The trophic state of the Vistula Lagoon: an assessment based on selected biotic and abiotic parameters according to the Water Framework Directive*

doi:10.5697/oc.53-3.881
OCEANOLOGIA, 53 (3), 2011.
pp. 881–894.

KEYWORDS
Trophic state indices
Phytoplankton functional groups
Vistula Lagoon
Water Framework Directive

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Received 28 April 2011, revised 4 August 2011, accepted 22 August 2011.

Abstract

The aim of the study was to determine the trophic state of the Vistula Lagoon in 2007–2009. The analysis of various trophic state indices, abiotic parameters and different water classifications indicated the eutrophy and even advanced hypereutrophy of the lagoon waters. The composition, abundance and biomass of phytoplankton likewise reflect the eutrophic nature of this water body. For this lagoon, Reynold's functional groups of phytoplankton were used as an indicator of eutrophication for the first time. The dominant phytoplankton organisms in the surface waters belong to 8 functional groups: S1, X1, F, J, K, H1, L_O, M. Some key concepts of the EU Water Framework Directive were implemented in this study.

* This work was supported by the Norway grants PNRF 82 A I.

1. Introduction

The Water Framework Directive 2000/60/EC commits European Union (EU) member states to assess the ecological state of their surface and ground waters. The evaluation of the ecological state of waters is based on biological elements, i.e. communities of organisms (phytoplankton, macrophytes, phytobenthos, benthic macroinvertebrates and fish) present in the water body. Hydromorphological, chemical and physical features are treated as parameters supporting the water quality assessment.

According to EU regulations, environmental data, such as the concentration of total phosphorus (TP), phosphates, total nitrogen (TN), and chlorophyll *a* (Chl *a*) as well as the Secchi depth are basic trophic state indices (Kratzer & Brezonik 1981, Kajak 1983, Zdanowski 1983, Vollenweider 1989). In addition to these basic ones, there are many other trophic state indices and empirical models that can be treated as a measure of the degree of water eutrophication.

There are many ways of classifying lakes (Vollenweider 1968, Chapra & Dobson 1981, Karabin 1985) and methods for assessing the trophic state of water bodies, e.g. Carlson's Trophic State Index (TSI) (Carlson 1977) modified by Kratzer & Brezonik (1981), the OECD eutrophication study (Vollenweider & Kerekes 1982), and the system of Lampert & Sommer (2001). However, Carlson's Trophic State Index is the trophic index usually used.

Physical parameters together with nutrient levels are factors controlling the structure of phytoplankton (Reynolds 1980). Structure analysis of phytoplankton has long been used for assessing trophic status (Thunmark 1945, Nygaard 1949, Järnefelt 1952, Heinonen 1980, OECD 1982, Hillbricht-Ilkowska & Kajak 1986, Tremel 1996). These autotrophic organisms react very quickly to changes in the environment, which are reflected by the temporal and spatial variability in the phytoplankton communities (Kawecka & Eloranta 1994). Higher nutrient levels in lakes lead to an increase in the abundance and biomass of phytoplankton, a process that also changes the taxonomic composition of a phytoplankton community (Trifonova 1998, Szeląg-Wasilewska 2007). The type of water body can be initially identified based on the presence or absence of an indicator species. Reynolds et al. (2002) drew up a set of phytoplankton functional groups characterizing various types of environments. This list was modified by Padisák et al. (2009).

There are no rigid standards of classification applicable to all water bodies (especially to lagoons): most classifications refer to lakes and rivers (Czoch & Kulesza 2006, Kulesza & Walczakiewicz 2006, Picińska-Fałtynowicz et al. 2006, Czaban 2008). In many EU countries integral trophic state indices of aquatic ecosystems have been developed, e.g. the Hungarian Q index (Padisák et al. 2006) or the German multi-parameter PSI index (Mischke et al. 2008). Analysis of the phytoplankton community structure, including potentially toxic cyanobacteria, is one of the means for monitoring the quality of Polish recreational waters according to EU Directive 2006/7/EC. In the present study the trophic state of the Vistula Lagoon in 2007–2009 was assessed on the basis of selected biotic and abiotic parameters according to the recommendations of the Water Framework Directive 2000/60/EC.

2. Material and methods

The Vistula Lagoon is a body of transitional water situated in the south-eastern part of the Baltic Sea. To the north it is separated from the Baltic Sea by the Vistula Spit, to the south it is bordered by the Elbląg Upland and to the west it abuts on the extensive Vistula Delta. The Polish-Russian border splits it roughly in two. The Vistula Lagoon covers an area of 838 km^2 (44% of this area belongs to Poland) and on average is 91 km long and 9 km wide (Łomniewski 1958). Its coastline is $\sim$ 270 km long, and it holds $\sim$ 2.3 km^3 of water. Its average depth is 2.5 m, its deepest point (5.2 m) being near the Baltiysk Strait, the only connection between the Baltic Sea and the lagoon. The volume of sea water entering the lagoon per day is equivalent to around 1% of the lagoon's total volume of water (Chubarenko & Chubarenko 1998). The Rivers Elbląg, Pasłęka, Nogat and Bauda are the main ones entering it. The Polish part of the Vistula Lagoon is an important bird nesting area and has been designated as a Special Conservation Area of the Natura 2000 network.

Figure 1. Sampling stations in the Vistula Lagoon

Surface water samples were collected at 5 stations in the Polish part of the lagoon each month from May to September in 2007, 2008 and 2009. The locations of the sampling stations are shown in Figure 1. Water transparency was measured using a Secchi disc (SD). Total phosphorus (TP) was analysed by the molybdenum blue method (*Standard methods...* 1960) after mineralization in perchloric acid in unfiltered water samples. The salinity was calculated on the basis of the concentration of chloride ions measured on a HACH DR/2000 spectrophotometer (Loveland, USA). The acetone extraction method (Golterman 1969) was applied to determine the chlorophyll concentration.

The trophic state was determined on the basis of Trophic State Indices (TSI) using a logarithmic transformation of the chlorophyll *a* concentration (Chl *a*), Secchi depth (SD) and total phosphorus (TP) (Carlson 1977) as well as the total nitrogen concentration (TN) (according to the modification by Kratzer & Brezonik 1981). The average values of TP, SD, Chl *a*, TN and TN:TP measured in the surface waters in summer (Kajak 1983, Zdanowski 1983) were also used in the assessment of the Vistula Lagoon's trophic state. Vollenweider's method for assessing a water body's trophic state (1989), accepted by the Organization for Economic Co-Operation and Development (OECD) and based on the average values of selected parameters measured in spring and summer, was also applied.

Samples for the microscopic determination of phytoplankton were fixed with Lugol's solution. Phytoplankton was analysed under an inverted microscope (Nikon TMS, Tokyo, Japan) with 200×, 400× and 600× magnification. The counting units (N) were cells, coenobia or trichomes 100 μm in length. To calculate the biomass, the species were approximated to simple geometric or combined forms. Counting and biomass determination were performed in accordance with the recommendations of the Baltic Monitoring Programme (HELCOM).

3. Results

3.1. Physical and chemical variables

The average concentration of total phosphorus (TP) during the whole measurement period was 160.32 ± 61.18 μg P dm^{-3}; in summer it exceeded 180 μg P dm^{-3}. The phosphorus content in the water was the highest in 2009 (av. 169 μg P dm^{-3}). The concentration of chlorophyll *a* was extremely variable, the highest value being noted in 2008 (54 μg dm^{-3}). The total nitrogen content of Vistula Lagoon waters was stable in 2008–2009 at an average level of 1.36 mg N dm^{-3}; the average level in 2007 was lower – 0.86 mg N dm^{-3}. During the study period the average salinity was

Table 1. Minimum (Min), maximum (Max), average, and standard deviation (SD) of selected physicochemical and biological parameters measured in the Vistula Lagoon in 2007–2009 (n=75)

Parameter	Min	Max	Average	SD
Secchi disc transparency [m]	0.20	1.00	0.45	0.17
temperature [°C]	12.00	24.40	18.19	3.4
salinity [PSU]	1.50	9.30	3.68	1.22
oxygen [mgO_2 dm^{-3}]	7.33	15.31	10.24	1.35
TP [μg dm^{-3}]	61.30	360.60	160.32	61.18
TN [mg dm^{-3}]	0.16	2.16	1.22	0.46
TN/TP	1.79	20.13	7.80	3.17
Chl *a* [μg dm^{-3}]	8.19	170.37	49.07	30.65
total biomass [mg dm^{-3}]	2.14	16.04	9.73	3.40
Cyanobacteria biomass [mg dm^{-3}]	0.97	9.89	5.42	2.68
Chlorophyta biomass [mg dm^{-3}]	0.88	6.39	3.20	1.61

$\sim$ 3.7 PSU, the water transparency low, the oxygen content high and the mean water temperature 18°C. The average value of the TN:TP ratio was < 10, but the maximum value was slightly in excess of 20 in June 2008 (Table 1).

The trophic state indices calculated for the summer months of 2007–2009 for the surface waters were: TSI (Chl *a*) 53–90, TSI (TP) 71–89, TSI (TN) 41–65 and TSI (SD) 65–83. These values are high, indicating that the Vistula Lagoon is at least eutrophic. The combined trophic index was the highest in 2009. The average value of TSI (TP) was 80, and even exceeded 82 in July. The mean value of TSI (Chl *a*) was also high (78) and in July it was 83. The same tendency was observed in the case of TSI (SD), its highest value being noted in June (83). The trophic states of the Vistula Lagoon waters were determined on the basis of the four classification systems described above and are presented in Table 2. The values of TSI were calculated based on the formulas given below the table.

3.2. Phytoplankton biomass and community structure

Analysis of the phytoplankton revealed a significant contribution of planktonic blue-green algae, especially colonial species with picoalgal and larger cell sizes belonging to the Chroococcales, Oscillatoriales and the typical bloom-forming Nostocales. In addition, small green algae belonging to the Chlorococcales and frequently forming coenobia occurred very often. These organisms belong to 8 phytoplankton functional groups: codon S1 (*Pseudanabaena limnetica* (Lemm.) Kom., *Planktolyngbya contorta*

Table 2. Trophic state of Vistula Lagoon waters according to the trophic state classification for lakes (P – polytrophy, H – hypertrophy, E – eutrophy, M – mesoeutrophy). The numbers given in brackets are the average values of TSI and environmental parameters

Factors	Carlson 1976 (summer)	Kratzer & Brezonik 1981 (summer)	Kajak 1983, Zdanowski 1983 (summer)	OECD (Vollenweider 1989) (spring-summer)
TSI (SD)[1]	**E** (73)			
TSI (Chl a)[2]	**E** (74)			
TSI (TP)[3]	**E** (78)			
TSI (SD)[1]		**P** (73)		
TSI (Chl a)[2]		**P** (74)		
TSI (TP)[3]		**P** (78)		
TSI (TN)[4]		**E** (58)		
TP [μg dm^{-3}]			**E** (170)	**H** (150)
SD [m]			**E** (0.7)	**H** (0.5)
Chl a [μg dm^{-3}]			**E** (61)	**H** (45)
TN [mg dm^{-3}]			**M** (1.3)	
TN/TP			**E** (7.8)	

[1]$\mathrm{TSI(SD)} = 10(6 - (\ln \mathrm{SD}/\ln 2))$
[2]$\mathrm{TSI(Chl}\,a) = 10(6 - (2.04 - 0.68\mathrm{Chl}a)/\ln 2)$
[3]$\mathrm{TSI(TP)} = 10(6 - (\ln 48/\mathrm{TP}/\ln 2))$
[4]$\mathrm{TSI(TN)} = 54.45 + 14.43 \times \ln(\mathrm{TN})$

(Lemm.) Anagn. et Kom., *Planktolyngbya limnetica* (Lemm.) Kom.-Legn et Cronb.); codon X1 (*Monoraphidium contortum* (Thur.) Kom.-Legn., *M. griffithii* (Brek.) Kom.-Legn., *M. minutum* (Näg.) Kom.-Legn., *M. arcuatum* (Kors.) Hindák, *Monoraphidium* sp.); codon F (*Oocystis lacustris* Chod., *O. parva* W. et G. S. West, *O. borgei* Snow, *Oocystis* spp., *Kirchneriella* sp., *Dictyosphaerium* spp., *Lobocystis* sp., *Elakatothrix* sp.); codon J (*Pediastrum* spp., *Scenedesmus* spp., *Crucigenia* spp., *Tetraëdron* spp., *Tetrastrum* spp.); codon K (*Aphanocapsa* spp., *Aphanothece* spp., *Cyanodictyon* sp.); codon H1 (*Anabaena flos-aquae* (Lyngb.) Breb., *A. planctonica* Brunnth., *Anabaena* sp. – currently according to Wackiln et al. (2009) *Dolichospermum flos-aquae* (Breb. ex Born. et Flah.) Wack., Hoff. et Kom., *D. planctonicum* (Breb. ex Born. et Flah.) Wack., Hoff. et Kom. and *Dolichospermum* spp. – *Anabaenopsis elenkinii* Miller, *Aphanizomenon flos-aquae* Ralfs ex Born. & Flah., *Aphanizomenon issatschenkoi* (Ussac.) Proschkina-Lavrenko, *Aphanizoemnon* sp.); codon L_O (*Merismopedia glauca* (Ehren.) Kütz., *M. punctata* Meyen, *M. tenuissima* Lemm., *Snowella lacustris* (Chod.) Kom. et Hind., *Woronichinia naegeliana* (Ung.) Elenk., *Woronichinia* sp.); codon M (*Microcystis aeruginosa* (Kütz.) Lemm., *Microcystis flos-aquae* (Witt.) Kirch., *Microcystis* sp.).

Phytoplankton abundance (4.13×10^5 N cm^{-3}) was the lowest in May 2007 and the highest (8.29×10^6 N cm^{-3}) in September 2009. The phytoplankton community was dominated by blue-green algae, the abundance of which varied between 2.69×10^5 and 4.12×10^6 N cm^{-3} (Figure 2a). The picoplanktonic species belonging to the colonial genera *Aphanocapsa*, *Aphanothece*, *Cyanodiction* and *Merismopedia tenuissima*, with cell sizes no greater than 0.8–2.0 μm, were the most abundant. These colonies usually consisted of 50–250 cells, but colonies formed by $\sim$ 2000 cells were also observed. Although these microorganisms made up 85% of the total phytoplankton abundance, their contribution to the total phytoplankton biomass was much lower (av. 22%) because of the small sizes of the cells.

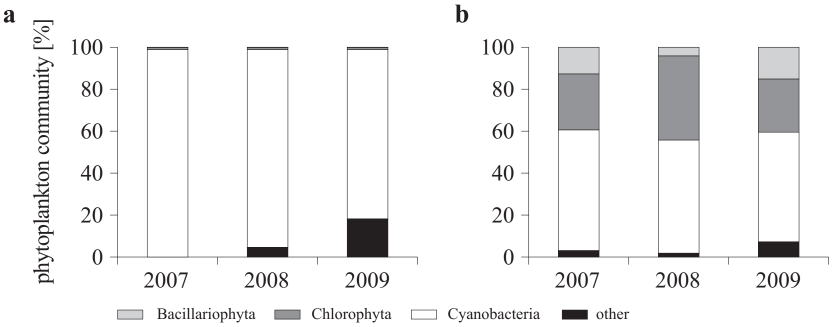

Figure 2. Percentage contribution of phytoplankton groups to the total abundance (a) and biomass (b) of phytoplankton in summer 2007–2009

The average phytoplankton biomass over the 2008–2009 period was high and varied between 5.55 and 16.04 mg dm^{-3} wet weight (av. 12.13 mg dm^{-3}); only in 2007 was it lower (av. 5.67 mg dm^{-3}). This 50% lower phytoplankton biomass in 2007 was related to the general low biomass of organisms observed that year. The phytoplankton biomass was most frequently dominated by Cyanobacteria (mean biomass 5.37 mg dm^{-3}) and *Chlorophyceae* (mainly *Chlorococcales*) (mean biomass 3.13 mg dm^{-3}). The diatom biomass of 1.16 mg dm^{-3} made up 10% of the total phytoplankton biomass. The contribution of other species belonging to Cryptophyta, Dinophyta, Euglenophyta and Flagellata was small, jointly making up 7.40% and 3.98%, on average, of the total abundance and biomass respectively (Figure 2b).

4. Discussion

As a member state of the European Union, Poland has been obliged to implement the Water Framework Directive. One of the main goals of this Directive is to achieve good water quality by 2015. The ecological and chemical state of waters should be assessed on the basis of monitoring measurements. Because of the lack of integral indicators for the trophic status of brackish waters, the trophic state of the Vistula Lagoon waters in this study was evaluated based on methods developed for lakes. This was possible because the Vistula Lagoon is not a typical brackish water body: owing to the low rate of water exchange with the sea, the salinity is relatively low (average 3.7 PSU), so freshwater organisms can flourish. Information on biological parameters in Polish coastal waters (including the Vistula Lagoon) is scarce and inconsistent. Therefore, the ecological state of these waters has been only roughly assessed, mainly on the basis of the knowledge of experts and existing monitoring programmes (Report... 2005).

The physicochemical parameters measured confirm the eutrophic state of these waters, indicated in earlier studies of the Polish part of the Vistula Lagoon (Margoński & Horbowa 2003a,b, Bielecka & Lewandowski 2004). The average values of the parameters (TP, SD, Chl *a*, TN, TN:TP) measured in summer indicate that Vistula Lagoon waters are eutrophic; TN is also an index of mesoeutrophy (Kajak 1983, Zdanowski 1983). However, according to Vollenweider's (1989) classification, the values of TP, SD and Chl *a* measured in spring and summer are characteristic of hypereutrophy; this was corroborated by the trophic state indices. According to Carlson's classification (1977), the TSIs calculated on the basis of Chl *a*, TP and SD indicate eutrophy (Figure 3a). TP values were very high: in all three years of measurements they were close to those characteristic of hypereutrophy. The situation was similar in the case of Chl *a* in 2007 and 2009. Only the water trophic state assessment based on water transparency seems doubtful because of the intensive resuspension of particles from the sediments, which leads to a decrease in water transparency unrelated to the presence of phytoplankton. TSI is generally used for assessing the trophic state of lakes, so the indices determined for the Vistula Lagoon should not be compared with their values obtained for lakes (Margoński & Horbowa 2003b). The analysis of the physicochemical parameters measured in the Vistula Lagoon waters according to both Zdanowski's (1983) and Vollenweider's (1989) classifications indicates a state of eutrophy. In spring and summer the concentrations of TP and Chl *a* were more than twice as high as the values indicative of hypereutrophy (Figure 3b). Therefore, based on the OECD

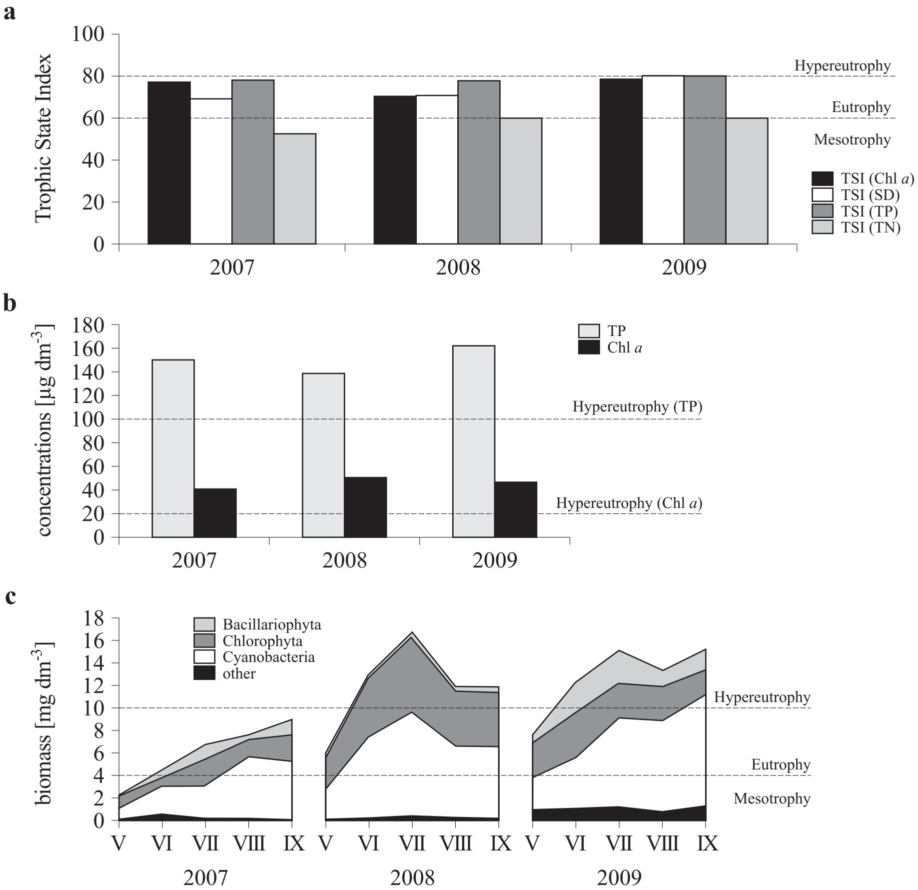

Figure 3. Assessment of the Vistula Lagoon's trophic state in 2007–2009 based on a) average values of TSI (Chl *a*), TSI(SD), TSI(TP), TSI(TN) according to Carlson's (1976) classification, b) average values of TP and Chl *a* concentrations [μg dm^{-3}] according to Vollenweider's (1989) classification, c) phytoplankton biomass [mg dm^{-3}] according to Heinonen (1980)

classification and the magnitudes of these concentrations we can state that the Vistula Lagoon waters are hypereutrophic.

With regard to the phytoplankton biomass, according to the limiting values for various trophic states introduced by Heinonen (1980), the Vistula Lagoon waters were eutrophic in 2007. However, in 2008 and 2009 the phytoplankton biomass increased and was greater than 10 mg dm^{-3} during the whole plant growth period. The hypereutrophy of the Vistula Lagoon waters in 2008 and 2009 is thereby confirmed by biotic parameters as well (Figure 3c). The dominance of blue-green algae and chlorophytes is characteristic of eutrophic waters (Tremel 1996, Lepistö & Rosenström

1998). The dominance of these phytoplankton groups in the Vistula Lagoon was also reported by Pliński (2005), Rybicka (2005), Nawrocka et al. (2009) and Kobos & Nawrocka (2010). However, no detailed studies of the phytoplankton community structure have been carried out that could confirm such a high trophic index.

The phytoplankton community structure in 2007–2009 indicated the eutrophic nature of Vistula Lagoon waters. The species characteristic of 8 out of 31 (according to Reynolds et al. 2002) or 40 (according to Padisák et al. 2009) functional groups of phytoplankton were present in the samples analysed. The contribution of group K (containing picoplankton) was significant in every sample. These organisms are characteristic of shallow and nutrient-rich waters, and significantly abundant colonial picoplankton is very common in eutrophic waters (Albertano et al. 1997, Komarková 2002). However, based on previous studies, these species can dominate phytoplankton communities in both oligotrophic and hypereutrophic waters (Padisák et al. 2009). Moreover, the contribution of the organisms from group J, which are common in shallow, mixed and highly enriched water bodies, was significant in all the samples. The species from codon S1 are characteristic of turbid, mixed environments, whereas those from codon R occur beneath the stratification in the metalimnion or upper hypolimnion of deep oligomesotrophic lakes. Their large contribution to the total biomass (up to 25%, av. 11%) in Vistula Lagoon waters indicates that phytoplankton species from the genera *Pseudanabaena* and *Planktolyngba* may also be found in eutrophic and even hypereutrophic waters. The species from codon X1 are characteristic of shallow, eu-hypereutrophic environments, whereas the organisms of group F are typical of clear and deeply mixed meso-eutrophic lakes. In the central part of the lagoon no blooms were noted of potentially toxic cyanobacteria of *Dolichospermum*/*Anabaena* (in 2000 and 2001) and *Microcystis* (in 2003, 2005 and 2006) species. Such blooms had been observed earlier in the coastal zone of the Vistula Lagoon (Rybicka 2005, Browarczyk & Pliński 2006, Browarczyk & Pliński 2007, Kobos 2007).

5. Conclusions

The phytoplankton structure and biomass, plus the chlorophyll *a* and nutrient concentrations indicate that the Vistula Lagoon ecosystem is stable and eutrophic. The quantitative analyses of phytoplankton provide more metrics for ecological classification. The dominant species belonging to 8 functional groups confirmed the eutrophic nature of this water body. The contributions of groups K (containing cyanobacterial picoplankton species) and J (green algae) were the most significant. In conclusion, several metrics are used to describe phytoplankton quantity or production, but only a few of them fulfil the requirements for being good indicators of eutrophication.

Acknowledgements

We wish to thank Anna Krakowiak for her technical assistance.

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