the Oder estuary. Very intensive summer precipitation in the river watershed and a very high Oder water outflow was recorded in summer 2001, and the peak reached 880 m³s⁻¹ in August (Chapter 9). The summer season 2001, in particular June and July, though wet were characterized by air temperatures well above the long-term average (even by 3°C higher than average) and consequently higher water temperature. The combination of these parameters must have been a cause of DSi concentrations being much higher in Oder in summer 2001 than in summer 2003 or 2004. The high summer DSi signal observed in the Oder waters could have even reached the Świna Strait in 2001 as the DSi peak found in the strait was the highest over the period studied (Pastuszak et al., 2008; Fig. 11.9A). Studies of Mortatti and Probst (2003), focused on seasonal and spatial variations in silicate rock weathering, prove a major role of runoff as factor controlling silicate weathering processes and show that the chemical erosion rates vary greatly from low discharge to high discharge.

BSi concentrations in the Świna Strait were considerably lower than in the Oder River and that was due enhanced biological production in the Lagoon and subsequent diatom frustules sedimentation, but also due to a dilution effect (Fig. 11.9B) (Pastuszak et al., 2008).

Seasonal changes in nutrient concentrations in the Oder estuary, the internal nutrient recycling included, mimic to a great extent nutrient behavior in the mixed, turbulent German Bight, fed by the Weser and Elbe Rivers (Ehrenhauss et al., 2004).

## Mass balance calculation of net DSi transport from the Oder estuary to the Baltic Sea

The budgeting was only possible for DSi; Pastuszak et al. (2008) were in a possession of BSi data for the Oder River and the Świna Strait but adequate numbers were not available for the Pomeranian Bay. BSi, in contrast to DSi, has never been an obligatory parameter in coastal Baltic monitoring, and till recently these nutrients have not been given much attention in the Baltic region.

The calculation of DSi transport through the Oder River estuarine system (Fig. 11.10) to the open Baltic Sea were done using LOICZ methodology (Gordon et al., 1996) based on Knudsen theorem (Knudsen, 1900) (the same methodology was used in mass budget calculations of N and P in the Oder estuary – see to Chapter 10). The budget calculations of DSi consisted of monthly loads introduced to the estuary compared with those exported from the estuary to the Pomeranian Bay. Monthly loads ( $L_{in}$ ) introduced into the estuarine system were determined based on measurements of DSi and BSi concentrations ( $C_R$ ) at river monitoring station in Krajnik Dolny, and based on measurements of water flows ( $Q_R$ ) at the Oder River cross-section in Widuchowa (Fig. 11.10). The following equation was used for calculations:

$$L_{in} = C_R * Q_R.$$

Loads exported from the estuary to the Pomeranian Bay were calculated based on measurements of nutrient concentrations in Świna Strait, which were corrected for the sea component, using salinity as a conservative parameter. The average monthly volumetric contribution of water of riverine origin  $(X_R)$  in the Świna Strait was calculated according to the following equation:

$$X_{R} = (S_{SEA} - S_{SWINA}) / (S_{SEA} - S_{R}),$$

where:  $S_{SEA}$ ,  $S_{SWINA}$ , and  $S_R$  – monthly mean salinity values in sea water, in the Świna Strait, and in the Oder River, respectively. Concentration of DSi in riverine water after passing through the estuary ( $C'_{R}$ ) can thus be described by:

$$C'_{R} = [C_{SWINA} - C_{SEA} * (1 - X_{R})] / X_{R}$$

where:  $C_{\text{ŚWINA}}$  and  $C_{\text{SEA}}$  – monthly mean concentrations of DSi in the Świna Strait and in seawater, respectively.

In order to simplify calculations, it was assumed that  $C'_R$  determined for Świna Strait is valid also for the remaining two outlets from the Szczecin Lagoon (i.e. Peene and Dziwna Straits), evaporation from the estuary was balanced by precipitation, groundwater seepage and inflows of small rivers can be neglected, and that the water volume in the estuary remained constant. Consequently, it was possible to assume that residual outflow from the Szczecin Lagoon to the Pomeranian Bay was equal to the Oder River flow  $Q_R$  and that loads exported from the estuary  $(L_{out})$  can be expressed by:

$$L_{out} = C'_{R} * Q_{R}$$

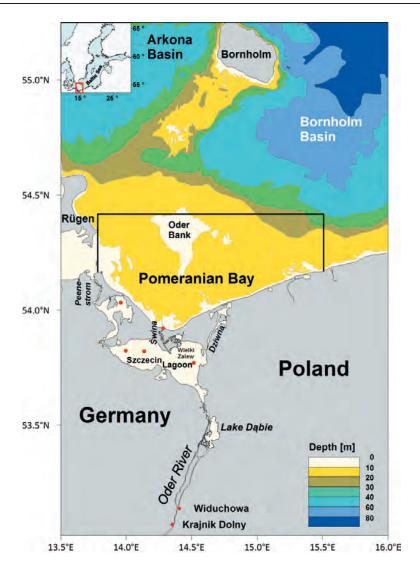


Fig. 11.10 The study area of the Oder estuary, Baltic Sea; four dots in the Szczecin Lagoon indicate sediment cores sampling sites, while a single dot in the Świna Strait and one in Krajnik Dolny show water sampling sites. The black frame in the Pomeranian Bay delimits the sea area taken into account for DSi budgeting (source: map prepared and made available by M.Sc. Lena Szymanek, NMFRI, Gdynia)

## Outcome of mass balance calculations

Mass balance calculations of DSi and BSi (for BSi – only net loads entering the Szczecin Lagoon) showed, that despite the complexity and the lake effect in the eastern branch of the Oder River, the Oder estuary is not an overall DSi trap (in contrast to artificial river constructions e.g. dams), but on the contrary is a DSi

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source. Mass balance calculations of DSi and BSi showed that DSi+BSi import to the estuary over a two-year period was 103.2 kt and that it can be compared with the DSi export of 98.5 kt. The difference between these numbers gives room for ca. 2.5 kt BSi to be annually exported to the Baltic Sea. Much higher DSi export from the estuary than import to the estuary in summer 2003 and 2004 is a proof of BSi accumulation during the diatom spring bloom and subsequent BSi sedimentation and conversion into DSi in the shallow Szczecin Lagoon, a largest component of the Oder estuary (Fig. 11.11). Sediment cores studies point to BSi annual accumulation on the level of 2.5 kt BSi. BSi import to the estuary is on the level of ca. 10.5 kt, thus ca. 5 kt of BSi is annually converted into the DSi, increasing the pool of DSi that leaves the system. BSi concentrations, which were ca. 2 times higher at the estuary entrance than at its exit, remained in a good agreement with the DSi and BSi budgeting. It is shown that temperature and volume of water discharged has a great impact on DSi outflow from the estuarine system to the Baltic Sea (Pastuszak et al., 2008).

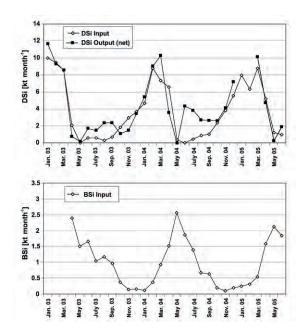


Fig. 11.11 Budget of dissolved silicate (DSi) for the Oder estuary and loads of biogenic silicate (BSi) introduced to the estuary during the period January 2003 - June 2005 (note different scales); 1kt=1000 tons (source: Pastuszak et al., 2008)

Summer regeneration of nutrients, expressed by summer DSi and DIP (dissolved inorganic phosphorus) (Chapter 9) maxima, was found in earlier studies carried out in the Szczecin Lagoon and the Pomeranian Bay (Kaczewiak and Wolnomiejski, 1977; Pastuszak et al., 1999, 2001, 2003, 2005; Grelowski et al., 2000). Those authors postulated that summer maxima in phosphate and DSi concentrations in the

Szczecin Lagoon, the Świna Strait, and the inner Pomeranian Bay resulted not only from P and Si regeneration in the system, but most probably were also generated by nitrogen-limited primary production and by succession of phytoplankton species in that period of the year, which in turn leads to ineffective P and Si uptake.

There are only few estuarine Si budgets available that can be compared with our results from the lagoon type Oder estuary. Nelson and Dortch (1996) as well as DeMaster et al. (1996) have shown that DSi loads from the Mississippi and the Amazon River are often fully consumed in the river plumes by autochthonous diatom production; dissolution of BSi from the coastal sediments is substantial (Milliman and Boyle, 1975). However, these are open estuaries where mixing between river waters and marine water occurs mostly on the seaward side of the estuary, hence, an estimate of the dissolution of the riverine fraction of BSi is not possible. Other studies on Si dynamics in enclosed bays such as the Gulf of Riga (Savchuk, 2002) have shown that almost all DSi delivered by Daugava, one of the major Baltic Sea rivers, are completely buried in the sediments of the Gulf of Riga; however the Gulf of Riga is not an estuary. Thus, the study on the shallow inland Oder estuary, that might be representative for the early stages of mixing within the upper part of many other estuaries with low salinities and still high sedimentation rates, indicates that much of autochthonous BSi becomes converted into DSi and thus is available for coastal diatom production.

## 11.6. Response of the Baltic Sea to changes in Si cycle in the river basins and the sea

## 11.6.1. Declining DSi concentrations

In the past, the importance of silicate as a limiting nutrient for new production in the ocean, i.e. production supported by nutrients coming into ecosystem or habitat from other ecosystems or habitats (new nutrients), and in determining global productivity and carbon budgets, has been relegated to the lower ranks compared to the role of nitrogen and, more recently iron (Dudgale et al., 1995; Domine et al., 2010). Perturbations of silicon cycling and response of coastal ecosystems to anthropogenic perturbations inclined the researchers to focus on the problem (e.g. Ragueneau et al., 2006b).

The Baltic Sea is one of the many aquatic ecosystems that show long-term declines in DSi concentrations (Conley et al., 1993). Using non-parametric analysis Sandén et al. (1991) reported significant declining trends in DSi concentrations throughout the Baltic Sea from 1970 to 1990. General decrease in DSi concentrations in both the surface and the bottom waters have been reported by Conley et al. (2008) (Fig. 11.12).

The non-parametric Mann-Kendall seasonal test, covering the period of the last three decades and focused on the pelagic DSi in different subregions of the Baltic Sea, clearly indicates that there are decreasing trends for the most areas and water depths, and the decrease ranges from 0.05 to 1.2 µmol Si dm<sup>-3</sup> yr<sup>-1</sup>. The trends have been leveling off over the last decade. Since the riverine load of DSi has not been changing at a corresponding rate during the subjected decades, the decrease is assumed to be mainly a result of eutrophication (Papush and Danielsson, 2006). It has been proven that DSi dropping to concentrations 1-2 µmol Si dm<sup>-3</sup> limit growth of diatoms as reported by e.g. Egge and Aksnes (1992).

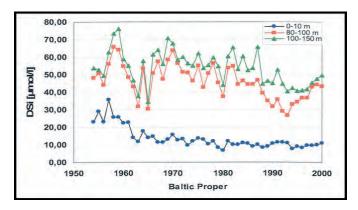


Fig. 11.12 Long-term declines of dissolved silicate (DSi) in the Gotland Deep, Baltic Proper in three water layers: 0-10 m, 80-100 m, and 100-150 m (source: Conley et al., 2008; graph modified)

## 11.6.2. Changes in Si:N and Si:P ratio – implications for the ecosystem

Changes in nutrient supply to the ecosystem gave rise to another problem: not only nutrient concentrations but also nutrient ratios are of particular importance to evaluate eutrophication and forecast algal successions during the given season (Justić et al., 1995a; Gilpin et al., 2004). As indicated by Redfield (1934) and Redfield et al. (1963), diatoms, which are silicified aquatic organisms, require Si in a special ratio to N and P for optimal growth. Molar ratio C:N:P:Si=106:16:1:16 was given for marine algae (Redfield, 1934; Redfield et al., 1963), and C:N:P:Si=106:16:1:42 for freshwater diatoms (Conley et al., 1989).

Pristine rivers generally deliver Si to coastal ocean in great stoichiometric excess over N and P, relative to the nutrient requirements of diatoms (Si:N:P = 16:16:1). In the Amazon, Mackenzie, Yukon, and Zaire Rivers the Si:N ratio is >12, while the Si:P ratio is >192. Consequently, pristine rivers tend to have N- or P-deficient plumes, and create N and P deficiency in the coastal waters strongly affected by these elements (Justić et al., 1995a). Deviation from the Redfield ratio (Redfield, 1934; Redfield et al., 1963) either in nutrients taken up, or available in the water column

in a dissolved form, indicate potential for N, P or Si limitation of phytoplankton growth (Howarth, 1988; Dortch and Whitledge, 1992; Justić et al., 1995a). Studies of nutrient uptake kinetics have shown that Si:N ratio <1 and Si:P ratio <3 are indicative of Si limitation (Levasseur and Therriault, 1987). Whereas total algal growth is primarily regulated by the availability of N and P, relative availability of Si and availability of Si relative to N and P (i.e. Si:N and Si:P ratios) can influence the composition of the coastal phytoplankton community (Conley et al., 1993). The decreasing Si:N ratio may be exacerbating eutrophication by reducing the potential for diatom growth, in favor of harmful flagellates (Officer and Ryther, 1980; Conley et al., 1993; Justić et al., 1995a; Anderson et al., 2008; Struyf et al., 2009). This has been well demonstrated, for example, by Billen et al. (1991) who compared the Si: N uptake ratios and diatoms/flagellates development during the spring bloom in the Southern Bight and in an offshore shelf area of the North Sea (Fig. 11.13).

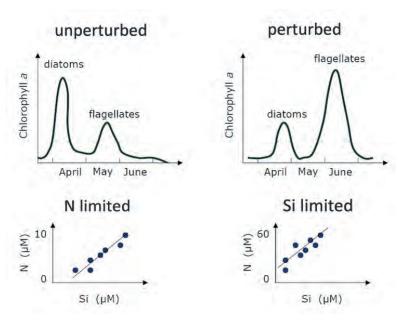


Fig. 11.13 Phytoplankton succession in unperturbed N limited systems and perturbed Si limited systems ( $\mu$ M= $\mu$ mol dm<sup>-3</sup>) (source: Billen et al., 1991)

Non-diatom species are known to be less desirable to higher trophic levels and some non-diatom based food webs are economically undesirable. An excessive increase in phytoplankton biomass which is not in line with its utilization in the food web in well oxygenated epipelagic layer, results in excessive sedimentation of organic matter and in consequence in excessive utilization of oxygen for respiration and decay (Kemp et al., 1992; Justić et al., 1993; 1995a,b; Dortch et al., 1994; Rabalais et al., 1994; Sen Gupta et al., 1996; Wiseman et al., 1997; Wasmund et al., 1998, 2001; Wasmund and Uhlig, 2003). Moreover, in coastal marine systems, these

algae produce either toxins or mucilage, escaping the normal grazing food web and leading to anoxic conditions at the decay of the bloom (Smayda, 1990; Maestrini and Granéli, 1991; Lancelot et al., 1994; Cugier et al., 2005). That leads to loss of recreational value of coastal regions.

Decreased DSi concentrations in the Baltic waters affected the DSi:DIN molar ratio which was approaching unity ratio prior to formation of the spring bloom (Rahm et al., 1996). The authors assumed that marine eutrophication was the primary reason for the decline in DSi concentrations; they expect further decrease in the DSi:DIN ratio with continued eutrophication of the Baltic Sea. This can be explained by an increased net sedimentation of biogenic silica due to increase in primary production attributable to increase in nutrient loading. While the Baltic Proper is generally assumed to be N limited, declining DSi:DIN ratios indicate that spring bloom diatoms growth may become DSi limited, as the optimal DSi:DIN ratio for diatom growth is approximately 1:1 (Rahm et al., 1996). Alterations of the molar ratios of nutrient are also documented by Danielsson et al. (2008) who carried studies in the Baltic Sea for the years 1970-2000. The author further state that annual long-term temporal trends in DSi:DIN and DSi:DIP show consistent decreasing patterns, with the largest slopes found in spring and summer for DSi:DIN, and during spring for DSi:DIP ratios. Moreover, in Gulf of Finland and Gulf of Riga there are areas where these ratios are found close to the Redfield ratios for diatoms and together with the evaluated trends these gulfs may become silica limited in relatively near future (Danielsson et al., 2008).

The spring bloom in the Baltic Sea is predominated by diatoms and dinoflagellates (Witek et al., 1993; Wasmund et al., 1998; Gromisz and Witek, 2001) and that was the case in the Pomeranian Bay in 1993-1997, with diatoms prevailing in the phytoplankton biomass in the colder months, i.e. early spring and autumn, while flagellated forms of cryptophytes, dinoflagellates and green algae, and blue-green algae playing a more conspicuous role in warmer seasons (Gromisz et al., 1999). As documented by Pastuszak et al. (2003), the depletion of P is characteristic in the Pomeranian Bay in spring, but also a considerable drop in silicate concentrations is observed; the DSi:DIN ratio can drop to values as low as 0.1-0.6.

- Alverson, A.J., 2007. Strong purifying selection in the silicon transporters of marine and freshwater diatoms. Limnol. Oceanogr., 52(4):1420-1429.
- Anderson, D.M., Burkholder, J.M., Cochlan, W.P., Glibert, P.M., Gobler, C.J., Heil, C.A., Kudela, R.M., Parsons, M.L., Rensel, J.E.J., Townsend, D.W., Trainer, V.L., Vargo, G.A., 2008. Harmful algal blooms and eutrophication: Examining linkages from selected coastal regions of the United States. Harmful Algae, 8:39-53.
- Andrén, E., 1999. Changes in composition of the diatom flora during the last century indivate increased eutrophication of the Oder estuary, south-western Baltic Sea. Estuar., Coast. Shelf Sci., 48:665-676.
- Anonymous, 2001. Studium kompleksowego rozwiązania problemów stopnia i zbiornika Włocławek Program skutków społeczno-ekonomicznych Synteza. Światowy Fundusz na Rzecz Przyrody (WWF), pp. 13-14.
- Berner, E.K., Berner, R.A., 1996. Global Environment. Water, Air, and Geochemical Cycles. Prentice Hall, Upper Saddle River, New Jersey.
- Billen, G., Lancelot, C., Meybeck, M., 1991. N, P, and Si retention along the aquatic continuum from land to ocean. [in:] Mantoura, R.F.C., Martin, J.M., Wollast, R. (eds.), Ocean Margin Processes in Global Change. Dahlem Workshop Reports, pp. 19-44.
- Billen, G., Dècamps, H., Garnier, J., Boët, P., Meybeck, M., Servais, P., 1995. Atlantic River Systems of Europe (France, Belgium, The Netherlands) [in:] Cushing, C.E., Cummins. K.W., Minshall, G.W. (eds.), River and Stream Ecosystems. Ecosystems of the World, 22:389-418.
- Broecker, W.S., Peng, T.H., 1982. Tracers in the sea, New York Eldigio Press, 690 pp.
- Broecker, W.S., Peng, T.H., 1993. Greenhouse puzzles. Columbia Press, New York, 85 pp.
- Brzezinski, M.A., Nelson, D.M., 1989. Seasonal changes in the silicon cycle with a Gulf Stream warm-core ring. Deep Sea Res., 36:1009-1030.
- Burska, D., Bolałek, J., 2011. Krzemionka biogeniczna [in:] Uścinowicz, S. (ed.), Geochemia osadów powierzchniowych Morza Batyckiego, Państwowy Instytut Geologiczny Państwowy Instytut Badawczy, Warszawa. pp. 205-213.
- Conley, D. J., 1988. Biogenic silica as an estimate of siliceous microfossils abundance in Great Lakes sediments. Biogeochemistry, 6:161-179.
- Conley, D.J., 1997. Riverine contribution of biogenic silica to the oceanic silica budget. Limnol. Oceanogr., 42:774-777.
- Conley, D.J., Malone, T.C., 1992. Annual cycle of dissolved silicate in Chesapeake Bay: implications for the production and fate of phytoplankton biomass. Mar. Ecol. Prog. Ser., 81:121-128.
- Conley, D.J., Schelske, C.L., 2001. Biogenic silica.[in:] Smol, J.P., Birks, H.J.B.,

- Last, W.M., (eds.), Tracking Environmental Change Using Lake Sediments: Biological Methods and Indicators. Kluwer Academic Publishers, Dordrecht, The Netherlands., Vol. 3, pp 281:293.
- Conley, D.L., Kilham, S.S., Theriot, E., 1989. Difference in silica content between marine and freshwater diatoms. Limnol. Oceanogr., 34:205-213.
- Conley, D.L., Schelske, C., Stoermer, E.F., 1993. Modification of the biogeochemical cycle of silica with eutrophication. Mar. Ecol. Prog. Ser., 101:179-192.
- Conley, D.J., Humborg, C., Smedberg, E., Rahm, L., Papuch, L., Danielsson, Å., Clarke., A., Pastuszak, M., Aigars, J., Ciuffa, D, Mörth C-M., 2008. Past, present and future state of the biogeochemical Si cycle in the Baltic Sea. J. Mar. Syst., 73:338-346.
- Cowan, J.L.W., Boynton, W.R., 1996. Sediment-water oxygen and nutrient exchanges along longitudinal axis of Chesapeake Bay: Seasonal patterns controlling factors and ecological significance. Estuaries, 19(3):562-580.
- Cowan, J.L.W., Pennock, J.R., Boynton, W.R., 1996. Seasonal and interannual patterns of sediment-water nutrient and oxygen fluxes in Mobile Bay, Alabama (USA): regulating factors and ecological significance. Mar. Ecol. Prog. Ser., 141:229-245.
- Crutzen, P.J., Stoermer, E.F., 2000. The "anthropocene". IGBP Newsletter 41:17-18.
- Cugier, P., Billen, G., Guillaud, J.F., Garnier, J., Ménesguen, A., 2005. Modelling the eutrophication of the Seine Bight (France) under historical, present and future riverine nutrient loading. J. Hydrol., 304(1-4):381-396.
- Danielsson, Å., Papuch, L., Rahm, L., 2008. Alterations in nutrient limitations Scenarios of a changing Baltic Sea. J. Mar. Syst., 73:263-283.
- Dean, W.E., Gorham, E., 1998. Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands, Geology, v.26-6, pp. 535-538.
- Del Amo, Y., Brzezinski, M.A., 1999. The chemical form of dissolved Si taken up by marine diatoms. J. Phycol., 35(6):1162-1170.
- DeMaster, D.J., 1981. The supply and accumulation of silica in the marine environment. Geochim. Cosmochim. Acta, 45:1715-1732.
- DeMaster, D.J., Smith, W.O., Nelson, D.M., Aller, J.Y., 1996. Biogeochemical processes in Amazon shelf waters: Chemical distributions and uptake rates of silicon, carbon and nitrogen. Cont. Shelf Res., 16:617-643.
- Domine, L.M., Vanni, M.J., Renwick, W.H., 2010. New and regenerated primary production in the productive reservoir ecosystem. Can. J. Fish. Aguat. Sci., 67:278-287.
- Dortch, Q., Whitledge, T.E., 1992. Does nitrogen or silicon limit phytoplankton production in the Mississippi River plume and nearby regions?. Cont. Shelf. Res., 12:1293-1309.
- Dortch, Q., Turner, R.E., Rowe, G.T., 1994. Respiration and hypoxia on the Louisiana Shelf. Estuaries, Vol. 17, No. 4: 862-872.
- Dudgale, R.C., Wilkerson, F.P., Minas, H.J., 1995. The role of a silicate pump in driving new production. Deep-Sea Res., 42:697-719.

- Dűrr, H.H., Meybeck, M., Hartmann, J., Laruelle, G.G., Roubeix, V., 2009. Global spatial distribution of natural riverine silica inputs to the coastal zone. Biogeosciences. Discuss., 6:1345-1401.
- Dynesius, M., Nilsson, C., 1994. Fragmentation and flow regulation of river systems in the northern 3rd of the world. Science, 266:753-762.
- Egge, J. K., Aksnes, D. L., 1992. Silicate as regulating nutrient in phytoplankton competition. Mar. Ecol. Prog. Ser., 83:281-289.
- Ehrenhauss, S., Witte, U., Janssen, F., Huettel, M., 2004. Decomposition of diatoms and nutrient dynamics in permeable North Sea sediments. Cont. Shelf Res., 24:721-737.
- Furnas, M.J., 1990. In situ growth rates of marine phytoplankton: approaches to measurement, community and species growth rate. J. Plankton Res., 12:1117-1151.
- Gallinari, M., Ragueneau, O., Corrin, L., DeMaster, D.J., Tréguer. P., 2002. The importance of water column processes on the dissolution properties of biogenic silica in deep-sea sediments I. Solubility. Geochemica et Cosmochimica Acta, 66:2701-2717.
- Garber, J.H., 1984. Laboratory study of nitrogen and phosphorus remineralization during decomposition of coastal plankton and seston. Estuar. Coast. Shelf. Sci., 18:685-702.
- Garnier, J., Leporcq, B., Sanchez, N., Philippon, X., 1999. Biogeochemical mass-balances (C, N, P, Si) in three large reservoirs of the Seine basin (France). Biogeochemistry, 47:119-146.
- Gerard, F., Ranger, J., 2002. Silicate weathering mechanisms in a forest soil. Oceanis, 28:384-415.
- Gilpin, L.C., Davidson, K., Roberts, E., 2004. The influence of changes in nitrogen: silicon ratios on diatom growth dynamics. J. Sea Res., 51:21-35.
- Goldman, J.C., 1993. Potential role of large oceanic diatoms in new primary production. Deep Sea Res., 40:159-186.
- Gordon, D.C, Jr., Boudreau, P.R., Mann, K.H., Ong, J.-O., Silvert, W.L., Smith, S.V., Wattayakom, G., Wulff, F., Yanagi, T., 1996. LOICZ Biogeochemical Modelling Guidelines. LOICZ/RS/95-5, vi+96pp. LOICZ, Texel, The Netherlands.
- Goudie, A., Cuff, A., 2002. Encyclopedia of Global Change. Environmental Change and Human Society. Oxford Univ. Press. Vol. 2:503-515.
- Grelowski, A., Pastuszak, M., Sitek, S., Witek, Z., 2000. Budget calculations of nitrogen, phosphorus and BOD<sub>5</sub> passing through the Oder estuary. J. Mar. Syst., 25:221-237.
- Gromisz, S., Witek, Z., 2001. Main phytoplankton assemblages in the Gulf of Gdańsk and the Pomeranian Bay from 1994 to 1997. Bulletin of the Sea Fisheries Institute 2(153):31-51.
- Gromisz, S., Witek, Z., Mackiewicz, T., 1999. Impact of the Oder River on phytoplankton composition and biomass in the Pomeranian Bay. Oceanologia, 41(3):403-427.

- Hajdu, S., Edler, L., Olenina, I., Witek, B., 2000. Spreading and establishment of the potentially toxic dinoflagellate Procentrum minimum in the Baltic Sea. Internat. Rev. Hydrobiol., 85(5-6):561-575.
- Hansen, P.J., Bjornsen P.K., Hansen, B.W., 1997. Zooplankton grazing and growth: Scaling within the 2-2,000 µm body size range. Limnol. Oceanogr., 42:687:704.
- Håkanson, L., Bryhn, A.C., 2008. Eutrophication in the Baltic Sea; Present situation, Nutrient transport, Processes, Remedial strategies. Environmental Science and Engineering; Subseries: Environmental Science. Springer-Verlag Berlin, Heidelberg, 261 pp.
- Heisler, J., Glibert, P.M., Burkholder, J.M., Anderson, D.M., Cochlan, W., Dennison, W.C., Dortch, Q., Gobler, C.J., Heil, C.A., Humphries, E., Lewitus, A., Magnien, R., Marshall, H.G., Sellner, K., Stockwell, D.A., Stoecker, D.K., Suddleson, M., 2008. Eutrophication and harmful algal blooms: A scientific consensus, Harmful Algae, 8:3-13.
- HELCOM, 2002. Environment of the Baltic Sea area 1994-98. Executive Summary. Baltic Marine Environ. Protection Com. Proc. No. 82B.
- HELCOM, 2009. Eutrophication in the Baltic Sea An integrated thematic assessment of the effects of nutrient enrichment in the Baltic Sea region. Baltic Sea Environ. Proc. No. 115B.
- Howarth, R.W., 1988. Nutrient limitation of net primary production in marine ecosystems. Annual Reviews of Ecology and Systematics, 19:89-110.
- Howarth, R. W., 2008. Coastal nitrogen pollution: A review of sources and trends globally and regionally. Harmful Algae, 8:14-20.
- Howarth, R.W., Billen, G., Swaney, D., Townsend, A., Jaworski, N., Lajtha, K., Downing, J.A., Elmgren R., Caraco, N., Jordan, T., Berendse, F., Freney, J., Kundeyarov, V., Murdoch, P., Zhao-Liang, Z., 1996. Regional nitrogen budgets and riverine N & P fluxes for the drainages to the North Atlantic Ocean: Natural and human influence. Biogeochemistry, 35:75-139.
- Humborg, C., Blomqvist, S., Avsan, E., Bergensund, Y., Smedberg, E., Brink, J., Mörth, C.M., 2002. Hydrological alterations with river damming in northern Sweden: Implications for weathering and river biogeochemistry. Global Biogeochem. Cy., 16(3):1-13.
- Humborg, C., Conley, D.J., Rahm, L., Wulff, F., Cociasu, A., Ittekkot, V., 2000. Silicon retention in river basins; Far-reaching effects on biogeochemistry and aquatic food webs in coastal marine environments. Ambio, 29:45-50.
- Humborg, C., Ittekkot, V., Cociasu, A., von Bodungen, B., 1997. Effect of Danube River dam on Black Sea biogeochemistry and ecosystem structure. Nature, 386:385-388.
- Humborg, C., Pastuszak, M., Aigars, J., Siegmund, H., Mörth, C.M., Ittekkot, V., 2006. Decreased silica land-sea fluxes through damming in the Baltic Sea catchment – significance of particle trapping and hydrological alterations. Biogeochemistry, 77:265-281.

- Humborg, C., Smedberg, E., Medina, M.R., Mörth, C.M., 2008. Changes in dissolved silicate loads to the Baltic Sea The effect of lakes and reservoirs, J. Mar. Syst., 73:223-235.
- Hurd, D.C., 1983. Physical and chemical properties of the siliceous skeletons. [in:] Aston. S.R. (ed.), Silicon geochemistry and biogeochemistry. London: Academic Press, pp. 187-244.
- ICES, 2001. Report of the Baltic Fisheries Assessment Working Group, ACFM:18, Part 3, 546 pp.
- Irigoien, X., Harris, R.P., Verheye, H.M., Joly, P., Runge, J., Starr, M., Pond, D., Campbell, R., Shreeve, R., Ward, P., Smith, A.N., Dam, H.G., Peterson, W., Tirelli, V., Koski, M., Smoth, T., Harbour, D., Davidson, R. 2002. Copepod hatching success in marine ecosystems with high diatom concentrations. Nature, 41:387-389.
- Ittekkot, V., Humborg, C., Schäfer, P., 2000. Hydrological alterations and marine biogeochemistry: A silicate issue? BioScience, 50(9):776-782.
- Justić, D., Rabalais N.N., Turner, R.E., 1994. Riverborne nutrients, hypoxia and coastal ecosystem evolution: biological responses to long-term changes in nutrient loads carried by the Po and Mississippi Rivers. [in:] Dyer, K. R., Orth, R. J. (eds.), Changes in fluxes in estuaries: implications from science to management. ECSA 22/ERF Symposium. Inst. of Marine Studies, Univ. Plymouth, pp. 161-167.
- Justić, D., Rabalais, N.N., Turner, R.E., 1995a. Stoichiometric nutrient balance and origin of coastal eutrophication. Mar. Poll. Bull., 30(1):41-46.
- Justić, D., Rabalais, N.N., Turner, R.E., Dortch, Q., 1995b. Changes in nutrient structure of river-dominated coastal waters: stoichiometric nutrient balance and its consequences. Estuary. Coast. Shelf Sci., 40:339-356.
- Justić, D., Rabalais, N.N., Turner, R.E., Wiseman W.J. Jr., 1993. Seasonal coupling between riverborne nutrients, net productivity and hypoxia. Mar. Poll. Bull., Vol. 26, No. 4, pp. 184-189.
- Kaczewiak, C., Wolnomiejski, N., 1977. Fosforany wód Zalewu Szczecińskiego w aspekcie eutrofizacyjnym (1969-1973). Stud. Mater. MIR, 17(A):33-49.
- Kahru, M., Horstmann, U., Rud, O., 1994. Satellite detection of increased cyanobacteria blooms in the Baltic Sea; natural fluctuations or ecosystem change". AMBIO, 23 (8):469-472.
- Kemp, W.M., Sampou, P., Garber, J., Tuttle, J., Boynton, W.R., 1992. Seasonal depletion of oxygen from bottom waters of Chesapeake Bay: roles of benthic and planktonic respiration and physical exchange processes. Mar. Ecol. Prog. Ser., Vol. 85:137-152.
- Knudsen, M., 1900. Ein hydrographischer Lehrsatz. Annalen der Hydrographie und Maritimen Meteorologie, 28:316-320.
- Lancelot, C.P., Wassmann, P., Barth, H., 1994. Ecology of Phaeocystis-dominated ecosystems. J. Mar. Syst. 5(1):1-4.

- Landsberg-Uczciwek, M. (ed.), 1997. Raport o Stanie Środowiska w Województwie Szczecińskim w latach 1995-1996. Państwowa Inspekcja Ochrony Środowiska w Szczecinie, Biblioteka Monitoringu Środowiska, pp. 48-59.
- Laruelle, G.G., Roubeix, V., Sferratore, A., Brodherr, B., Ciuffa, D., Conley, D.J., Dűrr, H.H., Garnier, J., Lancelot, C., Le Thi Phuong, Q., Meunier, J.-D., Meybeck, M., Michalopoulos, P., Moriceau, B., Ni Longphuirt, S., Loucaides, S., Papush, L., Presti, M., Ragueneau, O., Regnier, P., Saccone, L., Slomp, C.P., Spiteri, C., Van Cappellen, P., 2009. Anthropogenic perturbations of the silicon cycle at the global scale: Key role of the land-ocean transition. Global Biogeochemical Cycles, Vol. 23, GB4031, doi: 10.1029/2008GB003267, 2009.
- Levasseur, M.E., Therriault, J.C., 1987. Phytoplankton biomass and nutrient dynamics in a tidally induced upwelling: the role of the NO<sub>3</sub>:SiO<sub>4</sub> ratio. Mar. Ecol. Prog. Ser. 39:87-97.
- Li, M., Cheng, H.Q., 2001. Changes of dissolved silicate flux from the Changiang River into sea and its influence over the last 50 years. Chi. Environ. Sci. 21(3):193-197 (in Chinese with English abstract).
- Maestrini, S., Granéli, E., 1991. Environmental conditions and ecophysiological mechanisms which led to the 1988 Chrysochromulina polylepsis bloom: an hypothesis. Oceanologica Acta, 14(4):397-413.
- Meybeck, M.-H., 1981. River inputs to ocean systems. Pathways of major elements from land to ocean through rivers. Proceedings of A Review Workshop held at FAO headquarters, Rome, Italy, 26-30 March 1979.UNEP and UNESCO, pp. 18-30.
- Meybeck, M.-H., 1982. Carbon, nitrogen, and phosphorus transport by world rivers. Am. J. Sci., 282:401-450.
- Meybeck, M.-H., 1994. Studies on Geophysics Material Fluxes on the Surface of the Earth – Origin and variable Composition of Present day Riverborne Material. National Academy Press, Washington Press, 4:61-73.
- Meybeck, M.-H., 2001a. Global alterations of riverine geochemistry under human pressure. [in:] Ehlers, E., Kraft, T. (eds), Understanding the Earth system: Compartments, Processes, and Interactions, Springer, Hedelberg, pp. 97-113.
- Meybeck, M.-H., 2001b. River basins under anthropogenic conditions. [in:] von Bodungen, B., Turner, R.K. (eds.), Science and integrated management, Dahlem University Press, pp. 275-294.
- Meybeck, M.-H., 2002. Riverine quality at the Anthropocene: Propositions for global space and time analyses, illustrated by the Seine River. Aquat. Sci., 64:376-393.
- Meybeck, M.-H., 2004. The global change of continental aquatic systems: dominant impacts of human activities. Water Sci. Technol., 49(7):73-83.
- Meybeck, M.-H., Vörösmarty, C., 2005. External geophysics, Climate and Environment - Fluvial filtering of land-to-ocean fluxes: from natural Halocene variations to Anthropocene. C.R. Geoscience, 337:107-123.

- Michaels, A.F., Silver, M.W., 1988. Primary production, sinking fluxes and the microbial food web. Deep-Sea Res., 35:473-490.
- Milliman, J.D., Boyle, J.D., 1975. Biological uptake of dissolved silica in the Amazon River estuary. Science, 189:995-997.
- Mortatti, J., Probst, L., 2003. Silicate rock weathering and atmospheric/soil CO2 uptake in the Amazon basin estimated from river water geochemistry: seasonal and spatial variations. Chem. Geology., 197:177-196.
- Nelson, D.M., Dortch, Q., 1996. Silicic acid depletion and silicon limitation in the plume of the Mississippi River: Evidence from kinetic studies in spring and summer. Mar. Ecol. Prog. Ser., 136:163-178.
- Niemkiewicz, E., Wrzołek, L., 1998. Phytoplankton as eutrophication indicator in the Gulf of Gdańsk water. Oceanological Studies, 4:77-92.
- Nixon, S.W., Ammerman, J.W., Atkinson, L.P., Berounsky, V.M., Billen, G., Boicourt, W.C., Boynton, W.R., Church, T.W., Diroto, D.M., Elmgren, R., Garber, J.H., Giblin, A.E., Jahnke, R.A., Owens, N.J.P., Pilson, W.E.Q., Seitzinger S.P., 1996. The fate of nitrogen and phosphorus at the land-sea margin of the North Atlantic Ocean. Biogeochemistry, 35:141-180.
- Officer, C.B., J.H. Ryther., 1980. The possible importance of silicon in marine eutrophication. Mar. Ecol. Prog. Ser., 3:83-91.
- O'Neill, P., 1998. Chemia Środowiska. Wydawnictwo Naukowe PWN Warszawa-Wrocław, 308 pp.
- Panin, N., Jipa, D., 2002. Danube River sediment input and its interaction with the northwestern Black Sea. Estuar. Coast. Shelf Sci., 54:551-562.
- Papush, L., Danielsson, Å., 2006. Silicon in the marine environment: dissolved silica trends in the Baltic Sea. Estuar. Coast. Shelf Sci., 67(1-2):53-66.
- Papush, L., Danielsson, Å., Rahm, L., 2009. Dissolved silica budget fort he Baltic Sea. J. Sea. Res., 62:31-41.
- Pastuszak, M., Conley, D., Humborg, C., Witek, Z., Sitek, S., 2008. Silicon dynamics in the Oder estuary, Baltic Sea. J. Mar. Syst., 73:250-262.
- Pastuszak, M., Nagel, K., Grelowski, A., Mohrholz, V., Zalewski, M., 2003. Nutrient dynamics in the Pomeranian Bay (southern Baltic): impact of the Oder River outflow. Estuaries, 26(5):1238-1254.
- Pastuszak, M., Siegel, H., Sitek, S., Gerth, M., Tschersich, G., Grelowski, A., 1999. Impact of water temperature on nutrient concentrations in the Oder estuary in 1996-1998. Dtsch. Hydrogr., Z. 51(4):423-439.
- Pastuszak, M., Wielgat, M., Sitek, S., 2001. Nutrient status in the Szczecin Lagoon past, present, and future prospects. Oceanological Studies, 30(1-2):59-86.
- Pastuszak, M., Witek, Z., Nagel, K., Wielgat, M., Grelowski, A., 2005. Role of the Oder estuary (southern Baltic) in transformation of the riverine material. J. Mar. Syst., 57(1-2):30-54.
- Pliński, M., Jóźwiak, T., 1999. Temperature and N:P ratio as factors causing blooms of blue-green algae in the Gulf of Gdańsk. Oceanologia, 41(1):73-80.

- Poleszczuk, G., 1998. Środowisko abiotyczne toni wodnej Zalewu Szczecińskiego. Uniwersytet Szczeciński, Rozprawy i Studia., T. (CCCLXXVI) 292:1-207.
- Poleszczuk, G., Garbacik-Wesołowska, A., Sitek, S., Mutko, T., 1995. Status tlenowy wód estuarium Odry. Stud. Mat. Mor. Inst. Ryb., Gdynia, Seria A, No. 33, 101 pp.
- Rabalais, N.N., Turner, R.E., Dortch, Q., Wiseman, W.J. Jr., Sen Gupta, B.K., 1996. Nutrient changes in the Mississippi River and system responses on the adjacent continental shelf. Estuaries, 19(2B):386-407.
- Rabalais, N.B., Wiseman, W.J. Jr., Turner, R., 1994. Comparison of continuous records of near-bottom dissolved oxygen from the hypoxia zone along the Luisiana Coast. Estuaries, Vol. 17, No. 4:850-861.
- Ragueneau, O., Chauvaud, L., Leynaert, A., Thouzeau, G., Paulet, Y-M., Bonnet, S., Lorrain, A., Grall, J., Corvaisier, R., Le Hir, M., Jean, F., Clavier, J., 2002a. Direct evidence of a biologically active coastal silicate pump: Ecological implications. Limnol. Oceanogr., 47(6):1849-1854.
- Ragueneau, O., Conley, D.J., Leynaert, A., Longphuirt, S.N., Slomp, C.P., 2006a.
  Role of diatoms in silica cycling and coastal marine food webs. [in:] The Silicon Cycle: Human Perturbations and Impacts on Aquatic Systems. V. Ittekot, D. Unger, C. Humborg, N.T. An (eds.), Island Press, Washington, D.C., pp. 163-195.
- Ragueneau, O., Conley, D.J., Leynaert, A., Longphuirt, S.N., Slomp, C.P., 2006b. Response of coastal ecosystems to anthropogenic perturbations of silicon cycling. [in:] The Silicon Cycle: Human Perturbations and Impacts on Aquatic Systems. V. Ittekot, D. Unger, C. Humborg, N.T. An (eds.), Island Press, Washington, D.C., pp. 197-213.
- Ragueneau, O., De Blas Varela, E., Tréguer, P., Quéguiner, B., Del Amo, Y., 1994. Phytoplankton dynamics in relation to the biogeochemical cycle of silicon in a coastal ecosystem of Western Europe. Mar. Ecol. Prog. Ser., 106:157-172.
- Ragueneau, O., Lancelot, C., Egorov, V., Verlimmeren, J., Cosiasu, A., Déliat, G., Krastev, A., Daoud, N., Rousseau, V., Popovitchev, V., Brion, N., Popa, L., Cauwet, G., 2002b. Biogeochemical transformation of inorganic nutrients in the marine mixing zone between the Danube River and the northern Black Sea. Estuar. Coast. Shelf S., 54(3):321-336.
- Ragueneau, O., Tréguer, P., Leynaert, A., Anderson, R,F., Brzezinski, M.A., DeMaster, D.J., Dugdale, R.C., Dymond, J., Fischer, G., François, R., Heinze, C., Mainer-Reimer, E., Martin-Jézéquel, V., Nelson, D.M., Quéguiner, B., 2000. A review of the Si cycle in the modern ocean: recent progress and missing gaps in the application of biogenic opal as a paleoproductivity proxy. Global and Planetary Change, 26:317-365.
- Rahm, L., Conley, D., Sandén, P., Wulff, F., Stålnacke, P., 1996. Time series analysis of nutrient input to the Baltic Sea and changing DSi:DIN ratios. Mar. Ecol. Prog. Ser. 130:221-228.

- Redfield, A.C., 1934. On the proportions of organic derivatives in seawater and their relation to the composition of the plankton. [in:] James Johnstone Memorial Volume. University Press, Liverpool, England, pp. 176-192.
- Redfield, A. C., Ketchum, B.H., Richards, F.A., 1963., The influence of organisms on the composition of seawater. [in:] Hill, M.N. (ed.), The Sea, Vol. 2 John Willey, New York, pp. 26-77.
- Round, F. E., Crawford, R. M., Mann, D. G., 1990. The Diatoms. Cambridge Univ. Press, Cambridge.
- Saccone, L.D., Conley, D., Likens, G.E., Bailey, S.W., Buso, D.C., Johnson, C.E., 2008. Distribution of amorphous silica in soils of the Hubbard Brook Experimental Forest. Soil Sci. Soc. A. J., 72:1637-1644.
- Sandén, P., Rahm, L., 1993. Nutrient trends in the Baltic Sea. Environmetrics, 4:75-103.
- Sandén, P., Rahm, L., Wulff, F., 1991. Non-parametric trend test of Baltic Sea data. Environmetrics, 2:263-278.
- Savage, C., Leavitt, P.R., Elmgren, R., 2010. Effects of land use, urbanization, and climate variability on coastal eutrophication in the Baltic Sea. Limnol. Oceanogr., 55(3):1033-1046.
- Savchuk, O., 2002. Nutrient biogeochemical cycles in the Gulf of Riga: scaling up field studies with a mathematical model. J. Mar. Sys., 32:253-280.
- Schelske, C.L., Stoermer, E.F., 1971. Eutrophication, silica depletion, and predicted changes in algal quality in Lake Michigan. Science, 173:423-424.
- Schelske, C. L., Stoermer, E.F., Conley, D.J., Robbins, J.A., Glover, R.M., 1983. Early eutrophication in the lower Great Lakes: new evidence from biogenic silica in sediments. Science, 222:320-322.
- Sen Gupta, B.K., Turner, R.E., Rabalais, N.N., 1996. Seasonal oxygen depletion in continental-shelf waters of Luisiana: historical record of benthic foraminifers. Geology, Vol. 24, No. 3:227-230.
- Sferratore, A., Garnier, J., Billen, G., Conley, D., Pinault, S., 2006. Diffuse and point sources of silica in the Seine River watershed. Environ. Sci. Technol., 40(21):6630-5.
- Simpson, T.L., Volcani, B.E., 1981. Silicon and siliceous structures in biological systems, Springer, New York.
- Smayda, T.J., 1990. Novel and nuisance phytoplankton blooms in the sea: evidence for global epidemic. [in:] Graneli, E., Sundström, B., Edler, L., Anderson, D.M. (eds.), Toxic marine Phytoplankton. Elsevier Science Publishing Co., New York, pp. 29-40.
- Smetacek, V., 1998. Biological oceanography: Diatoms and the silicate factor. Nature, Volume 391, Issue 6664, pp. 224-225.
- Smetacek, V., 1999. Diatoms and the ocean carbon cycle. Protist, 150:25-32.
- Smith, V.H., Schindler, D.W., 2009. Eutrophication science: where do we go from here?. Trends in Technology and Evolution, Vol. 24, No. 4 pp. 201-207.

- Staresinic, N., Farrington. J., Gagosian, R.B., Clifford, C.H., Hulbert, E.M., 1983. Downward transport of particulate matter in the Peru coastal upwelling: role of the anchoveta, Engraulis ringens. [in:] Suess, A.E., Thiede, J., (eds.), Coastal upwelling, Plenum Press, pp. 225-241.
- Struyf, E., Smis, A., Van Damme, A., Meire P., Conley D.J., 2009. The global biochemical cycle: Silicon, v. 1, p. 207-213. DOI 10.1007/s12633-010-9035-x
- Tréguer, P., Pondaven, P., 2000. Global Change Silica Control of Carbon Dioxide. Nature, 406:358-359.
- Tréguer, P., Nelson, D.M., Van Bennekom, A.J., DeMaster, D.J., Leynaert, A., Quéguiner, B., 1995. The silica in the word ocean: A re-estimate. Science, 268:375-379.
- Turner, R.E., Rabalais, N.N., 1994. Coastal Eutrophication near the Mississippi river delta. Nature, Vol. 368:619-621.
- Van Bennekom, A. J., Salomons, W., 1981. Pathways of nutrients and organic matter from land to ocean through river. in River inputs to ocean systems,. [in:] Martin, J.-M., Burton, J. D., Eisma, D. (eds.), New York: UNEP, IOC, SCOR, United Nations pp. 33–51.
- Staresinic, N., Farrington. J., Gagosian, R.B., Clifford, C.H., Hulbert, E.M., 1983. Biogenic silica dissolution in the oceans: reconciling experimental and fieldbased dissolution rates. Global Biogeochem. Cy., 16:1075-1084.
- Vörösmarty, C.J., Meybeck, M-H., Fekete, B., Sharma, K., 1997a. The potential impact of neo-Castorization on sediment transport by the global network of rivers. Intl. Assn. Hydrol. Sci. Publ., 245:61-282.
- Vörösmarty, C.J., Meybeck, M-H., Fekete, B., Sharma, K., Green, P., Syvitski, P.M., 2003. Anthropogenic sediment retention; major global impact from registered river impoundments. Global Planet. Change, 39(1-2):169-190.
- Vörösmarty, C.J., Sharma, K., Fekete, B., Copeland, A.H., Holden, J. Marble, J., Lough, J.A., 1997b. The storage and aging of continental runoff in large reservoir systems of the world. Ambio, 26:210-19.
- Wasmund, N., Uhlig, S., 2003. Phytoplankton trends in the Baltic Sea. ICES J. Mar. Sci., 60:177:186.
- Wasmund, N., Andrushaitis, A., Łysiak-Pastuszak, E., Müller-Karulis, B., Nausch, G., Neumann, T., Ojaveer, H., Olenina, I., Postel, L., Witek, Z., 2001. Trophic status of the south-eastern Baltic Sea: a comparison of coastal and open areas. Estuar., Coast. Shelf Sci., 53:849-864.
- Wasmund, N., Nausch, G., Matthäus, W., 1998. Phytoplankton spring bloom in the southern Baltic Sea – spatio-temporal development and long-term trends. J. Plankton Res., 20(6):1099-1117.
- Wilding, L.P., Smeck, N.E., Drees, L.R., 1977. Silica in soils quartz, cristobalite, tridymite, and opal. In: Minerals in Soil Environments. Soil Sci. Soc. Amer., Madison, pp. 471-552.
- Wiktor, K., 1971. The primary production of the Szczecin Bay. Pol. Arch. Hydrobiol., 18:1-15.

- Wiktor, K., 1980. Biologia ogólna charakterystyka flory i fauny. [in:] Majewski, A. (ed.), Zalew Szczeciński. Wyd. Kom. i Łącz. Warszawa. pp. 286-300.
- Wiseman, W.J., Rabalais, N.N., Turner, R.E., Dinnel, S.P., MacNaughton A., 1997. Seasonal and interannual variability within the Louisiana coastal current: stratification and hypoxia. J. Mar. Syst., 12:237-248.
- Witek, Z., Bralewska, J., Chmielowski, H., Drgas, A., Gostkowska, J., Kopacz, M., Knurowski, J., Krajewska-Sołtys, A., Lorenz, Z., Maciejewska, K., Mackiewicz, T., Nakonieczny, J., Ochocki, S., Warzocha, J., Piechura, J., Renk, H., Stopiński, M., Witek, B., 1993. Structure and function of marine ecosystem in the Gdańsk Basin on the basis of studies performed in 1987. Stud. Mater. Oceanogr., 63:1-124.
- Wolnomiejski, N., Witek, Z. The Biotic Communities of the Great Lagoon (Szczecin Lagoon, Southern Baltic Sea) (monograph in preparation).
- Zembrzuska, D., 1962. Fitoplankton Zalewu Szczecińskiego. Prace Mor. Inst. Ryb., No. 11A:136-158.
- Yool, A., Tyrrell., T., 2003. Role of diatoms in regulating the ocean's silicon cycle. Global Biochem. Cy., Vol. 17, No. 4, 1103-1123.

12

**AUXILIARY TABLES** 

Mariusz Fotyma Jerzy Kopiński

## 12. AUXILIARY TABLES

Mariusz Fotyma, Jerzy Kopiński

### 12.1. International System of Units (SI)

The International System of Units, (SI), was adopted in 1960 at the XI General Conference on Weights and Measures and it was introduced in Poland in 1977 by Regulation of the President of the Polish Committee for Standardization and Measures. It is the sole system binding in Poland, although some other units of measurement not belonging to the SI system can be legally used (Table 12.1).

Table 12.1 Primary (printed in bold) and legal units of measurement used in this monograph (source: Filipek et al., 2001)

Quantity name	Unit name	Unit symbol	Conversion to SI units	Comments
Length	Metre	m	-	-
Mass	Kilogram	kg	-	-
Mass	Ton	t	$1t = 1 \text{ Mg} = 10^3 \text{ kg}$	
Mass	Deciton (Quintal)	Dt (q)	$ 1 dt = 10^2 kg  (1 q = 10^2 kg) $	-
Time	Second	S	-	-
Time	Minute Hour	1 min 1 h	1 min = 60 s 1 h = 3600 s	-
Temperature	Kelvin	K	-	-
Temperature	Degree Celsius	°C	$0^{\circ}\text{C} = 273.15 \text{ K}$	-
Amount of substance	Mole	mol <sup>1)</sup>	-	-
Area	Hectare	ha	$1 \text{ ha} = 1 \text{ hm}^2 = 10^4 \text{m}^2$	unit of land area
Volume	Litre	1	$11 = 1 \text{ dm}^3 = 10^{-3} \text{m}^3$	volume of dry goods and liquids

 $<sup>^{1)}</sup>$  it should be expressed as an amount of mol in the amount of substance, e.g. mol KCl·dm-3,  $mol(+)\cdot kg^{\text{-1}},$  etc.

Also the multiples of SI units can be used (Table 12.2). The unit formed by multiplying two units should be written as a product with a central dot, and the unit formed by dividing two units should be written in the form of a product of powers e.g.  $10 \text{ g} \cdot \text{kg}^{-1}$  (=1%) (Table 12.3).

(	,,	
Giga	G <sup>1)</sup>	$10^9 = 1000000000$
Mega	M	$10^6 = 1000000$
Kilo	k	$10^3 = 1000$
Hecto	h	$10^2 = 100$
Deca	da	$10^1 = 10$
Unit	-	$10^0 = 1$

Table 12.2 Prefixes, symbols, and multiples of SI units used in agronomic research (source: Filipek et al., 2001)

In agronomic research many derived units are used, and they are derived from the SI units, or other legal units (Table 12.3).

Table 12.3 The most important derived units used in agronomy (source: Filipek et al., 2001)

Quantity name	Unit name	Unit symbol
The content of components	Milligram per kilogram, gram per kilogram, kilogram per ton	mg•kg <sup>-1</sup> , g•kg <sup>-1</sup> , kg•t <sup>-1</sup>
The content of cations The content of anions	Millimoles per kilogram	mmol(+)•kg <sup>-1</sup> , mmol(-)• kg <sup>-1</sup>
The concentration of the solution	Mol per cubic decimetre	mol•dm <sup>-3</sup>
The dose of nutrient	Kilogram per hectare, ton per hectare	kg•ha <sup>-1</sup> , t•ha <sup>-1</sup>
The uptake of components	Gram per hectare, kilogram per hectare	g•ha <sup>-1</sup> , kg•ha <sup>-1</sup>
Anthropogenic acidification	Mol H <sup>+</sup> per hectare	molH⁺•ha⁻¹
Water content	Kilogram of water per kilogram of dry weight of soil, cubic meter of water per cubic meter of soil	kg•kg <sup>-1</sup> , m³•m <sup>-3</sup>

## 12.2. Recalculation coefficients for P, K, Ca, Mg compounds used in agriculture

In the monograph, with few exceptions, the concentration and content of mineral components are expressed in elemental forms and not in oxide forms (Table 12.4). The oxide form of indicating a component may currently be justified only with reference to CaO in calcium fertilizers. This is because the oxide form of lime (also the carbonate and silicate forms), and not e.g. the sulphate form, is the neutralizing factor.

<sup>&</sup>lt;sup>1)</sup> Frequently used is the unit  $Gg = 10^3$  t (thousand tons)

Component	Factor	Component	Factor
$P_2O_5$ to P	0.4364	P to P <sub>2</sub> O <sub>5</sub>	2.2915
K <sub>2</sub> O to K	0.8301	K to K <sub>2</sub> O	1.2047
CaO to Ca	0.7146	Ca to CaO	1.3994
MgO to Mg	0.6031	Mg to MgO	1.6581
SO <sub>3</sub> to S	0.4000	S to SO <sub>3</sub>	2.4990

Table 12.4 Conversion factors for mineral components forms (source: Filipek et al., 2001)

# 12.3. Content of nitrogen, phosphorus, and potassium in plant products

For the preparation of balances of mineral components in agriculture it is necessary to know the individual uptake of these components by plants. The unit uptake is expressed in relation to main crop yield unit or to main crop yield unit with adequate amount of crop residues yield (Table 12.5).

Table 12.5 N, P and K uptake per main crop yield unit or main crop yield unit with subsidiary crop yield (source: Fotyma and Kopiński own elaboration based on: Karklins, 2001; Fotyma and Mercik, 1995)

Plant	Product	Uptake per crop yield unit in kg•t <sup>-1</sup>			
Piant	Troduct	N	P	K	
	Grain	18.5	3.57	4.42	
Wheat	Straw	5.40	1.00	10.7	
	Grain + straw	23.6	4.45	14.2	
	Grain	15.5	3.50	4.95	
Rye	Straw	5.40	1.02	12.5	
	Grain + straw	21.7	4.65	18.7	
Carina	Grain	16.9	3.60	4.93	
Spring	Straw	5.87	1.1	13.2	
barley	Grain + straw	22.2	4.47	16.1	
	Grain	16.4	3.57	4.93	
Oats	Straw	6.02	1.33	16.3	
	Grain + straw	23.5	5.03	22.4	
Maine anavym	Grain	15.4	3.43	5.13	
Maize grown	Straw	11.3	2.03	18.0	
for grain	Grain + straw	28.6	5.37	23.3	
	Seeds	33.6	7.10	8.87	
Rape	Straw	7.03	1.45	18.1	
	Grain + straw	46.9	10.1	40.8	

D14	Dua 4	Uptake p	er crop yield uni	it in kg•t <sup>-1</sup>
Plant	Product	N	P	K
	Bulbs	3.47	0.50	4.87
Potato	Stalks	2.40	0.27	3.27
	Bulbs+stalks	3.83	0.61	5.55
	Beet roots	1.73	0.40	1.97
Sugar beet	Leaves	3.63	0.40	5.33
	Beet roots + leaves	4.59	0.73	5.50
Maize for silage	The entire mass	4.2	0.70	4.20
Grasses	The entire mass	4.9	0.70	5.65
Lucerne	The entire mass	6.3	0.63	5.17
Clover	The entire mass	5.3	0.55	4.72
Lucerne with grass	The entire mass	5.3	0.70	5.00
Clover with grass	The entire mass	4.93	0.53	4.83
Meadows and pastures	The entire mass	4.50	0.60	5.57
Meadows	Hay	22.7	3.50	23.5
Crop production <sup>1)</sup>	Cereal unit	2.21	0.41	1.55

<sup>1)</sup> with the average structure of Polish agricultural land (arable land and grassland)

## 12.4. Content of nitrogen, phosphorus, and potassium in animals' faeces, urine, and natural fertilizers

A very important element of the balance of mineral components is their quantity introduced into soil in the form of natural fertilizers and less often in the form of organic or organic-mineral fertilizers. The primary source of these components is their amount excreted by livestock animals in faeces and urine. The amounts of components excreted in the shed, on the pasture or in the farmstead are given in Table 12.6.

Table 12.6 The standard amounts of nutrients per different groups of livestock animals (source: Fotyma and Kopiński own study; Karklins, 2001)

The type and group of livestock animals	Livestock Unit [LU]	The average amount of the component in faeces at stable per head per average year [kg•head-1•yr-1]			The average amount of the component in urine at stable per head per average year [kg·head-l·yr-l]		
		N	P	K	N	P	K
Calves aged 0 - 3 months	0.14	3.84	0.60	0.61	2.60	0.003	2.45
Calves aged 3 - 6 months	0.28	7.67	1.20	1.22	5.20	0.006	4.89
Young heifers aged 6-12 months	0.50	7.52	2.51	3.48	15.47	0.15	22.09
Young bovine males aged 6-12 months	0.52	7.82	2.61	3.62	16.09	0.16	22.97
Older heifers aged 1 - 2 years	0.75	14.76	5.45	6.92	27.43	0.19	40.98
Bovine males for fattening (young bulls) aged 1 - 2 years	0.80	15.06	5.56	7.06	27.98	0.20	41.80
Heifers in calf aged over 2 years	1.0	19.57	7.22	9.17	32.17	0.22	48.07
Bulls for fattening and stud bulls aged over 2 years	1.4	21.29	7.70	12.31	39.62	0.24	49.25
Cows up to 3000 litres of milk per year	1.0	30.65	7.37	1.63	39.69	0.20	79.85
Cows from 3000 to 4000 litres of milk per year	1.0	33.07	9.73	1.71	42.84	0.24	83.83
Cows over 4000 litres of milk per year	1.0	37.83	13.08	1.82	49.00	0.29	85.11
Dry pregnant sows and covered sows (boars)	0.30	3.87	3.16	2.39	12.96	1.24	4.79
Lactating sows with piglets	0.35	11.43	6.56	5.17	25.96	2.81	10.13
Piglets weighing 20 - 30 kg	0.06	2.02	1.10	1.12	4.72	0.47	1.69

The type and group of livestock animals	Livestock Unit [LU]  The average amount of the component in faeces at stable per head per average year [kg·head-¹·yr¹]			The average amount of the component in urine at stable per head per average year [kg·head-¹·yr¹]			
		N	P	K	N	P	K
Fattening pigs weighing 30 - 70 kg	0.10	4.39	2.32	2.09	10.24	1.00	3.13
Fattening pigs weighing 70 - 110 kg	0.25	4.88	2.60	2.37	11.39	1.11	3.56
Ewes, rams and goats	0.10	2.09	0.57	2.29	3.89	0.30	4.17
Lambs aged up to 1 year	0.05	0.73	0.20	0.80	1.36	0.11	1.72
Ewe lambs, lambs aged over 1 years	0.08	1.57	0.42	1.72	2.92	0.23	3.13
Foals aged up to 0.5 year	0.30	3.44	1.13	3.29	7.31	0.63	5.02
Adult horse (light)	1.00	9.83	3.23	9.39	20.88	1.81	14.33
Work horse (heavy)	1.20	11.80	3.88	11.27	25.05	2.18	17.19
Poul	try (values pe	er 100 av	erage un	its per a	nnum)		
Laying hens	0.30	72.5	9.0	13.7	-	-	-
Broilers	0.40	43.5	5.2	12.3	-	-	-
Turkeys	1.20	155.4	19.3	29.3	-	-	
Geese	0.80	164.0	20.3	31.0	-	-	-
Ducks	0.50	138.1	17.1	26.1	-	-	-

Nutrients excreted by animals, including those contained in straw, can be found in manure, slurry or in liquid manure. During accumulation and storage of these fertilizers on manure plates or in tanks for slurry or for liquid manure certain losses occur, particularly of nitrogen, and the amount of the components in natural fertilizers ready to be transported to the field is significantly smaller (nitrogen) than the sum of their quantities contained in livestock animal faeces and in the straw used for bedding. The amounts of components contained in fermented natural fertilizers defined as gross quantities are given in Table 12.7. The data from this Table can be used in calculating components balances using "at the farm gate" method.

Table 12.7 The content of nutrients (gross) in natural fertilizers (total) for different groups of animals (source: Fotyma and Kopiński own study)

The type and group of livestock animals	Livestock Unit [LU]	The amount of component in natural fertilizers (on manure storage and in tanks) from head per average year  [kg·head-1·yr-1]		
Calves aged up to 0.5 year	0.15	N 9.75	P 1.50	<b>K</b> 10.04
Heifers aged from 0.5 to 1 year	0.30	21.74	3.31	31.46
Young cattle (bovine males) aged from 0.5 to 1 year	0.30	22.22	3.31	31.49
Heifers aged from 1 to 2 years	0.75	38.55	6.40	54.89
Bulls for fattening aged from 1 to 2 years	0.80	38.87	6.34	54.13
Heifers in calf aged over 2 years	1.0	46.90	8.57	67.55
Bulls for fattening and stud bulls aged over 2 years	1.4	54.88	9.03	71.51
Dairy cows - total	1.0	71.16	12.18	98.91
Sows - total	0.35	18.60	6.90	16.91
Piglets weighing 20 - 30 kg	0.05	5.89	2.02	6.86
Piglets weighing from 20 to 50 kg	0.07	7.12	2.42	7.54
Fattening pigs weighing 30 - 70 kg	0.10	11.36	3.83	9.89
Fattening pigs weighing over 50 kg	0.14	12.14	4.09	10.36
Fattening pigs weighing 70 - 110 kg	0.25	12.52	4.22	10.60
Sheep, goats - total	0.10	6.57	1.30	10.39
Foals aged up to 0.5 year	0.3	10.09	2.18	12.17
Horses - total	1.2	30.56	6.55	34.93
Laying hens	0.004	0.52	0.13	0.18
Broilers	0.004	0.31	0.07	0.15
Turkeys	0.024	1.07	0.22	0.32
Geese	0.008	1.06	0.21	0.31
Ducks	0.004	0.95	0.19	0.28
Animal production <sup>1)</sup>		64.6	14.2	73.0

<sup>1)</sup> with the average Polish structure of herds of livestock animals

Still another amounts are taken into account in calculating components' balances using "on the soil surface" method. These quantities defined as net quantities and agreed with the OECD Secretariat are presented in Table 12.8.

The average content of nutrients in natural fertilizers and synthetic livestock conversion coefficients are shown in Tables 12.9 and 12.10.

Table 12.8 The standard content of nutrients (net) in manures for different groups of animals used in calculating components' balances according to OECD methodology (source: Fotyma and Kopiński own study; Kopiński and Madej, 2006)

The type and group of livestock animals	Livestock Unit [LU]	The amount of nutrients from head per average year [kg·head·yr¹]			
animais		N	P	K	
Calves aged under one year	0.30	18.0	2	17.0	
Young cattle aged from 1 to 2 years	0.80	36.0	6	30	
Heifers in calf aged over 2 years	1.00	40.0	7	55	
Dairy cows - total	1.00	70.0	11	88	
Other cattle (bulls)	1.40	55.0	12	70	
Piglets weighing up to 20 kg	0.02	2.5	1	2.5	
Piglets weighing from 20 to 40 kg	0.07	9.0	3.2	8	
Fattening pigs for slaughter weighing over 40 kg	0.14	12.0	4	10	
Boars	0.40	15.0	5	12	
Sows – total	0.35	14.0	4.6	11.5	
Sheep – total	0.10	8.0	1.8	13	
Goats – total	0.10	7.0	1.7	12.5	
Horses – total	1.20	50.0	5	73	
Broilers	0.004	0.14	0.03	0.12	
Laying hens	0.004	0.70	0.26	0.33	
Ducks	0.004	0.70	0.43	0.35	
Turkeys	0.024	1.50	0.58	0.7	
Geese	0.008	1.50	0.65	2.2	

Table 12.9 The average content of nutrients in natural fertilizers (source: Fotyma and Kopiński own study; Maćkowiak, 1997; Jadczyszyn et. al., 2000)

Type of natural fertilizer	Origin of fertilizer	The content of macronutrients in kg per ton or per m³ of manure		
		N	P	K
Manure	Cattle	4.0	0.9	3.6
	Pigs	5.2	1.7	3.2
	Poultry	7.2	1.4	7.4
	Mixed	4.6	1.3	3.5
Liquid manure	Cattle	3.2	0.1	6.6
	Pigs	2.8	0.2	3.4
Slurry	Cattle	3.4	0.9	3.1
	Pigs	4.3	0.1	1.9

Types of	Head synthetic (average) livestock animal average unit is equivalent to:				
animals	Livestock Units	Livestock Units	Animal Manure	Animal Feeding	
	[LU] <sup>1)</sup>	$[LU]^{2)}$	Unit [AMU] <sup>3)</sup>	Unit [AFU]4)	
Cattle	0.77	0.8	0.88	0.90	
Pigs	0.104	0.15	0.14	0.29	
Sheep	0.09	0.08	0.08	0.12	
Horses	1.2	1.0	0.70	0.80	
Poultry	0.005	-	0.004	0.002	

Table 12.10 Synthetic livestock conversion coefficients (source: Fotyma and Kopiński own study; Fotyma et. al., 2001)

### 12.5. Abbreviations for countries and voivodeships of Poland

The abbreviations for the EU countries and voivodeships in Poland, which were used in the text, are listed in Table 12.11. The abbreviations for the countries have been officially adopted, whereas the abbreviations for voivodeships have been introduced by authors of this monograph in hope that they will be propagated at least in studies on agriculture.

Table 12.11 The abbreviations for the EU	countries and	l voivodeships of Poland
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EU country	Abbreviation	Voivodeship	Abbreviation
Austria	A	Dolnośląskie	DLN
Belgium	BL	Kujawsko - Pomorskie	KUJ
Bulgaria	BG	Lubelskie	LUB
Czech Republic	CZ	Lubuskie	LUS
Denmark	DK	Łódzkie	LOD
Estonia	EST	Małopolskie	MLP
Finland	FIN	Mazowieckie	MAZ
France	F	Opolskie	OPL
Germany	D	Podkarpackie	PDK
Great Britain	GB	Podlaskie	PDL
Greece	GR	Pomorskie	POM
Hungary	Н	Śląskie	SLS
Iceland	IS	Świętokrzyskie	SWT

<sup>&</sup>lt;sup>1)</sup> Livestock Units [LU] means a standard measurement unit that allows the aggregation of the various species of livestock in order to enable them to be compared (Dz. U. Nr 83 item. 453, 2011).

<sup>&</sup>lt;sup>2)</sup> The livestock on load units [LU] obtained by calculating the coefficients used by GUS (Central Statistical Office)

<sup>&</sup>lt;sup>3)</sup> Calculated animal manure unit is a unit for livestock defined according to the amount of nutrients excreted as dung and urine.

<sup>&</sup>lt;sup>4)</sup> Calculated animal feeding unit is a unit for feeding of which 3,500 of oats units are used annually.

EU country	Abbreviation	Voivodeship	Abbreviation
Ireland	IRL	Warmińsko - Mazurskie	WAM
Italy	I	Wielkopolskie	WLP
Latvia	LV	Zachodniopomorskie	ZAP
Lithuania	LT		
Luxembourg	L		
Malta	M		
Poland	PL		
Portugal	P		
Romania	RO		
Slovakia	SK		
Slovenia	SLO		
Spain	Е		
Sweden	S		
The Netherlands	NL		

### 12.6. Index of other abbreviations used in the monograph

AA – Agricultural Area

**AFU** – **A**nimal **F**eeding **U**nit

AL – Arable Land

AMU – Animal Manure Unit

AUL - Agriculturally Utilized Land

APSVI – Agricultural Production Space Valuation Index

ARMA - The Agency for Restructuring and Modernisation of Agriculture

BSi - Biogenic Silica

CAP – Common Agricultural Policy

CU - 1 Cereal Unit = 1 dt of cereals

DIN – Dissolved Inorganic Nitrogen

DIP – Dissolved Inorganic Phosphorus

DSi - Dissolved Silicate

EAFRD – European Agricultural Fund for Rural Development

EFMA – European Fertilizer Manufacturers Association

**EU** – European Union

FWC – Field Water Capacity

GUS – Główny Urząd Statystyczny (ang. Central Statistical Office)

GVA - Gross Value Added

**HELCOM** – **Hel**sinki **Com**mission or HELCOM is the executive body responsible for the "Convention for the Protection of the Marine Environment of the Baltic Sea"

HL - Hydraulic Load

IAFE-NRI – Institute of Agricultural and Food Economics - National Research Institute

IBMER – Instytut Budownictwa Mechanizacji i Elektryfikacji Rolnictwa (Institute for Building, Mechanization and Electrification of Agriculture), Warszawa

IEP - Inspectorate of Environmental Protection

**IERIGŻ-PIB** – Instytut Ekonomiki Rolnictwa i Gospodarki Żywnościowej (Institute of Agricultural and Food Economics - National Research Institute)

IMWM – Institute of Meteorology and Water Management

IUNG-PIB – Instytut Uprawy Nawożenia i Gleboznawstwa – Państwowy

Instytut **B**adawczy (Institute of Soil Science and Plant Cultivation - State Research Institute), Puławy

KCDRRiOW – Krajowe Centrum Doradztwa Rozwoju Rolnictwa i Obszarów Wiejskich (National Advisory Centre for Rural Development)

LHI – Large Heads Index

LFA - Less Favoured Areas

LU - Livestock Unit

MONERIS – MOdeling Nutrient Emissions in RIver Systems

MU – Manure Unit

NFRV - Nitrogen Fertilizer Replacement Value

NMFRI – National Marine Fisheries Research Institute, (MIR-PIB – Morski

Instytut Rybacki – Państwowy Instytut Badawczy), Gdynia

NPK – term expressing use of mineral fertilizers in kg of nitrogen N, phosphorus P, potassium K

**NU** – **Nutrition Unit** 

NVZ – Nitrate Vulnerable Zone

**OECD** – **O**rganization for **E**conomic **C**o-operation and **D**evelopment

**PM** – **P**ermanent **P**asture

PSU - Practical Salinity Units

RCAS - Regional Chemical-Agricultural Station.

RDP - Rural Development Programme

SAPARD – Special Accession Programme for Agriculture and Rural Development

SUS - Saltpetre-Urea-Solution

TN - Total Nitrogen

TOC – Total Organic Carbon

**TP** – **T**otal **P**hosphorus

TSS – Total Suspended Solids

UAA - Utilized Agricultural Area

**UAN** – Urea and Ammonium Nitrate solution

WWTP - Waste Water Treatment Plant

## References

- Dz. U. Nr 83 poz. 453, 2011: Rozporządzenie Prezesa Rady Ministrów z dnia 1 kwietnia 2011 r. w sprawie określenia wzorów formularzy sprawozdawczych, objaśnień, co do sposobu ich wypełniania oraz wzorów kwestionariuszy i ankiet statystycznych stosowanych w badaniach statystycznych ustalonych w programie badań statystycznych statystyki publicznej na rok 2011.
- Filipek, T., Gonet, S., Kucharski, J., Mocek, A. 2001. Ważniejsze jednostki miar i symbole stosowane w naukach o glebie. Nawozy i Nawożenie Fertilizers and Fertilization. 3:63-71.
- Fotyma, M., Mercik, S., 1995. Chemia Rolna. PWN, Warszawa, II wydanie.
- Fotyma, M., Jadczyszyn, T., Pietruch, Cz., 2001. A decision support system for sustainable nutrient management of farm level. Nawozy i Nawożenie Fertilizers and Fertilization. Puławy, 2:7-26.
- Jadczyszyn, T., Maćkowiak, Cz., Kopiński, J., 2000. Model SFOM narzędziem symulowania ilości i jakości nawozów organicznych. Pam. Puł., Puławy, 120/ I:169-177.
- Karklins, A., 2001. Model for the calculation of nutrient off take by crops. Nawozy i Nawożenie Fertilizers and Fertilization. Puławy, 1:63-74.
- Kopiński, J., Madej, A., 2006. Ilość azotu dostarczanego w nawozach naturalnych w zależności od obsady zwierząt. Nawozy i Nawożenie Fertilizers and Fertilization, Puławy, 4 (29):36-45.
- Maćkowiak, Cz., 1997. Rola nawożenia organicznego w kształtowaniu żyzności i urodzajności gleby. Mat. Szkol. IUNG, Puławy, 63/97.

13
SUMMARY

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## 13. SUMMARY

## Marianna Pastuszak, Tomasz Kowalkowski

Several problems have been taken up in this monograph and they are as follows: (i) long-term emission of nitrogen (N) and phosphorus (P) from Polish territory to the Baltic Sea, (ii) determination of reliable long-term (1988-2011) trends in riverine N and P loads introduced by Poland to the Baltic Sea - based on river basin oriented flow normalization of nutrient loads (Chapter 9), (iii) adoption of modeling (MONERIS) studies to evaluate long-term (1995-2008) emission of N and P into the Vistula and Oder basins via seven pathways (Chapter 8), (iv) interpretation of nutrient emission to the river basins and then to the Baltic Sea with respect to anthropogenic (regionally and temporarily diversified intensity of agricultural activity, spatially diversified structural changes in agricultural sector, spatially and temporarily diversified investment in waste water treatment plants) and natural (type of bedrock, type of soil, contribution of lake areas to overall basin areas, contribution of meadows to overall basin area) factors; land cover/use, physiographic features, water outflow are also given attention (Chapters 1, 8, and 9), (v) interpretation of long-term trends in N and P concentrations and loads with reference to reduced pressures on natural environment during the transition period (agricultural sector and point sources), (vi) changing role of silicon, a third very important macronutrient, in functioning of the Baltic ecosystem (Chapter 11), (vii) role of Polish estuaries in natural retention of N and P. Chapters 2, 3, 4, 5, and 6 show the real picture of Polish agriculture and emphasize the changes during the transition period; together with content of Chapter 7 they serve as reference material necessary for interpretation of the outcome of studies presented in Chapters 8 and 9.

We do hope that this monograph will constitute a reliable, fully comprehensive source of information, and that it will serve as the reference material not only for Poles, but first of all for our Baltic partners who perceive Poland mainly as a great contributor to N and P discharges to the Baltic Sea. It is obvious that the ecological state of the Baltic Sea depends very much on the ecological state of the environment in the river basins constituting the Baltic catchment. Therefore, protection of the Baltic Sea should be strongly linked with protection of inland waters, and that calls for river basin oriented studies, which should cover adequately long periods of time allowing detection of river response to mitigation measures introduced during the transition period. Such an approach is recommended and expected by the Helsinki Commission (HELCOM) and the European Union (EU) (Directives aiming at nutrient mitigation) and such an approach has been applied in Chapters 8 and 9.

Over the last years, we have been involved in many international projects, including the EU co-financed projects. We learnt from this experience that Poland is a unique country in the Baltic basin with respect to enormous long-term databases in all possible fields, just to mention river monitoring of nutrients and water outflows, precipitation, all aspects of agricultural activity (e.g. use of natural and mineral fertilizers, livestock stocking, crops, yields - all affecting N and P surplus), water withdrawal, handling of sewage, population dynamics etc.; these data can easily be supplemented with type of soils and physiographic features. At the same time, the international scientific market was lacking interdisciplinary sophisticated elaborations of these data. We are in the intensive process of filling up this gap, and numerous papers in peer reviewed journals, which have already been published or are in the process of publishing/preparation, as well as this monograph are a direct proof of the initiative. The

informal scientific body (partly formal due to an ongoing National Science Centre project no. N N305 300140), consisting of partners from marine (National Marine Fisheries Research Institute, Gdynia), agricultural institutions (Institute of Soil Science and Plant Cultivation - State Research Institute, Puławy; Fertilizer Research Institute, Puławy), as well as from universities (Nicolaus Copernicus University, Toruń; Pomeranian Academy, Słupsk), is fully determined to show the real picture of transforming Poland and its contribution to polluting the Baltic Sea. Depending on needs, we invite scientists from abroad e.g. from Bioforsk, Norway, who provide expertise in the fields of our interest.

An attempt has been made to provide the reader with a comprehensive set of observational and reference data, which may be valuable for further studies aiming at mitigation of diffuse nutrient emission. A lot of the presented data cover the transition period in Poland (24 years) but there are also numerous data that cover the former economic/political system. Apart from the overall scientific value, all the conclusions arising from the presented results, may be of great help for the decision makers in Poland dealing with environment protection issues, on both the local (at three levels of the administrative division of the country) and the central level (Ministry of Agriculture and Rural Development, Ministry of the Environment). Very comprehensive material presented in this monograph, focusing on reduced pressures on natural environment in Poland during the transition period and response of Polish rivers in terms of declining N and P loads introduced to the Baltic Sea, can serve as the reference material in official contacts with the EU and HELCOM representatives. We address this monograph to non-governmental and governmental bodies dealing with agriculture and environment, agricultural advisers, and all people interested in the interdisciplinary science concerning the environment. The monograph may constitute a comprehensive source of information for the educational purposes at Universities of Environmental Sciences, and may provide supplementing material for students from the following faculties: oceanography, biology, chemistry (environmental protection), and agriculture.

Unquestionable occurrence of athropopression in our natural environment over the past decades imposes necessity of a holistic approach (use of a "macroscope" – for references see to Chapter 8) in evaluation of e.g. the state of the Baltic Sea ecosystem. By definition, a holistic approach in ecosystem-based management is an environmental management approach that recognizes the full array of interactions within an ecosystem, including humans, rather than considering single issues, species, or ecosystem services in isolation. There are numerous physical, chemical, and biological processes involved in functioning of any ecosystem, and they interact non-linearly. Modern studies call for a holistic approach in specifying causes of perturbations in any ecosystem functioning and in interpreting the present or foreseeing the future consequences of such perturbations. It is evident in the light of recent studies that from the prospective of the Baltic ecosystem eutrophication not only excessive loads of nitrogen and phosphorus compounds delivered in riverine outflow must be given attention but also large-scale changes such as a decline in frequency of inflows of saline waters to the Baltic Sea or a decline in dissolved silicon concentrations (DSi), a third, after N and P, an extremely important player in the Baltic ecosystem functioning.

Large-scale changes resulted in a significant drop in frequency of saline water inflows to the Baltic Sea from the North Sea. That in turn affected the level of oxygenation of the bottom Baltic waters. Based on long-term oxygen data (1960-2011), a distinct regime shift has been identified in the Baltic Sea. During the first regime, 1960 to 1999, hypoxia affected large areas and volumes, while anoxic conditions affected only minor deep areas. After the regime shift in 1999, both the areal extent and volume of hypoxia and anoxia have been elevated to levels never recorded before. Further increase in the extent and volume of anoxic conditions can enhance the eutrophication of the Baltic Sea, due to released phosphorus from

the sediments that have previously been oxygenated (Chapter 1).

Another phenomenon which has been observed over the last decades is a decline in dissolved silicon concentrations with adverse serious effects to functioning of the entire ecosystem, the enhanced eutrophication included (Chapter 11). Tremendous efforts have been made to reduce overall discharges of N and P to the Baltic Sea in order to improve the ecological state of the sea, but little, if any attention has been paid to ecological consequences of the disturbed silicon (Si) fluxes from land and Si cycling in the sea. Human activities have caused dramatic changes in riverine geochemistry, which consequently affected the supply of constituents from rivers to the estuarine and coastal ecosystems (Chapter 11). Eutrophication in the Baltic Sea and in rivers feeding the sea, as well as river damming, have been responsible not only for excessive production of biogenic silicon (BSi) but also for its excessive sedimentation over the last decades, and consequently responsible for modifications of dissolved silicon (DSi) cycling in the Baltic Sea. Si is released back to the water column via the dissolution of BSi, which is a considerably slower process compared to the remineralisation of N and P. Regeneration of BSi is primarily a chemical phenomenon whereas the regeneration of N and P are biological mediated by grazers and bacteria. Loads of Si, reaching the Baltic Sea in riverine outflow, have drastically dropped over the last 50-60 years and so did dissolved silicate (DSi – is the form of Si that is taken up by phytoplankton). The Baltic Sea is one of the many aquatic ecosystems that show long-term declines in DSi concentrations. A decrease in DSi concentrations in both the surface and the bottom Baltic waters has been reported. The decrease ranges from 0.05 to 1.2 µmol Si dm<sup>-3</sup> yr<sup>-1</sup>. The trends have been leveling off over the last decade. Since the riverine load of DSi has not been changing at a corresponding rate during the subjected decades, the decrease is assumed mainly a result of eutrophication. It has been proven that DSi dropping to concentrations 1-2 µmol dm<sup>-3</sup> limit growth of diatoms. Scarcity of DSi during spring phytoplankton bloom, which is the case in several areas of the Baltic Sea, may have adverse effects for growth of a large group of primary producers (diatoms), which are responsible for about half the primary production in the world's oceans and which are preferably grazed upon by the macrozooplankton (copepods); the latter serve as a direct food source for higher trophic levels such as commercially exploitable fish species. Moreover, scarcity of DSi during spring phytoplankton bloom may lead to switching of the system from the N-limited to Si-limited, with adverse effects for the ecosystem functioning. The decreasing Si:N ratio may be exacerbating eutrophication by reducing the potential for diatom growth, in favor of harmful flagellates. Non-diatom species are known to be less desirable to higher trophic levels and some non-diatom based food webs are economically undesirable. Moreover, in coastal marine systems, these algae produce either toxins or mucilage, escaping the normal grazing food web and leading to anoxic conditions at the decay of the bloom. That leads to loss of recreational value of coastal regions. The content of Chapter 11 may serve as a source of very important information as regards plans of further damming of rivers in the Baltic catchment.

Excessive emission of nitrogen and phosphorus compounds to inland and then marine waters may lead to eutrophication in these water reservoirs, and may result in an increase in nitrate concentrations in drinking waters to the level, which becomes hazardous for human health. Emission of nitrogen compounds to atmosphere, from both the agricultural and the industrial sector, contributes to "acid rains" and greenhouse effect (Chapter 5). These serious threats inclined the EU and the HELCOM to actions aiming at mitigation of excessive N and P exports from the terrestrial environment. The Baltic Sea Action Plan is an ambitious program prepared by the HELCOM and its goal is to restore the good ecological status of the Baltic marine environment by 2021 (Chapter 8). The new strategy is a crucial stepping-stone for wider and more efficient actions to combat the continuing deterioration of the marine

environment resulting from human activities.

In the Baltic catchment, 62% of nitrogen and 54% of phosphorus in the riverine outflow originates from losses from diffuse sources, with agricultural activity playing a key role in nutrient emission (Chapters 8 and 9). The source apportionment of nitrogen and phosphorus losses into inland surface waters, made for all the Baltic countries, shows that the respective contribution of nitrogen from diffuse sources, point sources, and natural background constituted 62%, 18%, and 20% in Poland in 2000; the respective contribution of phosphorus from diffuse sources, point sources, and natural background constituted 54%, 29%, and 17%. Within the discharges of nutrients from point sources, contribution of wastewater treatment plants (WWTPs) was in Poland of uppermost importance, as it constituted ca. 92% of both N and P loads; contribution of industrial discharges accounted for ca. 8% of both N and P loads.

Agricultural systems leak nitrogen and phosphorus via three major routes (i) upward, via crop uptake and via transfer of gaseous nitrogen compounds ( $NH_3$ ,  $N_2$ ,  $N_2O$ ,  $NO_x$ ) to the atmosphere, (ii) laterally, via surface runoff, subsurface flow and tile drainage, and (iii) downwards, via leaching and percolating to groundwater (Chapters 3 and 4). The balance between these three different routes depends on farming system, nitrogen and phosphorus fertilizing history, climate, topography, soil type, and hydrology. Surface waters receive agricultural nitrogen via: (i) atmospheric deposition, (ii) subsurface flow and tile drainage, (iii) surface runoff and erosion, (iv) animal excreta, (v) seepage of nitrate containing groundwater from agricultural land.

In agro-ecosystems, land use changes affect pathways and quantities of nutrient transport, but in general, these effects do not become immediately visible. Additionally, the transport velocity of solutes depends on sorption and desorption, as well as on turnover processes in the soil. According to numerous authors, processes such as mineralization, immobilization and denitrification affect nutrient transportation from the root zone to surface water and it is unlikely that there will be a strong correlation between N balance surpluses and N losses at the catchment outlet in the short term (≤5 years). The studies presented in Chapters 8 and 9 cover the period of 14-24 years, so there is no risk that the authors were not able to notice the reaction of river systems to the implemented mitigation measures e.g. those introduced during the transition period (compliance with the EU Directives and/or the HELCOM declarations). It is obvious that lag time is much longer in so-called slow-flow systems, which are typical in flat countries like Poland. Nearly 84% of the entire Polish area has land slope below 3° (Chapter 2). That in practice means that majority of water (from precipitation) and nutrients percolate downwards, through the soil layers before they reach groundwater and surface water. That very much prolongs the time needed for the water/nutrient transport and that fact is in favor of substantial natural nutrient retention. Poland has the highest natural N and P retention in riverine systems in the entire Baltic catchment. Polish rivers belong to the least regulated rivers in the Baltic region, and great majority of them have grass/scrub overgrown riverbanks (Chapter 1).

In 2000, the total riverine nitrogen and phosphorus loads entering the Baltic Sea amounted to 706,000 tones and 31,800 tones, respectively. About 40% of the N load and 50% of the P load originated from the catchment area of the Baltic Proper. Approximately 75% of the riverine nitrogen and 83% of phosphorus were discharged by the region's three rivers: the Vistula, the Oder, and the Nemunas. In 2000, contribution of Poland to overall loads of N and P reaching the Baltic Sea constituted 26% and 37% for total nitrogen (TN) and total phosphorus (TP), respectively (Chapters 1 and 8).

For the past decades, high contribution of Poland to overall loads of nitrogen and phosphorus reaching the Baltic Sea has been a subject to severe, not fully justified, criticism

on an international level. The high annual loads of N and P have never been denied by Poles, but that truth requires explanation which should be based on scientific findings on a complexity of factors responsible for N and P emission from man utilized land to riverine systems and then to the sea. Among the main factors one must take into consideration the area of the catchment, the land use/cover, the area of agricultural land, the geomorphologic features, the geographical setting which is connected with climate, thus type and intensity of precipitation and consequently the volume of water drained from the catchment, and the population inhabiting the catchment. This is also part of a holistic approach, which is necessary to evaluate justly the contribution of particular Baltic States to emission of N and P to the Baltic Sea (Chapters 1, 8, and 9).

As much as 99.7% of Polish territory constitutes the Polish catchment in the Baltic Sea basin. Majority of Polish territory is drained by the Vistula and Oder, two out of the seven largest rivers feeding the Baltic Sea. The Polish part of the Baltic catchment (i) belongs to the four largest catchments in the Baltic basin, (ii) is similar, by its size, to the Russian and the Finnish parts of the Baltic catchment, and (iii) is by ca. 30% smaller than the largest Swedish catchment. The area covered by agricultural land in Poland constitutes over 50% of the overall agricultural land area in the entire Baltic catchment. Finland, Sweden, and Russia have in their catchments much larger forested and inland waters (lakes) areas than Poland; forests in Finland cover ca. 60% of the Finnish catchment area. Over 25% of the Swedish catchment is occupied by mountains and that is a distinguishing feature in the Baltic catchment. The urban area in Poland is the largest one in the Baltic basin, and that in turn is directly related to the population figure; 45% of the entire Baltic basin population inhabits territory of Poland (Chapter 1).

It is well documented in scientific literature that emission of nutrients from the forested areas, or from the regions with high contribution of lakes is incomparably lower than nutrient export from the agricultural land. Nitrate concentrations in open waters are positively correlated with percentage of arable land in the catchment; emission of nitrates from arable land is considerably higher than from meadows or pasture-land (Chapters 3, 8, and 9). Studies carried out in Finland and the US, indicate that land management for agricultural purposes results in approximately eight (the US) or tenfold (Finland) higher nitrogen losses per unit area compared to the forested land. It is also documented in literature that population and population density are positively correlated with emission of nutrients to riverine systems. Very high, statistically significant correlation coefficients between the average proportion of total nitrogen and total phosphorus discharges by the Baltic countries and the average proportion of arable land and population prove these findings (Chapter 9). The agricultural land and agriculturally utilized land in Poland account for 61% and 51%, respectively, of the entire Polish territory (Chapter 2). Interestingly, the agricultural land area and population in Sweden are 7 times and 4.5 times smaller than those in Poland but there was only 20% difference between TN loads discharged into the Baltic Sea by these two countries in the year 2000 (Chapter 9).

Comparisons of N, P loads, and N, P area specific loads (Chapter 9) by all the Baltic countries is a very clear indication that the extent of nutrient emission into river basins is an extremely complex issue, whose understanding requires sound knowledge in the subject. Therefore, great caution should be exercised before jumping into far reaching conclusions or criticism of a particular country for polluting the Baltic Sea by excessive N and P emission. Poland, with its huge catchment area and very substantial water discharge, would have to reduce nutrient concentrations in the riverine waters to values next to zero in order to get closer to countries with the lowest N and P discharges into the Baltic Sea (countries having the catchment area for example 10 times smaller than Poland). Such a situation has never

taken place in any densely populated, industrialized, and agriculturally utilized country on the globe, and the rivers draining Polish territory cannot be expected to present the same chemical properties as for example the rivers of Amazon & Tocantins region, which are characterized by the lowest anthropogenic input of nitrogen on the globe.

The area specific loads, but not riverine loads of TN and TP, are an indication of potential environment degradation in the catchment. In the HELCOM (2004) report, the area specific loads are divided into area specific diffuse losses, area specific point source discharges, and area specific background losses. The total riverine TN load introduced by Poland to the Baltic Sea in the year 2000, was the highest but the Polish area specific diffuse loss of N belonged to the low ones in the Baltic region. It was over fourfold and twofold lower than that in Denmark and Germany. The total area specific N load (the sum of the three sources) was over three times lower in Poland than the same specific N load in Denmark. If the Polish figure approached that in Demark, the country with exceptionally intensive agriculture, Poland would have introduced well over 600,000 tons of N but not the recorded ca. 190,000 tons of N in the riverine outflow in year 2000. Problem of natural environment degradation in Denmark in the 1980s and measures aiming at mitigation of nutrient emission from agricultural land implemented in the late 1980s in that country are extensively discussed in Chapter 9. This example should give Poland a warning, as in the transforming Polish economy there already appear conflicts of interest related to introduction of large-scale pig production based on western capital. In recent years, there has been a tendency towards concentration of milk production. Similar tendency towards concentration can also be seen in pig production but over the last years only less than 16% of Polish farms have had herds with more than 50 animals (Chapter 2).

In Denmark, problem of excessive emission of nutrients from agricultural sector does not result from the number of pigs because that was by 5 mil. lower in 2002 than in Poland. Problem lies in pigs density expressed in Livestock Units (LU) per 100 ha of agricultural land (Chapters 2 and 9). Polish average animal density is not high (in 2009-2011 - on average 45 LU per 100 ha) but regional differences are relatively high, with a minimum within a range 15-29 LU per 100 ha, and with a maximum value equal to 68-78 LU per 100 ha. The highest number of farms with intensive animal raising is in WLP and KUJ voivodeships (western/central Poland) (mainly pigs), and PDL voivodeship (eastern Poland) (mainly cattle) (Chapters 2 and 5). That automatically means that environmental pressures (agricultural activity, point sources, and natural factors such as erosion) must be looked into regionally and that fact is stressed in the modeling studies carried out in the Vistula sub-catchments (Chapter 8). Moreover, the results shown in Chapter 5 prove that farms with mixed production exert much lower pressure on the environment than farms that are specialized in livestock production.

The pattern of P loads reaching the Baltic Sea strongly deviates from the pattern of P diffuse area specific loads, with nearly the same highest values in Germany, Denmark, and Poland. Estonia is only slightly below these three highest contributors. If the drainage areas in Germany, Denmark, and Estonia were comparable to that in Poland, the P outflow from the agricultural land would have theoretically been identical, provided the geomorphologic and climatic features, the agricultural land area, the agricultural intensity, the fertilizing history etc. were the same, which is definitely not the case. The Danish and German catchment areas and agricultural land areas are ca. tenfold smaller than the Polish one and this single argument is sufficient to get away from a comparison of P loads discharged into the Baltic Sea by the subjected countries (Chapter 9).

The high area specific diffuse P loss in Poland in 2000, may have resulted from P surplus in Polish agriculture in 1984-1994, with particularly high values found in 1984/85 and 1989/1990, reaching 19.1 kg P ha<sup>-1</sup> and 15.5 kg P ha<sup>-1</sup>; similar high values of P surplus are reported

for the years 1985-1990 by the authors of Chapter 4. High P surplus may have led to P accumulation, making it long-term diffuse sources of P loss to water. Phosphorus surplus in 1991-2010 was much lower than in the 1980s and, with a few exceptions, it remained below 5 kg P ha<sup>-1</sup> (Chapter 4). Application of phosphorus fertilizer, though increasing after a drastic drop during the recession on the turn of the 1980s and 1990s, is still two times below the maximum of P application in the 1980s. Currently the consumption of P fertilizers in Poland amounts to about 25 kg  $P_2O_5 \cdot ha^{-1}$  of agricultural land and it is approx. two times lower than in the 1980s (Chapter 4).

Inorganic P is usually associated with Al, Fe, and Ca compounds of varying solubility and availability to plants. Phosphorus, when added to soil in the form of fertilizers can be rapidly fixed (adsorbed) in forms unavailable to plants. The fixation rate depends on soil pH and Al, Fe, and Ca content. Maximum of bio-available P in soil occurs at pH between 6 and 7. P surplus in combination with acidification could have caused P accumulation in soil and could have constituted a long-term source of P in its diffuse outflow (Chapter 9). Relatively high Polish area specific losses of P can additionally be explained by the following facts: (i) as much as 21% of agricultural land, mainly arable land, and 8% of forested area are imperiled with soil erosion (erosion caused by water flow), (ii) over 50% soils are acidified, with acidification originating from the type of the bed-rock and anthropogenic factors such as fertilization and "acid rains" (Chapters 2, 5, 8, and 9). High contribution of erosion pathway to overall P emission into Vistula and Oder basins (28-29%) proves the above statement. P emission by erosion is, however, highly diversified in Poland, with the highest emission values observed in the foothill regions characterized by a thin soil layer and high slopes (Chapters 2 and 8). The real threat of water erosion of soils in Poland is much smaller than the potential risks due to the fragmented structure of land use. Assuming continued exclusion from the use of arable land for afforestation, orchards, and permanent grassland with the soil protection function, a reduction of the extent and intensity of both water erosion and wind erosion should be expected (Chapter 2).

Phosphorus loss from agricultural non-point sources depends on the coincidence of source factors (functions of soil, crop, and management; soil P concentration, soil texture, structure, and permeability are of importance) and transport factors (surface and subsurface runoff, erosion, tile drainage, and channel processes) (Chapters 2, 4, 8, and 9). Phosphorus is transported from soil to surface water in two major forms: (i) as dissolved phosphorus – DIP, and (ii) as particulate P (organic and colloidal suspension). Unlike nitrogen, the major proportion (60-90%) of phosphorus transported from agricultural soils is generally in particulate form (Chapter 9). Also unlike nitrogen, only a fraction of the phosphorus transported from agricultural land is directly available to aquatic biota. However, a substantial portion of particulate P may also be released into an algal-available form, especially when the particles have entered anoxic sediment surface.

Contribution of agriculture to emission of ammonia is a well known and documented fact in international literature. Emissions of ammonia from agricultural sources cause a number of adverse consequences, therefore more and more attention is paid to this issue in countries that face the problem of intensive NH<sub>3</sub> emission. Proper storage of manure, slurry and dung, proper application of natural fertilizers to soil, and reducing the amount of nitrogen excreted in faeces per animal unit and per unit of livestock production, are stressed as factors limiting the NH<sub>3</sub> emission to the atmosphere (Chapter 5).

There are 1.5 million farms and 0.6 million of small settlements (possessing less than 1 ha of agricultural land) in Poland and all of them contribute to emission from so-called dispersed point sources in agriculture (Chapter 2). Farmyards and stables are the main sources of nutrient emission on farms (Chapters 5 and 6). The production of dung, liquid

manure, and slurry amounts to about 80.7 million tons, 18.2 million m³, and 7.5 million tons, respectively. As many as 408 projects, directly related to 827 investments which involved construction of manure plates and tanks for liquid manure or slurry, were carried out in Poland in 2002-2006 in the framework of the pre-accession aid programme (SAPARD). That resulted in construction of manure pits with the total volume of 55,000 m³, and tanks for liquid manure with the total capacity of approx. 52,000 m³. However, the most important for the development of infrastructure in the field of animal production in the years 2004-2006 was the Rural Development Plan (PROW). As a result, the investments were made on over 71,000 farms, including 3,467 farms located in areas at particular risk to nitrate pollution; manure pits area has increased by approx. 3.7 million m² and the capacity of tanks for liquid manure by about 3.1 million m³. The current surface of manure pits ensures proper storage of approximately 70% of manure (Chapter 6).

Polish farms have unique development in Eastern and Central Europe. Polish agriculture is dominated by small farms, of 1-5 ha. They constitute over 55% of the total number of farms, but hold only about 20% of agricultural land. The average area of the farm, in the group of farms with an area of more than 1 hectare, has been steadily increasing and now it amounts to 9.8 ha. Farms with an area over 20 ha (their number amounts to 120·10<sup>3</sup>) constitute only 5.7% of the total number of farms but use 47% of agricultural land. The largest fragmentation of individual farms is observed in southern and south-eastern part of the country (Chapter 2). Majority farms are mixed production entities growing fodder for their own animals. Cereals and winter rape predominate, and they are cultivated in crop rotation system. Polish farms are characterized by moderate consumption of mineral (90-109 kg NPK) fertilizers (Chapter 3). Different soil complexes have been grouped by their suitability for cereals production and therefore by the group of plants dominant in the structure of crops. Very good and good soils that do not pose restrictions on the selection of cultivated cereals account for nearly 50%, and medium soils, where cultivation of wheat is associated with considerable risk, account for about 16%. The share of poor soils is about 23%, and 11.6% are very poor. The weakest soils, due to very low productivity, will probably be excluded from agricultural use in future (Chapter 2). As a function of agroclimate and soil conditions the unit production potential of agriculture in Poland is not too large and is lower than the potential of most Western European countries. However, the global agricultural production potential is significant due to the large agricultural area representing about 11% of agricultural land area in the 25 European Union countries with the domination of arable land, and because of the large labour force available in agriculture (Chapter 2). The rainfalls on the prevailing area are insufficient and lower than the potential evapotranspiration. Moreover, 30-40 % of rain and snow fall in the winter period on practically bare soils. Vegetation period is rather short, between 193 days (northeast) and 223 days (south-west) (Chapter 2).

Rural population (14.7 million) accounts for 38.7 % of the total Polish population. This population is dispersed across the country and people live in 41 thousand villages, of which about 15% count less than 100, while 66% have from 100 to 500 inhabitants. This huge dispersion partly explains poor infrastructure in rural areas (Chapters 6 and 8). There is still a big gap between water supply and wastewater disposal in rural areas. The situation is improving by further expansion of individual sewage treatment plants serving single or multiple adjacent households in rural areas. It should be emphasized here that these individual treatment plants are not covered by the national statistics. Such plants are practically not found in cities, especially in large ones. In 2010, 24.8% of rural population was using sewerage system, whereas 28.8% was using wastewater treatment plans (Chapter 8).

Poland's economy has undergone a profound transition from a centrally planned to a market economy since 1989. This transition has led to major institutional and economic structural

changes over the last years. Reforms initiated in the early 1990s provided opportunities to revise and implement environmental management and legislation, and to achieve greater integration of environmental concerns into other policies (Chapter 7). Since the early 1990s Poland has made remarkable environmental progress, meeting most of its environmental targets and decoupling a number of environmental pressures from economic growth. Together with economic structural changes, these efforts have contributed to progress on a number of fronts e.g. reductions in air pollutants emissions, declines in water withdrawal, declines in N and P discharges from municipal WWTPs as a result of construction of 1864 very efficient WWTPs between the years 1995 and 2008 (Chapter 8), closure of obsolete factories and modernization of the remaining ones, thus substantial elimination of "hot spots" (Chapter 1), decline in N and P surplus as a result of drop in fertilizer application and drop in livestock number/density, but also as a result of higher nutrient use efficiency (Chapter 8), declines in nutrient emission into riverine systems via majority of N and P pathways, including those directly connected with agricultural activity, and declines in N and P discharges into the Baltic Sea (Chapters 8 and 9). The changes, which took place in Polish economy during the transition period, have not had the same spatial and temporal dynamics and that has been reflected in different spatial/temporal N and P emission to the river basins and consequently the response of Polish rivers to changed pressures in the river basins (Chapters 8 and 9).

The restructuring process was spatially diversified in agricultural sector during the transition period and the ownership changes deepened spatial polarization, as an increase in farm size took place in the regions where a large average farm area has long been a typical feature (western Poland – Oder basin) (Chapter 9). Large farms in Poland use modern machinery, thus different ways of soil cultivation; they are characterized by: much higher application of mineral fertilizers, larger tile drainage area, greater livestock density, greater congestion of concentrated pig farms, thus higher risk of environment polluting with excessive application or improper storage of manure. However, the problem must be look into also from a different angle. Following the restructuring and privatization of the State-owned Farms (great majority of State-owned Farms was located in western Poland i.e. in the Oder basin), local overloads of fertilizers decreased, and thus environmental threats from this source were diminished or eliminated. The other positive aspect is that larger farms achieve higher yields and are more efficient in absorbing EU money provided for their modernization and for environmental protection, both contributing to lower diffuse nutrient emission (Chapters 8 and 9).

Pressure of agricultural activity on natural environment is regionally diversified across Poland. Several measurable factors influencing directly or indirectly nitrogen and phosphorus diffuse losses in each of 16 voivodeships were grouped in order to identify regions with similar pressure on the environment. The cluster analysis was applied to aggregate the regions. There are 5 voivodeships (KUJ, LUS, LOD, WLP, ZAP) that represent high risk, and 11 voivodeships (DLN, LUB, MLP, MAZ, OPL, PDK, PDL, POM, SLS, SWT, WAM) that show low risk of excessive nitrogen emission (Chapter 3). As to phosphorus, 7 voivodeships show high (KUJ, LUS, LOD, MAZ, POM, WLP, ZAP) and 9 voivodeships (DLN, LUB, MLP, OPL, PDK, PDL, SLS, SWT, WAM) that exhibit low risk of emission. All regions classified into the low risk cluster are situated in eastern Poland that means in the Vistula River catchment. Generally, the Vistula catchment is under lower pressure of agricultural activity on surface and groundwater than the Oder River catchment (Chapters 3, 4, and 8).

Apart from the restructuring process with its consequences, the transition period in Poland was characterized by a significant drop in livestock number/density and a decline in application of mineral fertilizers at the beginning of the 1990s, both affecting the N and P balance in Polish agriculture (Chapters 3, 4, and 8). Application of nitrogen and phosphorus mineral fertilizers dropped from its maximum of ca.75 kg N ha<sup>-1</sup> and 50 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> in the

1980s to 35 kg N ha<sup>-1</sup> and 12 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> at the beginning of the 1990s (Chapters 3 and 4). Though application of nitrogen mineral fertilizer has been increasing over the last decade, the tendency is not reflected in a significant increase in N surplus in Polish agriculture and that is explained by higher N use efficiency (Chapters 3 and 8).

The diffuse outflows, as well as point sources are the main sources of anthropogenic nitrogen and phosphorus discharged by the Vistula and Oder River to the Baltic Sea (Chapters 1 and 9). In the case of both rivers, there is a positive correlation between nitrate concentrations and water outflows, pointing to a predominance of diffuse origin of N in both basins (Chapter 9). Recent modeling (MONERIS) studies, performed for the Vistula and Oder basins for the years 1995-2008, have shown that ca. 70% of TN emission into both river basins was via groundwater and tile drainage. Though three pathways of N emission i.e. groundwater, tile drainage, and WWTPs, showed the highest average contribution in the Vistula and Oder basins in 1995-2008, the average percentage contribution of groundwater was much higher in the Vistula (40%) than in the Oder (24%) basin, while the average percentage contribution of tile drainage pathway was considerably higher in the Oder (48%) than in the Vistula (29%) basin. Different types of bedrock in the subjected river basins are responsible for different groundwater contribution, whereas different percentage of tillage areas, in combination with different permeability of soils and different agricultural intensity in the river basins, explain much different contribution of tile drainage in N pathway (by 19% higher in the Oder basin) (Chapter 8).

Phosphates vs. water outflow scatter-plots in the Vistula and Oder River exhibited a weak and negative correlation, which indicates an important role of non-agricultural sources (point sources, urban systems) in PO<sub>4</sub>-P emissions (Chapter 9). In 1995-2008, the percentage contribution of particular TP pathways did not show as great difference between the Vistula and Oder basins as in the case of nitrogen. There were four main pathways of P emission into the Vistula and Oder basins i.e. urban systems, WWTPs, overland flow, and erosion. The average (1995-2008) percentage contribution of overland flow to P emission reached 19% in the Vistula and 15% in the Oder basin, while the percentage contribution of WWTPs amounted to 19% in the Vistula and to 24% in the Oder basin; the percentage contribution of urban systems (16-17%) and erosion (28-29%) were comparable in the subjected basins. Higher contribution of WWTPs in the Oder basin is directly related to higher percentage of population connected to WWTPs (Chapters 8 and 9). WWTPs were the second largest contributor to TP emission into the river basins but their role has been diminishing thanks to investment in WWTPs infrastructure during the last two decades. The investment in WWTPs was quite different in the river basins, with much more efficient actions in the Oder basin and that greatly affected the temporal dynamics of P emission into the river basins (Chapters 8 and 9). At the diminishing contribution of point sources to P emission, a relative contribution of diffuse sources will increase. Therefore, any comments on the percentage contribution of agricultural sector to P emission must also take into consideration the temporal variability in P loads.

The drop in N emission between two sub-periods i.e. 1995-2002 and 2003-2008, was comparable in both basins and it amounted to 16-17%. Between 1995-2002 and 2003-2008 sub-periods N emission *via* groundwater dropped by 30% and 37%, while N emission from WWTPs dropped by 15% and 40% in the Vistula and Oder basin. A significant decline in N and P emission *via* groundwater is an indication of reduced nutrient leaching which in turn could have been connected with reduced pressure in agricultural sector. More effective N removal from WWTPs in the Oder basin is a result of more advanced measures in nutrient mitigation from point sources in that basin. Between 1980 and 2003-2008 the N emission into the Oder basin dropped by 23% (Chapters 8 and 9).

The decline in P emission between two sub-periods i.e. 1995-2002 and 2003-2008 reached 26% in the Vistula basin and 32% in Oder basin. The most spectacular decrease in P emission was observed in the case of WWTPs pathway and the decline reached 48% in the Vistula and 61% in the Oder basin between the two sub-periods i.e. 1995-2002 and 2003-2008. The decreasing trends in P emission into the Vistula and Oder basins were also noted in the case of overland flow (by 34-37%), erosion (by 5-7%), and urban systems (by 21-23%). Between 1990 and 2003-2008, a 3.3-fold decline in P emission into the Oder basin was observed (Chapter 8).

The temporal variability in N and P emission into the Vistula and Oder basins, as well as the percentage contribution of particular pathways of N and P emission in these basins (particularly: *via* surface runoff, tile drainage, groundwater, WWTPs) showed substantial differences between the basins. This temporal/spatial diversity is explained by different natural (type of bedrock and soil, area occupied by lakes) and different anthropogenic factors (intensity of agricultural activity, area covered by meadows and pastures, tillage area, spatially different restructuring process in agricultural sector, and spatially different investment in WWTPs) (Chapter 8).

In the above paragraphs, we presented emission into the river basins. It has to be remembered that N and P loads that reach river network undergo further retention in the river systems. So, concentrations that are measured at the lowermost river monitoring stations are a resultant of both, the enhanced or reduced emission into the river basins and the retention in the river networks due to numerous biogeochemical processes e.g. denitrification (Chapter 9).

Lower emission of N and P to the river basins resulted in lowering of nutrient concentrations in Polish rivers (Chapter 9). Concentrations of TN and TP, dissolved inorganic nitrogen (DIN) and phosphorus (DIP) in the Vistula and Oder Rivers (at the lowermost river monitoring stations) have dropped significantly, with more dramatic changes being seen in the Oder waters. Over the years 1988-2011 the average TN concentrations in the Vistula and Oder dropped from 3.1 to 2.2 mg N dm<sup>-3</sup> and from 4.7 to 3 mg N dm<sup>-3</sup>, respectively. The average TP concentrations in these rivers dropped from 0.22 mg P dm<sup>-3</sup> to 0.17 mg P dm<sup>-3</sup> and from 0.55 to 0.18 mg P dm<sup>-3</sup>, respectively. Very much pronounced is the decrease of the average DIP concentrations in the Oder waters, those declining from 0.2 mg P dm<sup>-3</sup> in 1990 to 0.04 mg P dm<sup>-3</sup> over the last 7 years of study. During the entire period of studies, TN, NO<sub>3</sub>-N, TP concentrations in the Vistula were lower than in the Oder River and that is attributed to lower pressure on natural environment in the Vistula basin. The Vistula basin is characterized by: (i) larger contribution of lake area, (ii) larger contribution of area with wetlands and meadows, (iii) higher contribution of more permeable bedrock favoring higher downwards water infiltration, thus prolonging the transit time, (iv) lower contribution of area of tillage drainage, (v) less intensive agriculture (lower consumption of mineral fertilizers, smaller sizes of farms oriented at less intensive production, lower number of farms with intensive pig raising) (Chapters 2, 3, 4, 5, and 8).

It should be emphasized here that nutrient concentrations in the Vistula and Oder waters feeding the Baltic Sea were low in the last two decades in comparison with values detected in other eutrophied European rivers (5-8 mg N dm<sup>-3</sup> in Thames, Rhine, Elbe or Seine) which drain the catchments characterized by higher fertilization than in Poland. Average nitrate concentrations in the basin of Humber River in northwestern England are in the range 3.3-18.8 mg N dm<sup>-3</sup>, while phosphate concentrations vary between 0.023 and 1.96 mg P dm<sup>-3</sup> (Chapter 9).

A decrease in nutrient concentrations in Polish rivers was followed by a decrease in nutrient loads. The overall TN and TP loads discharged into the Baltic Sea by the Vistula,

the Oder, and the Pomeranian rivers exhibited temporal variability, with an increasing trend in 1990-1998 and a decreasing tendency in the years that followed. The year 2002 diverged from an overall declining trend in TN loads, and so did the water outflow, which was record high in January 2002 (ca. 3400 m³s⁻¹). The declining tendency in TN and TP loads occurred 10 years after a drastic drop in mineral fertilizers application, and practically at the same time when the volume of untreated sewage started to decrease, while volume of treated sewage with new efficient technologies started to increase (Chapters 3, 4, 8, and 9).

N and P concentrations and loads show natural fluctuations caused by both seasonal variability in biological activity in river watersheds and variability in water discharge. Considering that natural variation in water discharges can have a profound impact on the observed concentrations and loads, the authors of the Chapter 9 applied recently developed statistical methods (calculation of flow normalized concentrations and loads of nutrients) to account for this variability. The applied flow-normalization made it possible to estimate the load at the "normal" water discharge. Such removal or reduction of irrelevant variation in the collected data can help to clarify the impact of human pressures on the environment (in our case, the impact on riverine loads of nutrients). The trend lines, given as smoothers, were obtained by statistical cross-validation that minimizes the residuals in the statistical modeling determined according to the newly developed method, which was applied by the authors (Chapter 9). A substantial fraction of the inter-annual variation in TN and TP loads was removed in both rivers when the load data were flow normalized, especially in the years with very high or low water flows.

In both rivers, flow normalized nutrient concentrations and loads showed statistically significant declining trends in the period 1988-2011. The presented data show that flow normalized loads of TN decreased by ca. 34% (40,000 tons) and 28% (21,000 tons) in the Vistula and Oder; the TP loads dropped by ca. 18% (1,200 tons) and 80% (6,500 tons) in the Vistula and Oder waters directed to the Baltic Sea over the years 1988-2011. Flow normalization covering a shorter period (1988-2008) (Pastuszak et al., 2012 – see to Chapter 9) gave the following numbers: TN decreased by ca. 20% (20,000 tons) and 25% (20,000 tons) in the Vistula and Oder; the TP loads dropped by ca. 15% (900 tons) and 65% (5,400 tons) the Vistula and Oder water directed to the Baltic Sea. Comparison of all these numbers shows that the response of Polish rivers to reduced anthropogenic pressures is an ongoing process and it is still very well pronounced.

The reduction in flow-normalized phosphorus loads was particularly pronounced in the Oder basin, which was characterized by efficient management systems aiming at mitigation of nutrient emission from the point sources and greater extent of structural changes in agricultural sector during the transition period. The trend lines for TP and DIP loads in the Oder River were descending, with well-pronounced slopes, during the entire period of studies (1988-2011); this is an indication that there is a continual progress in P mitigation in western Poland. The decline in TP loads was much less pronounced in the Vistula basin while the response of the river to delayed investment in WWTPs (DIP loads) appeared not earlier than in 1998. Less spectacular was a decrease in flow-normalized loads of TN in both river basins and NO,-N loads in the Oder basin; that indicates that new mitigation measures must be introduced in agricultural sector in order to reduce pressures from this sector. There was a significant decline in flow-normalized loads of NO<sub>3</sub>-N in the Vistula basin; the loads dropped from ca. 58,000 tons in 2004 to ca. 32,000 tons in 2011 (Chapter 9). NH<sub>4</sub>-N loads in both rivers showed a strong declining tendency. It is very likely that the observed substantial decrease in NH<sub>4</sub>-N loads was caused by the decrease in loading of organic matter from point sources and the implementation of nitrification in WWTPs. The trends in riverine loads are discussed in relation to socio-economical changes during the transition period, and with respect to physiographic features (Chapter 9).

The decline in N and P emission from Polish territory to the Baltic Sea quantified through adoption of the internationally approved flow normalizing methodology facilitates drawing of reliable conclusions from the evaluated trend lines (Chapter 9). One should, however, be aware of the fact that flow normalization facilitates reliable conclusions provided certain methodological conditions are fulfilled: (i) it requires a river basin approach, (ii) flow normalization must be based on monthly nutrient concentrations and monthly water flows in a given river; such data constitute a reliable base for calculating monthly and then annual flow normalized nutrient loads, (iii) long-term data are indispensable for mathematical evaluation of trend lines in N and P loads, and the longer the time series the more reliable the outcome; this statement is particularly crucial in the case of Polish slow-flow systems which greatly predominate in the country, (iv) any segmenting of a long period and calculation of short-term trends must lead to doubtful and highly speculative conclusions. All these conditions were met in elaboration of the Polish data presented in Chapter 9. We have proven that (i) in the case of e.g. long-lasting very dry periods even sophisticated mathematical approach is not able to fully compensate for the "artificially reduced" N loads (e.g. the Vistula basin in the early 1990s), (ii) despite the fact that the transition period in Poland has lasted 24 years, the two largest Polish rivers still strongly respond to positive changes in Polish economy, and (iii) the response of two largest Polish rivers to reduced pressures was different in time and the reasons of such behavior are extensively discussed in Chapter 9.

All these remarks should be thought over by the Polish decision makers at all possible levels as well as by the contact persons with the EU and HELCOM, while the conclusions drawn by us should seriously be taken into account prior to any actions related to preparation of the next Pollution Load Compilation (PLC-6) by the HELCOM. All our conclusions are of great importance, particularly in the light of compliance with obligations resulting from the Baltic Sea Action Plan. Obligations must be relevant not only to reliably estimated river basin oriented long-term flow normalized N and P loads reaching the Baltic Sea, but also to all other parameters which are listed in Chapter 1, and which have enormous impact on N and P emission to river basins and then to the Baltic Sea (area of the Baltic sub-catchments, land cover/use in a given sub-catchment, agricultural land area and population in a given sub-catchment) (Chapters 8 and 9).

Loads of nitrogen and phosphorus introduced to the Baltic Sea and presented in the HELCOM elaborations are the values estimated at the lowermost river monitoring stations. About 35% of monitored river waters in Poland flow through lagoons and coastal lakes before they reach the Baltic Sea. These regions are characterized by few-weeks' water residence time, which favors reduction of N and P loads. Mass balance calculations made for the Oder estuary clearly point to the fact that over the years 1993-1998 the TN and TP retention in the Oder estuary reached 45% and 37%, respectively; the remaining amounts were exported to the Baltic Sea. Nitrogen loss due to denitrification constituted 30% of total N load introduced to the estuarine system from land and atmosphere. It should be mentioned that length of the Oder estuary, measured from the river monitoring station (Krajnik Dolny) to the outlets of Świna Strait equals to 106 km, while the area of the entire inland estuary is ca. 1000 km³. Out of TN and TP loads reaching the Gulf of Gdańsk as much as 23% and 34% become retained in the gulf and never reach the open Baltic; as much as 50% of nitrates becomes retained in the Vistula estuary (Chapter 9).

Over the last years, Poland has been investing a lot of money in protection of natural environment (Chapter 8). The pro-ecological awareness of the decision makers and the society is incomparable to what we faced two decades ago. Process of cleaning the country, particularly the agricultural sector, is in progress and that may greatly contribute to reduction

of diffuse nutrient emission (Chapters 5, 6, and 7). The prognoses of animal production up to 2020 show only slight increase in cattle, pigs, and poultry as compared to the data from 2007 (Chapter 2). The milk production, therefore the cattle number, is largely regulated by the EU (Chapter 2). However, it must be pointed out that the pig market is not regulated by the Common Agricultural Policy, therefore the market conditions depend very much on a situation on the world market. In countries like China, Russia or India there appear new demand/supply relations and in practice it means that these countries may become a new market for European meat. This fact may stimulate pig production in Poland and may result in possible enhanced N, P emission, particularly from concentrated big farms. The farm enlargement as well as specialization in agricultural production has also been observed in the country over the last years (Chapter 2). Crop production and consequently consumption of mineral fertilizers, particularly N fertilizers may increase (Chapters 3 and 4).

All these processes may have positive as well as negative impact on the natural environment in Poland. There are two reasons for which Poland by all means should avoid intensive concentrated raising of animals: (i) maintenance of a very good quality of food that wins international markets, (ii) introduction of large-scale intensive pig raising will result in increased N and P emission (an example – Denmark; Chapter 9) not only to Polish rivers but also to the Baltic Sea; we must always remember that we have one of the four largest subcatchments in the Baltic basin and that we have 50% of agricultural land. Increased N and P emission would be against obligations arising from implementation of the EU Directives and the HELCOM declarations. It must be kept in mind that the response of rivers to changes in pressure onto natural environment is delayed and it may take 10-15 years, as it took nearly the same time period to see the positive reaction of Polish rivers to positive changes during the transition period (Chapters 3, 4, 8, and 9). All the changes taking place in Polish agriculture must be monitored and the studies focused on impact of agriculture on N and P emission must be continued and expanded to case studies and modeling studies in the Vistula and Oder sub-catchments.

We hope, this monograph, as well as numerous papers published in peer-reviewed journals (new ones will be published soon) will reduce or stop the internationally heard, not fully justified, criticism of Poland for polluting the Baltic Sea. We also hope that international opinion-forming bodies, such as HELCOM, will make a good use of the peer reviewed papers published by scientists from all the Baltic countries, Poland included, and that HELCOM will make a good use of this monograph.

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