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REVIEW PAPER

Indicators of water quantity and quality for monitoring, management and reduction of diffuse pollution – a review*

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Abstract

The Water Framework Directive (WFD) focuses on ensuring good qualitative and quantitative health, i.e. on reducing and removing pollution and ensuring that there is enough water to support wildlife at the same time as human needs. It directly links to the EU Nitrates Directive, which aims also to protect waters (ground- and surface waters) from nitrate pollution by setting limits on agricultural nitrogen inputs. Therefore, the indicators used in water quantity and quality monitoring are necessary for sustainable water management and helpful in reduction of diffuse pollution. The study focused on reviewing the crucial indicators concerning water resources, water temperature and its pollution in Europe. The water balance shaped by geographic conditions result from climatic and hydrological processes. The water resources of rivers, lakes, and groundwater respond to precipitation, which determines the water supply and natural renewal. In agro-hydro systems, the amount of nitrogen released into the environment can be assessed based on the amount of macronutrients in natural fertilizers, and the size and structure of the livestock population. The ecological status/potential of surface waters expressed the criteria used to assess the quality of the structure and functioning of surface water ecosystems, which are influenced by pollution and habitat degradation. A large proportion of European surface waters failed to achieve at least good ecological status, i.e. 62% on average. Concerning chemical monitoring of waters, 68% of river water bodies had good chemical status, and 18% of lake water bodies had good chemical status. The European groundwaters are not as polluted as surface waters with good quantitative status (91%), and good chemical status (78% of groundwaters compared to 30% of surface waters).

Keywords: Nitrates, water resources, climate changes, temperature, ecological and chemical monitoring systems

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INTRODUCTION

The European Union legal system has granted special protection to all surface water and groundwater resources, which cannot be treated as a commercial product, but as a heritage that must be protected and defended. The framework for Community action in the field of water policy is established by Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000. The WFD stipulates that EU Member States should strive to achieve at least good status for surface waters and groundwater. "Good surface water status" means the status achieved by a body of surface water when both its ecological and chemical status are at least "good." In contrast, "good groundwater status" means the status achieved by a body of groundwater when both its quantitative and chemical status are at least "good." The classification of surface waters is based on the determination of the quality parameters assigned to identify the ecological status in each surface water category. For these waters, good chemical status means that no concentrations of priority substances exceed the relevant values set in the Environmental Quality Standards Directive 2008/105/EC (as amended by the Priority Substances Directive 2013/39/EU). For groundwater, good chemical status means that hazardous substances should not be present, and the input of any other pollutants (e.g. nitrates) and the impact on surface waters associated with the groundwater or on terrestrial ecosystems dependent on groundwater should be limited.

The protection of water quality from agricultural pressures is regulated by Directive 91/676/EEC of 12 December 1991, known as the Nitrates Directive. Its aim is to reduce water pollution from nitrates used for agricultural purposes by limiting the use of natural and mineral fertilizers to 170 kg N/ha/year. To achieve this, Member States must monitor nitrate concentrations and eutrophication in water bodies, identify polluted waters and designate nitrate-sensitive zones, establish codes of good agricultural practice and action programs to prevent and reduce nutrient pollution.

These actions, along with the priorities: (1) sufficient water availability, (2) combating pollution, (3) river basin management, and (4) ensuring sustainable use for the benefit of people and nature, build the foundation for a modern approach to water management known as Integrated Water Resources Management (IWRM). The importance of this approach in Poland is emphasized by the fact that water resources in Poland are among the lowest in Europe (Kubiak-Wójcicka 2021). Long-term average total surface water resources (including tributaries from outside Poland) were estimated at 61.6 km^3, including Poland's own domestic resources at 53.9 km^3 (87.5%) and resources originating from outside Poland at 12.7 km^3 (12.5%) – Gutry-Korycka et al. (2014). These resources are characterized by high temporal and spatial variability, which results from geographical conditions and the climatic and hydrological processes, including the variable distribution of atmospheric precipitation over time and space. Their course is random (Kubiak-Wójcicka 2021). The average annual total runoff from Poland during the years 1951-2015 was about 61 km^3, ranging from 37.5 km^3 in 1954 to 89.9 km^3 in 1981. Most of these resources (95.5%) flowed directly into the Baltic Sea, with the remaining 2.8 km^3 (4.5%) reaching neighboring countries. The average specific runoff during the years 1951-2015 in the Vistula River basin was 5.4 $dm^3/s\ km^2$, and in the Oder River basin – 4.7 $dm^3\ s^{-1}\ km^{-2}$ (Gutry-Korycka et al. 2014). During the years 1946-2011, the average total water resources per capita were 1,839.3 m^3 per year. According to data from the Central Statistical Office, in the years 2015-2023, renewable freshwater resources per capita in Poland amounted to only 1.1-1.6 thousand m^3 per year, which classify Poland among the three EU countries (after Cyprus and Malta) with the smallest amount of freshwater per capita (European Commission 2025).

The purpose of this study was to review the key indicators of water resources and water quality related to pollution in the agro-hydro system. Key assumptions were based on the (1) indicators of water resources, (2) indicators of the IT system for water management, (3) monitoring of water temperature, (4) indicators of water quality, (5) nutrients in freshwater and (6) nitrogen threats for maintaining good water quality, i.e. in line with the goals of Water Framework Directive and Nitrates Directive. Special attention was placed on Polish situation.

MATERIALS AND METHODS

The methods for this review consisted of the authors' perusal of the literature, selecting articles, documents, and statistical data. For indicators of water resources and water quality, dedicated websites were also searched, especially:

1) https://drought.emergency.copernicus.eu/tumbo/edo/map/
2) https://climate-adapt.eea.europa.eu/en/metadata/indicators/mean-temperature
3) https://susza.iung.pulawy.pl
4) https://water.europa.eu/freshwater/europe-freshwater/water-framework-directive/groundwater-quantitative-status
5) https://water.europa.eu/freshwater/europe-freshwater/water-framework-directive/characterisation-of-water-bodies/heavily-modified-water-bodies-and-artificial-water-bodies
6) https://water.europa.eu/freshwater/europe-freshwater/water-framework-directive/surface-water-chemical-status
7) https://imgw.pl/strona-glowna/osrodki-i-stacje/

8) https://danepubliczne.imgw.pl/
9) https://www.eea.europa.eu/en/analysis/indicators/nutrients-in-freshwater-in-europe.

INDICATORS OF WATER RESOURCES

The most common European indicators specifically connected with assessment of water resources include the following aspects:

1) precipitation: 30-day precipitation; average monthly rainfall (AMR); mean annual precipitation (MAP);
2) drought: combined drought indicator (CDI);
3) hydrology: low-flow index (LFI); flow duration curve (FDC);
4) soil moisture: soil moisture index (SMI);
5) water scarcity: water exploitation index plus (WEI+);
6) groundwater resources: quantitative status of groundwaters (QSG).

The current data on the above-mentioned indicators are available at European Drought Observatory; (information available at https://drought.emergency.copernicus.eu/tumbo/edo/map/) for all European countries.

The water resources also correlate well with air temperature, which is an essential climate variable. The air mean temperature (AMT) plays the role of a fundamental indicator for the climate variability and change (information available at https://climate-adapt.eea.europa.eu/en/metadata/indicators/mean-temperature).

In 2024, drought patterns revealed a clear east-west divide: Eastern Europe and the eastern Mediterranean experienced widespread dryness, while Western Europe was comparatively wetter relative to the 2000-2020 period (EEA, 2025). In Poland, the issue of drought is monitored on an ongoing basis (with historical archived data) within the Agricultural Drought Monitoring System (SMSR) available at https://susza.iung.pulawy.pl/. In the SMSR, drought-causing meteorological conditions are defined using the climatic water balance (CWB), which expresses the difference between precipitation and potential evapotranspiration.

The indicator WEI+ measures the water consumption expressed as a percentage of renewable freshwater resources at the river basin or other level, across each quarter of the year. In 2023, the WEI+ in Poland amounted to 8% (EEA 2025).

The assessment of quantitative status of groundwater bodies in the 3rd River Basin Management Plan (3rd RBMP) of 27 European countries indicated that around 90.7% area of total groundwater bodies currently reported (i.e. in 2022) had good quantitative status (https://water.europa.eu/freshwater/europe-freshwater/water-framework-directive/groundwater-quantitative-status). Then, 9.2% of the area had quantitative status and 0.1% of the area was considered as having unknown status.

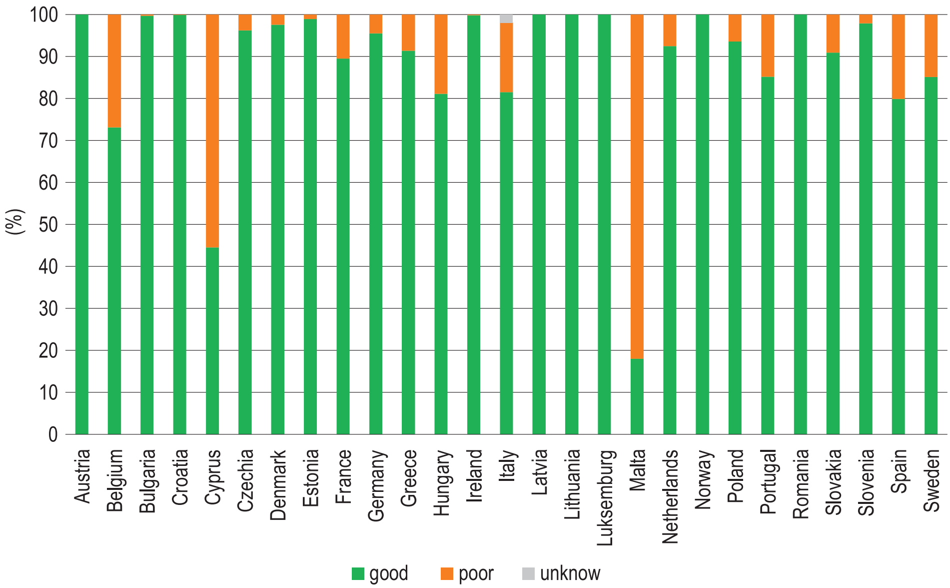

Fig. 1. The quantitative status of groundwaters in European countries (expressed in % of the total area) in 2022
(source: https://water.europa.eu/freshwater/europe-freshwater/water-framework-directive/groundwater-quantitative-status)

The area of groundwater bodies being in good quantitative status by country ranged from 100% (Austria, Latvia, Lithuania, Luksemburg and Romania) to 18% (Malta) – Figure 1. It means that available groundwater resource should not be reduced by the long-term annual average rate of abstraction and should be with little or no human impact. The groundwaters failing to achieve good quantitative status were in majority in Malta (82%) and in Cyprus (56%).

The quantitative status of groundwaters is linked to the type of rock and soil through which water flows. Different geological formations affect both the water storage and access to water. Therefore, spatial differentiation is also present. For example, according to the 3rd RBMP, in Poland the groundwaters failed to achieve a good quantitative status in the Vistula River basin over an area of 1.32% (2423.358 km^2) whereas in the Oder River basin, this corresponded to 14.92% (17570.919 km^2).

INDICATORS OF FRESHWATER QUALITY IN EUROPE

The most common European indicators specifically connected with assessment of water quality include the following aspects:

1) natural surface water bodies: ecological status;
2) heavily modified and artificial surface water bodies: ecological potential;
3) all surface water bodies: chemical status;

4) groundwaters: chemical status;

5) nutrients in freshwater in Europe.

In European countries (3rd RBMP), 84.6% of all surface water bodies were classified as natural, 12.3% heavily modified and 3.1% artificial (https://water.europa.eu/freshwater/europe-freshwater/water-framework-directive/characterisation-of-water-bodies/heavily-modified-water-bodies-and-artificial-water-bodies). Heavily modified water bodies refer to alterations such as land drainage, land reclamation, locks, weirs, channelization and dredging. Artificial water bodies refer to those that did not exist before, e.g. a canal built for navigation.

Ecological status/potential and chemical status of waters

The river basin management plans (RBMPs, the first RBMPs in 2009, the second RBMPs in 2018, and the third RBMPs in 2022) were published to identify the achievement of the environmental objectives of the WFD in EU countries.

Generally, the data available from the first and second RBMPs confirmed that EU Member States have reported status for 13 400 groundwater bodies and 111 000 surface water bodies including 80% of rivers, 16% of lakes and 4% of coastal or transitional waters (EEA 2018). It was found that approximately 40% of the surface water bodies were in at least good ecological status or potential, while 60% failed to achieve the goal of a good status/potential. Similarly, 38% of surface water bodies were classified into good chemical status, while 46% failed in achieving good chemical status (Napiórkowska-Krzebietke 2022). Furthermore, 16% of surface waters had unknown status. Regarding the groundwater bodies in the EU, a total of 74% of their area was in good chemical status.

In 2022, the 100 443 surface water bodies were reported, and their ecological status in the 3rd River Basin Management Plan in Europe (EU - 27 countries) indicated that around 38% of the surface water bodies were in good or high ecological status (Figure 2). A large proportion of surface waters failed to achieve at least good ecological status, i.e. 62% on average.

In Europe, around 30% of all surface water bodies reported in 2022 were in good chemical status (Figure 3). Whereas 52% of surface waters failed to achieve a good chemical status, and 18% of them were in unknown status. This was mainly due to widespread pollution by mercury and brominated diphenyl ethers (flame retardants).

Concerning the chemical status of groundwater bodies in European countries, around 78% of them reported in 2022 were in good chemical status. Then, 21.8% of groundwater bodies failed to achieve good chemical status mainly due to the presence of nitrates and pesticides, and only 0.2% were in unknown state.

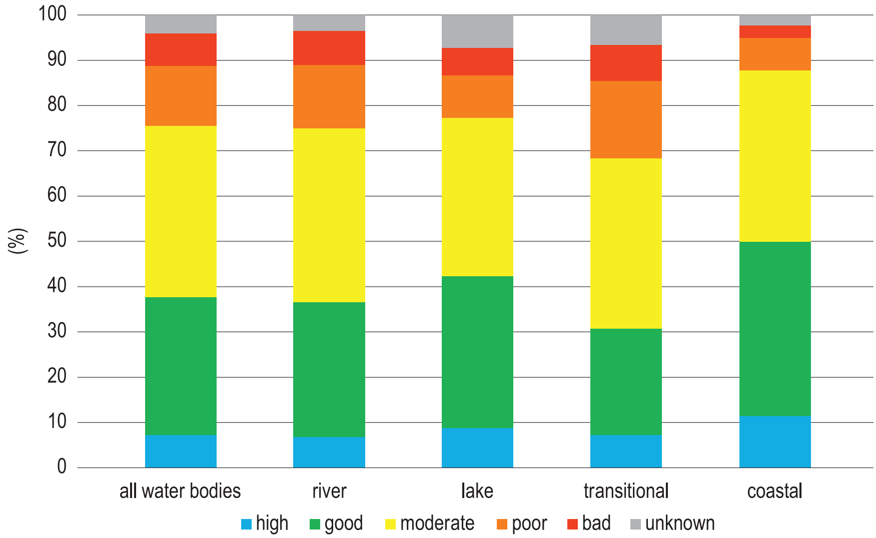

Fig. 2. Ecological status assessment of surface water bodies in Europe according to the 3rd River Basin Management Plan (in 2022)

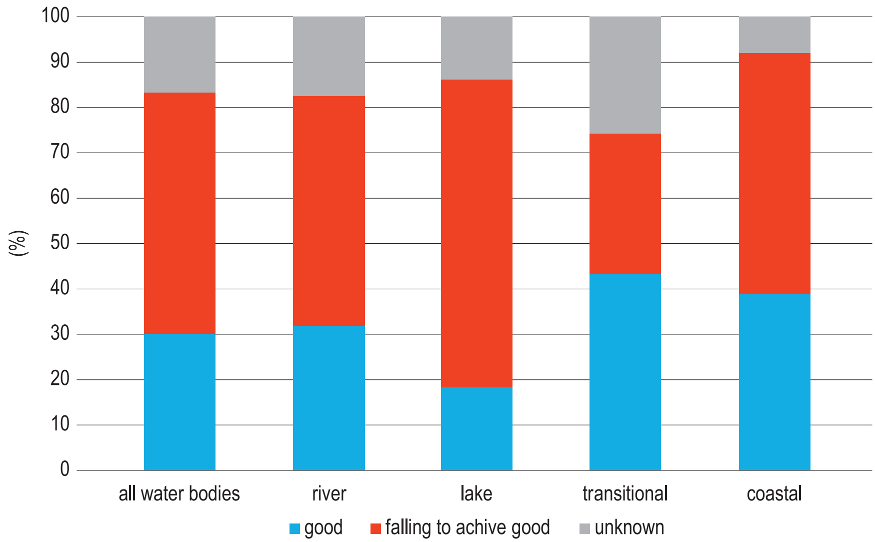

Fig. 3. Chemical status assessment of surface water bodies in Europe according to the 3rd River Basin Management Plan (in 2022)

Nutrients in freshwater in Europe

A decreasing trend of nutrient pollution in European surface waters was recorded since 1992. The decrease refers to average concentrations of both the nitrates and phosphates in river water bodies, and to the total phosphorus content in lake water bodies (https://www.eea.europa.eu/en/analysis/

indicators/nutrients-in-freshwater-in-europe). These changes were mainly caused by wastewater treatment improvements and the reduction of phosphorus in detergents. The average nitrate concentration in European rivers decreased from 1.57 mg NO_3-N dm^{-3} (2007) to 1.35 mg NO_3-N dm^{-3} (2023). The average phosphate concentration in European rivers decreased significantly in the period 1992-2012 (from 0.104 mg PO_4-P dm^{-3} to 0.047 mg PO_4-P dm^{-3}), but it increased from 2013 (0.048 mg PO_4-P dm^{-3}) to 2023 (0.067 mg PO_4-P dm^{-3}). The changes were recorded also in the total phosphorus concentration in European lakes, which has decreased since 1992, but with an apparent stabilization at 0.038-0.032 mg P dm^{-3} in 2007-2023. Stabilization on a relatively high level was related to diffuse run-offs from agricultural land and phosphorus storage in lake sediments despite a visible reduction in inputs from point sources.

In European groundwaters, the nitrate concentration was related to agricultural activities, especially to fertilizer overuse. In 2007-2023, the average concentration in these waters decreased from 19.21 mg NO_3 dm^{-3} to 18.04 mg NO_3 dm^{-3}.

INDICATORS OF THE SYSTEM FOR WATER MANAGEMENT IN POLAND

In accordance with Article 331.1. of the Act of 20 July 2017 - Water Law, Journal of Laws of 2025, item 960, 1535 (Water Law 2025), the obligation to collect and compile data for Poland’s water management information system is fulfilled through registers and datasets maintained by the minister responsible for water management and Polish Water Management - Polish Waters, and also by:

1) water gauge stations, synoptic stations, climatological stations, and precipitation stations – forming the basic measurement and observation network;
2) assessment of the quantitative and chemical status of groundwater bodies by the Environmental Protection Inspectorate and the State Environmental Monitoring System;
3) assessment of hydrogeological conditions, groundwater resources, and the chemical and quantitative status of groundwater by the State Geological Survey and the Groundwater Observation and Research Network;
4) monitoring of water levels and flows at water gauge stations by the State Hydrological and Meteorological Service;
5) assessment of the quality of surface water used as drinking water supply in the State Environmental Monitoring System;
6) area assessments of the quality of drinking water by the State Sanitary Inspectorate;
7) assessment of the biological and chemical condition of surface water

bodies by the Environmental Protection Inspectorate as part of the State Environmental Monitoring.

The basic measurement and observation network – within the networks of hydrological stations, meteorological stations, aerological stations, actinometric stations, limnological stations, evaporometric stations, phenological observations, POLRAD meteorological radars and the network of PERUN lightning detection and location stations – includes approximately 1,750 measurement stations throughout the country.

As of November 2024, the network of hydrological measurements and observations consisted of 905 stations of the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI), including 82 first-order stations maintained for the calculation of Poland's water balance, 634 second-order stations (automatic with continuous data transmission), 73 third-order stations (automatic without continuous data transmission), and 116 fourth-order stations, where measurements are conducted exclusively manually by an observer (https://imgw.pl/strona-glowna/osrodki-i-stacje/). By the end of 2025, 950 stations were to be operational within IMWM-NRI, of which approximately 92% should be equipped with automatic measurement devices and a telemetric data transmission system (IMWM-NRI Hydrological Measurement and Observation Network). The hydrological network measures and observes:

1) water level (at water gauge stations, water level is measured using a staff gauge, which is the basic device for this purpose). Stations required for basic hydrological protection are equipped with automatic water level sensors with real-time data transmission. Selected lower-level stations perform measurements using automatic equipment. Measurement results from these stations are transmitted at specific time intervals, e.g., once a month;
2) riverbed overgrowth phenomena;
3) riverbed ice cover;
4) water temperature;
5) hydrometric measurements of riverbed flow volume.

The meteorological station network consists of 981 stations (as of November 2024), including 63 first-order synoptic stations, 220 second-order climatological stations, 690 third-order precipitation stations, and 8 fourth-order special stations (https://imgw.pl/strona-glowna/osrodki-i-stacje/). The network has been expanded and modernized as part of the Odra-Vistula River Basin Flood Protection Project (POPDOW). By 2025, the IMWM-NRI should have over 1,000 stations, approximately 70% of which should be equipped with automatic measurement devices and a telemetric data transmission system (IMWM-NRI Meteorological Measurement and Observation Network).

The IMWM-NRI provides a summary of synoptic and climatological station metadata (in preparation), enabling the tracking of basic metadata for stations operating within the IMWM-NRI network. This information includes the code, name, geographic coordinates, elevation, and rank of a station in the Central Historical Database (defining the scope of measurement and observation data available in the CBDH from stations in specific periods). Additional information allows for detailed tracking of a station's history, and each change (described in the Notes) results in a new record in the database. Each record is supplemented with basic information about the station from before and after the change (in some cases, stations were relocated with a name change, or their rank changed, resulting in a change in the code). This summary of information enables unambiguous identification of a station in any period since 1951 (archived measurement and observation data are made available via the IT system at: https://danepubliczne.imgw.pl/ and on the website www.meteo.imgw.pl.). In practice, analyses of changes in meteorological conditions can be conducted for several dozen stations since 1951. Szwed (2019) used a set of 50 time series of monthly precipitation totals from 1951-2013, and Ziernicka-Wojtaszek and Kopcińska (2020) used data from 47 stations to describe changes in precipitation in 2001-2018.

Monitoring of water temperature in lakes in Poland

In Poland, because of a crucial role of lakes in the landscape and the potential effects of global warming on the functioning of these ecosystems, direct observations (temperature measurements) have been undertaken since 1956 as part of a nationwide observation network. Initially, however, these covered only two lakes, nine lakes in the late 1960s, 36 lakes in the 1980s and 1990s, and 29 lakes at the beginning of the 21st century (Skowron 2011, Sobolewski et al. 2014). Water temperature measurements are taken in the coastal zone (at a depth of 0.4 m, most often from platforms) once a day at 7:00 AM (6:00 AM GMT) – Skowron, Piasecki (2016), Skowron (2017). However, the literature indicates data gaps of several days, several months, or even several years caused by interruptions in measurements (Skowron 2011). The number of monitored lakes also changed. During the reorganization of the observation network of the Institute of Meteorology and Water Management, new observation points were opened, and existing ones were closed (Ptak et al. 2025).

Based on data collected in this way, surface water temperature changes in 31 Polish lakes between 1971 and 2010 were identified. The course of the annual mean values for five-year time intervals, the differences between the annual mean for the multi-year period 1971-2010 and the annual means in individual years, and the course of the average monthly surface water temperatures were analyzed (Sobolewski et al. 2014). Based on this type of data, Ptak et al. (2020) determined an increase in the mean annual water temp. (by 0.44°C dec^{-1}) in Lake Śniardwy, the largest lake in Poland, between 1972 and 2019. This increase was significantly greater than the air temperature increase observed during that period (0.33°C dec^{-1}). The largest changes in water temperature (0.77°C dec^{-1}) were recorded in April (Ptak et al. 2020).

Based on the Air2Water model, an attempt was made to reconstruct the surface water temperature in six lakes from 1994 to 2023, when direct measurements taken since 1972 or 1973 were discontinued. This model established a statistical relationship between the lake surface water temperature and air temperature, ultimately with high predictive accuracy (Nash-Sutcliffe efficiency > 0.92 and root mean square error ranging from 0.97°C to 2.13°C for all lakes). This led to the demonstration of a statistically significant warming trend in all lakes, with an average increase of 0.35°C per decade, and monthly trends most visible in June, September, and November, in some cases exceeding 0.50°C per decade (Ptak et al. 2025).

However, it has been shown that temperature differences between the coastal and pelagic zones in spring and summer at noon can reach 3.0-3.5°C, although they most often fall within the range of 0.8-1.5°C (Skowron, Piasecki 2016). This suggests that the results obtained in the littoral zone should not be used as the basis for assessing water temperature changes in the central parts of lakes. Therefore, in 2020, a mathematical model was proposed to estimate the base water temperature in the 0-3 m layer (corresponding to the mean daily temperature), calculated according to the available water temperature data in vertical profiles from 931 Polish lakes from 1951-1968 (Hutorowicz 2020). By building an analogous model based on contemporary, identically collected data, water temperature changes over time can be estimated. For example, based on data on average water temperature from 56 thermal profiles from 10 lakes measured in 2010-2019, it was estimated that the increase in water temperature in these lakes between 1951 and 1968 was 0.24-0.30°C dec^{-1} (Hutorowicz 2020).

Since 1971, the Institute of Meteorology has been conducting similar water temperature measurements in the Vistula River, Poland's longest river at 1,047 km in length. Water temperature is measured daily at 6:00 UTC at a depth of 0.4 m below the water surface (the reference point is the daily water level on the water gauge). Analysis of these data from 11 hydrological stations along the entire length of the river showed that average monthly and annual water temperatures from 1971 to 2017 followed an upward trend (Ptak et al. 2022). The average water temperature increase at all measurement points during the analyzed multi-year period was 0.31°C dec^{-1}, with the rate of this process varying from 0.11°C dec^{-1} at the Szczucin point at 292.7 km to 0.60°C dec^{-1} at the Skoczów point at 35.75 km (Ptak et al. 2022).

Long-term daily measurements in feeder rivers are also conducted by at least some fish farming centers. The salmonid breeding center in Rutki has been measuring water temperature on a feeder river daily at 7:00 a.m. since 1985. An analysis of temperature changes between 1985 and 2014 showed a statistically significant increase of 0.22°C dec^{-1} in the summer half-year and 0.32°C dec^{-1} in autumn. The largest increases in average temperature were recorded in November (0.55°C dec^{-1}) and April (0.45°C dec^{-1}) – Radke and Dobosz (2015).

Monitoring of surface waters, including rivers, in Poland

The monitoring of surface waters, including rivers, in Poland is governed by the Regulation of the Minister of Infrastructure of 13 July 2021 on the forms and methods of monitoring surface water bodies and groundwater bodies. The Chief Inspectorate for Environmental Protection is responsible for monitoring surface water quality. River monitoring is based on a network of integrated measurement and control points, strategically located along their courses. For the Oder River, this monitoring is carried out at 33 measurement points (Adamczyk, Jamry 2025). Since 1996, an automatic monitoring station has been operating at the Widuchowa point, equipped with devices having measurement sensors placed in a head immersed directly in the river current, supplemented by automatic analyzers in the station room. In total, the station records 17 indicators. In addition to the basic ones, such as water level, water temperature, electrical conductivity, pH, dissolved oxygen, and turbidity, it also records phosphates, ammonium ions (ammonium nitrogen), nitrates (nitrate nitrogen), UV absorption – 254 nm, chlorophyll, and dissolved oils). Furthermore, from April to November, water samples are collected once a month at six Polish measurement points in the Great Lagoon and six German measurement points in the Little Lagoon, as well as four points in the Bay of Pomerania within 4.5 nautical miles of the shore at the Polish-German border in the Świnoujście region (Siemianowski 2020).

Moreover, analyses were undertaken in the late 20th century to determine loads of various forms of nitrogen and phosphorus entering the Baltic Sea from the Polish coastal drainage basins. These analyses were based on variables describing land use, population density, and atmospheric pollution, that is the variables that clearly correlate with the magnitude of diffuse pollution loads and indicate the intensity of economic use of the basin (Świątkowska, Magnuszewski 2002). In the basins of the rivers Rega, Parsęta, Słupia, Reda, and Pasłęka, a strong correlation was found between agricultural intensity (yields and livestock density) and nitrate loads. An increase in total phosphorus loads was clearly associated with increasing sewer density (Świątkowska, Magnuszewski 2002).

Ecological status/potential and chemical status of waters in Poland

The water monitoring system in Poland follows the methods validated by international intercalibration procedures and described in Polish law. These include assessing the ecological status/potential, chemical status based on biological quality elements (phytoplankton, phytobenthos, macrophytes, macrozoobenthos, and fish) and chemical quality elements. Permissible values of surface water quality indicators are specified in the Regulation of the Minister of Infrastructure of 25 June 2021 on the classification of ecological status, ecological potential, and chemical status and the method of classifying the status of surface water bodies, as well as environmental quality standards for priority substances (Rozporządzenie… 2021).

In Poland, only 31% of rivers and 34% of lakes, that is freshwater surface water bodies, met the WFD standards required to assign good ecological status or potential good ecological status (WISE electronic reports from the second RBMPs, 2018). In 2022, only 8% of rivers and 9% of lakes had good ecological status.

Concerning the chemical status, 68% of river water bodies had good chemical status, while 32% failed to achieve good chemical status. In turn, 18% lake water bodies had good chemical status, whereas 4% and 78% were classified as failing to achieve good chemical status and with unknown chemical status, respectively. In the case of coastal and transitional waters in Poland, 29% achieved good chemical status, whereas 32% and 39% were classified as failing to achieve good chemical status and with unknown chemical status, respectively.

In the 3rd RBMP, 24.8% of surface water bodies in Poland had good chemical status, whereas 53.5% and 21.7% were classified as failing to achieve good chemical status and unknown, respectively (https://water.europa.eu/freshwater/europe-freshwater/water-framework-directive/surface-water-chemical-status).

The most frequent pressures on surface waters and groundwaters included:
1) diffuse pollution, such as from agriculture or the burning of coal and other organic matter;
2) point source pollution, such as discharges from urban wastewater treatment plants, industries, contaminated land;
3) changes to natural flow and physical features, called "hydromorphology" in the WFD, such as river dams, land drainage, dredging;
4) water abstraction for land irrigation, industrial use, drinking water.

Evaluation of nitrogen content in natural fertilizers in Poland

In accordance with the Council Directive of 12 December 1991 on the protection of waters against pollution caused by nitrates from agricultural sources (Document 31991L0676), research is being conducted to assess the level of nitrogen consumption in natural fertilizers in Poland (Czekała 2015). Fertilizer nutrients contained in manure and slurry are an important element of rational fertilizer management. It has been assumed that the amount of nitrogen released into the environment can be estimated based on the macronutrient content of natural fertilizers and the number and structure of livestock populations (Czekała 2015). The estimates are based on such data as:
1) average manure and slurry production volume, calculated per animal

in groups and types of animals per year (Czekała 2015), where the amount of natural fertilizers produced and their agricultural value is converted to the so-called large unit (LU) based on the body weight of a dairy cow (Estimination of production… 2012);

2) the amount of fertilizers produced, which is estimated using appropriate models based on data on the structure of the animal population, the density and housing system, primarily for cattle and pigs, as well as the type and amount of bedding used (Jadczyszyn et al. 2000);
3) published statistical data from the Central Statistical Office (Means of Production in Agriculture... 2019-2020);
4) the chemical composition of natural fertilizers (e.g., Kopiński, Witorożec 2021).

Based on the territorial differentiation of livestock populations in Poland, expressed in large livestock units (LU) – Figure 4 and the level of nitrogen production from 1 LU, which is 50 kg year^{-1} (according to estimates: 5 kg in 1 ton of manure, at 10 t per LU year^{-1}), it is possible to estimate the number of kg of nitrogen in natural fertilizers per 1 ha of area (IERGŻ-PIB 1602 study, RENURE 2025 scenarios). For example, in 2020, it ranged from approximately 12 kg N ha^{-1} in the Dolnośląskie Voivodeship to approximately 60 kg N ha^{-1} in the Wielkopolskie Voivodeship (IERGŻ-PIB 1602 study, RENURE 2025 scenarios).

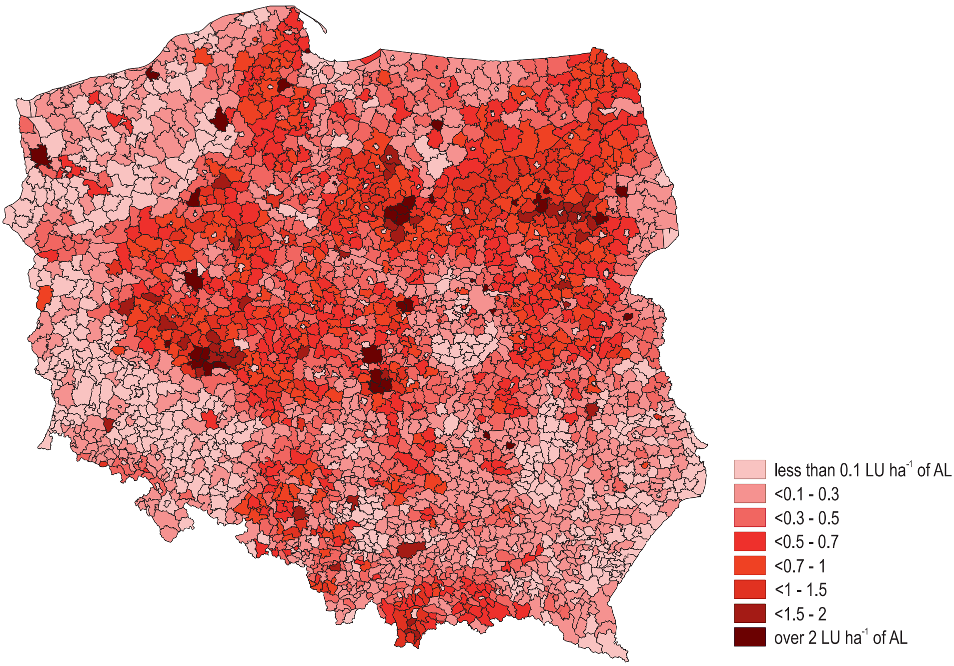

Fig. 4. Density of cattle, pigs, sheep, and goats (LU ha^{-1} of AL) in municipalities in Poland in 2020

The dynamics of the consumption of natural fertilizers over the years and thus the fertilizer components they contain in Poland's regions, broken down by types of fertilizers (manure, bird droppings, liquid manure, slurry), is estimated on the basis of data from the Central Statistical Office, which includes data on land use, sown area, livestock population, and the number of livestock (Wach, Kopiński 2024). However, in 2020, using the municipality (*gmina*) as the basic unit of area, the density of cattle, pigs, sheep, and goats (LU ha^{-1} of UAA) was in the range of 1.5-2 LU ha^{-1} of UAA in 33 municipalities and exceeded 2 LU ha^{-1} of UAA in several others, reaching a maximum of 15.5 LU ha^{-1} of UAA (Figure 4). This meant that the upper permissible limit of 170 kg ha^{-1} specified in the Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources was exceeded in these municipalities.

Nitrogen threats to maintaining good water quality in Poland

Since the implementation of the Nitrates Directive is mandatory throughout Poland, the water quality and changes occurring during this period have been analyzed spatially, also in comparison to previous reporting periods. This analysis is based on data from monitoring and assessing water status across the country, obtained from the State Environmental Monitoring (SEM), which is implemented by the Chief Inspectorate of Environmental Protection.

The State Environmental Monitoring covers groundwater, with the number of measurement and control points of the chemical status of groundwater in the years 2012-2023 ranging from 1421 to 1563. Of these, measurements were performed at 879 measurement and control points (PPK) throughout the entire period (Table 1).

Table 1

Number of groundwater measurement and control points

Parameter	Periods			Common measurement and control points
	2012-2015	2016-2019	2020-2023	
Number of measurement and control points	1563	1421	1457	879

These included groundwater types (as divided according to the EC Guidelines) and their depths: groundwater: 0-5 m; 5-15 m; deep groundwater 15-30 m and >30 m, utility groundwater, and karst water.

The distribution of these points across Poland (Hobot et al. 2024) showed that the average nitrate nitrogen concentration in water did not exceed 25 mg NO_3 dm^{-3} in 87% of the points, was in the range of 25-39.99 mg

NO_3 dm^{-3} in 5.2% of the points, between 40 and 49.99 mg NO_3 dm^{-3} in 3.2% of the points, and it was greater than 50 mg NO_3 dm^{-3} in 4.7%.

In 70.6% of groundwater samples, changes in nitrate nitrogen concentration between 2020 and 2023 ranged from -1 to 1 mg NO_3 dm^{-3}. A significant increase of +5 mg NO_3 dm^{-3} was recorded in 5.5% of samples, and a significant decrease of -5 mg NO_3 dm^{-3} was recorded in 5.9% of samples.

The surface water monitoring in 2020-2023 covered a total of 4,357 points, of which measurements were conducted at 2,000 points since 2012 (Table 2). After 2015, the network of control and measurement points was modified, which resulted from the changes in the number (boundaries) of homogeneous water bodies caused by the need to adapt the PPK network to the requirements of the Water Framework Directive.

Table 2

Number of surface water PPKs divided into water categories

	2012-2015	2016-2019	2020-2023	Common measurement and control points
Rivers/Reservoirs	2053	3596	3646	1660
Lakes	473	684	664	298
Transitional/coastal waters	19	19	21	11
Marine waters	–	26	25	24
Total	25453	4325	4356	2000

In more than half of the PPKs (53.1%) located on rivers or in dam reservoirs, the average annual nitrate nitrogen concentration was in the range of 2-9.99 mg NO_3 dm^{-3}. In 22.7% of the PPKs, it ranged from 10 to 24.99 mg NO_3 dm^{-3}, whereas concentrations not exceeding 1.99 mg NO_3 dm^{-3} were determined in only 17% of the PPKs (Hobot et al. 2024) On the other hand, in 91.6% of the PPKs located in lakes (they are concentrated in the northern part of Poland, within the boundaries of the last glaciation), the average annual nitrate nitrogen concentration was in the range of 0-1.99 mg NO_3 dm^{-3}, and in 7.7% – in the range of 2-9.99 mg NO_3 dm^{-3}. As an example of inadequate protection against nitrate influx from the immediate surroundings is the high concentration of nitrates often measured in drinking water on farms. According to Szymczyk (2024), average concentrations may reach 69.09 mg NO_3^- dm^{-3}, exceeding drinking water standards and potentially rendering it unsuitable for consumption.

CONCLUSIONS

Both the European Union Water Framework Directive and the Nitrates Directive aim to monitor and protect ground- and surface waters from pollution. The main tools are based on indicators used in water quantity and quality monitoring, which are essential for sustainable water management and helpful in reduction of diffuse pollution. The main indicators concerning water resources, water temperature and its pollution in Europe were verified. The most common European indicators specifically connected with water resources are monitored and shared on an ongoing basis at dedicated European websites or local websites. Consequences of pollution and habitat degradation are reflected in the assessment of the quantitative and chemical status of groundwaters and ecological status/potential of surface waters. Values of the indicators obtained in these assessments demonstrated that a large proportion of European surface waters failed to achieve at least good ecological status (62% on average). The chemical monitoring of these waters indicated that 68% of river water bodies had good chemical status, and 18% of lake water bodies had good chemical status. Good quantitative status was determined for 91% of European groundwaters, whereas good chemical status was found for 78% of groundwaters. In the agro-hydro system, special attention was paid also to the amount of nitrogen as the main pollutant released into the environment.

Author contributions

A.N-K. – conceptualization, methodology, investigation, writing – original draft preparation, A.H. – formal analysis, methodology, investigation, writing – original draft preparation, M.Z. – software, writing – review and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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