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The role of a eutrophic lowland reservoir in shaping the composition of river phytoplankton

Magdalena Grabowska

Department of Hydrobiology, Institute of Biology, University of Białystok,
Świerkowa 20B, 15-950 Białystok, Poland, e-mail: magra@uwb.edu.pl

Abstract

The manuscript documents the role of a shallow eutrophic reservoir, Siemianówka Dam Reservoir, in deterioration of water quality in a dammed lowland river basin. Changes in phytoplankton composition and abundance were observed along a 152.5 km section of the Narew River. Favourable conditions for phytoplankton growth (TN > 1.5 mg dm^{-3}, TP > 100 µg dm^{-3}, water temperature between 18-25°C, pH 6-9) in the reservoir resulted in a more than one hundred fold increase in phytoplankton biovolume. The significant effect of limnoplankton on potamoplankton was manifested by the dominance of Cyanobacteria from mid-summer to autumn in the river reach below the dam. Water retention time, daily water outflow and molar TN:TP ratio were the factors favouring mass development of Cyanobacteria in the reservoir. However, the meandering character and low flow velocities in the outflowing river, together with the way of operating the dam gates, favoured the Cyanobacteria development in the river reach below the dam. The study demonstrated that water retention time exceeding 3 months in shallow dam reservoirs significantly increases the risk of river water quality deteriorating as a result of mass development of Cyanobacteria.

Key words: river continuum, long water retention time, eutrophication, change of phytoplankton composition.

1. Introduction

Succession of riverine phytoplankton during downstream transport is determined by changes in many abiotic and biotic parameters in time and space (Bahnwart *et al.* 1999; Ietswaart *et al.* 1999; Reynolds 2000; Everbecq *et al.* 2001; Istvánovics *et al.* 2010). Reservoirs and fluvial lakes have been shown to fulfil a major role in shaping water parameters in rivers. In general, a river flowing through a lake or dam causes an increase in the amount of phytoplankton and chlorophyll *a* concentration within the impounded portion of the waterway and in the outflowing river (Kawara *et al.* 1998; Bahnwart *et al.* 1999; Grabowska *et al.* 2003; Hindák *et al.* 2006; Chmiel *et al.* 2009; Grabowska, Mazur-Marzec 2011). However, in the reservoirs with short retention times decline in both parameters were recorded (Dembowska 2009; Kentzer *et al.* 2010). Changes in phytoplankton resulting from water retention in shallow reservoirs strongly depended on the presence of macrophytes within the reservoir (Gołdyn, Szeląg-Wasilewska 2005; Sabater *et al.* 2008). In addition, tributaries can significantly modify the composition and amount of river phytoplankton (Skidmore *et al.* 1998; Bahnwart *et al.* 1999; Messyasz 2003; Messyasz *et al.* 2010; Hindák *et al.* 2006; Istvánovics *et al.* 2010).

Genuine riverine phytoplankton is mainly dominated by diatoms and/or green algae due to water turbulence (Ietswaart *et al.* 1999; Messyasz 2003, Hindák *et al.* 2006; Dembowska 2009; Istvánovics *et al.* 2010). In eutrophic rivers, during summer at low flow velocities (< 0.5 m s^{-1}) and higher water temperatures (> 15°C), mass development of Cyanobacteria has been recorded (Bahnwart *et al.* 1999; Köhler, Hoeg 2000; Salmaso, Braioni 2008; Grabowska, Mazur-Marzec 2011). The presence of cyanobacterial microcystins in the eutrophic Warta River (Poland) below the Jeziorsko dam was described by Szelag-Wasilewska *et al.* (2009). The mass development of Cyanobacteria strongly aggravate water quality in the river because of the potential threat from their toxins, not only to the aquatic environment, but also for human health and life (Kuiper-Goodman *et al.* 1999; Jurczak *et al.* 2005). In accordance with the ecohydrology concept (Zalewski *et al.* 1997) reduction of harmful algal blooms in dammed rivers can be performed by an internal control of the ecosystem in the reservoir by manipulation in the pelagic ecosystem predators/planktivores/zooplankton/phytoplankton which can be also connected with hydromanipulation (Zalewski 1995). Additionally, an ecological strategy for the improvement of water quality in the river, according to first rule of ecohydrology, which is identification of threats, quantification and understanding of evolutionary shaped processes, should be based on a calculation of catchment loads (Zalewski 2000).

Planktonic algae have varied environmental requirements. Even within Cyanobacteria some species tolerate intensive mixing of water masses (*Planktothrix*) while others require greater stability (*Anabaena, Aphanizomenon, Microcystis*) (Köhler, Hoeg 2000). Phytoplankton species do not tolerate sudden changes in environmental conditions in river-reservoir or river-lake systems. The detrimental effect of damming on species richness was observed by Dembowska (2009) and Istvánovics *et al.* (2010).

Phytoplankton species are potentially selected by intensity of turbulent mixing, water discharge (Ibelings *et al.* 1998), changing nutrient supply (Teubner *et al.* 1999; Köhler, Hoeg 2000), light availability (Everbecq *et al.* 2001, Nixdorf *et al.* 2003), and grazing by zooplankton and filter benthic feeders (Teubner *et al.* 1999; Sabater *et al.* 2008). Potamoplankton is subject to continuous dilution, sedimentation, and washout during its riverine transport. Bahnwart *et al.* (1999), for example, determined that species of similar morphology, even within the same taxonomic group, exhibited different loss rates in a lowland river-lake system.

The objectives of the present study were to: 1) estimate the role of a lowland eutrophic Siemianówka Dam Reservoir in shaping the composition of Narew River phytoplankton, and 2) determine the scope of development of reservoir phytoplankton in the outflowing river. The study also attempted to explain the causes of long-term and seasonal variability in the dominant phytoplankton.

2. Materials and methods

2.1.Study area

The Narew River (NR) is the largest tributary of the Vistula River in NE Poland. The upper part of the meandering and anastomozing Narew River is characterized by low flow velocities ranging from 0.21 to 1 m s^{-1} (Grabowska, Mazur-Marzec 2011) and discharges from 5 to 21 m^3 s^{-1} (Mioduszewski *et al.* 2004). The river drains a periglacial sandy-loam catchment with different percentage of forests and wetlands. The catchment of the analyzed reach ranged from 1050 (station 1) to 4302 km^2 (station 13) (Zielinski *et al.* 2003). Most tributaries in this section are small or very small streams with a discharge less than 0.8 m^3 s^{-1} (Mioduszewski *et al.* 2004) and with chlorophyll *a* concentrations not exceeding 4.5 µg dm^{-3} (Grabowska, unpublish. data). The shallow Siemianówka Dam Reservoir (SDR) (52º55'N, 23º50'E) was constructed on the upper course of the river, near the Polish-Belarusian border in 1990. With the maximum water level reaching 145 m.a.s.l., the reservoir's capacity amounts to 79.5 million m^3 (Górniak, Piekarski 2006). The reservoir and the river below the dam are highly eutrophic in terms of physical and chemical indicators (Grabowska *et al.* 2003; Jekatierynczuk-Rudczyk, Górniak 2006). In terms of the phytoplankton in the reservoir, a strong permanent dominance of potentially toxic Cyanobacteria was observed from its beginning (Grabowska 2005; Wołowski, Grabowska 2007; Grabowska, Mazur-Marzec 2011). A study performed in 2008 revealed the presence of microcystins (MCs) in water samples collected not only from the reservoir, but also from six riverine stations located along a 100 km reach of the river below the dam (Grabowska, Mazur-Marzec 2011).

2.2. Field measurements

Phytoplankton composition, abundance, and biovolume were studied once a month from June to October in 2003, 2004, and 2008. Thirteen sampling sites located along the watercourse, one above the reservoir, at its inflow (station 1, INR), next two in the reservoir (stations 2 and 3, SDR), and the remaining ten at the outflowing river (stations 4-13, ONR) (see Table I, Fig. 1). Five of the riverine stations downstream the reservoir (No. 8-12) were located in the Narew National Park. In the reservoir, samples were taken from the upper water layer (5-50 cm) from a boat, and at the river stations – from a midstream. Water samples from all of the stations were collected during the same day. At each of the stations field measurements of water temperature and pH were taken with a Hydrolab Data Sonde 4 (2003-2004), and a Hach Lange Sonde (2008).

2.3. Physico-chemical analysis of water

Laboratory analyses of nitrogen and phosphorus were only conducted in 2008 according to methods described by Hermanowicz *et al.* (1999). The concentration of total phosphorus was determined after acidification and mineralization with UV radiation. The total nitrogen content was determined using a Tecator 2300 Kjeldahl Analyzer. Chlorophyll *a* concentration was determined by the spectrophotometric method. Samples were filtered on GF/C filters and extracted with boiling 90% ethanol (Lorenzen 1965; Nusch 1980).

2.4. Phytoplankton and statistical analysis

Water samples for phytoplankton analysis (500--1000 cm^3) were fixed with Lugholes' iodine and after 2 days condensed to a known volume by repeated siphoning. Phytoplankton was identified when possible and counted using a Fuchs-Rosenthal chamber

Table I. Water and phytoplankton parameters along a 152.5 km reach of the Narew River in 2003, 2004 and 2008; values of nitrogen and phosphorous only for July-October 2008.

Station	Lacation	Distance (km)	Temp. (°C)	pH	TN (mg^3 dm^{-3})	TP (mg dm^{-3})	Molar TN :TP	Chl a (µg dm^{-3})
INR 1	inflow	0	11-20.9	7-8.11	1.71-1.96	0.122-0.693	5.7-43.7	1.8-11.7
SDR 2	reservoir	3.5	11.9-25.8	7.3-8.91	3-4.9	0.054-0.659	13-50.4	13.2-106
SDR 3	reservoir	11	11-24.1	7.57-8.9	3.32-4.87	0.173-0.605	13.2-51	24.7-133
ONR 4	outflow	20.1	11-22.3	7.5-8.4	2.99-5.35	0.161-0.429	26.6-42.5	11-124
ONR 5	outflow	36.5	11-22.2	7.38-8.3	2.46-5.1	0.123-0.419	27.8-45.8	8.6-60
ONR 6	outflow	67	11.2-22.2	7.39-8.4	2.09-4.76	0.125-0.405	26.9-38.3	9.1-69.8
ONR 7	outflow	82.4	11-24.6	7.52-8.5	2.02-4.33	0.108-0.234	37.8-61.7	12.2-54
ONR 8	outflow	99.2	11-24.2	7.27-8.6	2.77-4.09	0.145-0.339	18-41.4	9.2-85.3
ONR 9	outflow	108.6	11-22	7.41-8.6	1.82-5.61	0.135-0.386	18.9-49.1	6.8-75.5
ONR 10	outflow	118	11.3-23.3	7.25-8.7	1.49-3.99	0.147-0.343	23.1-35.5	8.3-59.9
ONR 11	outflow	129	11-23.1	7.27-7.99	n.d.	n.d.	n.d.	29.1-64.4
ONR 12	outflow	143.6	11.2-21.7	7.37-8.2	2.24-5.38	0.189-0.315	16.2-42.9	3.9-58.5
ONR 13	outflow	152.5	11.2-21.7	7.20-8.2	1.12-3.94	0.156-0.339	11.7-39.4	3.9-69.3

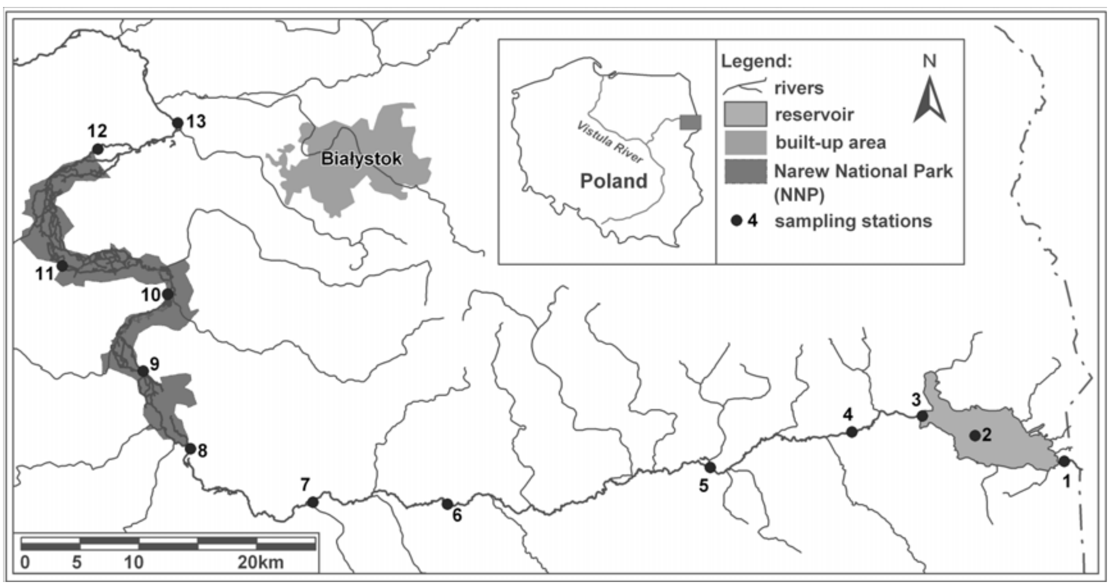

Fig. 1. Map of the study sites with the location of the sampling points.

(6.4 mm^3) and an Olympus BX-50 microscope. In each samples 200 individuals were counted. The biovolume of the phytoplankton species was determined using a method of calculating the volume of cells based on the author's own measurements (Grabowska 2001).

The index of percentage similarity of community (PSC) (Whittaker, Fairbanks 1958) was used:

$$PSC = 100 - 0.5 \sum(a\text{-}b) = \sum \min. (a, b)$$

where a and b are percentages of individuals of each species in the total numbers of the communities at stations A and B, compared in pairs.

Statistical analyses as Spearman correlations, cluster analysis and One-Way ANOVA test were run with STATGRAPHICS 1.4 PL software. Ward's method (Ward 1963) of cluster analysis were used. Probability levels of ≤ 0.05 were considered significant.

3. Results

3.1. Physical and chemical parameters

Water temperature at all the sampling stations, in the reservoir and in the river, was similar (Table I). The highest values, however, ($\geq$ 24°C) were recorded in the reservoir (SDR 2-3) in June and July 2003, and the lowest (11°C) at all stations in October 2008. Values of pH ranged from 7.0 to 8.9. The highest values of pH were recorded at the SDR, the lowest – at the inflowing river (INR 1) and the last four riverine stations below the dam (ONR 10-13; Table I). Total phosphorus concentrations (TP) ranged from 0.122 to 0.693 mg dm^{-3} at the inflow to the reservoir, from 0.054 to 0.659 mg dm^{-3} at the reservoir, and from 0.108 to 0.429 mg dm^{-3} at the stations located below the dam (ONR 4-13). Total nitrogen concentrations (TN) recorded were from 1.71 to 1.96 mg dm^{-3}, from 3.0 to 4.9 mg dm^{-3}, and from 1.12 to 5.61 mg dm^{-3}, respectively. The molar ratio of TN:TP varied from 6:1 to 44:1 at INR 1, from 13:1 to 51:1 at SDR 2-3, and from 12:1 to 62:1 at ONR 4-13, but its values usually exceeded 16 at all of the stations (Table I).

3.2. Phytoplankton parameters with statistical analysis

The longitudal and seasonal changes of biovolume of phytoplankton (PB) are shown in Fig. 2. At the first station (INR 1) the PB values were lowest (0.071-1.187 mm^3 dm^{-3}). Definitely higher values of PB were reported in the reservoir (6.31-79.1 mm^3 dm^{-3}) and the outflowing river (0.46-69.03 mm^3 dm^{-3}). Similarly the average PB values were lowest for all the seasons at the station 1 (INR 1) (2003: 0.245 mm^3 dm^{-3}, 2004: 0.537 mm^3 dm^{-3}, 2008: 0.108 mm^3 dm^{-3}). In the reservoir, however, and in the outflowing river these values were more diversified. The highest biovolume of phytoplankton was recorded in July and August 2008 at the reservoir and at the first river station below the dam (Fig. 2c). Slightly lower values were recorded in the SDR during September and October 2004 (Fig. 2b). Total phytoplankton biovolume was usually three-four times higher in the water collected from the reservoir than in samples taken from the outflowing river. The opposite phenomenon was observed in 2003 in June and August, where the PB often was higher in the outflowing river than in the reservoir (Fig. 2a).

Composition of species in the samples collected from above the reservoir consisted mainly of diatoms, cryptophytes, and (to a lesser extent) chlorophytes (Table II). In 2003-2004, Cyanobacteria were recorded mainly in summer, reaching up to 10.6% of the phytoplankton biovolume. In 2008, they were, however, an important component (24-63%) of the phytoplankton from July to September.

In the reservoir and the river below the dam, substantial changes in phytoplankton composition in comparison to the first – reference station were recorded. In 2003 Cyanobacteria remained a clear dominant species in the reservoir during the study period (min. 32%, Table II). At the river stations in turn, the main component of phytoplankton, except for July, were diatoms. In 2004, both in the reservoir and at the river stations below the dam Cyanobacteria were a predominating species during the whole season except for July. The share of Cyanobacteria usually exceeded 50%. Smaller values were only recorded at the six most distant stations. However, the highest predominance of Cyanobacteria was observed in 2008 when contribution of other algal groups did not exceed 10% of the total phytoplankton biovolume.

In 2003 in the SDR, the main phytoplankton components were Cyanobacteria from Chroococcales (*Microcystis wesenbergii*, *M. aeruginosa*, and *M. flos-aquae*). Species of Nostocales (*Aphanizomenon flos-aquae*, *Anabaena flos-aquae*, *A. planctonica*, *A.* c*ircinalis*), and Oscillatoriales (*Planktothrix agardhii*, *Pseudanabaena limnetica* and *Planktolyngbya* spp.) were less numerous. Except for June, the same algal composition was observed in the SDR and the outflowing river (from station 5). In June, in the outflowing river (from station 6), co-dominance of centric diatoms (*Stephanodiscus* spp., *Aulacoseira* spp.) with Cyanobacteria and chlorophytes (mainly from genera *Scenedesmus*, *Pediastrum*, *Kirchneriella* and *Tetrastrum*) were observed. In June through July 2004, a stronger development of species from the Oscillatoriales, such as *P. agardhii*, *Limnothrix redekei*, and *P. limnetica* and *Planktolyngbya* spp., occurred. From August to October 2004, a predominance of Chroococcales over Oscillatoriales was recorded. In addition to *Microcystis* spp., high abundance of

a) b) c)

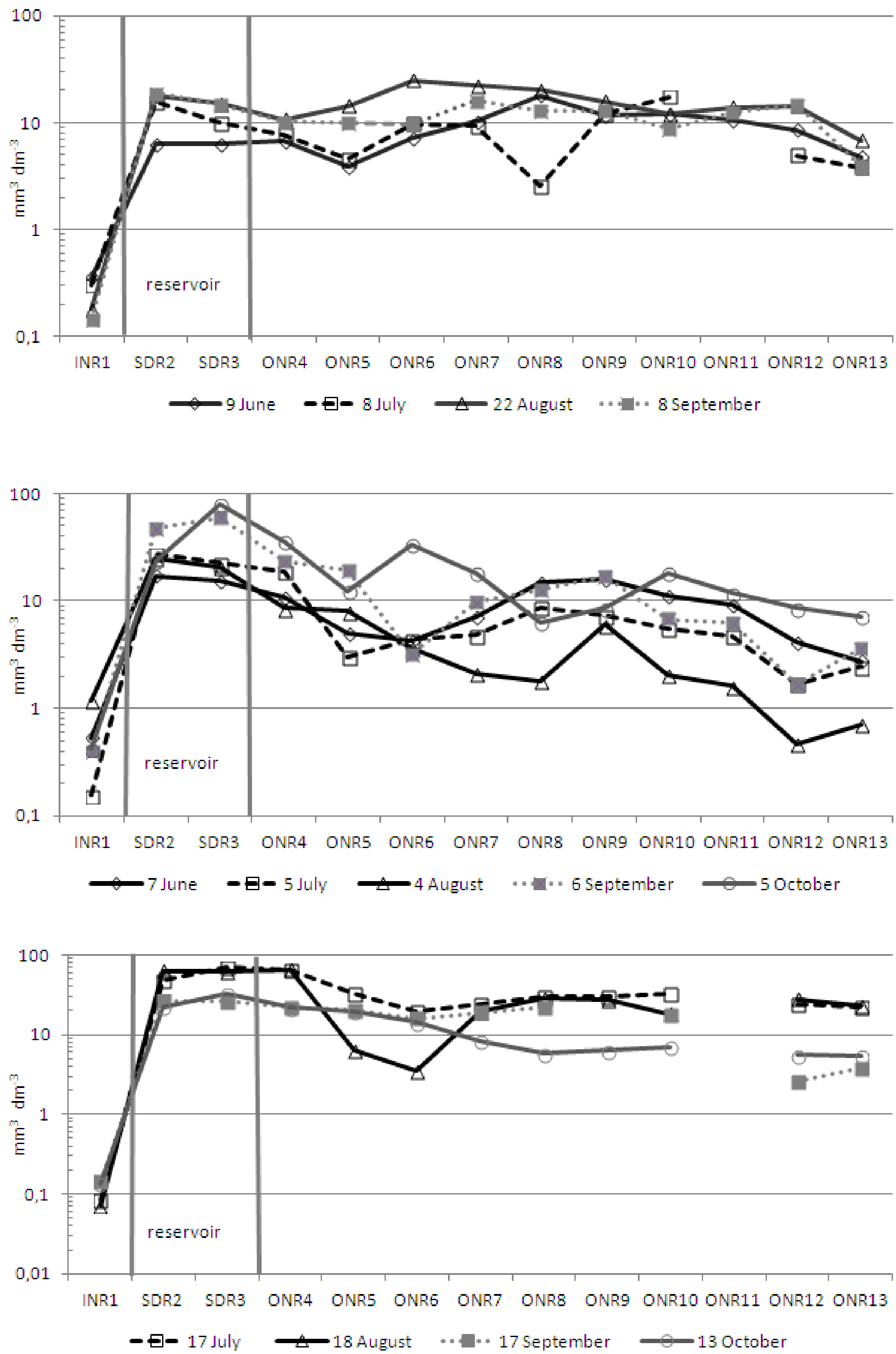

Fig. 2. Seasonal and longitudinal changes of total phytoplankton biovolume in 2003 (a), 2004 (b) and 2008 (c).

Woronichinia naegeliana was recorded. Oscillatoriales taxa predominated during the whole season in 2008 with *P. agardhii* as the main representative, at all stations 2-13. The contribution of this species to cyanobacterial biovolume varied between 86% and 100% and the highest biovolume and abundance of *P. agardhii* occurred in July (max. 60.4 mm^3 dm^{-3}, 1230.8 × 10^6 cells dm^{-3} or 30.7 × 10^6 individuals dm^{-3}). Thin filaments of *L. redekei*, *P. limnetica*, *Planktolyngbya limnetica*, and *Planktolyngbya* sp. reached significantly lower biovolumes.

Total phytoplankton abundance (PA) above the reservoir fluctuated from 162 × 10^3 to 664 × 10^3 cells dm^{-3}, reaching the values from 81 × 10^6 to 1014.9 × 10^6 cells dm^{-3} in the reservoir, and the slightly lower values below the dam (from 6.0 × 10^6 to 1026.4 × 10^6 cells dm^{-3}). In the same time, the chlorophyll *a* concentrations above the reservoir reached values 1.8-11.7 µg dm^{-3}, reaching up to 13.2-133 µg dm^{-3} in the SDR, and the lowered values below the dam (3.9-124 µg dm^{-3}) (Table I). In the three river reaches, the highest chlorophyll *a* concentration was recorded in 2004.

The lowest number of species was observed in the river before it flows into the reservoir (12-30 taxa per sample, average 22), and the highest number of species was found in the reservoir (19-39 taxa per sample, average 27). At the stations 4-13, the number of taxa was slightly higher than at the inflow to the reservoir (12-36 per sample, average 24). Most of the species found in the SDR were also observed in the outflowing river.

The similarity analysis showed that the species composition in the SDR was closer to that in the river below the dam than to those observed above the reservoir (Fig. 3a, b). Higher similarities between the phytoplankton composition in the SDR and in the river were found during the mass development of Cyanobacteria from the Oscillatoriales (in 2008) than from the Chroococcales and/or the Nostocales (2003-2004). Also the index of percentage similarity of community (PSC) between the inflowing river and the reservoir was higher during the period of Oscillatoriales dominance (Fig. 3a, b). Cluster analysis comparing the phytoplankton variables (PB and biovolume of five algae groups) for 13 sampling stations, showed a good division between the reservoir and the river with the first station below the dam falling into the reservoir cluster (compare Fig. 4). The river cluster was further divided into three lower order clusters. One of them included the upstream river station (no. 1) and the furthest down outflowing river station (ONR 13), the other two included stations 5-7 below the dam and stations 8-12 below the dam, setting the division at a distance of about 70-80 km from the dam. In these river sections a gradual increase of PB and Cyanobacteria domination were noted. The reservoir cluster, on the other hand, was characterized by the highest phytoplankton biovolume and the strongest predominance of Cyanobacteria over the other algal groups.

Through the entire season the PB and the biovolume of Cyanobacteria were significantly higher in the reservoir than in the inflowing river. Furthermore significant differences in biovolume of cryptophytes, euglenophytes or chlorophytes in the three study periods were noted between the inflowing river and the SDR (Table III). Similarly, significant differences in PB between the reservoir

Table II. Groups with the highest share (%) of total phytoplankton biovolume along a 152.5 km stretch of the Narew River in 2003, 2004, and 2008; Cyanobacteria – white background, chlorophytes – light gray background in frame, cryptophytes – dark gray background, and diatoms – black background; n.d. – not determined.

Station	INR 1	SDR 2	SDR 3	INR 4	INR 5	INR 6	INR 7	INR 8	INR 9	INR 10	INR 11	INR 12	INR 13
2003													
June	**49**	61.7	46.6	42.1	**54.1**	**69.4**	**66.9**	**65.9**	**68.7**	**73.1**	**74.9**	**68.9**	**41.7**
July	**49.8**	38.2	32	36	40.7	39.7	42.9	44.0	46.6	57.2	n.d.	36.4	37.8
August	**45.2**	37.8	57.9	**49.2**	**59.2**	**34.7**	**38.5**	**42.2**	**40.2**	**40.5**	**46.2**	**40.2**	40
September	**77.6**	70.9	79.8	48.1	**35.7**	36	**58.5**	**36.9**	**41.5**	**43.5**	**62.3**	**59.7**	**53.3**
2004													
June	**62.2**	63.1	56.9	63.1	62.1	39	**68.5**	**53.3**	**67.4**	**64.8**	**71.5**	**59.3**	**70.7**
July	**66.9**	76.2	75.6	97.2	87.2	60.4	59.9	45.4	59.2	54.5	48.6	51.1	69.7
August	**87**	65.1	84.4	55.7	62	64.8	68.2	58.6	44.1	66.3	47	64.4	52.5
September	**49.6**	78.5	91.5	85.2	96.2	86.1	97.3	92.6	81.7	95	89.9	82.1	80.5
October	**52.6**	48.6	62.1	95.2	87.1	87.6	95.3	64.6	71.1	79.7	75.6	52.4	86.6
2008													
July	**50.6**	97.5	96.6	97.3	93	90	94.2	87.8	88.4	88.1	n.d.	88.2	86.5
August	62.9	98	97.5	98.6	83.7	81.6	91.7	90.3	83.3	79.7	n.d.	85.7	85.2
September	**57**	98.3	97.8	96.2	95.7	95.6	93.3	99.2	n.d.	96.6	n.d.	84.3	83.6
October	**47.1**	97.9	95.6	93.1	95.3	93.7	87.7	87.9	73.7	81.5	n.d.	68.9	66.5

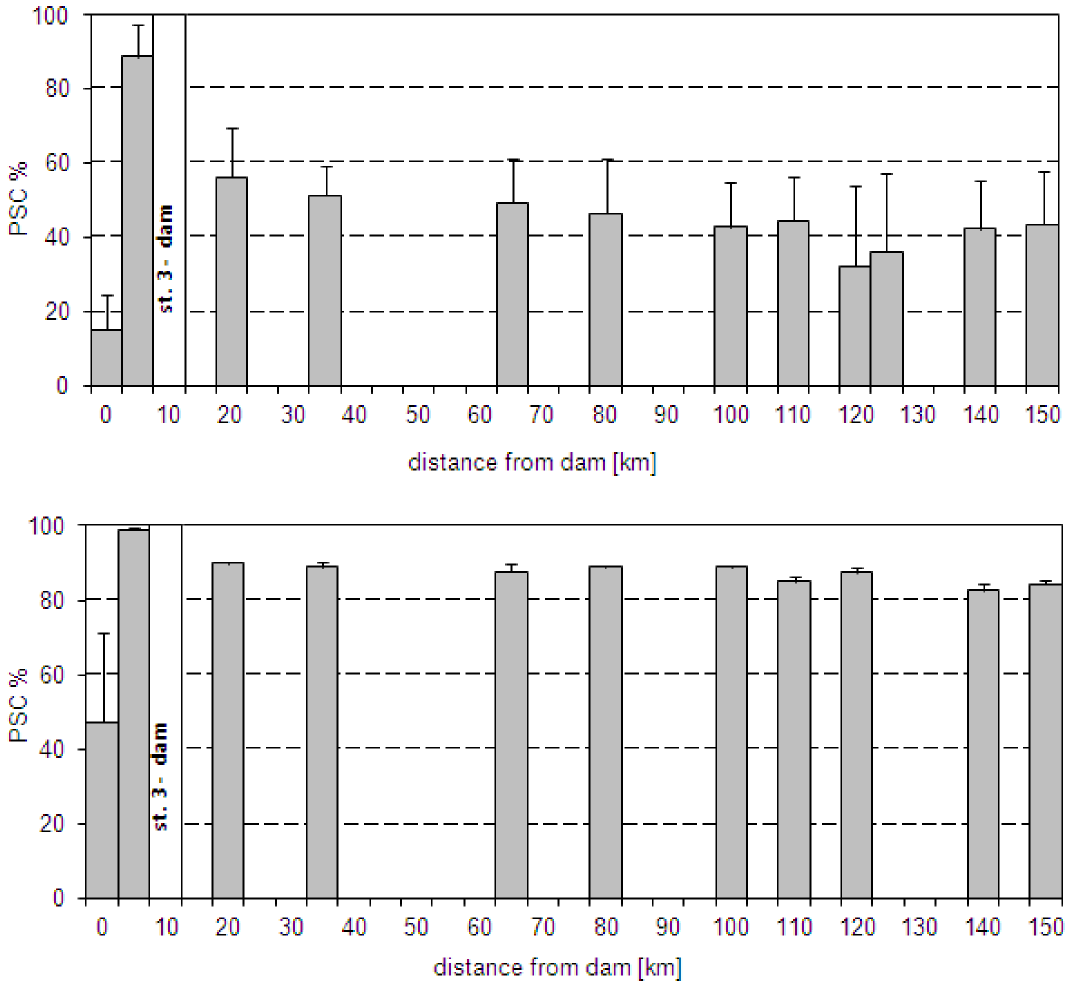

Fig. 3. Index of percentage similarity of community (PSC) for phytoplankton communities in 2003-2004 during Chroococcales and Nostocales predominance (A), and in 2008 during Oscillatoriales predominance (B) at the dam in the Siemianówka Dam Reservoir and along the Narew River.

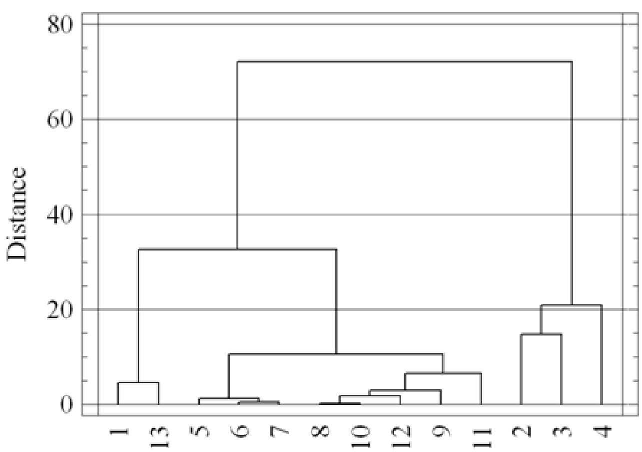

Fig. 4. Cluster analysis of the phytoplankton variables (PB, biovolume of Cyanobacteria, Cryptophyta, Euglenophyta, Bacillariophyceae and Chlorophyceae) from 13 sampling stations in 2003-2008; distance metric: Squared Euclidean.

and the downstream river were recorded (Table III). In early summer Cyanobacteria biovolume significantly decreased and an increase of diatoms was noted below the dam (downstream from ONR 7; Table III). In mid-summer there were no significant differences between the reservoir and the river except for the stations located just by the dam and furthest downstream (ONR 4 and ONR 13). In autumn again statistically significant differences between stations in PB and the four algal groups biovolume records were noted; in the case of euglenophytes and chlorophytes they have occurred at single stations (Table III).

The present study confirmed the positive significant correlation between the Oscillatoriales biovolume and the molar ratio TN:TP and negative non-significant correlation for Chroococcales and Nostocales (Table IV). There are also a positive correlations between water retention time in the reservoir (3-28 months) and PB in autumn (September-October), and between average daily outflow (0.87-3.76 m^3 s^{-1}) from the reservoir and PB at the first two downstream stations (ONR 4-5) (Table IV).

4. Discussion

4.1. Role of Siemianówka Dam Reservoir in shaping Narew River phytoplankton

The composition and biovolume of phytoplankton in Narew River above the Siemianówka Dam Reservoir (INR 1) is typical of lowland rivers. Due to water turbulence, potamoplankton is mainly dominated by diatoms and/or green algae (Ietswaart *et al.* 1999; Hindák *et al.* 2006; Dembowska 2009; Istvánovics *et al.* 2010). In summer, a stronger development of slowly-growing Cyanobacteria is sometimes observed in the stagnant zone, backwaters or reservoirs (Messyasz 2003; Hindák *et al.* 2006; Szeląg-Wasilewska *et al.* 2009; Grabowska, Mazur-Marzec 2011). However, mass development of phytoplankton and Cyanobacteria dominance appeared only in the SDR reservoir. During this study, the impounding of reservoir above 144 m.a.s.l. resulted in the presence of Cyanobacteria also at this riverine reach. This station is located approximately 500 m upstream of the reservoir, and is obviously exposed to temporary backwater from the reservoir. The phytoplankton composition is developed entirely by that within the SDR reservoir, and its effects are also visible along the 140 km reach below the dam. Thus, water quality and flow in the Narew River is strongly regulated by the dam. In previous studies conducted during 1993-1996 it was confirmed that long retention times (usually 4-6 months) and high concentrations of nutrients from decomposing mineral-organic polymers significantly stimulate an increase of phytoplankton biovolume in the SDR (Grabowska *et al.* 2003). The present study confirmed the positive correlation between water retention time in the SDR reservoir (3-28 months) and PB.

4.2. Scope of development of reservoir phytoplankton in the outflowing river

In present study it is suggested that the eutrophic SDR reservoir is the main and rich source of phytoplankton for the downstream river. Due to the release of eutrophic water from the dam, the downstream river exports large loads of phytoplankton over long distances. Consequently, from mid-summer to autumn the species composition in the river below the dam was very similar to that in the eutrophic reservoir. Rivers remain autotrophic as long as their hydrodynamics, morphometry, and nutrients allow photosynthesis and the growth of algae (Ibelings *et al.* 1998). The slowly flowing and meandering (ONR 4-8, 13) and anastomozing (ONR 9-12) Narew River (average velocity 0.5 m s^{-1}) provides very good conditions for the development of reservoir phytoplankton. Rivers with natural meanders create many sites where velocities are close to 0. These zones, called 'dead zones', have very important biological consequences for a river, for example, they can prolong planktonic residence (Reynolds 2000). High nutrient concentrations in the SDR and downstream, together with alike water flow conditions create similar habitats in both ecosystems, favouring phytoplankton growth, and thus resulting in the same eutrophic phytoplankton species. Additionally, phytoplankton in the small tributaries of the downstream reach of the river is not numerous and mostly devoid of Cyanobacteria (Grabowska, unpubl. data). This suggests that, the tributaries do not add to the enrichment of the Narew River phytoplankton.

Phytoplankton abundance and biovolume in the downstream reach of the Narew River are much higher than those recorded in other large European rivers (Table V). Reservoirs like the SDR with a retention time exceeding 30 days strongly modify the downstream potamophytoplankton composition due to the transport of phytoplankton and nutrients from the reservoir. Similar impacts of long retention times in reservoirs on Cyanobacteria mass development in the summer was described by Hindák *et al.* 2006 along the Dyje River (a major tributary of the Morava River), and by Gołdyn and Szeląg-Wasilewska (2005) along the Warta River. In the present study the impact of the SDR on the downstream river phytoplankton was recorded. The weakest impact was recorded in early summer, the strongest in mid-summer when Cyanobacteria were dominant group at the all analyzed river sections. In

Table III. Average biovolume (mg dm^{-3}) of total phytoplankton (PB) and the main phytoplankton groups and the results of the One-Way ANOVA test; a – statistically significant differences between INR1 and other stations; b – statistically significant differences between reservoir station SDR 3 and downstream stations (ONR 4-13); $P \leq 0.05$.

Station	PB	Cyano.	Bacill.	Crypt.	Eugl.	Chloro.
Early summer (June)						
Reservoir inflow						
INR 1	0.45	0.01	0.64	0.09	0.03	0.61
Reservoir						
SDR 2	11.7 **a**	7.36 **a**	0.39	1.33 **a**	0.14	0.99
SDR 3	10.9 **a**	5.85 **a**	0.13	1.72 **a**	0.05	1.27
Downstream stations						
ONR 4	8.78 **a**	4.84 **a**	0.78	0.42 **b**	0.17	1.7
ONR 5	4.64	2 **b**	1.21	0.12 **b**	0.05	0.84
ONR 6	5.72	1.3 **b**	3.15	1.03 **b**	0.13	0.86
ONR 7	8.61	0.47 **b**	5.82 **ab**	0.38 **b**	0.21	1.62
ONR 8	16.4 **a**	2.97	9.87 **ab**	0.26 **b**	0	2.89 **ab**
ONR 9	13.6 **a**	1.14 **b**	9.25 **ab**	0.29 **b**	0	2.63 **a**
ONR 10	11.6 **a**	0.7 **b**	8 **ab**	0.21 **b**	0	2.11
ONR 11	9.84 **a**	0.32 **b**	7.21 **ab**	0.25 **b**	0	1.96
ONR 12	6.31	0.51 **b**	3.94 **b**	0.27 **b**	0.07	1.41
ONR 13	3.77	0.26 **b**	1.97	0.32 **b**	0	1.13
Mid-summer (August)						
Reservoir inflow						
INR 1	0.48	0.02	0.37	0.08	0.01	0.01
Reservoir						
SDR 2	35.2 **a**	28.1 a	3.22	0.74	0.66 **a**	2.13
SDR 3	32.7 **a**	28.9 **a**	1.19	0.43	0.64 **a**	1.1
Downstream stations						
ONR 4	28.1 **a**	23.9	2.01	0.4	0.46	1.17
ONR 5	9.52	4.45	2.92	0.22	0.29	1.35
ONR 6	10.6	4.13	2.93	0.2	0.32	2.54
ONR 7	14.4	8.58	3.01	0.11	0.3	2.1
ONR 8	16.9	10.6	3.38	0.24	0.38	2
ONR 9	16.3	9.84	3.1	0.44	0.24	2.37
ONR 10	10.7	6.4	2.33	0.15	0.27	1.39
ONR 11	7.77	1.18	3.34	0.12	0.57	2.23
ONR 12	14.2	9.11	2.15	0.29	0.09	2.2
ONR 13	10.2	7.61	0.99	0.17	0.03 **b**	1.4
Autumn (October)						
Reservoir inflow						
INR 1	0.28	0	0.11	0.14	0.01	0.01
Reservoir						
SDR 2	23.1 **a**	16.8 **a**	5.08	0.1	0.28 **a**	0.61
SDR 3	55.8 **a**	40.1 **a**	2.12	1.11 **a**	0.11	12.4 **a**
Downstream stations						
ONR 4	28.7 **ab**	27.1 **a**	0.73	0.28 **b**	0.31	0.29
ONR 5	16.1 **ab**	14.9 **b**	0.38	0.33 **b**	0.25	0.25
ONR 6	23.8 **ab**	21.3 **ab**	0.79	0.11 **b**	0.56 **a**	0.83
ONR 7	13.4 **ab**	12.5 **b**	0.34	0.15 **b**	0.19	0.26
ONR 8	6.08 **b**	4.61 **b**	1.09	0.19 **b**	0.06	0.2
ONR 9	7.41 **b**	5.35 **b**	1.18	0.33 **b**	0.07	0.48
ONR 10	12.6 **b**	10.1 **b**	1.41	0.15 **b**	0.09	0.66
ONR 11	11.8 **b**	8.9 **b**	1.7	0.12 **b**	0.18	0.87 **b**
ONR 12	7.07 **b**	4.17 **b**	1.52	0.29 **b**	0.02	0.98
ONR 13	6.31 **b**	4.92 **b**	0.76	0.26 **b**	0	0.38

eutrophic rivers, the stronger development of Cyanobacteria is limited to the summer period (Messyasz *et al.* 2003; Salmaso, Braioni 2008) while in ONR, their dominance was also recorded in autumn.

The range of Cyanobacteria dominance in the outflowing river was similar in all of the years analysed. It included species both better and less adapted to river transport. Even species with similar morphologies behaved differently. Numbers of the filamentous species of *Aphanizomenon* and *Anabaena* genera were reduced in the river below the dam more quickly than the numbers of *P. agardhii*, because they are specialized to live in stagnant water when *P. agardhii* is specialized to turbulent conditions. A similar phenomenon was described by Bahnwart *et al.* (1999) in the lowland Warnow River (Germany). They determined that species with similar morphologies exhibited different loss rates in a lake-river system. For example, species of filamentous Cyanobacteria such as *P. agardhii* and *L. redekei* diminished to a lesser extent under turbulent river conditions than *P. limnetica* and *Anabaena* sp. Weaker growths of *Aphanizomenon* in the Spree River than in Lake Müggelsee were also observed by Köhler and Hoeg (2000). According to Rücker *et al.* (1997) and Nixdorf *et al.* (2003), *P. agardhii* can be more successful in very shallow, eutrophic, wind-exposed lakes with intensed sediment-water interactions and induced short-term nutrient pulses. Köhler and Hoeg (2000) described the intensive development of *P. agardhii* both in the eutrophic, polymictic Lake Müggelsee in Berlin and in the inflowing lowland Spree River. *P. agardhii* was often able to persist throughout the year as a monoculture (Nixdorf *et al.* 2003). In the present study its dominance in the SDR and below the dam was apparent. Other Cyanobacteria were only present in trace amounts, as described by Teubner *et al.* (1999) in their study of the riverine lakes in Berlin. *P. agardhii* also occurs in other rivers, but the period of its development is much shorter and its amount is much lower (Ibelings *et al.* 1998; Köhler, Hoeg 2000). For example, the summer occurrence of *P. agardhii* in the phytoplankton of the Meuse River along a river reach with a less turbulent character was described by Ibelings *et al.* (1998), although at a hundred times lesser density (max. 12.0×10^6 cells dm^{-3}) than in NR.

In this study uneven distribution of the phytoplankton abundance along the river below the reservoir was observed. This might have resulted from the fact that water sampling was done at all stations in the same day (beginning from station 1 to 13), while water requires approximately three days to move along this 140 km section of the river downstream of the dam. Long-term observations of the reservoir reveal the appearance of phytoplankton peaks in downstream sections related to the way the water is released from the dam (Grabowska, unpublish. data). Often large accumulations of phytoplankton in forms of visible green patches or scums in the surface layer at the dam (SDR 2), are discharged into the river through the upper control gates of the dam. Based on long-term field observations (Grabowska, unpublish. data) of the reservoir and river, and calculation of flow velocity of water in the river, it is possible to determine the time of discharge of accumulated matter from the reservoir. The phytoplankton peak observed at station 6 (67 km) in August 2003 suggests the discharge of surface water from the reservoir on the day before (Fig. 2).

4.3. Long-term and seasonal variability in the dominant phytoplankton

During the study period, a high biovolume of Cyanobacteria was recorded in the SDR reservoir,

Table IV. Spearman correlations between phytoplankton biovolume and water parameters; significance level at 0.05* and 0.005**.

Parameter	Water retention time in the SDR	daily outflow	molar TN : TP
PB at SDR 2-3 (September-October)	0.667*		
PB at ONR 4-5		0.401**	
Cyanobacteria at SDR 2-3 (September-October)	0.739*		
Oscillatoriales			0.857 **
Chroococcales			-0.539
Nostocales			-0.478

Table V. Comparison of phytoplankton parameters in some European rivers.

Parameter	PA (cells dm^{-3})	Cyanobacteria (cells dm^{-3})	PB (mm^3 dm^{-3})	Cyanobacteria (mm^3 dm^{-3})
Narew River (ONR) (this study)	max. 1026.4×10^6		max. 69	max. 64.2
Morava River (Hindák *et al.* 2006)	max. 29.3×10^6		max. 16	
Warta River (Szeląg-Wasilewska *et al.* 2009)		max. 188×10^6		max. 12.5

and consequently in the outflowing river during 2003-2004 (mainly Chroococcales and Nostocales co-dominance), and in the period of clear dominance of one species *P. agardhii* during 2008. In the years 2005-2006, a shift in the reservoir's phytoplankton composition was observed from the Chroococcales and Nostocales regime to an Oscillatoriales-dominated community (Grabowska, Pawlik-Skowrońska 2008). Oscillatoriales, mainly *P. agardhii*, permanently dominated over other Cyanobacteria during the summer and autumn in the subsequent years (until the year 2012). One of the most important factors determining phytoplankton composition in the SDR could be a change in the molar ratio of TN:TP. In 2008 the highest concentrations of TN resulted in a significant increase in Oscillatoriales biovolume. In 2003-2004, during the period of Chroococcales and Nostocales co-dominance, the molar ratio did not exceed 16:1 (except for July 2004, when TN:TP = 30.5:1) (Jekatierynczuk-Rudczyk, Górniak 2006). In 2008, during a period of clear Oscillatoriales dominance, it increased substantially, exceeding 16:1 (average 33.4:1; Table I). The present study confirmed the positive correlation between the Oscillatoriales biovolume and the molar ratio of TN:TP. Based on a study of two German lakes, Teubner *et al.* (1999) distinguished two distinct communities of Cyanobacteria, one dominated by *P. agardhii* and the other by *Aphanizomenon flos-aquae*/*Microcystis* spp. They proved that in hypertrophic lakes, *A. flos-aquae* reached high biovolumes only in the cases when the molar ratio of TN:TP < 16:1, and a low biovolume of *P. agardhii* coincided. When this critical ratio TN:TP = 16:1 was reached, and *P. agardhii* biovolume exceeded 6 mm^3 dm^{-3}, mass development of this Cyanobacterium continued during summer and autumn.

Conclusions

This study of the inflowing Narew River – Siemianówka Dam Reservoir – outflowing Narew River dammed river system shows the influential role of shallow eutrophic reservoirs in changing the composition of phytoplankton a lowland river below the reservoir. The strongly eutrophic lowland Siemianówka Dam Reservoir is the main and rich source of phytoplankton for the downstream Narew River. The significant effect of limnoplankton on potamoplankton is manifested by the occurrence of the same species along a 140 km section of the outflowing river. Based on the present study and literature reports, it is revealed that in the case of shallow reservoirs with long water retention periods, there is a significant risk of deterioration in the quality of river water as a side-effect generated by the mass development of Cyanobacteria in the reservoir. Development of a sound management strategy for the reduction of Cyanobacteria biovolumes in the Siemianówka Dam Reservoir, based on an ecohydrological strategy (Zalewski 1995, 2000) of limiting nutrient availability and hydrobiomanipulation, is still necessary.

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