Comparative characteristic of plankton microbial community in the waterway and coastal areas of the Kama reservoirs cascade

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Abstract. The comparative analysis of indicators of development of various components of plankton community in reservoirs of the Kama cascade in various hydrological seasons, and on various sites (in coastal and waterway) was carried out. The difference in the quantitative development of unicellular pro- and eukaryotes in different areas (coastal and riverbed) was more pronounced than in different hydrological seasons (spring flood and summer low water). Cyanobacteria make the greatest contribution to the formation of the total biomass of phytoplankton in the waterway. The contribution of heterotrophic component (bacteria and ciliata) is more significant in the coastal area. It was shown the significant correlation of the biomass of unicellular plankton and picodetritus particles, which was present in considerable amounts in the waters of the Kama reservoirs cascade.

1. Introduction
Organisms carried with water current (plankton) together with inorganic and organic suspended particles (detritus) make up the seston, which plays a significant role in the functioning of aquatic ecosystems. It is composed of unicellular pro- and eukaryotic organisms (hetero- and autotrophic bacteria, protists, including algae and ciliates), organic particles of a polysaccharide nature (including picodetrital particles < 2 µm) and some other components. Seston components are involved in biogeochemical reactions occurring in the water column, thereby having a significant impact on the formation of habitat properties. Complex trophic relationships are established between the components of seston, which largely determine the rates and directions of flows of matter and energy in aquatic ecosystems [1].

Kama is the largest left-bank tributary of the Volga and one of the largest rivers in the European part of Russia. Most of the river is regulated and is a cascade of three reservoirs. Systematic studies of several components of seston in all reservoirs of the Kama cascade are rare and therefore of great interest. This paper presents the results of the study of unicellular pro- and eukaryotic plankton and picodetritus in Kama cascade of reservoirs, in their waterway and coastal parts, in different biological seasons (summer low water and spring tide).
2. Materials and methods
Samples were collected in the coastal zone during periods of summer low water (August 2009) and the end of the spring tide (June 2012), and in waterway part of reservoirs only in the low-flow period (August 2016). The research was carried out at 58 stations: 19 at Kama Reservoir, 21 at Votkinsk Reservoir and 18 at Nizhnekamsk Reservoir. Vertically integrated samples were used for the analysis; they were obtained by mixing of water samples with a step of 1 m from layers of 0-10 m and with a step of 2 m below. Subsamples for the determination and enumeration of phytoplankton, bacterioplankton, planktonic ciliates and picodetritus were taken from the integrated samples and fixed and analyzed using standard methods [2-6]. Samples for the determination of the content of photosynthetic pigments, main ions and nutrients were also analyzed [7-9]. Measurements of physical and chemical parameters (water temperature, dissolved oxygen content, active reaction (pH) and redox potential (Eh)) were carried out by field devices and submersible sensors.

3. Results and discussion
In reservoirs of the Kama cascade, the water is fresh, with medium to moderate mineralization, generally of calcium-bicarbonate type. Local deviations of the type of mineralization were observed in the coastal zone during the summer low-water period of 2009; they were apparently due to the influence of tributaries and point discharges of wastewater from the upper Kama salt deposit and coastal gypsum outcrops [10]. The water of the Kama reservoir is as a rule the most mineralized: the average water conductivity in its coastal zone (488 µSm cm⁻¹) is higher than in the waterway (460 µSm cm⁻¹). In contrast, in other reservoirs the average conductivity is higher in the waterway (230-280 µSm cm⁻¹) compared with the coastal area (157-247 µSm cm⁻¹)[10, 11].

The water temperature in the summer low water period in 2009 and 2016 was 20-25°C with small variations by the depth and station position. During the flood, it was somewhat lower (Table 1). The greater warming of the water column in 2016 led to oxygen oversaturation of the surface layers in the waterway area and oxygen deficiency at the bottom layers of deepwater stations of the Kama and Votkinsk reservoirs [12]. In the coastal area, regardless of the hydrological period, the water column was well aerated and the content of dissolved oxygen was close to 100% saturation. In general, the average oxygen content in the Kama and Votkinsk reservoirs is higher in the coastal area, while in Nizhnekamsk reservoir - in the waterway (table 1).

### Table 1. Some environmental parameters of water of the Kama water reservoirs in 2009-2016.

| Reservoir | Kama | Votkinsk | Nizhnekamsk |
|-----------|------|----------|-------------|
| area      | coastal | waterway | coastal | waterway | coastal | waterway |
| year      | 2009 | 2012 | 2016 | 2009 | 2012 | 2016 | 2009 | 2012 | 2016 |
| period    | low | tide | low | low | tide | low | low | tide | low |
| Temp (°C) | 20.3 | 19.1 | 23.3 | 23.5 | 19.7 | 23.6 | 21.5 | 19.2 | 24.3 |
| pH        | 7.2 | 7.6 | 8.3 | 8.9 | 7.7 | 8.1 | 8.3 | 8.3 | 8.1 |
| Color (°Pt) | 155 | 61 | 35 | 135 | 59 | 40 | 84 | 34 | 38 |
| O₂ (mg L⁻¹) | 8.8 | 8.1 | 7.8 | 10.2 | 8.2 | 8.1 | 8.5 | 7.0 | 9.4 |
| Chl a (µg L⁻¹) | 4.81 | 7.71 | 18.90 | 16.10 | 7.96 | 22.60 | 4.56 | 4.91 | 17.20 |

Note: The average values for the period are given. Chlorophyll concentrations in 2016 are from [11].

The water color was the highest in the summer low water period in the coastal zone, especially in the Kama reservoir (up to 227 °Pt in the Berezinki area), which is probably due to the inflow of humic bog waters [10]. The content of chlorophyll a (Chl a) in all three reservoirs in the channel part exceeded that in the coastal area (table 1). According to Chl a concentration, the trophic conditions at the coastal areas in 2009 and 2012 were meso-eutrophic at most stations [10], while the waterway areas were eutrophic in 2016 [11].

During the studied period, 295 species of phytoplankton (cyanobacteria and eukaryotic algae) and 129 species of ciliates were identified in the Kama reservoirs: 226 and 108 species, respectively, were
detected in the coastal area, and 202 and 96 species – in the waterway area of the reservoirs. For all three Kama reservoirs the Sørensen coefficient was 0.55-0.59 for phytoplankton in different years and ~0.70 for ciliates, indicating the stability of the core communities, regardless of the hydrological period and the habitat preferences. The least coenotic similarity of plankton communities was observed in the spring flood period of 2012. Regardless of the biotope and season, communities of plankton ciliates in the Kama and Votkinsk reservoirs have a fairly close species composition and differ markedly from that in the Nizhnekmansk reservoir. The greatest variations of species composition in different periods of observation and in different biotopes were found in the Nizhnekmansk reservoir (the Sørensen coefficient – 0.45-0.62).

The spread of values of indicators for all investigated components of seston on stations within each reservoir was rather large. The minimal and maximal abundances differed at least by two orders of magnitudes, leading to very high standard deviation values (table 2). The number of picodetrital particles was also quite variable: 20-1250 ×106 particles per L, corresponding to its mass of 150-670 µg L⁻¹. The mass of picodetritus in the reservoirs of the Kama cascade averages 174±147 µg L⁻¹ in the coastal area and 259±211 µg L⁻¹ in the waterway.

The distribution of the seston components as a whole was mosaic [13]. Nevertheless, we have tried to identify some patterns of development of unicellular plankton in the channel and coastal parts of reservoirs at the level of average values; although, due to the lack of synchronous sampling in the coastal part and in the riverbed, the revealed patterns may be due to interannual or climatic features (for example, large water heating in 2016, table 1), instead of the spatial distribution.

According to our data, during the summer low water phase the average concentration of Chl a, the biomasses of individual groups of unicellular plankton and its total biomass were all higher at the waterway in 2016 than in the coastal area in 2009 (table 2). However, the work of our colleagues on the study of Chl a content in the coastal part and the riverbed in 2016 showed the opposite picture, which may be due to more intense water heating in 2016 [11, 12]. Unfortunately, the data on composition and abundance of unicellular plankton is absent from their work, making it difficult to compare the results.

The biomass of the unicellular plankton community as a whole and of its individual components is generally comparable with that in the Volga reservoirs [14-16]. According to the average values for the reservoir for the entire period of observation, the total biomass of unicellular plankton decreased from the Kama to the Nizhnekmansk reservoir. However, in 2009 the biomass was maximal in Votkinsk reservoir, and minimal in the Nizhnekmansk one. Perhaps the deviation from the common trend is due to differences in the grid of stations in different years.

According to our results, the mass of picodetrital particles in the reservoirs of Kama cascade is higher than that in the upper Volga reservoirs [1]. Besides, in the Kama and Votkinsk reservoirs, the mass of picodetritus was 1.5-2 times less than the biomass of heterotrophic bacteria, whereas in Nizhnekmansk reservoir picodetrital mass exceeded the bacterial biomass 1.4 times in average and up to 3.3 times at individual stations. In general, the mass of picodetritus, in contrast to the total biomass of unicellular plankton, increased from upstream to the downstream of the Kama River and reaches the highest values in the Nizhnekmansk reservoir (figure 1 A, B, H). Increased content of picodetritus was also found earlier in the mouths of smaller left-bank tributaries of the Volga River in the Kuibyshev reservoir, rivers Maina and Utka.

In the picophytoplankton of all Kama reservoirs eukaryotic species were almost absent and only single-cell picocyanobacteria were revealed. Picocyanobacteria formed 88.5-99.8 % of the total abundance of cyanobacteria in the coastal area and 74.6-80.7% – in waterway. The biomass of picocyanobacteria in all reservoirs was less than the biomass of both heterotrophic bacteria and the picodetrital mass. A similar ratio was observed in the Volga reservoirs [1]. The biomass of picocyanobacteria in the coastal area from upstream to downstream increases non-monotonously, and decreases on the riverbed (figure 1 A, B). The contribution of picocyanobacteria to the total biomass of single-celled plankton in the coastal area is higher than in the riverbed in all reservoirs of Kama cascade (figure 1 D, E, G).
Table 2. Unicellular planktonic pro- and eukaryotes abundance and biomass (mean values ± standard deviation) of Kama reservoirs in different hydrological periods.

| Reservoir | 2009, summer low level, coastal area | 2012, spring tide, coastal area | 2016, summer low level, waterway |
|-----------|-------------------------------------|---------------------------------|---------------------------------|
| Abundance |                                     |                                 |                                 |
| Eukaryotic phytoplankton, $10^6$ cells L$^{-1}$ | 0.81±0.70 | 1.10±0.70 | 0.45±0.28 |
| Cyanobacteria (> 2µm), $10^6$ cells L$^{-1}$ | 0.20±0.15 | 3.3±3.0 | 0.41±0.26 |
| Picocyanobacteria, $10^6$ cells L$^{-1}$ | 87.2±64.3 | 125.1±64.7 | 112.9±57.6 |
| Geterotrophic bacterioplankton, $10^6$ cells L$^{-1}$ | 2.72±0.89 | 3.04±1.27 | 2.5±0.32 |
| Ciliates, $10^3$ spec. L$^{-1}$ | 1.19±0.87 | 2.69±2.69 | 1.95±1.6 |
| Total, µg L$^{-1}$ |                                     |                                 |                                 |
| Eukaryotic phytoplankton, µg L$^{-1}$ | 667±510 | 881±635 | 379±270 |
| Cyanobacteria (> 2µm), µg L$^{-1}$ | 19±25 | 212±183 | 191±16 |
| Picocyanobacteria, µg L$^{-1}$ | 76.7±57.2 | 101.2±30.6 | 83±53.5 |
| Geterotrophic bacterioplankton, µg L$^{-1}$ | 210±40 | 270±80 | 190±80 |
| Ciliates, µg L$^{-1}$ | 29.1±21.8 | 121.4±66.0 | 46.1±32.4 |
| Total, µg L$^{-1}$ | 1002 | 1585 | 889 |

The spatial differences between waterway and riparian zones in the ratio of biomass of the individual components of unicellular plankton for all of the Kama reservoirs were generally more pronounced than seasonal ones (table 2). Total cyanobacteria (including picocyanobacteria) make a greater contribution to the formation of biomass in the channel area, while the share of geterotrophic
components (bacteria and ciliates) was significantly lower compared to the coastal region (figure 1 D, E, G). Perhaps this is a result of “intermediate disturbance” effect due to the hydrological and hydrochemical instability of the coastal zone because of lateral inflows and local inhomogeneities of the type and level of mineralization. The contribution of eukaryotic phytoplankton was quite stable both in different hydrological periods and in the coastal zone and riverbed (figure 1 D-G).

In the structure of seston as a whole, a significant decrease in the fraction of diatoms from the upper reaches downstream of the Kama was observed both in the coastal and on the riverbed area. The share of ciliates increases slightly from the Kama reservoir to Nizhnekamsk one in the coastal part and in the riverbed. Bacterioplankton share however changes in opposite directions in different parts of the reservoirs of the cascade: the greatest contribution of heterotrophic bacteria was observed in the waterway part of the Votkinsk reservoir, but in its coastal area the minimum bacterioplankton fraction was detected.

**Figure 1.** Seston composition and its components ratio in the reservoirs of Kama cascade during the studied period.

Legend: Picoseston components ratio in the coastal (A) and waterway (B) parts of the different reservoirs of Kama cascade and in the Kama cascade as a whole (C). Structure of unicellular plankton community (by share in the total biomass): in coastal (D) and waterway (E) parts of the different reservoirs of Kama cascade; in different reservoirs (F) and biotopes (G) during the whole studied period. The total plankton biomass and mass of picodetritus during the whole studied period (H).

The Kama reservoir was distinguished by the structure of the unicellular plankton community during the whole study period. The share of diatoms there was significantly higher while contribution of prokaryotes (total cyanobacteria and heterotrophic bacteria) was much lower compared to other two reservoirs (figure 1 F).
The structure of the unicellular plankton is more diverse and more even in the coastal region (figure 1 G). Diatoms (34% in coastal and 45% in riverbed zone), heterotrophic bacteria (23% and 13%) and the total cyanobacteria (16% and 30%) make the greatest contribution to the total biomass of plankton components in the coastal and riverbed for the entire study period (figure 1 G). The contribution of heterotrophic bacteria to the total biomass was higher in the coastal zone, and cyanobacteria in the waterway. At the same time, the share of picocyanobacteria in the coastal area was more significant (figure 1 D, E, G). Ciliate biomass makes up about 2% of the total biomass in the riverbed and about 5% in the coastal zone (figure 1 G). The share of chlorophytes and euglenids in the total biomass was slightly higher in the coastal area, compared with the waterway.

On the basis of the obtained data array for biomass, the correlation analysis was performed which revealed significant correlations (p<0.05) between the various components of unicellular plankton and dead organic matter (picodetritus). Positive correlation of ciliate biomass with total cyanobacteria presumably reflects their trophic relationships (R= +0.34 - +0.69 in various conditions) and, possibly, the absence of cyanotoxins at the time of research. During the summer low-water period, the development of cyanobacteria and heterotrophic bacteria occurs inphase (R= +0.40 - +0.47). Perhaps this is due to the predominant development of heterotrophic bacteria in the mucus of colonies of different species of cyanobacteria during their mass development. The presence of a large number of picodetrital particles negatively influence the abundance of heterotrophic bacterioplankton (R= -0.50); similar effect was earlier observed by us in the Upper Volga reservoir. Although the significance of correlations between unicellular plankton components may vary, their direction in different hydrological periods and in different biotopes is generally preserved.

4. Conclusion
According to presented results, the biomass of microbial plankton community of the Kama cascade reservoirs is comparable with that in the reservoirs of the Upper and Middle Volga, but the content of picodetritus in the Kama cascade is significantly higher. Downstream the Kama cascade the total biomass of microbial plankton is reducing and the detrital mass is increasing. The structure of the plankton also changes: from upstream to downstream a decrease in the contribution of diatoms is observed while the role of prokaryotes, both heterotrophic bacteria and cyanobacteria is increasing.

The difference in the quantitative development of planktomic microorganisms between the coastal and riverbed areas is more pronounced than between different hydrological seasons (spring flood and summer low water). The evenness of the planktonic microbial community of the Kama cascade of reservoirs is higher in the coastal compared with the waterway zone; in the waterway, a strong dominance of diatoms and/or cyanobacteria is observed. The contribution of heterotrophic components (heterotrophic bacteria and ciliates) and also of picocyanobacteria is higher in the coastal stations. Significant correlations are found between the biomass of different components of microbial community. This work makes a certain contribution to the study of the structure and functioning of plankton communities of unicellular microorganisms of Volga basin, and especially of the Kama reservoirs cascade, in which microbial communities were previously studied rather fragmentary.

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