Chapter 4
Water Resources in Poland and Their Use

Zdzisław Michalczyk and Joanna Sposób

Abstract Water resources in Poland are directly related to the features of the natural environment, particularly the hydrogeological and climatic conditions. The territory of Poland is characterised by relatively low water resources, and the outflow of rivers is among the lowest in Europe. In the context of the occurring climatic changes, measures aimed at water retention in the catchment are recommended. Changes in the conditions of water circulation should be towards its retention in the soil and bedrock, leading to a decrease in surface runoff and an increase in exploitable resources in catchments. In addition to the construction of retention reservoirs, this purpose can be met by changes in the land use structure, application of suitable agrotechnical measures, as well as the construction of corrective steps slowing down water outflow. All water resources are subject to strong human pressure leading to their quantitative and qualitative transformations. They result from an increase in the water needs accompanying an increase in the standard of life and development of industrial infrastructure and raw material extraction. It is important to reduce the water consumption at every stage of its use: in households, industry and agriculture. The level of exploitation, especially on the regional scale, should not endanger the stability of low flows and natural functioning of hydrogenic ecosystems. The water safety of the country requires the maintenance of the quantity and quality of water resources on a good level and effective protection against the effects of drought and floods.

Keywords Water resources · Water use · Water protection · Poland

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4.1 Introduction

Water – as a chemical compound of an atom of oxygen and two atoms of hydrogen – occurs in nature in three states of concentration. It participates in physical, chemical, and biological processes occurring in nature. It is used in the economy and in recreation. It is the basic component of the natural environment with unique and irreplaceable properties. It is also necessary for the functioning of life. Water determines the physical and chemical processes occurring in the natural environment, as well as the development of the life and health of all ecosystems. It affects the development of agriculture and food production. It is used for transport. It participates in industrial processes and is necessary for maintaining personal hygiene. Its resources in the hydrosphere, atmosphere, lithosphere, and biosphere are constant on the global scale. They are theoretically unlimited, although acceptable by living organisms, they are always subject to reduction by human pressure. Water existed on our planet long before any life form appeared. It alone created the environment of development of biological and biophysical processes leading to the creation of life, its maintenance, and development. The origin of water in the atmosphere and the history of its precipitation on the Earth's surface resulting in the development of the hydrosphere are still uncertain. The erosion of rocks and deposition of sediments suggest deep changes in the manner of interaction between the atmosphere and hydrosphere in the prehistoric times, determining the conditions of life on Earth. Water is one of the treasures of nature with the slow renewal of resources, forcing its rational and economical use. The occurring periods of both water excess and deficits are dangerous for the economic growth of the region and country. The right to access to safe, clean, and affordable drinking water and sanitary infrastructure is commonly considered the fundamental human right.

The problem of access to water of suitable quality is currently becoming one of the most critical challenges for humanity, particularly in the context of the observed climate changes [1, 2]. According to the United Nations Organisation, approximately 2 billion people on Earth currently have no access to safe drinking water. Lack of access to good water caused the proclamation of the years 2005–2015 as the International Water for Life Decade by the General Assembly of the United Nations. On 22 March 2018, members of the UN General Assembly inaugurated the Water Decade, officially described as the International Decade of Action "Water for Sustainable Development", with emphasis on sustainable development and development of the integrated process of management of water resources [3].

The undertaken measures aimed at better management of freshwater resources, and providing humanity with good quality and healthy water. This requires the protection of water sources, and construction of systems of storage and transport of suitably treated water, as well as the provision of use of sanitary infrastructure.

4.2 Water Resources in Selected European Countries

The abundance of water in a given area depends on the factors of the geographic environment such as climate, geological structure, land relief, and land use. Water resources of an area are particularly dependent on climatic conditions, shaped by the amount of solar radiation, distance from seas and oceans, land relief, including height above sea level, and course of mountain ranges. In reference to Europe, it should be emphasised that it is located in only one climatic zone, and is surrounded by seas having a warming effect on the continent. The mountains have latitudinal distribution facilitating airflow of both marine and oceanic air.

Atmospheric precipitation and the related outflows are distributed over continents, including Europe and therefore Poland, very unevenly. On the Earth, dry areas occupy almost ¼ of the land surface, and a constant deficit of freshwater is recorded on more than half of the surface area of continents.

The assessment of water resources considers the absolute amount of precipitation water is reaching the surface of a given country, the amount of outflow and potentially inflow of water, as well as the amount of water per capita in a year. The assessment of particular values is imprecise. The starting material comprised data collected in materials of the Central Statistical Office [4], including absolute values of atmospheric precipitation, evapotranspiration, own resources of the country, and water inflow in selected countries. Based on hydrometeorological data and comparison of the surface area and size of the population, precipitation and outflow indices were calculated, expressed in millimetres of the water layer, as well as annual water resources per one resident.

Among the selected European countries, atmospheric alimentation somewhat exceeding 1400 mm·year^{-1} was determined in Switzerland and Slovenia. In Croatia, Austria, UK, Norway, and Ireland, it is maintained at a level of 1000–1300 mm. In Poland, Romania, Hungary, and several other countries (Fig. 4.1), it approximates 600–700 mm·year^{-1}. In reference to the climatic conditions of the countries, and particularly to high potential evaporation, the amount of outflow (own resources of a country) is low, because it does not reach 200 mm. In countries with higher precipitation, the amount of outflowing water is maintained at a level of 600–1000 mm per year.

The absolute amount of water resources is equivalent to the amount of mean outflow from a given country. The outflowing water can originate from internal resources, i.e. from atmospheric alimentation of the territory of the country, and outflow from outside its borders. Discharge of transit rivers (having its springs in another country) increases the water resources of the country, sometimes very radically. Figure 4.2 presents a comparison of water resources developing in the territory of the country and total renewable resources, i.e. with water outflow from parts of catchments located outside of the national borders. A particularly favourable situation concerns Slovakia, Bulgaria, Hungary, Netherlands, Serbia, and Croatia. Their resources are small, and the rivers flowing through the territories carry high amounts

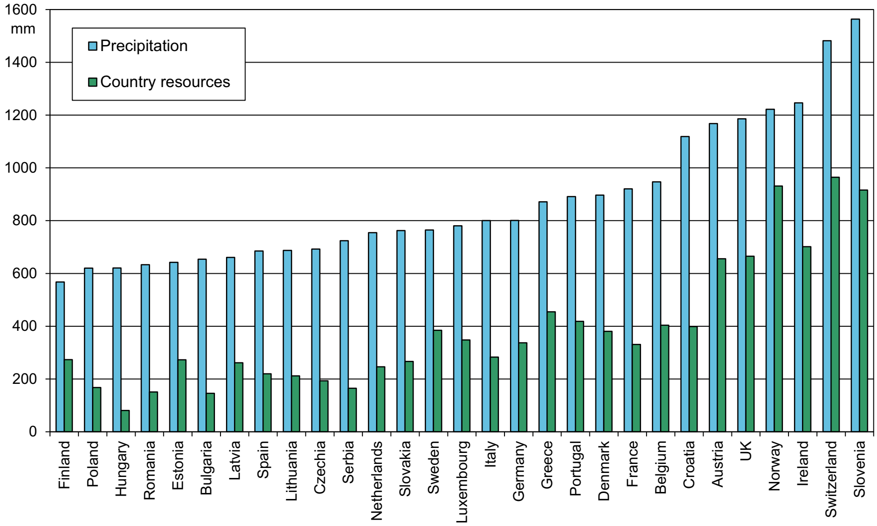

Fig. 4.1 Mean annual values of precipitation and water resources (total runoff) from the territories of selected European countries (OECD Environmental Data. Compendium 2017, after [4])

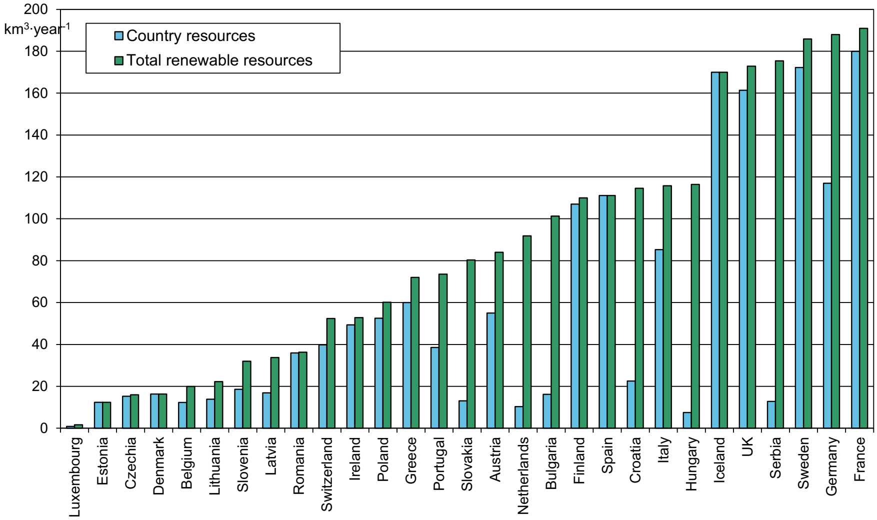

Fig. 4.2 Mean annual resources of surface waters in selected European countries (OECD Environmental Data. Compendium 2017, after [4])

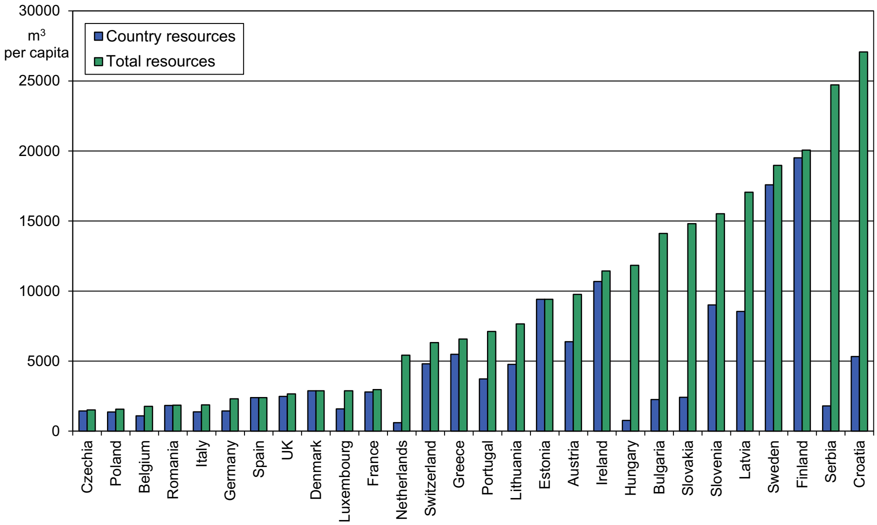

Fig. 4.3 Mean annual water resources per capita in selected European countries (OECD Environmental Data. Compendium 2017, after [4])

of water. Water resources of Poland, both own and total, are small, also in reference to smaller neighbouring countries.

The relative amount of water resources of a country is provided by the water abundance index, expressing the amount of water per capita in a year. Its amount can be referred only to own resources, or to total renewable resources (Fig. 4.3). Among European countries, Poland together with the Czechia and Belgium are included in a group of countries with the smallest water resources – approximately 1500 m^3 per capita. It should be emphasised that the level of resources of 1000–2000 m^3 per capita is considered very small. The highest index of total water resources concerns Finland and Sweden. For Europe, the index is 4500 m^3 per year.

Water resources on particular continents per capita in a year are mostly different, averaging 18.1 $m^3 \cdot d^{-1}$ per resident [5, 6]. This results both from the conditions of the natural environment and from the number of residents. They are the highest in Australia and Oceania (199.6 $m^3 \cdot d^{-1}$ per resident), twice lower in South America (88.4), and three times lower in North America (65.6). On the remaining continents, they are considerably lower: in Asia (9.5), Europe (10.9), and Africa (12.2 $m^3 \cdot d^{-1}$ per resident).

4.3 Water Resources of Poland

Water resources of an area depend on features of the geographic environment, and particularly the geological structure, land relief, soils, land use, atmospheric precipitation, and evapotranspiration, and from the retention capacity of the ground. The territory of Poland is a lowland area – areas with a height from 0 to 300 m amsl occupy 91.3% of the territory. Upland areas, elevated from 300 to 500 m amsl, occupy 5.6%, and mountain areas – the remaining 3.1% of the area of Poland. The highest point in the country is Rysy (2499 m amsl) in the Tatra Mountains, and the lowest the depression in Żuławy (−1.8 m amsl). Despite the small elevation of the territory of Poland above sea level (173 m amsl), the land relief of Poland shows considerable variability, with a belt arrangement of geomorphological regions. The system of the main features of land relief, arranged in latitudinal zones, results from the geological structure. The Sudetes and Carpathians occupy the southern part of the country. The Sudeten mountain ranges with a character of tectonic horsts, developed during the Hercynian orogeny, are built of metamorphic stones. The Carpathians, developed in the Alpine folding, are built of flysch formations (sandstones, slates, conglomerate rocks) with low permeability. The highest part of the Carpathian range are the Tatra Mountains, built in the eastern part of massive granitoids, and in the western part of Mesozoic carbonate formations with high water drainage. A belt of uplands is located to the north, mainly built of Mesozoic carbonate deposits: limestones, dolomites, and margles. The Świętokrzyskie Mountains are also built of Palaeozoic carbonate rocks as well as sandstones and quartzites. The area of uplands is connected with a belt of extensive lowlands with diverse morphology, shaped by the Pleistocene ice sheet. Post-glacial formations occur on the surface, particularly moraine clays and sandy formations constituting reservoirs of groundwaters with moderate and locally high water capacity.

The land use structure of the territory of Poland is dominated by arable land and forests (Table 4.1). They are areas with good conditions for precipitation water retention, i.e. areas where groundwater resources develop, feeding rivers, springs, and water intakes. Areas with low permeability and built-up areas occupy approximately a dozen percent of the area. The surface area of rivers, ponds, ditches – land under waters slightly exceeds 2.0% of the area of Poland.

The factor directly affecting water resources are climatic conditions, particularly precipitation and air temperature, determining the amount of evapotranspiration. Despite a relatively small area, the basic parameters describing climate features show high spatial and seasonal variability. In the territory of Poland, mean precipitation in the years 1901–2000 equalled 628 mm, and outflow 175.2 mm, providing the outflow coefficient of 0.278 [7]. In a year with an average humidity, the amount of precipitation in the territory of the country varied from approximately 500 mm in the lowland belt to more than 1000 mm in the mountains. The highest monthly precipitation and evapotranspiration totals in Poland occur in July. The lowest precipitation and evapotranspiration occur in January and February.

Table 4.1 Land use structure in 2017 [4]

	Total area	Agriculture land							
		Total	Arable lands	Orchards	Meadows	Pastures	Agricultural built-up areas	Agricultural lands under ponds	Woody and bushy lands
thousads hectares	31,268.0	18,810.1	13,684.3	294.7	2243.7	1589.5	547.7	211.7	238.6
%	100.00	60.15	43.76	0.94	7.18	5.08	1.75	0.68	0.76

	Forest, woody and bushy lands			Lands under waters				Ecological arable lands	Miscellaneous and waste lands
	Total	Forests	Woody and bushy lands	Total	Internal waters	Flowing waters	Standing waters		
thousads hectares	9513.2	9382.1	131.3	650.6	79.2	514.0	57.4	43.1	550.2
%	30.43	30.01	0.42	2.08	0.25	1.65	0.18	0.14	1.76

	Built-up and urbanised areas									
	Total	Industrial					Transport areas			Minerals
		Residential areas	Industrial	Other build-up	Urbanized non-residential	Recreation and leisure	Roads	Railways	Others	
thousads hectares	1700.6	340.4	123.6	152.4	56.8	66.3	808.3	102.6	13.8	28.4
%	5.44	1.10	0.40	0.49	0.18	0.21	2.59	0.33	0.05	0.09

The outflow module is the most accurate estimate of water resources. Its value constitutes the difference between atmospheric precipitation and evapotranspiration. The amount of outflow is calculated based on multiannual observations and hydrometric measurements performed in river channels where both very high and extremely low flows can occur. Precipitation falling on the land surface in the country determines the development of own water resources. In the environmental cycle, precipitation water can directly flow to rivers, return to the atmosphere in the process of evaporation and transpiration, or can be retained in the soil cover, and then retained in the bedrock. The contribution of precipitation water in particular phases determines the rate of water inflow to river channels.

Almost the entire area of Poland is located in the catchment of the Baltic Sea (99.7% of the area), and only small fragments are incorporated in the catchment of the North Sea (0.1%) and Black Sea (0.2% of the territory of the country). The surface of catchments of the Oder and Vistula Rivers constitute 89.6% of Poland's territory, and the remaining part is occupied by those of rivers of the Pomeranian and Masurian Lake Districts [8], draining water directly to the Baltic Sea or to the catchment of the Neman and Pregolya River [9]. Water resources of the territory of Poland are associated with the amount of mean outflow from the area of the country, i.e. 312,677 km^2. They develop as a result of alimentation with atmospheric precipitation as own renewable resources. Own resources are increased by internal resources, i.e. by the volume of water introduced through rivers to the territory of Poland, where part of catchments is located outside the national borders. After adding the parts of catchments located in the neighbouring countries, the area from which Polish rivers collect water occupies 351,208 km^2, i.e. it is 12.3% larger than the territory of Poland.

Amounts of outflowing water are calculated based on daily water gauge observations and flow measurements performed in the scope of the network of the Institute of Meteorology and Water Management. The data are collected in water gauge profiles established in river channels. The number of water gauges and way of registration of water stages changes with technical progress. At the beginning of the current century, daily water stages and discharges were determined in 611 water gauge stations [7] distributed on Polish rivers. Their catchment areas occupy from several tens to 194 thousand km^2.

Discharge of Polish rivers fluctuates in annual and multi-annual periods. Cyclical occurrence of years with high and low discharges is registered, and seasonal discharge fluctuations are observed. According to calculations performed by IMGW, mean total water outflow in Polish rivers in the twentieth century was 61.5 km^3, whereas outflow from the area of the country equalled 53.9 km^3 [7]. The difference between mean river outflow and outflow from the area of Poland equals 7.6 km^3. It results from the outflow of water introduced by rivers inflowing to the territory of Poland, i.e. they are resources developed outside of the national borders. Total annual outflows showed a series of several years with high or low discharges, and following annual values showed a significant level of autocorrelation. This points to significant environmental conditions of development of water resources, and particularly to the way of alimentation of rivers with a high contribution of the groundwater component. The outflow module of Polish rivers in the twentieth century was 1950 $m^3 \cdot s^{-1}$, and from the territory of Poland 1710 $m^3 \cdot s^{-1}$ [7]. Out of the entire volume of waters outflowing in rivers, approximately 55% concerns the catchment of the Vistula River, and 25% the catchment of the Oder River. The rivers of Przymorze and the Vistula Lagoon carry respectively 9.5 and 5.9% of waters of Poland [10].

Annual outflow of Polish rivers in particular years and decades of the period 1901–2017 fluctuated in a very broad range, averaging 61.1 km^3. The lowest and highest annual outflows occurred in the second half of the previous century: lowest – 37.6 km^3 in 1954, and highest – 89.9 km^3 in 1981. No significant differences were determined in the frequency and duration of dry and wet periods in the first and second half of the twentieth century. The driest periods were 1932–1937 and 1989–1993 [7, 11]. High values of outflowing water were determined in the 1970s and at the turn of the centuries. Outflow in the second half of the twentieth century was higher by 1.5% than the average calculated from the entire period. In recent years, river outflow fluctuated in a vast range (Fig. 4.4), from 41 $km^3 \cdot year^{-1}$ (years 2015–2016) to almost 87 km^3 (2010).

A measure of variability of water resources in the area is unitary outflow expressed in unitary outflow in one second from one square kilometre. Mean unitary outflow from the multi-annual period 1951–2000 in the Vistula catchment was 5.56 $dm^3 \cdot s^{-1} \cdot km^{-2}$. It was somewhat higher than in the catchment of the Oder River (4.83 $dm^3 \cdot s^{-1} \cdot km^{-2}$), whereas in the territory of the country it is higher, equalling 5.64 $dm^3 \cdot s^{-1} \cdot km^{-2}$ [7]. The lowest unitary outflow concerns catchments of rivers of lowlands in the central parts of Kujawy and Wielkopolska and the highest in the Tatra Mountains. In the lowland area, mean unitary outflows vary from 3 to 4 $dm^3 \cdot s^{-1} \cdot km^{-2}$, whereas, in the Upper Noteć River catchment, they do not reach 3

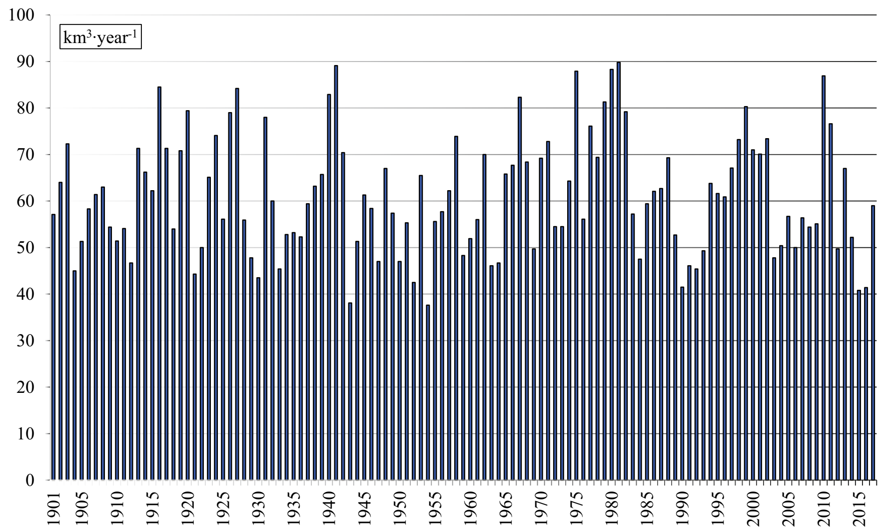

Fig. 4.4 Annual outflow of rivers in Poland in 1901–2017 [4, 11, 12]

$dm^3 \cdot s^{-1} \cdot km^{-2}$. In the Masurian Lake District, they increase to 6 $dm^3 \cdot s^{-1} \cdot km^{-2}$, and in the Pomeranian Lake District to 10 $dm^3 \cdot s^{-1} \cdot km^{-2}$. In the zone of uplands, values of unitary outflows consequently increase with height from 4 to 8 $dm^3 \cdot s^{-1} \cdot km^{-2}$. In the Carpathian Foothills, Carpathians, and Sudeten Foothills and Sudeten, outflow increases with height, from 6 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in the boundary zone of the mountain area to 15–30 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in the Carpathians and Sudeten. In the Tatra Mountains, mean unitary outflow exceeds 40 $dm^3 \cdot s^{-1} \cdot km^{-2}$.

In the southern part of Poland, the height of the outflow layer increases with land elevation as a consequence of an increase in atmospheric precipitation in the mountains. In the Tatra Mountains, the annual outflow layer exceeds 1000 mm, in the Carpathians and Sudeten it equals 300–500 mm. In the zone of Uplands of Central Poland, the outflow layer is 150–220 mm. It is somewhat higher in the Lake District, where it exceeds even 300 mm. The lowest outflow, below 100 mm, is observed in the zone of Lowlands of Central Poland, and in some of its parts, it does not even reach 70 mm (part of Kujawy and central Wielkopolska).

The value of river discharge, mainly dependent on the amount of atmospheric precipitation and the surface area of the catchment, changes seasonally, which is directly related to the type of alimentation of rivers. Outside the mountain area, the highest discharges occur in spring as a result of the release of water retained in the snow cover. In the mountains, the highest river discharges occur during intensive rainfalls at the beginning of summer. High variability of discharges in rivers makes it challenging to manage the entire mass of outflowing water, and causes problems with water excess or deficits. A particularly difficult situation occurs both during flood flows and low flows. In the remaining period, rivers are relatively evenly fed from the groundwater resources. Discharges of the largest Polish rivers in their mouth sections, together with the length of the rivers and size of their catchment areas, are presented in Table 4.2. Polish rivers with the most abundant water resources are the Vistula and Oder Rivers, and their tributaries, namely Narew and Warta.

Atmospheric waters are retained in rocks, lakes, ponds, and reservoirs, and part of them flows directly to rivers. The amount of groundwater resources is mainly determined by natural conditions: the amount of atmospheric precipitation, type of rocks and land relief, soil permeability, and retention capacity of the catchment, as well as anthropogenic factors: water bodies, meliorations and river regulation, urbanisation, and the related change of land use structure and others. The distribution of groundwater resources in the territory of Poland refers to conditions resulting from the geological structure, and particularly the range and thickness of aquifers and their water capacity. Water resources of a given area can occur in rocks of different ages, and be renewed through infiltration of precipitation waters. The exploitable resources of the main aquifers occurring in the territory of Poland and their area of occurrence are presented in Table 4.3.

In the territory of Poland, groundwaters of the first aquifer occur in rocks of different ages. The largest area is occupied by waters of the Quaternary aquifer the resources of which exist over 75% of the area of the country (Table 4.3), and collect 51% of exploitable resources. Over a somewhat smaller area, often underlying Quaternary deposits, wet rocks of the Palaeogene and Neogene occur (61%). Wet

Table 4.2 Principal rivers in Poland [4]

River	Recipient	Basin area (km^2)	River length (km)	River discharge (m^3·s^{-1})
Vistula	Baltic sea	193 960	1 022	1 080.0
Dunajec	Vistula	6 796	249	85.5
Wisłoka	Vistula	4 110	173	35.5
San	Vistula	16 877	458	129.0
Wieprz	Vistula	10 497	349	36.4
Pilica	Vistula	9 258	333	47.4
Narew	Vistula	74 527	499	313.0
Bug	Narew	38 712	774	155.0
Bzura	Vistula	7 664	173	28.6
Drwęca	Vistula	5 697	231	30.0
Brda	Vistula	4 665	245	28.0
Oder	Baltic sea	119 074	840	567.0
Nysa Kłodzka	Oder	4 570	189	37.7
Barycz	Oder	5 547	136	18.8
Bóbr	Oder	5 874	279	44.8
Nysa Łużycka	Oder	4 403	246	31.0
Warta	Oder	54 520	795	216.0
Noteć	Warta	17 302	391	76.6
Parsęta	Baltic sea	3 084	143	29.1
Łyna	Pregolya	7 126	264	34.7

Table 4.3 Main muliti-aquifer formations in Poland and related disposable groundwater resources [13]

Resources	Area	Disposable resources	Disposable resources in main groundwaters reservoirs	Approved resources (as of 31st December 2001)
Resources (km^3·rok^{-1})		12.5	7.35	16.17
Multiaquifer formation	Thousands km^2	%		
Quaternary	234	65.0	51.3	65.9
Neogene	191	11.0	5.5	10.1
Cretaceous	70	13.0	23.1	13.5
Jurassic	60	5.0	11.7	10.5
Triassic	15	3.0	7.1	
Older formations		3.0	2.3	

Cretaceous, Jurassic, and Triassic formations occur over a total of 46% of the area of the country (Cretaceous 22%, Jurassic 19%, Triassic 5%), and collect 41.9% of exploitable resources occurring in the main groundwater reservoirs (Table 4.3).

According to materials presented in the Hydrogeological atlas of Poland [14], total infiltration of precipitation was evaluated as 100 $km^3 \cdot year^{-1}$, and the amount of renewable groundwater resources within useful aquifers was estimated for approximately 18 ± 3 $km^3 \cdot year^{-1}$. In balance calculations concerning the possibilities of use of groundwater, exploitable resources of useful aquifers should not exceed 15 $km^3 \cdot year^{-1}$. In periods of moderate and low discharges, rivers are fed from groundwater resources, and floods occur during the runoff of precipitation and meltwaters. Random occurrence of such events forces undertaking measures for regulating river discharge. In addition to the construction of retention reservoirs, the regulation should cover measures aimed at water retention in catchments, i.e. mainly in agricultural and forest areas.

An essential role in water retention and development of water resources is played by lakes, ponds, and retention reservoirs. There are 7081 lakes (larger than 1 ha) in Poland, with a surface area of 2813.8 km^2 [15, 16]. Their number in the last century considerably decreased, and Majdanowski [17] provides their number of 9296 and total surface area of 3169.3 km^2. K. Dębski [18] mentions that lakes in Poland occupy the area of approx. 3400 km^2 and their total volume is estimated for 33 km^3. Whereas, the capacity of soil and groundwaters in the water balance for Poland is evaluated for 36.6 km^3 [18]. Total static resources of lakes in Poland are 18.747 km^3, 99% of which is located inside the range of Weichselian glaciation [19]. A large amount of surface water is retained in wetlands, which is estimated for 15.5 km^3 [20]. The basic parameters of the largest lakes in Poland are presented in Table 4.4.

To increase surface retention, dam reservoirs are constructed, potentially substantially contributing to a reduction of the irregularity of outflow. Retention reservoirs increase exploitable water resources, particularly in the period of the lowest discharge in the river, or when the periodical demand increases. Several tens of thousands of different hydrotechnical constructions have been built on Polish rivers and lakes.

Table 4.4 The largest lakes in Poland [4]

Lake	Basin	Area (km^2)	Depth (m)	Capacity (mln m^3)
Śniardwy	Pisa	113.4	23.4	660.2
Mamry	Węgorapa	102.8	43.8	1009.8
Łebsko	Łeba	71.4	6.3	117.5
Dąbie	Odra	56.0	4.2	168.0
Miedwie	Płonia	35.3	43.8	681.7
Jeziorak	Iławka	32.2	12.0	141.6
Niegocin	Pisa	26.0	39.7	258.5
Gardno	Łupawa	24.7	2.6	31.0

Table 4.5 The largest artificial water reservoirs in Poland [4]

Reservoir	River	Area (km^2)	Total capacity (hm^3)
Solina	San	22.0	472.4
Włocławek	Wisła	75.0	453.6
Czorsztyn	Dunajec	12.3	231.9
Jeziorsko	Warta	42.3	202.8
Goczałkowice	Wisła	32.0	161.3
Rożnów	Dunajec	16.0	159.3
Dobczyce	Skawa	10.7	141.7
Otmuchów	Nysa Kłodzka	20.6	131.5
Nysa	Nysa Kłodzka	20.7	124.7
Turawa	Mała Panew	20.8	106.2

hm^3 – cubic hectometres, 1,000,000 m^3

According to the Central Statistical Office [4], a total of 32,272 of objects of so-called small retention exist in Poland, concentrating water with a volume of 0.826 km^3. An increase in retention resources was obtained through damming 360 lakes, construction of 4176 small water reservoirs, 8317 ponds, and 18,760 damming structures on rivers. From the point of view of water management, the largest 60 reservoirs are of vital importance for hydrology and water management. They have a substantial effect on the level of exploitable resources, including 10 with a volume of more than 100 hm^3 (Table 4.5). The total volume of the reservoirs exceeds 4 km^3, which constitutes approximately 6.5% of annual outflow.

Water resources occurring in rivers, lakes, ponds, retention reservoirs, rocks, and in wetland areas are subject to seasonal fluctuations. They are usually interrelated, and a disturbance in some places of occurrence of water in the environment results in consequences in others. The economic use of water requires its supply during the entire period of work, i.e. also in the case of low and high resources. It is possible to increase water resources to a certain extent through regulating river discharge, water retention in reservoirs of different ranks, and through other measures favouring water retention in the catchment. In the case of firm regulation of river discharge, the amount of water resources available for use can be determined by the amount of outflowing water. In the case of cyclical occurrence of dry and humid periods, the amount of water resources of the country, and therefore also the possible level of use of the resources for economic purposes, should be determined based on discharges with a high probability of occurrence. Economic balancing must consider so-called inviolable (biological) river discharges, determined for Polish rivers at a level of 15 km^3. Kaczmarek [21] adopted the amount of outflowing water that can be supplied to users over 95% of time in each year as the amount of exploitable resources. The outflow of Polish rivers at such a level of probability was determined as 22 km^3. A similar amount of exploitable resources is obtained by adopting their value as groundwater outflow in the year with the lowest outflow. After subtracting the value of biological discharge from exploitable resources, we obtain the amount of exploitable resources of Poland for irreclaimable use equalling 7 $km^3 \cdot year^{-1}$. The value can be increased to 9–10 $km^3 \cdot year^{-1}$ after regulating discharges of Polish rivers, i.e. after an increase in reservoir and soil retention.

4.4 Water Resources Balance and Use

The amount of water in the natural environment changes in a seasonal and annual scale. Performing its balance requires the determination of the time and areas for which the value of water inflow and outflow is assessed. The water balance equation components may be expressed as a mean depth of water over the basin or water body (mm), as a volume of water (m^3), or in the form of discharge ($m^3 \cdot s^{-1}$) [22]. Therefore, it is possible to present components of water circulation for different areas and time intervals. It is the most efficient, due to the unambiguously determined water runoff area, to prepare water balances for catchments. Balances for other areas are also based on calculations performed in catchments within the analysed area. Basic information on water resources of the area is included in normal water balance, prepared based on data from the multi-annual period in which precipitation is balanced by outflow and evapotranspiration. In the case of presentation of parameters for shorter periods, they should consider the change in retention in the balancing period, described as the difference between the amount of resources at the end and beginning of balancing.

In an average year, atmospheric precipitation supplies approximately 190 km^3 of water to the territory of Poland, and approximately 7 km^3 inflows from the neighbouring countries. In the years 1901–2000, mean precipitation in the territory of Poland was 628 mm, and outflow 175.2 mm [7]. Approximately 450 mm corresponds to evapotranspiration, i.e. field evaporation. In a year with average humidity, the amount of precipitation in the territory of the country varies from approximately 500 mm in the lowland belt to more than 1000 mm in the mountains, which directly affects the amount of regional water resources. In an average year [23], mean river outflow is dominated by water supply from groundwater resources (95 mm, 55%). The remaining part is accounted for by surface runoff (76 mm, 45%). The percent contribution of both components varies in a regional scale. The mountain areas surface runoff is prevalent, and on uplands – groundwater outflow.

Satisfying municipal, industrial, and agricultural water needs of the population and economy of Poland occurs from groundwater and surface water resources. They develop from atmospheric precipitation, within particular regions and places of occurrence of water which in water management should be treated jointly. A separate calculation of surface water and groundwater resources is only justified in valleys of large transit rivers, i.e. in situations when flowing water resources development in different precipitation regions. Water intake for economic purposes is only possible in the case of relevant values of its discharge occurring in river channels or in rock pores and fissures, with the maintenance of biological flow.

In the second half of the previous century, water use rapidly increased as a result of the "planned" urbanisation and industrialisation of the country. In 1965, controlled water intake was 7.6 km^3, and from 1977 it regularly exceeded 14 $km^3 \cdot year^{-1}$ [24]. The occurrence of low flows at the turn of the 1980s and 1990s, and the resulting periodical water shortages and its heavy pollution, determined the directional transition to economic water management, as well as more effective sewage treatment. The decrease in the amount of collected water, however, was to the greatest extent determined by the economic crisis and the related restructuring of the industry, and liberalisation of prices of water at the beginning of the 1990s. These factors caused considerable limiting of water use for different purposes and led to substantial changes in the structure and amount of water use in Poland. The approach of society and state administration to the resources of the natural environment and increase in the standard of life of residents also changed.

The country's economy is particularly supplied with surface waters that currently satisfy the needs of approximately 83.6%. Groundwaters, together with waters from drainage of mines, accounting for 16.5% [4]. In 2016, 70.81% of total water intake was used for production purposes, 19.34% for municipal and irrigation purposes, and 9.85% for supplementation of water in fish ponds. Amounts of water intake and use in different sectors of the national economy in three-time intervals were compared in Table 4.6. Values from 1980 were adopted as the reference level.

Data concerning 1980 include information on the highest level of water use that in the 1960s annually exceeded 14 km^3, including groundwaters of approximately 2.0 km^3. At the turn of the 1980s and 1990s, the approach to water resources changed. This was undoubtedly partially determined by changes in the economic system, as well as the occurrence of a series of very dry years which caused serious problems in the municipal economy, industry, and agriculture. At the end of the twentieth century, the water needs of the country stabilised at the annual level of 11 km^3. Over the last decade, due to the introduction of new production technologies, the amount of water intake for the purposes of the industry has slightly decreased. Water intake for the purposes of agriculture and municipal economy has been maintained on a similar level. Total annual water intake in the years 1980–2016 decreased from 14.2 km^3 to 10.6 km^3. Moreover, the amount of water collected for the agricultural irrigation purposes is dependent on the humidity of a given period. Over the last twenty years, atmospheric alimentation was relatively high, which positively translated into the resources of shallow groundwaters. Data of the Central Statistical Office [4] show that the total water intake in the years 1980–2016 for agriculture and forestry for the purpose of irrigations and for supplementation of water in fish ponds decreased from 1.323 to 1.043 km^3. In the same period, the amount of groundwater intake for the purposes of the economy decreased from 1.958 to 1.688 km^3.

The use of groundwaters accounts for approximately 10% of their exploitable resources. Nonetheless, areas exist, particularly in the vicinity of large cities, where overdrying of the ground occurred, and therefore the possibilities of agricultural land use decreased. Reserves of groundwaters usually exist in non-urbanised areas not affected by human pressure.

Table 4.6 Water withdrawal for national economy and population purposes [4]

Water withdrawal	1980		2000		2016	
	hm^3	%	hm^3	%	hm^3	%
Total	14,183.6	100.0	11,048.5	100.0	10,581.4	100.0
Surface waters	11,899.0	83.89	9150.6	82.82	8840.8	83.55
Groundwaters	1958.3	13.81	1747.3	15.82	1687.9	15.95
Waters from mines drainage – used for production	326.2	2.30	150.6	1.36	52.8	0.50
Production purposes	10,137.6	71.47	7637.9	69.13	7492.8	70.81
Sufarce waters	9168.5	64.64	7221.5	65.36	7228.7	68.32
Groundwaters	642.9	4.53	265.8	2.42	211.3	2.00
Water from mine and building constructions drainage – used for production	326.2	2.30	150.6	1.36	52.8	0.50
Irrigation in agriculture and forestry and filling and completing fishponds	1323.4	9.33	1060.6	9.60	1042.7	9.85
Surface waters	1323.2	9.33	1060.6	9.60	1039.9	9.82
Groundwaters					2.7	0.02
Exploitation of water supply network – withdrawal in water intakes	2722.6	19.20	2350.1	21.27	2045.9	19.34
Surface waters	1407.2	9.92	868.5	7.86	572.2	5.41
Groundwaters	1315.4	9.28	1481.5	13.41	1473.8	13.93

hm^3 – cubic hectometres, 1,000,000 m^3

According to the materials of the Ministry of the Environment, the total registered intake of groundwaters in the area of the country as at the end of 2013 was more than 2.6 $km^3 \cdot year^{-1}$ [25]. This value includes:

- registered intake in more than 18,500 groundwater intakes functioning for the purposes of provision of the population and industry with water to the amount of more than 1.6 $km^3 \cdot year^{-1}$,
- intake of more than 0.95 $km^3 \cdot year^{-1}$ in the scope of meliorations of mines exploiting more than 90 largest deposits in Poland,
- intake from meliorations of inactive mines in the Upper Silesian Coal Basin with a value of more than 0.08 $km^3 \cdot year^{-1}$.

In the Vistula River catchment area, according to the state from 2013, groundwater intake exceeded 1.25 $km^3 \cdot year^{-1}$, and in the Oder River catchment 1.31 $km^3 \cdot year^{-1}$.

A systematic increase in water intake should be expected in the upcoming years, particularly for agriculture, up to a level of 13.4 km^3 in 2025 [26]. An increase in water use, also in agriculture (irrigation) and fish farming, must consider the rules of the basic economic calculation. It is particularly important in lowland areas of

Table 4.7 Primary melioration [4]

Year	Rivers and canals		Embankments		Usable capacity of water reservoirs in dam^3	Drainage pump stations	
	Lenght (km)	Of which regulated (km)	Lenght (km)	Protected area in thousands ha		Number	Area of interaction in thousands ha
1990	72,577	37,923	8148	1004.3	163,408	609	571.4
2003	73,812	39,972	8450	1074.9	261,334	574	601.4
2016	75,297	43,442	8451	1091.2	279,955	579	616.1

the country experiencing structural water deficits. The intensification of agriculture requires securing water supply in the period of growth of plants, which occurs through land melioration. The measures involve the application of the regulation of water outflow and inflow, in accordance with the production requirements of crops. Incomplete functioning of melioration facilities leads to negative changes in the environment, and particularly to the overdrying of the ground, which is extremely dangerous for organic soils. Their dehydration reduces the retention resources of the catchment and launches an intensive process of mineralisation of organic substance, degrading natural water resources.

The area of meliorated arable land is slowly increasing. This results from the intensification of agricultural production, currently also related to the profitability of agricultural and breeding production. Inconsiderable changes also occur in the state of the environment covered by so-called basic meliorations (Table 4.7). The value is too low for overtaking the rapidly developing surface runoff. It is estimated that the basic melioration requires the reconstruction or modernisation of 15,551 km of rivers, 3,657 km of embankments, and 1,443 thousand ha of arable land in need of modernisation [4]. It should be emphasised that the existing hydrotechnical infrastructure can mitigate the effects of drought only to a low degree. The most efficient direction of action is works aimed at a decrease and slowing down of water outflow from small catchments, an increase in forest cover, maintenance and reconstruction of wetlands, and water retention in the existing small reservoirs in upper parts of the catchment. It should be emphasised that as a result of inappropriately performed meliorations, particularly in periods of hydrological drought, the area of wetlands and peat bogs is subject to continuous and permanent reduction.

Approximately 8.5 thousand km of anti-flood embankments have been constructed in Poland, protecting around 4% of the territory of the country. It is estimated that 40% of the embankments are in a good technical state, and the remaining ones require renovation or modernisation. The existing embankments protect approximately 75% of areas threatened with floods [27].

4.5 Summary and Conclusions

The territory of Poland is characterised by relatively low water resources at the European scale. This results from the amount of precipitation and evapotranspiration, and their seasonal variability. Mean outflow in Polish rivers in the period 1901–2000 was 61.5 km^3, and that from the area of Poland equalled 53.9 km^3. The value corresponds to the layer of outflow of 175.2 mm and unitary outflow of 5.56 $dm^3 \cdot s^{-1} \cdot km^{-2}$. The outflow of rivers, expressed both in the outflow layer and per resident, is among the lowest in Europe.

Water resources of Poland are directly related to the features of the natural environment, particularly the hydrogeological and climatic conditions. They determine the amount of resources and their temporal and spatial variability. This is of particular importance in the observed climate changes that will affect the renewability of groundwaters and surface waters, especially in the conditions of increasing uncertainty of precipitation. Particular importance is gained by groundwater resources, showing higher inertia in the conditions of changes in precipitation and evapotranspiration. They can satisfy the water needs of the population and economy with respect for the rules of sustainable use of waters.

In the context of the occurring climatic changes, measures aimed at water retention in the catchment are recommended. Changes in the conditions of water circulation and outflow should be towards its retention in the soil and bedrock, leading to a decrease in surface runoff and an increase in exploitable resources in catchments. In addition to the construction of retention reservoirs, this purpose can be met by changes in the land use structure – particularly through forestation of areas with high slope inclination, application of suitable agrotechnical measures, and observing the term of their performance, as well as the construction of corrective steps slowing down water outflow.

All resources, of both surface and groundwaters, are subject to strong human pressure leading to their quantitative and qualitative transformations. They result from an increase in the water needs accompanying an increase in the standard of life and development of industrial infrastructure and raw material extraction. It is important to reduce the consumption levels at every stage of its use, i.e. in households, and particularly in the industry and agriculture. The level of exploitation, especially on the regional scale, should not endanger the stability of low flows and natural functioning of hydrogenic ecosystems. The water safety of the country requires the maintenance of the quantity and quality of water resources on a good level and effective protection against the effects of drought and floods.

4.6 Recommendation

In the aspect of climate change and low water resources, actions aiming at improvement of water balance structure of in Poland, mainly reduction of water losses and increase of retention, are necessary. Changes of water outflow conditions show cause increase of retention possibilities of soils, as well as aeration zone and groundwater retention, which will led to decrease of surface runoff and increase of water disposable resources in the catchment. Indicated direction of changes, construction of water reservoirs and correction sills slowing down the outflow, can be archived by land use structure changes (afforestation of areas of high gradient of slopes and reduction of surface runoff from urbanized areas). In order to water resources protection, rational management of available resources in catchments, elimination or limitation of influence of point, linear and diffuse sources of pollution, decision processes simplification in spatial management and exploitation of water-economic systems are necessary.

References

1. Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global Water resources: vulnerability from climate change and population growth. Science 289(5477):284–288. https://doi.org/10.1126/science.589.5477.284
2. Oki T, Kanae S (2006) Global hydrological cycles and world water resources. Science 313(5790):1068–1072. https://doi.org/10.1126/science.1128845
3. www.unic.un.org.pl/dekada-wody/miedzynarodowa-dekada-wody-2018%E2%80%932028/3220. Accessed 24 Nov 2018
4. Ochrona Środowiska (Environmental protection). Wyd. GUS, Warszawa (in Polish) (2017)
5. Shiklomanov IA (2000) Appraisal and assessment of world water resources. Water Inter 25(1):11–32. https://doi.org/10.1080/02508060008686794
6. Kowalczak P (2007) Konflikty o wodę (Water conflicts). Wyd. Kurpisz Przeźmierowo (in Polish)
7. Fal B, Bogdanowicz E (2002) Zasoby wód powierzchniowych Polski (Surface water resources in Poland). Wiad IMGW 3:3–37 (in Polish)
8. Bajkiewicz-Grabowska E (2020) Geoecosystems of Polish lakes. In: Korzeniewska E, Harnisz M (eds), Polish river Basins and lakes—Part I. Handbook Environ Chem 86, 57–67. Springer, Cham. https://doi.org/10.1007/978-3-030-12123-5_3
9. Bajkiewicz-Grabowska E, Markowski M, Golus W (2020) Polish rivers as hydrographic objects. In: Korzeniewska E, Harnisz M (eds), Polish river Basins and lakes—Part I. Handbook Environ Chem 86:27–55. Springer, Cham. https://doi.org/10.1007/978-3-030-12123-5_2
10. Gutry-Korycka M, Sadurski A, Kundzewicz ZW, Pociask-Karteczka J, Skrzypczyk L (2014) Zasoby wodne a ich wykorzystanie (Water resources and their use). Nauka 1:77–98 (in Polish)
11. Fal B (1993) Zmienność odpływu z obszaru Polski w bieżącym stuleciu (Changeability of outflow from the Poland territory in present century). Wiad IMGW 16:3–20 (in Polish)
12. Biuletyn Państwowej Służby Hydrologiczno-Meteorologicznej (Bulletin of the State Hydrological and Meteorological Service). IMiGW-PIB, Warszawa (2017) (in Polish)
13. Szczepański A (2008) Współczesne problemy gospodarki wodnej i zasobów wód (Present problems of water management and water resources). In: Kotarba MJ (ed) Przemiany środowiska naturalnego a rozwój zrównoważony (Changes of natural environment and sustainable development), pp 53–64. Wydawnictwo TBPŚ GEOSFERA Kraków (in Polish)
14. Paczyński B (ed) (1995) Atlas hydrogeologiczny Polski (Hydrogeological atlas of Poland). Wyd. PIG Warszawa (in Polish)
15. Choiński A (2007) Katalog jezior Polski (Catalogue of lakes in Poland). Wyd. UAM Poznań (in Polish)
16. Choiński A (2017) Geneza i rozmieszczenie jezior (Origin and location of lakes). In: Jokiel P, Marszelewski W, Pociask-Karteczka J (eds), Hydrologia Polski (Hydrology of Poland), pp 223–229. Wyd. Naukowe PWN Warszawa (in Polish)

17. Majdanowski S (1954) Jeziora Polski (Lakes of Poland). Przegl Geogr 26(2):17–50 (in Polish)
18. Dębski K (1970) Hydrologia (Hydrology). Wyd. Arkady Warszawa (in Polish)
19. Borowiak D (2017) Zasoby i bilans wodny jezior (Resources and water balance of lakes). In: Jokiel P, Marszelewski W, Pociask-Karteczka J (eds), Hydrologia Polski (Hydrology of Poland), pp 229–234. Wyd. Naukowe PWN Warszawa (in Polish)
20. Kowalewski G (2017) Rola mokradeł w obiegu wody (The role of wetlands in water circulation). In: Jokiel P, Marszelewski W, Pociask-Karteczka J (eds), Hydrologia Polski (Hydrology of Poland), pp 264–269. Wyd. Naukowe PWN Warszawa (in Polish)
21. Kaczmarek Z (1978) Zasoby wodne Polski i zasady ich racjonalnego użytkowania (Water resources in Poland and rules of their rational use). Nauka Polska 8:43–54 (in Polish)
22. Sposób J (2011) Water balance in terrestrial ecosystems. In: Gliński J, Lipiec J (eds), Encyclopedia of agrophysics, pp 955–959. Springer Science and Business Media. https://doi.org/10.1007/978-90-481-3585-1
23. Mikulski Z (1998) Gospodarka wodna (Water management). Wyd. PWN Warszawa (in Polish)
24. Wilgat T (1984) Ochrona zasobów wodnych Polski (Protection of water resources in Poland). Wyd. PWN Warszawa-Łódź (in Polish)
25. Gospodarowanie wodami w Polsce w latach 2012–2013 (Water management in Poland in 2012–2103) Ministerstwo Środowiska Warszawa (2014) (in Polish)
26. Kaczmarek Z (2005) Gospodarka wodna w Polsce u progu XXI wieku (Water management in Poland on the threshold of 21st century). Monografie Komitetu Inżynierii Środowiska PAN 32:27–40 (in Polish)
27. Strategia gospodarki wodnej (Strategy of water management). (In:) Światowy dzień wody (2005) (World water day 2005), 7–32. Wyd. KGW PAN Warszawa (in Polish)