Total Organic Carbon in the Water of Polish Dam Reservoirs

Andrzej Górniak

Contents

Abstract Total organic carbon (TOC) resources in Polish water reservoirs are presented as an important factor affecting water quality and ecosystem trophic state. The study is based on hydrochemical and biological data from 47 reservoirs from the years 2005–2017 and collected from the archives of the Polish National Monitoring Program, provided by the Chief Inspectorate of Environment Protection. The mean (by weight) TOC concentration in reservoirs is 6.3 mg dm^{-3}, with a range from 2.3 mg C dm^{-3} in the mountains, the Czorsztyn and Sromowce reservoirs, up to 18 mg C dm^{-3} in the hypereutrophic, lowland Siemianówka reservoir, varying according to reservoir elevation. Although reservoirs are large and deep, there is a significant negative correlation between mean reservoir depth and TOC. Seasonality and national TOC dynamics were strongly related to the rate of precipitation, with maximal concentrations in late spring and minimal in autumn or winter. The first global warming symptoms of TOC changes in reservoirs are noted, which will manifest as increased TOC and greenhouse gas emissions. Increased water retention time, which promotes water eutrophication, increases TOC resources in most Polish

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dam reservoirs as well as in flooded areas. Mean TOC concentrations are related to certain biological reservoir water parameters, such as phytoplankton index or diatom index. In future planning, Polish reservoirs should be placed outside lowlands, and their capacity should provide a high water exchange, in less than 2 to 3 months.

Keywords Dam · Reservoir · Total organic carbon · Water

1 Introduction

1.1 *Aims of Study*

Water resources are among the most frequently modified elements of the natural environment. Currently, there are more 14 million dam reservoirs in the world, with this number expected to increase in the next decades [1]. More than half of the world's global river systems are regulated by dams, which mostly lie in basins where irrigation and economic activities take place. Hydropower reservoirs and those for irrigation are dominant. The total cumulative storage of large dams is about 20% of global annual runoff [2]; in consequence of global warming and increase of deglaciated land area, a large global sea level rise of 30 mm is observed [3].

The reservoirs created by damming a preexisting river resemble a basin water storage and run-of-river system. Dam reservoirs become active modifiers of energy and mass runoff [4]. Sediment accumulation, primary productivity, and carbon mineralization along the river continuum are major effects of the perturbation of organic carbon cycling caused by damming of rivers [5]. A recent estimation shows that nearly 13% of total organic carbon global flux, carried by rivers to the oceans, has been eliminated by reservoirs, and the rate of this loss will increase with time.

European or regional studies on organic carbon cycling in dam reservoirs are not yet available. In this study, I present a first evaluation of the organic carbon resources in Polish dam reservoirs of different ages, volumes, and basin conditions. Varied environmental drivers created new organic cycle features during water storage, dependent on landscape types. Regional and hydrological conditions for organic carbon processing are presented for better reservoir management that can limit environmental disturbance and energy production costs.

1.2 *Organic Matter in Water*

Water, as an ideal natural solvent, contains two types of components: dissolved and not dissolved (particulate), and mineral and organic substances are found in each of these types. Next to natural organic matter (NOM), an anthropogenic organic matter (AOM) appears in waters from increased human activity, with a new, synthetic matter origin. Mineral proportions dominate over organic compounds in most of the water bodies, with the exception of dystrophic waters [6].

Organic matter in water is a mixture of organic carbon compounds, produced in the catchment soils, or terrigenous plants (allochthonous), or within water ecosystems (autochthonous). Hydrological situation, time, season and organic matter origin determine the relationship between dissolved (DOC) and particulate organic matter (POC); thus, the ratio DOC/POC, with a mean of 10:1, varies over a large range [6].

Humification of the organic matter of different origins is the most common known process, when humic and fulvic acids (HA and FA, respectively) are formed biochemically and with the active participation of bacteria, fungi, and also invertebrate organisms [7]. HA and FA, as new organic structures, together with detritus and products of incomplete decomposition, create a rich resource for autotrophs and heterotrophs [8]. Humus substance (HS) interactions with water plants and microorganisms are various, determined by humus acid concentrations, origin, pH, and mineral compound richness [8, 9]. HS are important chemical stressors in water ecosystems with effective impact on water color and photic zone density [6, 8]. Also, HS has a strong relationship with acidity and pH in the case of low water conductivity [7]. Humus substances account for 60–80% of dissolved organic carbon (DOC) [6, 7]. The presence of higher HS concentrations in waters affects the nitrogen and phosphorus cycles, because both elements are naturally associated with organic matter. In natural conditions, the increase of total organic carbon (TOC) concentration in water is connected with increasing N and P resources, primarily in particulate forms in rivers. Each high flow of the river delivers a new flux of organic matter to the reservoirs, which can become a driver of water eutrophication depending on reservoir volume and basin type. Increase of TOC concentrations often causes an increase of the easily assimilated energy pool for heterotrophs and mixotrophs, but reduces the rate of primary productivity in aquatic ecosystems [8].

1.3 Water Reservoirs in Poland

Surface water accumulation by man has had a long tradition in Poland territories, and reservoir functions change over time, according to human needs, possibilities, and technological progress. River water storage in small reservoirs was first connected with the existence of watermills, and the oldest one, from 1071, was documented in Zgorzelec on the Oder River. Also in the eleventh century the oldest Polish fishpond was built in Lower Silesia in Southwest Poland. These functions were dominant for water reservoirs up to the year 19 (XIX), when the water wheel was superseded by the water turbine for electric energy production. Hydropower reservoirs began energy production for industry and private use and at first were located in the western part of Poland. The oldest water reservoirs still functioning in recent times were built in the first years of the twentieth century as hydropower reservoirs on the Rivers Bóbr and Kwisa (Table 1), as are most of the largest Polish reservoirs. After the high

Table 1 Morphological features of the largest dam reservoirs in Poland

No.	Name	River	Year	Basin	Volume	Area	Depth [m]		Stratification	*T*
				10^3 km^2	10^6 m^3	km^2	Max	Mean		
1	Besko	Wisłok	1978	0.21	13.7	1.3	25.0	10.5	+	60
2	Brody Iłżeckie	Kamienna	1965	0.62	7.6	1.9	8.1	4.0	–	22
3	Bukówka	Bóbr	1987	0.06	16.8	2.0	22.4	8.4	+	194
4	Chańcza	Staszowska	1985	0.47	24.2	4.7	12.8	5.1	–	218
5	Cieszanowice	Luciąża	1998	0.08	9.1	2.6	10.4	3.5	–	106
6	Czaniec	Soła	1967	1.15	1.3	0.5	6.5	2.8	–	1
7	Czchów	Dunajec	1949	5.32	12.0	3.4	9.5	3.5	–	1.3
8	Czorsztyn	Dunajec	1997	1.20	231.9	12.3	54.5	18.9	+	116
9	Dobczyce	Raba	1986	0.77	141.7	10.7	27.9	13.2	+	146
10	Dobromierz	Strzegomka	1987	0.08	11.4	1.1	26.7	10.4	+	113
11	*Domaniów*	*Radomka*	*2001*	*0.74*	*14.4*	*5.0*	*8.6*	*2.9*	–	*31*
12	Dzierżno Małe	Drama	1938	0.18	12.6	1.7	13.1	7.4	+	24
13	*Goczałkowice*	*Wisła*	*1956*	*0.43*	*161.3*	*32.0*	*13.0*	*5.0*	–	*80*
14	*Jeziorsko*	*Warta*	*1986*	*8.39*	*202.0*	*42.3*	*11.5*	*4.8*	–	*56*
15	Klimkówka	Ropa	1994	0.18	42.6	3.1	33.3	13.7	+	148
16	Kozłowa Góra	Brynica	1939	0.14	17.6	5.8	6.5	3.0	–	307
17	Leśna	Kwisa	1907	0.29	16.8	1.4	35.8	12.0	+	38
18	Lubachów	Bystrzyca	1917	0.15	8.0	0.5	38.0	16.0	+	55
19	Łąka	Pszczynka	1986	0.17	11.2	3.5	6.9	3.2	–	80
20	Mietków	Bystrzyca	1986	0.72	71.9	9.1	15.3	7.9	+	128
21	Niedów	Witka	1962	0.32	4.9	1.9	12.5	2.6	–	13
22	Nielisz	Wieprz	2008	1.19	28.5	9.9	8.6	2.9	–	107
23	Nysa	Nysa Kłodz.	1971	3.27	124.7	20.7	13.3	6.0	–	59
24	Otmuchów	Nysa Kłodz.	1933	2.36	130.5	20.6	18.4	6.3	–	61
25	Pilchowice	Bóbr	1912	1.21	50.0	2.4	46.7	20.8	+	37

26	Pławniowice	P. Toszecki	1975	0.12	29.2	2.4	2.2	12.2	+	281
27	Poraj	Warta	1978	0.39	20.8	5.1	12.0	4.1	–	97
28	Porąbka	Soła	1936	1.10	27.2	3.3	21.2	8.2	+	22
29	Przeczyce	Przemsza	1963	0.30	20.4	4.7	12.5	4.3	–	109
30	Rożnów	Dunajec	1942	4.86	159.3	16.0	31.5	10.0	+	31
31	Rybnik	Ruda	1972	0.31	23.5	4.6	11.8	5.1	–	76
32	Rzeszów	Wisłok	1973	2.00	1.8	0.7	10.0	2.6	–	0.6
33	*Siemianówka*	*Narew*	*1991*	*1.05*	*79.5*	*32.5*	*9.2*	*2.4*	–	*198*
34	Słup	Nysa Szal.	1978	0.38	38.7	4.9	19.1	7.9	+	22
35	Solina	San	1968	1.19	472.4	22.0	60.0	21.5	+	299
36	Sosnówka	Czerwonka	2002	0.05	14.0	1.8	18.0	7.8	+	162
37	Sromowce W.	Dunajec	1994	1.30	6.4	0.9	8.5	7.1	+	3
38	Sulejów	Pilica	1973	4.90	84.3	23.8	11.3	3.5	+	38
39	Topola	Nysa Kłodz.	2003	2.14	26.5	3.4	7.8	7.8	+	Nd
40	Tresna	Soła	1967	1.03	96.1	9.6	23.8	10.0	+	90
41	*Turawa*	*Mała Panew*	*1938*	*1.42*	*106.2*	*20.8*	*13.6*	*5.1*	–	*115*
42	Wióry	Świślina	2007	0.36	35.0	4.1	23.4	8.5	+	Nd
43	Wisła-Czarne	Mała Wisła	1973	0.03	4.9	0.4	34.0	12.3	+	Nd
44	*Włocławek*	*Wisła*	*1970*	*168.9*	*453.6*	*75.0*	*12.7*	*6.0*	–	*4.5*
45	*Zegrzyński*	*Narew*	*1963*	*69.6*	*96.0*	*33.0*	*7.0*	*2.9*	–	*8*
46	Zemborzyce	Bystrzyca	1974	0.73	6.3	2.8	7.0	2.3	–	26
47	Złotniki	Kwisa	1924	0.29	12.1	1.2	27.5	10.1	+	27

T, mean water retention (days). *Italics* indicate lowland reservoirs floods in the Vistula River basin in 1920 and 1930, the next new reservoirs had an important role in limiting flood effects. The next function of reservoirs was an accumulation of potable water and for communal use for developing agglomerations in southern Poland. Water shortage in the second part of the twentieth century prompted the construction of the next large water reservoir on the main tributaries of the Vistula River, and just like on the river itself near Włocławek in the lower part of the river course. A long-time water reservoir began to become multifunctional wherein recreation use and fish farming were also significant. Among Polish water reservoirs, some of them serve for retention of mine waters, for transport, or to improve waterway quality.

In the last years in the twentieth century, nearly 140 water dam reservoirs with a total capacity greater than 10^6 m^3 and total area near 500 km^2 existed in Poland [10]. Most of these are located in the Sudety and Karpaty Mountains or in sub-mountain regions in the southern part of Poland. Only a few water reservoirs were built on lowland or upland rivers, but there are a significant number of reservoirs in the Silesia region. In the Silesia Upland an "anthropogenic Lakeland" has formed as a result of long-term surface mining of minerals, with permanent development of post-mining depression, affected by deep coal mining [11]. Around 20% of Polish reservoirs were built before the year 1945, mainly in the Sudety Mountains, but larger ones are situated in the Vistula River basin.

The dams of Polish dam reservoirs are not very high, mostly in the range of 20–30 m, but the highest are 54.5 m (Czorsztyn Reservoir on Dunajec River) and 60 m (Solina Reservoir on San River). The largest Polish water reservoirs have an area of 30–40 km^2, and only the Włocławek Reservoir on Vistula River exceeds 70 km^2. The ten largest Polish reservoirs have a capacity greater than 0.1 km^3 and only two have storage for 0.45–0.47 km^3 water (Włocławek Reservoir and Solina Reservoir) (Table 1). Reservoir morphology depends on geographic location, because mountain reservoirs are deep, with maximal depth more than 40–50 m, summer thermic stratification of the water column, and intensive sedimentation of sand and gravels. Lowland reservoirs, such as Jeziorsko, Siemianówka, and Turawa, are shallow, polymictic, with large area changes during a year, with sandy silt deposits and local bays with wetlands development. Some reservoirs, such as Goczałkowice, Nysa, and Otmuchów, have a morphology typical for lowland reservoirs, but their hydrology is connected with the mountain area.

Reservoir location on the cascade system is a specific of selected mountain valleys, formed by reservoirs Porąbka–Żywieckie–Czaniec on the Soła River (a Vistula River tributary) and another one by Topola–Otmuchów–Nysa on the Nysa Kłodzka River (Oder River tributary). Four reservoirs are situated on the Dunajec River course with a total capacity greater higher than 0.4 km^3 (nos. 7, 8, 30, and 37 in Table 1).

High multiannual variability of precipitation and available water for reservoir retention is observed in Polish territory [11, 12]. Therefore, the water volume in dam reservoirs is characterized by significant long-term variability (Fig. 1). In the past 9 years (2009–2017), extreme precipitation was noted in 2010 (including a flood in the Vistula River basin) and extremely dry years in 2012 and 2016. The variability of

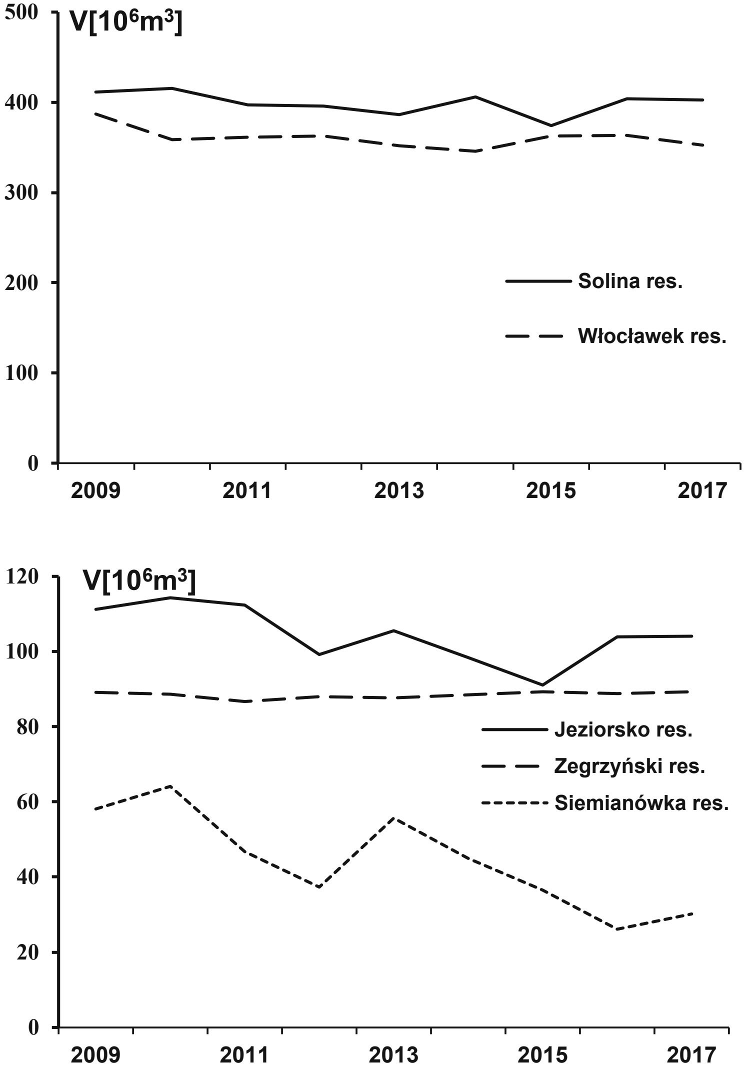

Fig. 1 Changes of mean annual water retention in the years 2009–2017 in largest (*upper panel*) and lowland (*lower panel*) reservoirs

atmospheric water supply is most visible in smaller reservoirs ($<50 \times 10^6$ m^3) where the variation coefficient ranged from 20% to 80%. Lower variation of retained water was observed in the largest reservoirs, such as Włocławek or Solina reservoirs (Fig. 1). Low variability was also noted in reservoirs whose main function is energy production. In seasonal terms, the largest reservoir filling takes place in the spring period (April, May) and lowest level is most often in September or October (Fig. 2).

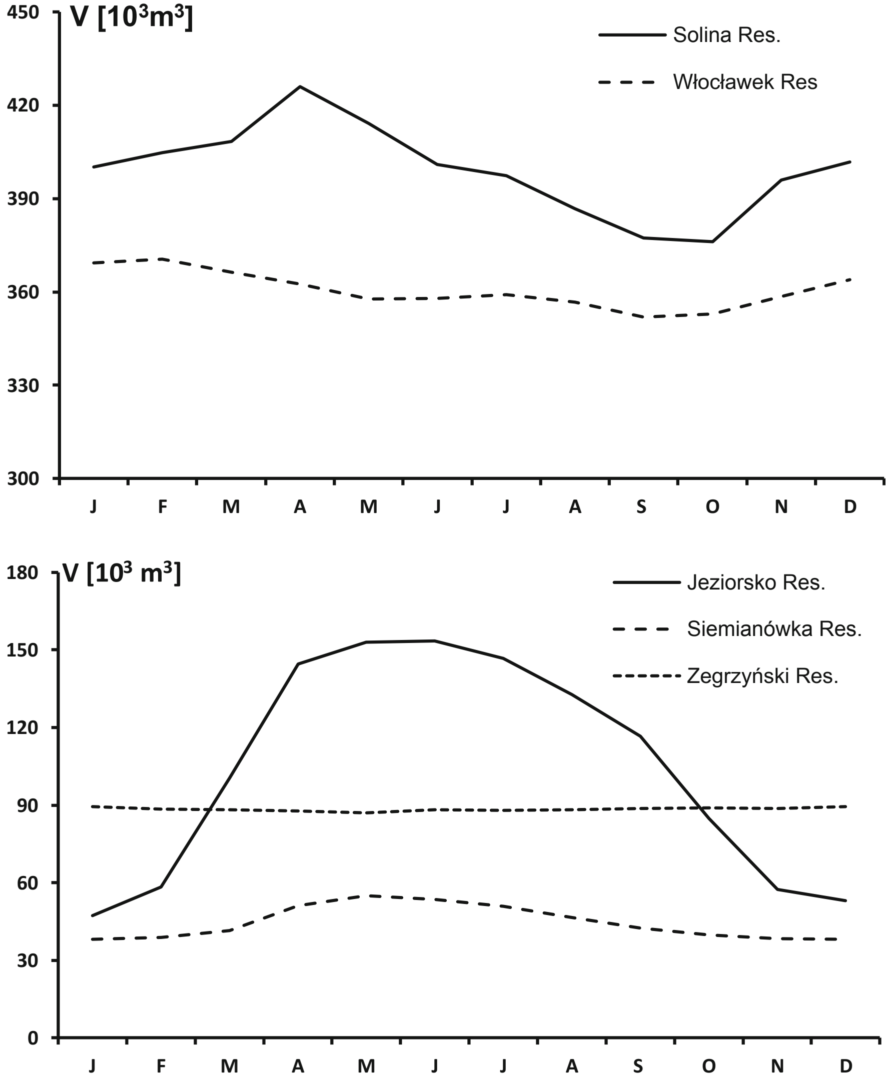

Fig. 2 Mean monthly water volume in the largest (*upper panel*) and lowland dam (*lower panel*) reservoirs in Poland in the years 2009–2017

Average water retention time is significantly differentiated in reservoir conditions, because some of them (such as reservoirs no. 6, 32, and 37 in Table 1) have a short retention time, less than 4–5 days. Among Polish reservoirs presented in Table 1 are those in which theoretical full water exchange is very long, 7–9 months. It is worth emphasizing that in the analyzed Polish reservoirs ice phenomena occur in wintertime, which is especially dangerous for reservoir dams. Extremely dangerous ice jams, affected by local floods, occur in the Włocławek Reservoir in the lower Vistula River.

2 Total Organic Carbon in Reservoirs of Poland

2.1 Data Collection and Methodological Comments

Data for this paper are a part of the data collection of the Polish National Monitoring Network and contain results from the years 2004–2015. I have collected all available data from the 47 dam reservoirs, which main features are presented in Table 1. Reservoirs with a minimum 1 year of sampling in the period 2006–2017 were selected. The number of TOC data for each reservoir varied greatly, from 4 to 120 results. In all, 1280 units of TOC data for reservoir water were analyzed, representing chiefly the largest reservoirs with capacities greater than 10^6 m^3 and located in the central and south parts of Poland. Analyzed reservoirs have about 3.2 km^3 with area of 473 km^2, which corresponds to 90% water volume cumulated in Poland. Dammed lakes functioning as a water dam reservoir and “small retention” objects were omitted in the present analysis. High water volume storage, 54%, exists in mountain or sub-mountain reservoirs; in lowlands this is 36%, and in uplands, 10%.

Sampling frequency was varied, depending on reservoir function; most of the reservoirs used for a potable water supply were sampled once per month. Reservoirs with an energy-dominated function were sampled 4 to 6 times per year, according to the National River Monitoring Protocol [13]. Samples were taken from the surface water layer (0–1 m depth) and located near the dam; on some occasions, samples were taken near the towers used for water supply. Automatic TOC measurements were made using the Polish Norm for direct analyses of TOC in water samples (not filtrated), using high-temperature fittings and measurement of CO_2 by a UV detector. Available data of water conductivity were also collected. Laboratories of the Voivodship Inspectorates of Environment Protection, where TOC analyses were provided, have a national certification of quality.

Original daily hydrological data for 25 reservoirs were provided from the national company “Polish Waters,” the National Centre for Flood Protection in Warsaw. Averages of monthly water volume and outflow from reservoirs were calculated. Mean yearly water retention time for each reservoir was calculated as a ratio of the volume of water to the volume of water outflow in each calendar year. Mean TOC resources in the main hydrological regions were calculated on the basis of average TOC concentrations and available hydrological data for the period 2005–2017. When actual hydrological data were not available, the official normal water volume of the reservoir was used for calculation.

2.2 TOC Variability in Dam Reservoirs

Variability of TOC concentrations for each reservoir is presented in Table 2. The range of TOC concentrations from collected data varied from less than 1 mg C dm^{-3}

Table 2 Total organic carbon concentrations and water conductivity in water of Polish reservoirs

No.	Reservoirs	Years	*n*	TOC [mg C dm^{-3}] Min	Max	Mean	Conductivity [µS cm^{-1}]
1	Besko	2010–2015	36	2.5	8.2	4.9	294
2	Brody	2006–2015	29	3.6	54.0	11.5	334
3	Bukówka	2012, 2014	6	2.6	5.6	4.4	123
4	Chańcza	2006–2015	19	6.7	19.4	8.9	279
5	Cieszanowice	2011	4	12.1	13.9	13.3	252
6	Czaniec	2010–2015	60	2.0	4.3	2.8	196
7	Czchów	2007–2011	20	1.0	6.0	2.7	155
8	Czorsztyn	2008–2012	14	1.3	3.3	2.3	240
9	Dobczyce	2005–2014	119	2.3	5.0	3.4	266
10	Dobromierz	2011–2015	15	1.5	8.1	4.8	263
11	Domaniów	2004–2006	34	4.8	16.3	10.0	378
12	Dzierżno	2010–2015	9	4.7	7.7	5.8	526
13	Goczałkowice	2010–2016	63	2.6	6.8	4.7	201
14	Jeziorsko	2011, 2014	22	6.7	11.3	9.3	382
15	Klimkówka	2008–2012	14	1.2	5.0	3.7	202
16	Kozłowa G.	2010–2015	63	2.1	32.0	13.0	342
17	Leśna	2012, 2014	6	3.9	10.8	7.0	124
18	Lubachów	2011–2015	15	2.4	22.5	5.4	200
19	Łąka	2010–2015	9	7.6	12.0	10.3	646
20	Mietków	2012, 2014	6	3.8	7.2	5.7	435
21	Niedów	2011–2015	15	2.1	14.2	4.8	170
22	Nielisz	2012, 2015	13	4.5	7.2	5.8	463
23	Nysa	2009, 2012, 2015	9	2.1	21.0	7.5	254
24	Otmuchów	2009, 2012, 2016	9	4.1	18.2	8.1	263
25	Pilchowice	2012, 2014	6	1.8	8.6	6.2	196
26	Pławniowice	2010–2015	9	6.1	7.3	6.6	530
27	Poraj	2010–2015	9	6.2	12.0	8.6	403
28	Porąbka	2010–2015	12	2.2	4.8	2.7	201
29	Przeczyce	2010–2015	9	6.8	13.0	9.5	383
30	Rożnów	2007–2012	19	1.2	5.0	2.9	162
31	Rybnik	2010–2015	9	7.6	9.6	8.7	1210
32	Rzeszów	2005–2012	17	3.8	8.9	5.5	505
33	Siemianówka	2009–2014	47	11.5	46.6	18.1	286
34	Słup	2012, 2014	8	5.9	12.0	9.0	359
35	Solina	2010–2014	28	1.1	6.3	3.1	197
36	Sosnówka	2011–2015	15	2.8	9.3	5.0	98
37	Sromowce W.	2008–2011	12	1.2	3.7	2.3	278
38	Sulejów	2005–2015	120	3.3	26.5	9.5	319
39	Topola	2011, 2013	12	1.4	8.0	4.6	294
40	Tresna	2010–2015	18	1.9	9.2	3.5	193
41	Turawa	2009, 2011, 2014	9	7.0	21.4	11.4	299

(continued)

Table 2 (continued)

No.	Reservoirs	Years	*n*	TOC [mg C dm^{-3}] Min	Max	Mean	Conductivity [μS cm^{-1}]
42	Wióry	2012–2015	10	4.5	7.1	5.8	390
43	Wisła–Czarne	2007–2014	111	0.9	7.0	3.3	74
44	Włocławek	2005–2014	89	5.1	14.0	8.6	620
45	Zegrzyński	2010–2014	89	4.9	20.6	11.7	596
46	Zemborzyce	2012–2013	8	3.9	11.6	7.8	360
47	Złotniki	2012	4	6.8	10.5	8.9	111

n, number of samples

up to 54 mg C dm^{-3}; the mean value (weight by volume) for a reservoir is 6.3 mg C dm^{-3}.

The Czorsztyn and Sromowce reservoirs had the lowest TOC levels; in the Siemianówka reservoir, TOC concentrations were ten times higher. Increase of TOC resources in the reservoirs was related to decrease of basin elevation (Fig. 3); thus, water dammed in lowland, upland, and mountain reservoirs had TOC mean (by weight) concentrations of 10.0, 8.1, and 36 mg C dm^{-3}, respectively.

These data confirm the role of soil carbon resources in the basin, because eroded soil material is the main source of the organic carbon load to surface waters [14]. Also, significant differences in reservoir TOC concentrations are derived from various characteristics of size and mass of river deposits in the upper part of each reservoir. The coarse material and that poor in organic content is buried in the upper reference part of mountain reservoirs and has a only small part in water enrichment by TOC in the reservoir during the active process of mineralization, caused by variations in dam water level. In upland, and especially in lowland, reservoirs that are more shallow, riverine material is distributed through most of the impoundment area and creates more available conditions to additional bottom TOC influx. Furthermore, lowland reservoirs with more varied flooded areas favor intensive macrophyte or other hygrophyte colonization and become “hotspots” of nutrients as well as organic compounds. Mineralized detritus of water plants and organic matter of shore-wetted soils also become sources of greenhouse gases (GHG) [15]. It is not without significance that lowland water retention usually occurs in shallow, polymictic water bodies, where multiple whole column mixing accelerates the microbiological mineralization and utilization of organic particles [4, 6], parallel to UV photobleaching of DOC components [7].

There are statistically significant relationships (negative) between TOC and mean reservoir depth (Fig. 4), but larger TOC variability (four- to sixfold) was observed in a group of shallow reservoirs than for deeper ones (two- to threefold). The same relationships, but for highly rheolimnic reservoirs, exist with a slightly lower concentration range.

Water retention time is important in the creation of TOC resources in the lowland, upland, and smaller mountain reservoirs, where statistically significant positive correlations are present (Fig. 5). Long water residence activates development of

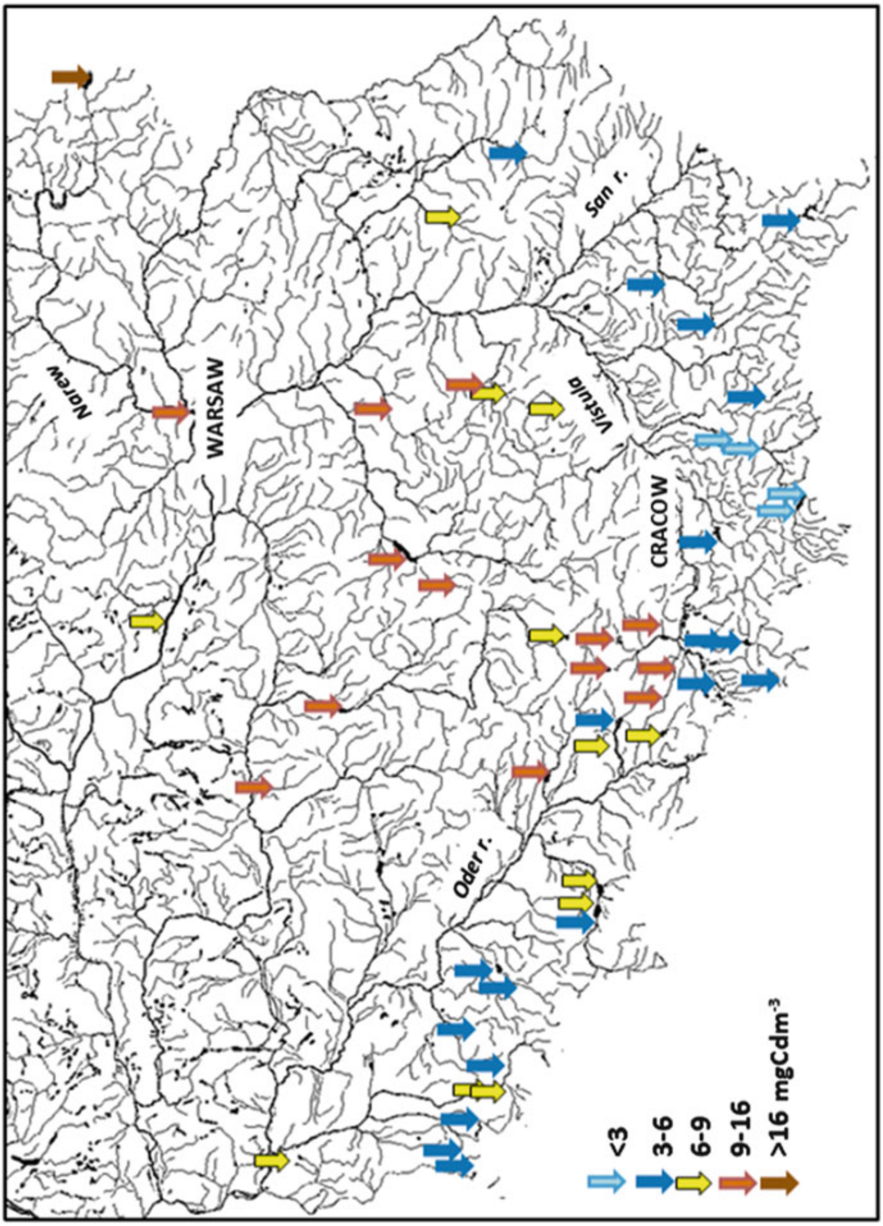

Fig. 3 Mean TOC concentrations in water of Polish reservoirs

bacteria and phytoplankton [6, 16, 17] and in consequence starts the eutrophication process gradually [18], resulting from an increase of organic matter resources not utilized by consumers in the food web [6]. An intensive allochthonous organic

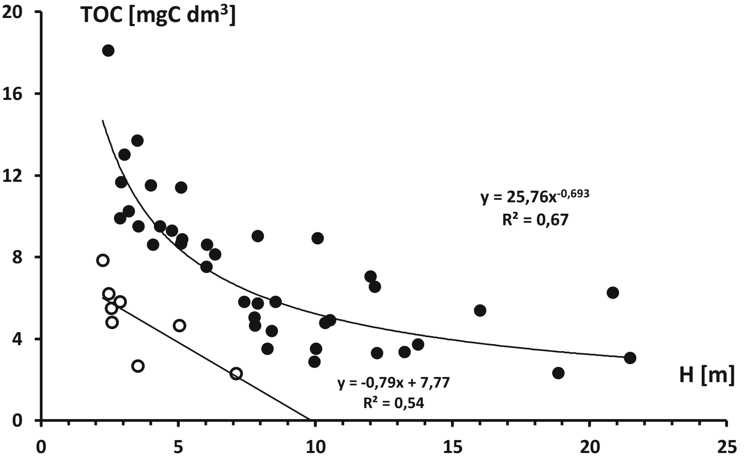

Fig. 4 Correlation between mean depth of reservoir and average TOC concentration in Polish water reservoirs; *open circles* indicate Low Silesia region

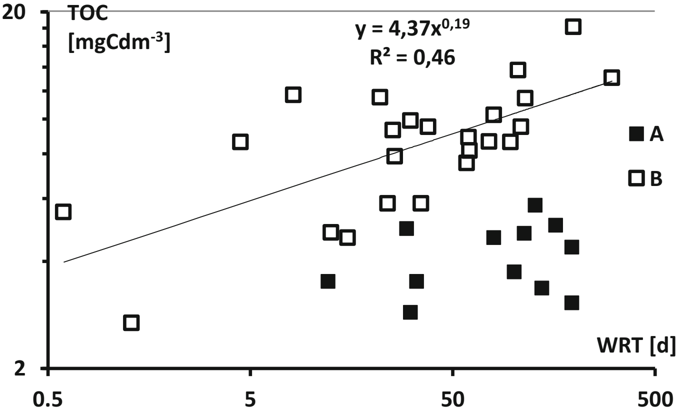

Fig. 5 Relationships between water residence time (days) and mean TOC concentrations in water of Polish reservoirs: (A) deep and large mountain reservoirs; (B) lowland, upland, and smaller mountain reservoirs

matter supply of water bodies, common with organic nitrogen and phosphorus, resulted in especially high *Cyanophyta* development. Because blue-green algae is mixotrophic, easily utilizes organic materials, and tolerates low water transparency, it becomes dominant in phytoplankton eutrophic lakes [6]. This type of eutrophic "organic" water, without additional anthropogenic water pollution, is named humeo-eutrophication [9].

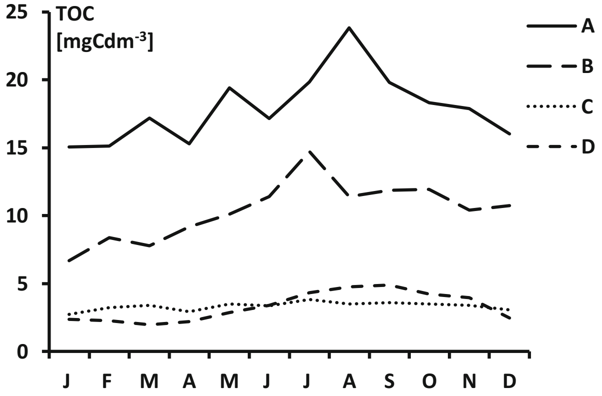

Fig. 6 Mean monthly TOC concentrations in selected reservoirs in the years 2009–2015: A, Siemianówka reservoir; B, Sulejów reservoir; C, Dobczyce reservoir; D, Wisła–Czarne reservoir

2.3 TOC Seasonality and Multiannual Changes

Reservoir ecosystems are very dynamic because of their strong dependence on the river hydrological regime and their main proposed function. A more objective analysis of TOC dynamics in Polish dam reservoirs is limited, because only in a few reservoirs is long-term monitoring provided. I have collected monthly data only from a few reservoirs: Wisła–Czarne and Dobczyce in the mountains and Sulejów, Włocławek, and Zegrzyński in the lowlands.

With increasing average TOC concentrations, seasonality is increased. Increase of water TOC concentrations is observed in the spring and summer months (Fig. 6). The spring period is affected by snow melting, and the summer months are associated with heavy rains and stormy season, locally inducing floods. It is noted that the spring water inflow most significantly increases TOC concentrations in lowland reservoirs, whereas in the mountains TOC increases during summer floods. A variation coefficient of TOC calculated for a few reservoirs with more frequent data indicated that mean variability variation is in the range of 22% to 55%, the highest coefficients being characteristic of basins with wetlands. Long-term data for the lowland Siemianówka reservoir showed that the organic load entering this type of reservoir with spring waters determined the resources of organic matter in reservoirs for the entire vegetation season [18].

The seasonal repetition of the TOC cycle in dam reservoirs is typical for semi-natural basins, as observed in the Wisła–Czarne reservoir with protected forest areas (Fig. 7). The greater variability of TOC resources in particular seasons was recorded in reservoirs with significant changes in basin management. Urban and agricultural areas become more reactive to rainwater supply than forests or wetlands; then, a rapid response of TOC export becomes significant [19, 20].

Despite the short period of research and analysis, characteristic elements of multiannual TOC variability in Polish reservoirs were noted. In the discussed period there were clear differences in TOC concentrations in reservoir waters under different hydroclimatic conditions. The highest TOC values were observed in all

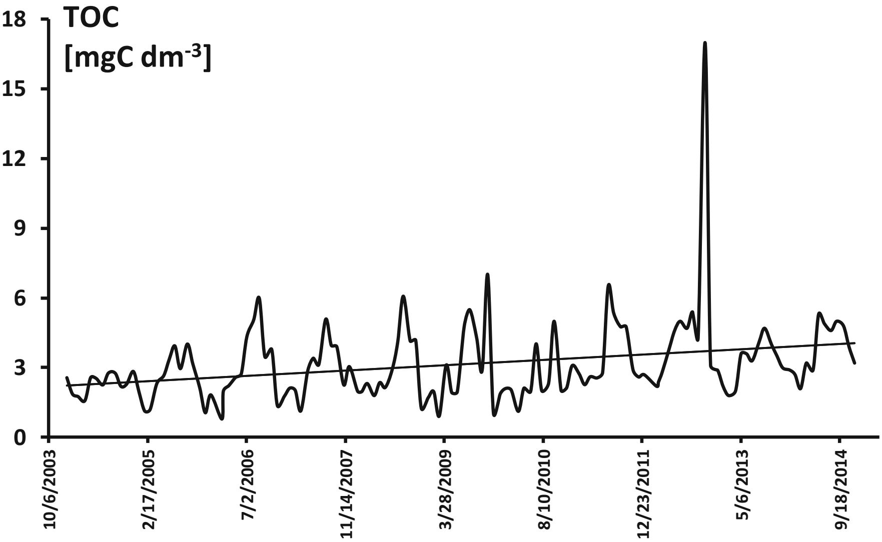

Fig. 7 Long-term variation of TOC in Wisła-Czarne reservoir in years 2003–2014

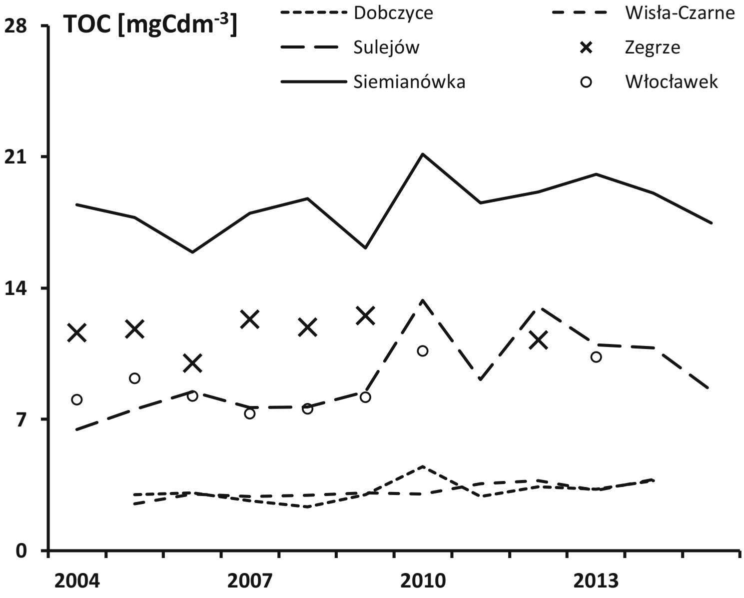

Fig. 8 Yearly mean TOC concentrations in selected Polish reservoirs

reservoirs in the year 2010 with high summer precipitation and floods (Fig. 8), when intensive soil organic carbon erosion takes place. In the dry year 2012, with low atmospheric water supply (precipitation less than 50% of multiannual mean), TOC concentrations were also low. Similar results for a drought period were presented earlier for rivers in northeast Poland [21].

2.4 Resources of Total Organic Carbon in Polish Reservoirs

Water dammed in Polish reservoirs of different regions had variable TOC mean (weight) concentrations (Table 3). Lowlands reservoirs have a TOC concentration four times higher than that observed in mountain reservoirs. Reservoirs located in the Odra River basin had significantly higher TOC concentrations than reservoirs in the Vistula River basin, 3.65 and 6.61 mg C dm^{-3}, respectively. This difference is related to the differences in the clay content in the weathered rocks, fertility, and organic carbon resources in the soils formed on them.

I have estimated that there is 1.29 t of organic carbon in the water of Polish reservoirs. In the waters of six dam reservoirs, that is, Jeziorsko, Siemianówka, Solina, Sulejów, Włocławek, and Zegrzyński, 60% of the total TOC resources of the water of Polish reservoirs is found. Additionally, nearly 40% of these resources was in the Włocławek reservoir. It should be noted that the indicated TOC resource concerns waters leaving the reservoirs and it must be assumed that they are greater in reality. TOC concentrations in the water near the dam resulted in a balance of the allochthonous basin TOC load and in-reservoir processes in which both the utilization and autochthonous production of organic matter take place [22]. Reservoir morphology, water retention time, and upstream water composition determine the real relationship between river, transitional, and lacustrine longitudinal zones usually highlighted in dam reservoirs. Globally, it is considered that in a reservoir carbon mineralization exceeds carbon fixation ($P < R$), next to the carbon burial processes [5]. Generally, longitudinal TOC concentration decrease was observed within the reservoir, but in some eutrophic reservoirs with large flooded areas TOC increase was present, as in Siemianówka reservoir [9, 18, 23], which confirms the significant role of flooded areas in the trophic state of reservoirs [5, 15, 24, 25].

Table 3 Regional differentiation of TOC and water resources in the investigated dam reservoirs in Poland

Region	*n*	Average ± SD	Mean (weight)	Water	TOC
		[mg C dm^{-3}]		[%]	
Mountains	4	2.75 ± 0.51	2.85	27.2	12.2
Sub-mountains	23	5.17 ± 1.61	4.68	30.4	22.4
–Vistula R. basin	10	3.91 ± 0.92	3.65	19.9	11.4
–Oder R. basin	13	6.18 ± 1.37	6.61	10.5	11.0
Uplands	11	8.52 ± 2.00	8.34	6.3	8.2
Lowlands	9	11.48 ± 2.88	10.00	36.2	57.2
Mean	47	6.97 ± 3.38	6.34		

Earlier evaluation of water TOC export along the Vistula River clearly showed the large role of Włocławek reservoir in elimination of organic carbon carried from Poland to the Baltic Sea [26], where approximately 20% of annual TOC export is reduced.

3 Perspectives

This positive aspect of functioning Polish dam reservoirs in protection of the Baltic Sea is connected also with an active "hotspot" of greenhouse gas (GHG) emission, together with other Polish dam reservoirs. During global warming, from one aspect, increase of soil organic carbon erosion is forecast, contributing to a slow increase of the TOC pool in dammed waters. The first symptoms of that increase are being observed now in selected Polish reservoirs (Fig. 8). Also forecast is an increase of air temperature that will generate additional emission of greenhouse gases from water reservoirs, while increasing the costs of electricity production. As recently globally calculated, the carbon footprint of hydropower is greater than previously assumed and in global warming this effect will increase [27]. Moreover, an increase of basin TOC flux to reservoirs affected by climatic and hydrological changes will cause an increase of water utilization costs, in consequence of changes in water treatment technologies. A more intensive organic carbon monitoring network is needed, covering water, sediments, and GHG emissions, in diverse Polish dam reservoir ecosystems, especially where TOC resources are highest.

The present evaluation of TOC resources in Polish dam reservoirs was closely related to other chemical and biological parameters of water collected by ecological monitoring from the years 2010–2015 and provided by the Chief Inspectorate of Environmental Protection. Average TOC concentrations in reservoirs were positively correlated with water conductivity ($r = 0.58$, $p < 0.05$). Among the biological parameters there was an inversely proportional relationship between TOC in waters and values of the phytoplankton index (IFPL) ($r = 0.79$, $p < 0.001$). A less strong correlation was observed between TOC and the benthic diatom index (IOPL) ($r = 0.51$, $p < 0.05$). Established significant correlations confirm the possibility of a wider use of the TOC parameter in assessment of the status or ecological potential of dam reservoir ecosystems.

This first evaluation of TOC assets conducted in Polish dam reservoirs offers conclusions for location of the next planned water reservoirs. The reservoirs should be located outside the lowland areas, where there are vast areas of peat soils abundantly supplying water to the TOC. The same problem of high TOC concentrations in lowland dam reservoirs exists in large reservoirs in the Volga River basin [28] or in dammed rivers in Lithuania, Latvia, or Estonia.

Most of the lowland Polish dam reservoirs have low water quality and natural high TOC resources, accelerating the eutrophication process with late summer heavy blooms of toxic *Cyanophyta*, examples of which are the Sulejów, Siemianówka, or Zemborzyce reservoirs [18, 29]. Future Polish reservoirs should be placed on rivers where relationships between the catchment areas over a reservoir area have rates higher than 1000 (data not presented), ensuring high water exchange, and preventing intensive phytoplankton development, especially of *Cyanobacteria*.

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