

Water resources of the Struga Toruńska river (Central Poland) in the context of climatic changes in 1994-2012

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Abstract: This article provides an analysis of the water resources of the Struga Toruńska (ST), a small river in Central Poland. The ST is 51 km long and its catchment area covers 371 km². The area of the ST basin is intensely cultivated – arable land makes up 71.6%. The studies of the water resources held in the catchment area were carried out in the years 1993 – 2012 as part of investigations into the climate change. The spatial diversity of the water balance was analysed using a SWAT model. Physical and chemical properties of the water in the ST were studied as well. The water resources of the ST were found to rely on changeable weather conditions and, particularly, on the distribution of atmospheric precipitation, snow cover and the rate of evapotranspiration. The agricultural exploitation of the catchment area leads to the high concentrations of biogenic compounds (particularly nitrates) and causes a progressing deterioration of the water in the ST, which results in reduced functional qualities of the river. Water below the lakes characterised by a high degree of eutrophication, an increase in the organic content was observed, along with a reduction in oxygenation of the water.

Key words: water resources, quality of water, climate change, Struga Toruńska, Poland

1. Introduction

Poland has quite small water resources with surface waters supplying approx. 62 km³ and ground waters approx. 16 km³. With just 1,580 m³ of water per person per year these are some of the lowest values in Europe [2,3,4,7]. Central Poland is affected the most due to the smallest amount of atmospheric precipitation (approx. 500 mm) and their unfavourable distribution throughout

the year. The maximum amount of rainfall in Poland is observed in summer, when the greatest evapotranspiration occurs [4,5]. Besides, there is a limited possibility to use the water resources because of a considerable pollution of the water. The purpose of this article is to provide an assessment of the water resources within the small catchment basin of the Struga Toruńska River, which flows into the Wisła (Vistula) River, the main Polish river.

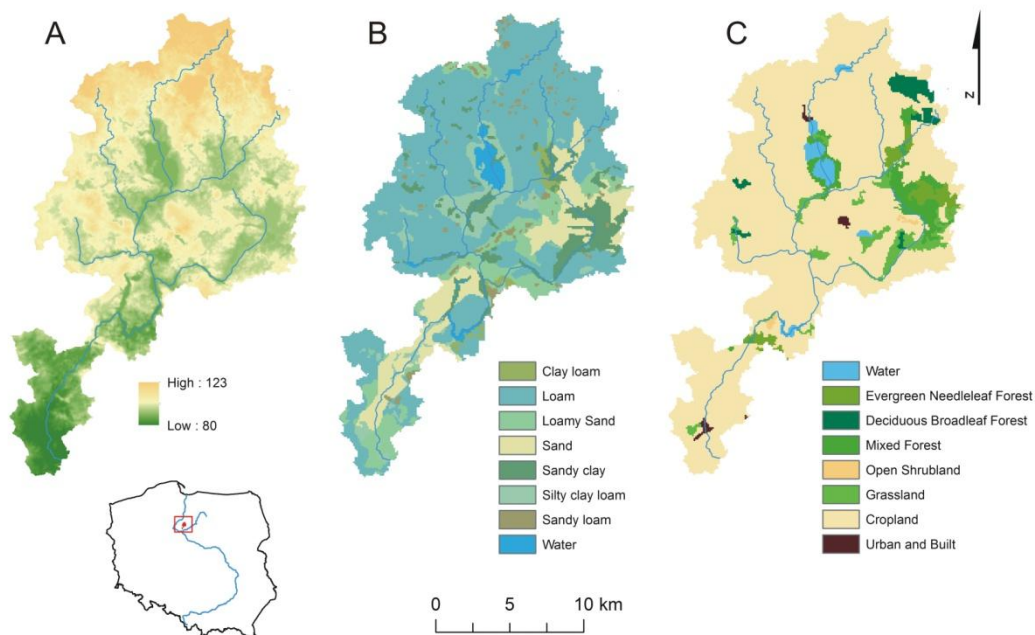


Fig. 1. Struga Toruńska catchment: A - hipsometry, B - surface features, C - land use

2. Research area and methodology

The ST is a small, 51-km-long river in Central Poland, flowing into the Wisła (Vistula) River (fig. 1). Its catchment area is 371 km² and – in its upper and central part – entails a morainal upland of the Weichsel glaciation, in the lower part, the river flows on an outwash plain and the terraces of the Vistula Valley. There are 19 lakes with a total area of 11.9 km² within the catchment basin. The area of the ST basin is intensely cultivated – arable land makes up 71.6% and grassland 8.5% of the area. Forest land, represented by two stands, covers 11.8 km² (forestation rate 3.4%) [8] - fig. 1. An abundance of ditches and drains disturbs the natural water circulation pattern within the catchment basin.

The state of environment in the ST catchment area, including the water balance and water quality have been studied since 1993, as part of the Integrated Environmental Monitoring Programme. As many as 11 research programmes are being conducted within the catchment area, comprising both abiotic and biotic elements of the environment. Meteorological observations were carried out at Konieczynka from 1993 until 2012. Their representative character was demonstrated in comparison with a longer period of measurements from the nearby weather station of the Institute of Meteorology and Water Management in Toruń (1951-2012). The water flow was calculated

using daily measurements of the water flow in the ST at Konieczynka and monthly measurements of the flow, using a current meter. The water quality, on the other hand, is examined every month at 2 points by the Provincial Inspectorate of Environmental Protection in Bydgoszcz.

3. Meteorological conditions

In the years 1994-2012 at Konieczynka, the mean annual temperature of the air was 8.5°C, changing from 6.5°C in 1996 to 9.6°C in 2000. In an annual course, the maximum mean temperature was observed in July (19.1°C), whereas the minimum occurred in January (-1.6°C) - table 1. The absolute range of air temperature reached 65°C, from -28.3°C to 36.9°C. The degree of cloudiness was high at that time (7.2 in a scale of 0 to 10), especially in the autumn and winter months. The sunshine duration was 1,609.2 hours, and the relative humidity of the air reached 78.4%, with the lowest values in the warm half of the year (68% in May, 69% in April and 70% in August). The mean annual sum of atmospheric precipitation amounted to 546.6 mm, with the maximum in the warm half of the year (95.4 mm in July). The snow remained on the ground, on average, for 27.2 days in a year, from October until April. Its maximum thickness reached 40 cm in February 2010. The mean wind speed of 3.3 m s⁻¹ was rather low.

Table 1. Mean values of meteorological elements at Konieczynka in the years 1994-2012

Months	Cloudiness (0-10)*	Sunshine duration (hours)#	Air temperature (°C)			Air humidity (%)	Precipitation (mm)	Snow cover		Wind velocity (m s ⁻¹)
			max	mean	Min			days	max (cm)	
J	8.1	30.9	12.0	-1.6	-28.3	87.6	32.2	8.3	38	3.9
F	7.6	59.1	13.0	-0.8	-23.0	84.7	27.1	6.8	40	4.0
M	7.0	128.0	20.9	2.7	-19.9	80.1	30.5	3.0	18	4.0
A	7.0	189.0	31.8	8.7	-8.0	69.2	30.3	0.1	3	3.5
M	6.2	234.1	30.9	13.6	-3.6	67.7	56.4	.	.	3.2
J	6.8	221.3	34.4	16.6	4.0	71.2	51.0	.	.	3.0
J	6.5	213.0	36.9	19.1	4.6	71.5	95.4	.	.	2.8
A	6.3	215.3	35.6	18.5	6.2	70.1	68.0	.	.	2.8
S	7.1	163.1	31.5	13.8	0.0	76.8	49.6	.	.	2.9
O	7.2	95.0	24.1	8.5	-6.1	82.0	33.7	0.1	1	3.1
N	8.1	38.0	16.9	3.6	-17.6	88.1	35.4	2.0	9	3.3
D	8.2	22.4	12.5	-0.7	-20.5	88.7	36.9	6.9	35	3.6
Year	7.2	1609.2	36.9	8.5	-28.3	78.4	546.6	27.2	40	3.3

*-1994-2002, # -1996-2012

In Poland, like in most regions of the world, the temperature of air has been found to increase. In the years 1951-2012, at the Toruń weather station the increase amounted to 0.26°C/10 years (the statistically significant trend was <0.05) - fig. 2. In the patterns of atmospheric precipitation both dry periods and periods

of escalated rainfall without a significant trend were observed. For example, in the years 1994-2012 at Konieczynka, the annual sum of precipitation varied from 410.7 mm in 1996 to 766.3 mm in 2010 (fig. 2).

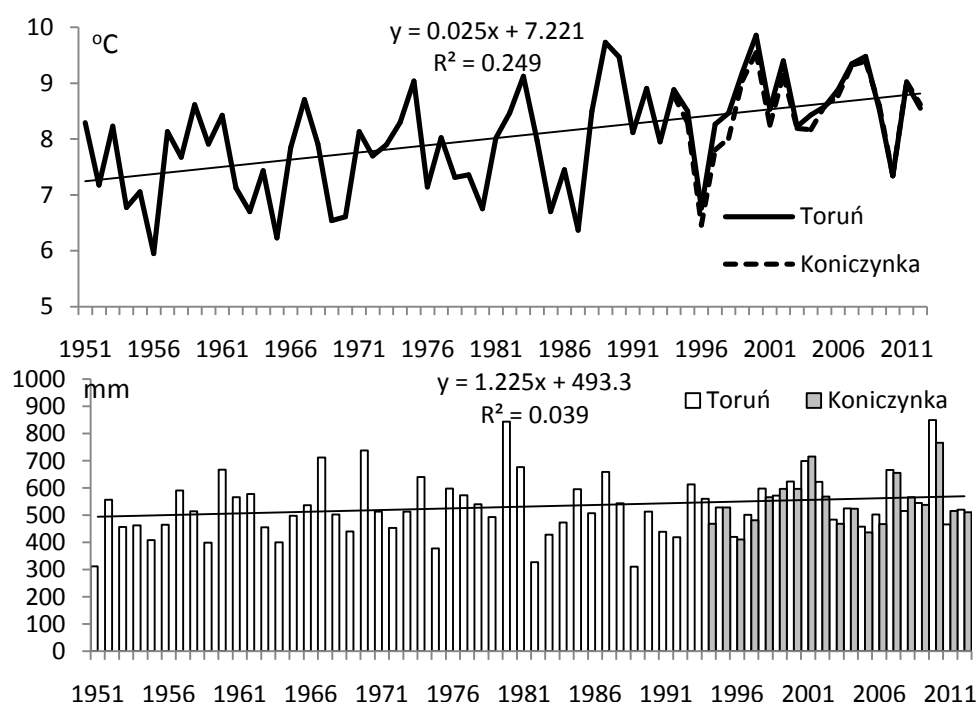


Fig. 2. Course of air temperature and precipitation at Toruń (1951-2012) and Koniczynka stations (1994-2012)

3. Runoff

In the years 1994 – 2012, the mean water flow in the ST was $0.59 \text{ m}^3 \text{ s}^{-1}$ (table 2). The highest flow is typical of spring (i.e. March and April), when it exceeds $1 \text{ m}^3 \text{ s}^{-1}$, which is connected with the springtime melting of snow cover. A clear decrease in the water flow was observed in summer ($0.35 \text{ m}^3 \text{ s}^{-1}$ in June) and in autumn ($0.38 \text{ m}^3 \text{ s}^{-1}$ in November). In analyzed period the mean

water flow ranged from $0.28 \text{ m}^3 \text{ s}^{-1}$ in 2000 to $0.99 \text{ m}^3 \text{ s}^{-1}$ in 2011. The highest value of monthly flow ($2.7 \text{ m}^3 \text{ s}^{-1}$) was recorded in February 2007. On average, $18.69 \times 10^6 \text{ m}^3$ of water runs off from the ST. The river has a moderately developed nival regime of the runoff with a maximum in spring ($2.72 \times 10^6 \text{ m}^3$). The mean contribution of the springtime runoff amounted to 152% of its mean monthly value. The least water runoff in summer ($0.91 \times 10^6 \text{ m}^3$ in June).

Table 2. Monthly values of precipitation and runoff in Struga Torunska river (in Koniczynka) in the years 1994-2012

Month	Precipitation [mm]	Outflow $\text{m}^3 \text{ s}^{-1}$	Runoff $\text{m}^3 \times 10^6$	Drain water unit $\text{l} \cdot \text{s}^{-1} \cdot \text{km}^{-2}$	mm	% Precipitation
N	35.4	0.38	0.98	1.22	3.2	8.9
D	36.9	0.45	1.20	1.47	3.9	10.5
J	35.4	0.68	1.80	2.21	5.8	19.1
F	36.9	0.93	2.30	2.98	7.4	24.6
M	30.5	1.02	2.72	3.33	8.8	15.6
A	30.3	1.01	2.62	3.26	8.5	16.6
M	56.4	0.67	1.80	2.20	5.8	6.1
J	51.0	0.35	0.91	1.14	3.0	4.4
J	95.4	0.36	0.96	1.17	3.1	6.2
A	68.0	0.43	1.15	1.41	3.7	11.0
S	49.6	0.48	1.23	1.54	4.0	11.3
O	33.7	0.40	1.07	1.32	3.5	9.4
Year	546.6	0.59	18.69	1.92	60.5	11.1

The mean individual runoff was small and amounted to $1.92 \text{ l}\cdot\text{s}^{-1}\cdot\text{km}^{-2}$, which is a typical value for lowland rivers in Central Poland [5]. For the whole Poland, the mean value of runoff is $5.6 \text{ l}\cdot\text{s}^{-1}\cdot\text{km}^{-2}$ [4,5]. The small individual runoff results from the geological structure and an abundance of lakes within the catchment area of the ST (the river flows through a number of lakes) [8]. The greatest amount of runoff is observed in spring

($3.33 \text{ l}\cdot\text{s}^{-1}\cdot\text{km}^{-2}$ in March), and the smallest in June ($1.14 \text{ l}\cdot\text{s}^{-1}\cdot\text{km}^{-2}$) - table 2.

The ST carries just 60.5 mm of water from the surface of the catchment area, which is 11.1% of the precipitation. The highest rate of runoff occurs in spring (7.4 mm in February, which makes 24.6% of the precipitation total) and the lowest in summer (3.0 mm in June; 4.4%).

Table 3. Mean yearly values of air temperature, precipitation in Koniczynka and runoff from Struga Toruńska river in the years 1994-2012

Year	Air temperature (°C)	Precipitation [mm]	Outflow m^3s^{-1}	Runoff $\text{m}^3\cdot\text{s}^{-1}\cdot\text{km}^{-2}$	Drain water unit $\text{l}\cdot\text{s}^{-1}\cdot\text{km}^{-2}$	mm	% Precipitation
1994	8,3	498,7	0,62	19,51	2,00	63,1	12,6
1995	9,1	577,8	0,45	14,18	1,45	45,9	7,9
1996	6,1	405,0	0,66	20,80	2,13	67,3	16,6
1997	7,6	444,4	0,31	9,70	0,99	31,4	7,1
1998	8,5	562,8	0,51	16,20	1,66	52,4	9,3
1999	8,5	579,6	0,85	26,69	2,74	86,3	14,9
2000	9,2	558,7	0,28	8,98	0,92	29,0	5,2
2001	8,9	762,0	0,54	17,02	1,74	55,0	7,2
2002	9,3	593,8	0,73	22,87	2,34	74,0	12,5
2003	7,5	468,6	0,39	12,20	1,25	39,4	8,4
2004	8,3	496,1	0,60	19,05	1,95	61,6	12,4
2005	8,7	413,0	0,77	24,29	2,49	78,6	19,0
2006	8,2	497,8	0,65	20,47	2,10	66,2	13,3
2007	10,0	670,7	1,03	32,45	3,33	104,9	15,6
2008	9,2	592,6	0,52	16,51	1,69	53,4	9,0
2009	8,7	500,2	0,37	11,65	1,19	37,7	7,5
2010	7,9	674,9	0,56	17,65	1,81	57,1	8,5
2011	8,4	647,2	0,99	31,16	3,19	100,8	15,6
2012	8,9	484,2	0,46	14,58	1,50	47,2	9,7
Mean	8,5	548,8	0,59	18,69	1,92	60,5	11,0

The runoff and its rates for the Struga Toruńska River are substantially varied year after year (table 3). The greatest runoff, which reached 32.45 million m^3 , occurred in 2007 (fig. 3). That year was marked by huge amounts of atmospheric precipitation (762.0 mm). On a diurnal course, the primary peak was observed in spring, which was connected with ample rain and snow falls in January and the melting of the snow cover, and the secondary maximum value was observed in September, after generous rainfalls that occurred from May until September. The least water ran off in 2000 (8.98 million m^3) - fig. 3. The precipitation total was nearly standard (558.7 mm), however its distribution over the year was unfavourable. The winter of 1999/2000 was a mild one, as only in January the temperatures fell below zero (-0.7°C), and the snow cover was not solid and reached a maximum thickness of 9 cm in November and 8 cm in March. Therefore, the amount of spring thaw water was exceptionally small. After a period of deficient precipitation (from April to June), quite a high amount of rainfall from July to September did not enhance the flow of the ST, as most of the precipitable water

evaporated or supplied the lakes that the river flows through, or augmented the groundwater resources.

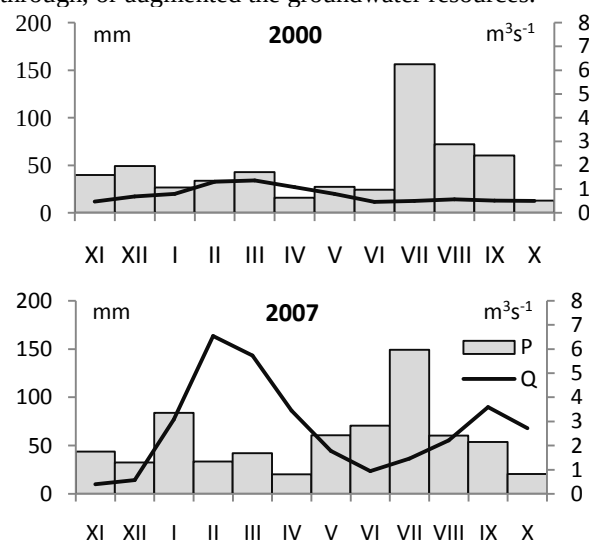


Fig. 3. Course of precipitation (P) and outflow (Q) on Struga Toruńska river in Koniczynka in 2000 and 2007

4. SWAT model

As part of the study, the water balance of the sub-catchments of the ST was calculated using a SWAT model (Soil and Water Assessment Tool) developed by the Soil and Water Research Laboratory, Temple, USA [1]. The water balance for the ST river basin was determined on the basis of meteorological data, a digital terrain model (resolution 30 m), ground cover, and types of soil (fig. 1). Data concerning the amount of atmospheric precipitation, snowfalls, evaporation, percolation and immediate runoff were obtained for individual sub-catchments. The amount of potential

evaporation in the catchment basin ranged from 326.4 mm to 614.3 mm. The mean value of percolation was 191.7 mm, and immediate runoff 54.5 mm (fig. 4). It was determined that the greatest evaporation occurs in the sub-catchments with the greatest area of lakes and marshes. The surface runoff is small and depends on the slope of land. Seepage depends on the geological structure and reaches its highest values in sandy soil formations. In the studied period a negative water retention occurred in the basin.

The water balance for the catchment is negative, and ranges from -4.1 to -191.5 mm in the sub-catchments.

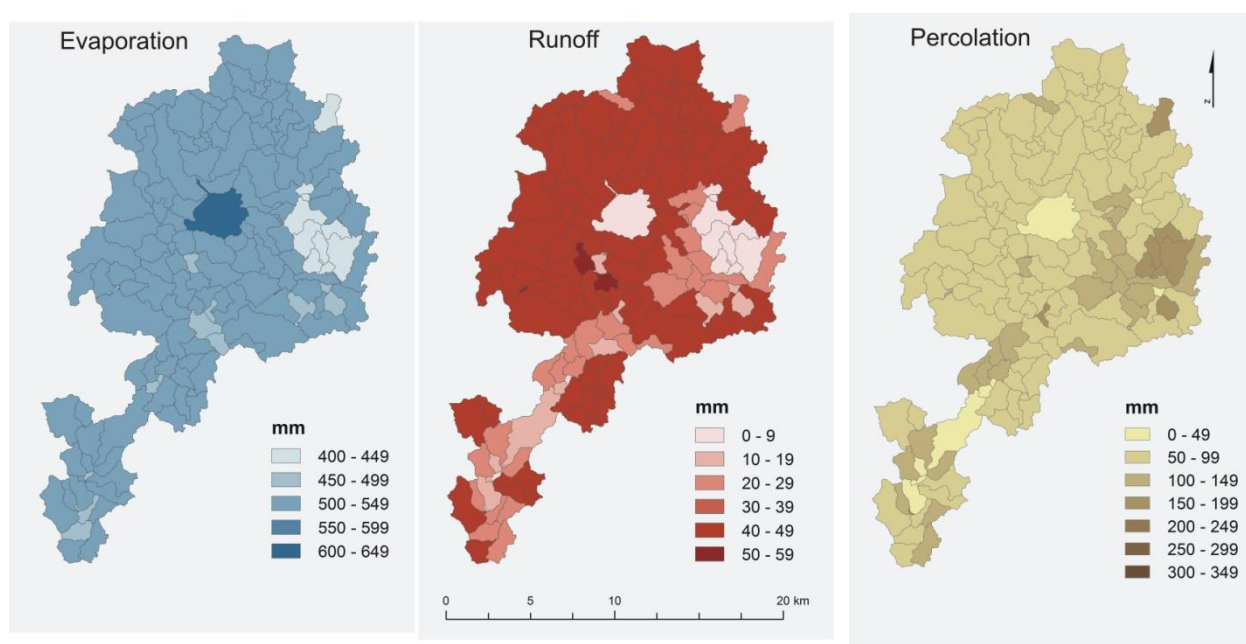


Fig. 4. Evaporation, runoff and percolation on the Struga Toruńska catchment, 1994-2012

5. Water quality

Using monthly chemical analysis reports for water sampled from the ST the following average concentrations were found for the years 1993 – 2012: S-SO_4 – $35.4 \text{ mg}\cdot\text{dm}^{-3}$, N-NO_3 – $3.83 \text{ mg}\cdot\text{dm}^{-3}$, N-NH_4 – $0.17 \text{ mg}\cdot\text{dm}^{-3}$, HCO_3 – $313.5 \text{ mg}\cdot\text{dm}^{-3}$, P – $0.19 \text{ mg}\cdot\text{dm}^{-3}$, Cl – $45.7 \text{ mg}\cdot\text{dm}^{-3}$, Na – $17.5 \text{ mg}\cdot\text{dm}^{-3}$, K – $9.3 \text{ mg}\cdot\text{dm}^{-3}$, Mg – $18.4 \text{ mg}\cdot\text{dm}^{-3}$, and Ca – $132.7 \text{ mg}\cdot\text{dm}^{-3}$. Electrolytic conductivity was $76.4 \text{ mS}\cdot\text{m}^{-1}$, pH 7.9, oxygen content $8.3 \text{ mg}\cdot\text{dm}^{-3}$, and the amount of organic compounds, expressed by BZT_5 – $3.1 \text{ mg}\cdot\text{dm}^{-3}$. The water in the ST manifests a high electrolytic conductivity and amount of dissolved compounds of: calcium, magnesium, sodium, chlorides and sulphates. In the analysed period, an increasing trend was observed in the concentration of nitrates, phosphates and total phosphorus. In the sections located below the lakes, characterised by a high degree of eutrophication of the water, an increase in the organic content was observed, along with a reduction in oxygenation of the water. The agricultural exploitation of the catchment area leads to the high concentrations of biogenic compounds (particularly nitrates) and causes a progressing

deterioration of the water in the ST, which results in reduced functional qualities of the river.

Summary

The catchment area of the ST (309.3 km^2) receives 169 million m^3 of water from the atmosphere (546.6 mm), 18.69 million m^3 of which, or 11.1% of the precipitable water (60.5%), is carried away by the river. On average, $1.92 \text{ dm}^3\cdot\text{s}^{-1}\cdot\text{km}^{-2}$ of water runs off an area of 1 km^2 , while the rest of the water is evaporated, absorbed by the soil or retained by the lakes. The mean values of individual runoff for the rest of Poland are distinctly higher and reach $5.56 \text{ dm}^3\cdot\text{s}^{-1}\cdot\text{km}^{-2}$ [2].

The values of individual components of the water balance, obtained using a SWAT model, indicate that evaporation within sub-catchments ranges from 326.4 mm to 614.3 mm. Some of the water seeps through the soil and supplies underground water resources (with maximum values reaching 191.7 mm), whereas the surface runoff does not exceed 54.5 mm. The water balance for the catchment is negative, and ranges from -4.1 to -191.5 mm in the sub-catchments.

The water resources in the Struga Toruńska River change over the year and year after year, depending on meteorological conditions (atmospheric precipitation in particular), water resources held in the snow cover and the intensity of evapotranspiration. The average water runoff of the ST is $0.59 \text{ m}^3\text{s}^{-1}$. During the year, the greatest water flow is observed in spring ($1.02 \text{ m}^3\text{s}^{-1}$ in March), and the smallest in summer ($0.35 \text{ m}^3\text{s}^{-1}$ in June). The lowest runoff occurred in 1997 (9.70 m^3 , $0.31 \text{ m}^3\text{s}^{-1}$), and the highest in 2011 (31.16 m^3 , $0.99 \text{ m}^3\text{s}^{-1}$). The water quality is inappropriate due to intensive agricultural activities, which result in a high concentration of biogenic elements (predominantly

nitrites) and the water that leaves the lakes has a high degree of hypertrophication, increased amounts of organic content and a reduced amount of oxygen. In Poland, a considerable variability of flow is a main cause of water shortages. Most of the water runs off in the winter and spring melting of the snow, whereas in summer, the time of increased growth and the greatest demand for water, the flows are the smallest [4].

Acknowledgments

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