Spatial heterogeneity of hydrochemical and trophic characteristics of the Kuibyshev reservoir in summer

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Abstract. Non-uniform distribution of water chemistry and plankton in water areas of big reservoirs occurs under intensive flow regulation that, generally, pre-defines their productivity, self-purification and trophic behavior. This article represents the results of hydro-chemical and trophic spatial non-uniformity studies in morphometrically different areas of the Kuibyshev reservoir in summer periods of 2015 and 2016 years. Chemical and trophic parameters of the reservoir ecosystem were compared in years with different water content. Observation data show increase in water temperature, pH and organics content, as well as decrease in water specific conductivity and mineral nitrogen and phosphor contents from north to south along the length of the reservoir. The biggest values of phytoplankton biomass, integral primary production and integral destruction are observed in lower and central parts of the reservoir, while the upper part is featured by lower values pf photosynthesis. It was found that in hot period daily phytoplankton production of the Kuibyshev reservoir twice exceeds daily influx of allochthonic organic substance with water afflux. In the Kuibyshev reservoir, which receives an influx of allochthonous matter, the intensity of destruction processes is higher than that of production processes, which indicates a good ability to self-purify the Volga waters.

1. Introduction
Since the last century, anthropogenic eutrophication of aquatic ecosystems has remained one of the urgent problems of water resources protection. A special place is given to biogenic and organic substances entering water bodies from various sources. Buildup of biogenic elements and organic substances compounds leads to water quality degradation and dangerous toxic effects appearance due to massive blue-green algae development. It is known that phytoplankton rapidly reacts to changes in environmental conditions and its production pre-defines trophic level of water bodies and its composition and abundance describes sanitary condition [1]. However, primary plankton production, together with allochthonic organic substance, inflowing to water body, forms material and energetic base for the next stages of production process in water body [2]. When hydrobiont communities functionate, organic substances balance forms, with which biogenic and other element balances are closely connected [3]. Accordingly, ecological state of water bodies depends on both hydrobiocenoses activity and physical and chemical anthropogenic factors variety. Thereat, chemical-biological processes in water ecosystems and connected so tightly that, sometimes, it’s hard to define distinct boundaries between them [4].

Hydro-chemical regime and phytoplankton development in the Volga reservoirs cascade have been studied since the middle of the last century [5-9]. Inspections of primary plankton production in the
Kuybyshev reservoir have started in 1957 [10, 11] and continued further in years with different control regimes. Last regular annual inspections were made in 2009-2011 [8].

The purpose of this study is to analyze spatial distribution of hydro-chemical parameters and plankton production profile in the Kuybyshev reservoir in summer periods of 2015-2016 in different hydrological and weather conditions, as well as evaluate primary products contribution into common stock of organic matter.

2. Materials and Methods

The Kuybyshev reservoir is located in the central part of the Middle Volga (56°09´–53°16´ N, 47°28´–52°17´ E) and is the biggest in the Volga cascade. In the period of the Volga damming and reservoir filling (1955-1957), a number of alternating expansions and sharp narrowing of the water area were formed along its entire length. Two reaches predominantly represent variable channel-type full water sections, which are located along the drowned Volga and Kama waterways. Other reaches in lower and central parts of the Kuybyshev reservoir are formed as wide lake-shaped extensions (figure 1). Morphometric profile of the reaches of the reservoir is represented in table 1.

Table 1. The main characteristics of the reaches of the Kuibyshev reservoir

| Water areas     | Volume (km³) | Area (km²) | Length (km) | Depth (Z) (m) | Water exchange period in summer (day) |
|-----------------|--------------|------------|-------------|---------------|---------------------------------------|
|                 |              |            |             | Average      | Maximum                               |
| Volzhsky        | 4.6          | 725        | 188         | 6.4          | 21                                    | 33                                    |
| Kamsky          | 3.8          | 824        | 184         | 4.6          | 20                                    | 17                                    |
| Volzhsko-Kamsky | 5.3          | 966        | 45          | 5.5          | 26                                    | 14                                    |
| Tetyushsky      | 6.4          | 877        | 79          | 7.3          | 32                                    | 17                                    |
| Undorsky        | 6.3          | 812        | 48          | 7.7          | 31                                    | 17                                    |
| Ulyanovsky      | 7.7          | 564        | 64          | 13.6         | 35                                    | 20                                    |
| Novodevichy     | 9.5          | 1019       | 95          | 9.3          | 37                                    | 25                                    |
| Priplotinnyny   | 6.0          | 417        | 34          | 14.5         | 42                                    | 17                                    |

Material is collected during summer field studies in the Kuybyshev reservoir in 2015 and 2016. Inspections were made from board of the research vessel Biolog of RAS’s Institute of Ecology of the Volga River Basin from 20 August to 9 September 2015 and from 7 to 31 July 2016 over 25 stations. Inspection covered the water area of eight broads of Kuybyshev reservoir: Volzhsky, Kamsky, Volzhsko-Kamsky, Tetyushsky, Undorsky, Ulyanovsky, Novodevichy and Priplotinnyny (figure 1).
Water samples were taken by GR-18 bathometer. Hydro-chemical profile and photosynthetic pigments content were defined by applicable regulatory documents and methods [12], and photosynthesis intensity ($A$) and destruction ($R$) by oxygenic light and dark method [13]. pH indexes and specific conductivity were measured by sensors (in situ) using DS-5X sounding unit. Primary products ($\sum A$) shall be calculated by multiplying $A$ to transparency of water ($\phi$) and destruction ($\sum R$) – by multiplying $R$ to average depths of reservoir’s broads [6]. When evaluating organic matter (OM) content in water to convert oxygenic units to carbon units, conversion constant of 0.33 was used [3].

3. Results and Discussion
One of the characteristic features of the Kuibyshev reservoir is seasonal, weekly and daily flow regulation. In spring period, the reservoir is filled up to full normal level and in other time of the year water reserves are released by Zhygulevsk hydroengineering complex [14].

Substantially all water masses, entering to the Kuibyshev reservoir are released from Cheboksary and Nizhnekamsk reservoirs, whereon 41% and 42% of annual inflow falls, respectively. 12% of total water inflow fall to the waters of the Vyatka River, entering to the Kama branch of the reservoir; the
rest small rivers of the reservoir take 5%. Hydro-chemical properties and water volume within a year are not constant and vary with seasons. The share of side afflux in spring time increases to 25% for the Vyatka River and 8% for all small rivers and summer-autumn and winter low waters decreases to 7% and 3%, respectively.

Average annual water flow \( (Q) \) amounted to 6,236 m³ s⁻¹ in 2015, 8,320 m³ s⁻¹ in 2016, while long-term annual average water flow for all time of the Kuybyshev reservoir operation amounted to 7,674 m³ s⁻¹. Water content in 2016 was significantly higher than that in 2015 and formed at the expense of spring flood water. For the time of field survey in summer low waters, average water flow did not differ significantly and amounted to 5,674 m³ s⁻¹ in 2015 and 5,116 m³ s⁻¹ in 2016 (figure 2).

![Figure 2. Hydrographers of the Kuybyshev reservoir 2015-2016](image)

Depending on water content and yearly climate, hydrodynamical and hydro-chemical reservoir’s regimes differ. Distribution of specific conductivity of water (SCW), featuring common water mineralization, along the length of Kuybyshev reservoir depends on both water exchange intensity in hydrological phases of water content, and inflow waters mineralization. In spring, mineralization of the Volga, Kama and Vyatka mater masses decreases and depends of flooding extent (yearly water content). Reservoir length and big volume do not facilitate fast exchange of winter and spring water masse, consequently, spatial SCW distribution in summer low waters becomes non-uniform. Specifically, the period of reservoir’s water exchange amounted to 71 days in spring of low-water 2015, and 37 days in high-water 2016. SCW value in 2015 was more (304-370 \( \mu \text{S cm}^{-1} \)) than in 2016 (256-370 \( \mu \text{S cm}^{-1} \)). Meanwhile, in 2016, more expressed horizontal non-uniformity was observed due to plentiful flooding and in mid-summer, SCW decrease from upper reaches to lower ones was observed along reservoir length (table 2). Max. non-uniformity was observed in the Tetyush reach, where the Volga and Kama water masses are mixed.

For the moment of field survey works (from the beginning of July to the beginning of September), water transparency amounted to 1.5 - 2.6 m in 2015 and 1.1 to 2.1 m in 2016. Air temperature in 2016 was 5-7 °C higher than in 2015 (figure 3) and water temperature (\( T \)) 5.1-5.9 °C higher. This impacted...
to spatial distribution of phytoplankton and primary products and, therefore, oxygen profile and content of biogenic (BM) and organic matters (OM) in the reservoir (table 2 and table 3).

**Table 2.** Average hydrochemical indicators of water for the reaches of the Kuibyshev reservoir

| Water areas        | Z (m) | φ (m) | T (°C) | O₃ (g m⁻³) | pH | SCW (μS cm⁻¹) | WCI (°Pt) | PI (gO₂ m⁻³) | PO₄ (gP m⁻³) | NO₃ (gN m⁻³) |
|--------------------|-------|-------|--------|------------|----|---------------|-----------|--------------|--------------|--------------|
|                    |       |       |        | Surface    |    | Bottom        |           |              |              |              |
| Volzhsky           | 6.4   | 2.0   | 18.5   | 8.22       | 7.66 | 8.33          | 364       | 30.0         | 9.68         | 0.087        | 1.30         |
| Kamsky             | 4.6   | 1.2   | 18.9   | 8.06       | 7.14 | 7.90          | 304       | 31.8         | 8.70         | 0.034        | 1.03         |
| Volzhsko-Kamsky    | 5.5   | 1.7   | 18.1   | 8.06       | 7.73 | 8.13          | 331       | 29.4         | 8.89         | 0.051        | 1.08         |
| Tetyushsky         | 7.3   | 1.6   | 17.1   | 8.25       | 7.86 | 8.17          | 345       | 33.7         | 8.37         | 0.059        | 0.93         |
| Undorsky           | 7.7   | 1.6   | 17.0   | 8.29       | 7.73 | 8.10          | 366       | 33.5         | 9.22         | 0.048        | 1.18         |
| Ulyanovsky         | 13.6  | 2.0   | 17.6   | 7.80       | 7.40 | 8.10          | 370       | 32.2         | 8.80         | 0.052        | 1.06         |
| Novodevichy        | 9.3   | 2.6   | 18.3   | 8.13       | 7.66 | 8.13          | 380       | 34.2         | 9.07         | 0.059        | 1.13         |
| Pryplotinny        | 14.5  | 2.3   | 19.0   | 7.50       | 7.28 | 8.15          | 379       | 34.8         | 8.54         | 0.066        | 0.98         |
| **Cv%**            | **22.4** | **4.0** | **3.1** | **3.1** | **1.4** | **7.0** | **5.7** | **4.4** | **25.4** | **10.1** |

|                   |       |       |        | Surface  |    | Bottom        |           |              |              |              |
| Volzhsky           | 6.4   | 2.1   | 22.2   | 7.13     | 6.75 | 8.02          | 334       | 66.7         | 11.53        | 0.078        | 0.98         |
| Kamsky             | 4.6   | 1.2   | 23.4   | 8.40     | 7.32 | 8.14          | 370       | 53.8         | 9.42         | 0.023        | 1.27         |
| Volzhsko-Kamsky    | 5.5   | 1.1   | 23.5   | 8.26     | 6.69 | 8.10          | 370       | 52.6         | 8.30         | 0.017        | 0.71         |
| Tetyushsky         | 7.3   | 1.3   | 23.2   | 7.93     | 7.26 | 8.17          | 313       | 54.6         | 10.00        | 0.035        | 2.62         |
| Undorsky           | 7.7   | 1.2   | 23.7   | 9.81     | 5.11 | 8.58          | 292       | 46.3         | 13.06        | 0.021        | 1.76         |
| Ulyanovsky         | 13.6  | 1.3   | 23.5   | 10.05    | 6.55 | 8.79          | 244       | 67.0         | 12.40        | 0.011        | 1.92         |
| Novodevichy        | 9.3   | 1.2   | 24.3   | 10.99    | 6.43 | 9.08          | 240       | 51.8         | 14.61        | 0.010        | 1.80         |
| Pryplotinny        | 14.5  | 1.4   | 24.9   | 10.23    | 4.33 | 8.58          | 256       | 69.9         | 11.75        | 0.009        | 1.49         |
| **Cv%**            | **22.1** | **3.2** | **13.8** | **15.5** | **4.3** | **16.4** | **14.1** | **16.9** | **84.7** | **35.6** |

Following the results of filed studies in 2015-2016y, average summer concentrations of phosphates (PO₄) varied from 0.009 to 0.087 g m⁻³, nitrates (NO₃) from 0.71 to 2.62 gN m⁻³, water color index (WCI) from 29.4 to 69.9 °Pt, permanganate index (PI) from 8.30 to 14.61 gO₂ m⁻³, soluble oxygen (O₃) from 7.13 to 10.99 gO₂ m⁻³ and pH from 7.9 to 9.1. Average spatial variation factors (Cv) for hydro-chemical parameters varied from 1.4 to 25.4 % in 2015 and from 3.2 to 84.7 % in 2016 (table 2). Hence, spatial non-uniformity of the Kuibyshev reservoir wasters in 2016 was more tangible in some indexes than that in 2015.
Table 3. Trophic characteristics of the Kuibyshev reservoir

| Water areas        | Z (m) | φ (m) | T (°C) | Chl a (mg m⁻³) | A (g m⁻³) | R (g O₂ m⁻² day⁻¹) | ΣA (g O₂ m⁻² day⁻¹) | ΣR (g O₂ m⁻² day⁻¹) | ΣA/ΣR |
|-------------------|------|------|--------|--------------|---------|--------------------|--------------------|--------------------|--------|
|                   |      |      |        |              |         |                    |                    |                    |        |
| Volzhsky          | 6.4  | 2.0  | 18.5   | 9.23        | 1.98    | 0.77               | 3.93               | 4.95               | 0.75   |
| Kamsky            | 4.6  | 1.2  | 18.9   | 4.18        | 2.01    | 0.46               | 2.41               | 2.12               | 1.14   |
| Volzhsko-Kamsky   | 5.5  | 1.7  | 18.1   | 5.21        | 1.51    | 0.66               | 2.75               | 3.61               | 0.82   |
| Tetyushsky        | 7.3  | 1.6  | 17.1   | 2.35        | 0.48    | 0.30               | 0.75               | 2.17               | 0.45   |
| Undorsky          | 7.7  | 1.6  | 17.1   | 6.94        | 1.09    | 0.80               | 1.84               | 6.16               | 0.54   |
| Ulyanovsky        | 13.6 | 2.0  | 17.6   | 4.74        | 0.69    | 0.26               | 1.39               | 3.54               | 0.50   |
| Novodevichy       | 9.3  | 2.6  | 18.3   | 6.13        | 0.84    | 0.59               | 2.16               | 5.46               | 0.40   |
| Pryplotinny       | 14.5 | 2.3  | 19.0   | 3.32        | 1.31    | 0.32               | 3.02               | 4.64               | 0.65   |
|                  |      |      |        | CV%         |         |                    |                    |                    |        |
| 2015 year         |      |      |        | 22.4        | 4.0     | 38.6               | 43.3               | 38.9               | 40.6   |
|                   |      |      |        |             |         |                    |                    | 33.9               | 34.5   |
|                   |      |      |        |       |         |                    |                    |                    |        |
| Volzhsky          | 6.4  | 2.1  | 22.2   | 3.44        | 1.54    | 0.66               | 3.16               | 4.21               | 0.83   |
| Kamsky            | 4.6  | 1.2  | 23.4   | 14.08       | 4.95    | 1.40               | 5.01               | 6.43               | 0.92   |
| Volzhsko-Kamsky   | 5.5  | 1.1  | 23.5   | 10.83       | 6.12    | 0.87               | 6.31               | 4.79               | 1.35   |
| Tetyushsky        | 7.3  | 1.3  | 23.2   | 15.37       | 4.18    | 0.95               | 3.86               | 6.95               | 0.70   |
| Undorsky          | 7.7  | 1.2  | 23.8   | 34.75       | 5.19    | 1.54               | 6.08               | 11.86              | 0.51   |
| Ulyanovsky        | 13.6 | 1.3  | 23.5   | 28.18       | 5.49    | 2.09               | 6.84               | 28.36              | 0.75   |
| Novodevichy       | 9.3  | 1.2  | 24.3   | 37.31       | 6.52    | 2.80               | 7.06               | 26.07              | 0.32   |
| Pryplotinny       | 14.5 | 1.4  | 24.9   | 16.24       | 1.89    | 2.00               | 2.62               | 28.95              | 0.10   |
|                  |      |      |        | CV%         |         |                    |                    |                    |        |
| 2016 year         |      |      |        | 22.1        | 3.2     | 56.2               | 38.6               | 44.2               | 31.5   |
|                   |      |      |        |             |         |                    |                    | 70.7               | 52.4   |

Observations demonstrate that for the same period of summer low waters in different years hydrochemical parameters can be several times different. Max WCI and PI values in 2016 were 1.5-2 times higher than in 2015. In 2016, PO₄ concentration along reservoir length from headstream to dam decreased 9 times and PI value increased 1.8 times. WCI distribution had no evident trend. The highest NO₃ concentrations (2.62 g m⁻³) were observed in the area of the Volga and Kama waters mixing at Tetyush broad, and the lesser ones (0.71 g m⁻³) in the Volga-Kama reach. Max. O₂ increase in water surface layer up to 11.0 g m⁻³ and decrease in bottom layer below maximum permissible concentration (6.0 g m⁻³) up to 4.33 g m⁻³ was observed in lower part of the reservoir. Meanwhile, for the time of survey, water temperature difference between upper and lower parts of the reservoir amounted to 2.75 °C in average with highest values in the Priplotinny reach (table 2). Therefore, under poor water exchange in the Kuibyshev reservoir, processes, from the one hand, connected to water
mass movement and mixing, from the other hand, connected to water temperature increase and biochemical transformation, which more intensively happen in lower broads, play primary role in hydro-chemical parameters distribution along reservoir axis.

![Seasonal variation of air temperature in 2015-2016](image)

**Figure 3.** Seasonal variation of air temperature in 2015-2016

Studies of summer plankton properties are of significant interest, as they are connected to negative effects of anthropogenic eutrophication of the reservoir. Usage of main photosynthetic pigment, chlorophyll-a (Chl a), reflecting trophic profile of water bodies [2, 15-17] is common to describe phytoplankton development and functioning. Chl a content, biomass and phytoplankton photosynthetic rate (A) has tight connection, which is traced within water area of the whole reservoir with different phytoplankton composition. Based on field data, proved correlation between Chl a content and phytoplankton biomass (figure 4), as well as Chl a and photosynthetic rate (figure 5) is detected in Kuybyshev reservoir in 2015-2016. This makes chlorophyll the basic marker of trophic profile and primary products calculation in water bodies.

Abiotic factors impact to phytoplankton development and primary production shall be, generally, pre-defined by thermal and hydrodynamic conditions, biogenic elements content and solar energy ingress [6, 18]. Within summer low waters, phytoplankton biomass in Kuybyshev reservoir is predominantly represented by blue-green algae, which growth rate is limited by high current velocities and low heating of water layer. Abiotic profile analysis shows that average volume of summer flow in low-water 2015 and high-water 2016 was approximately the same (figure 2) and did not impact to the differences in phytoplankton productivity rates in summer water content phase for these years. Basically, decreased phytoplankton development and primary production level in 2015 as compared to that in 2016 was due to the differences in water temperature and, to lesser extent, to other factors (table 2 and table 3). It worth noting that phytoplankton biomass growth leads to decrease in, first of all, mineral phosphor concentration; afterwards, this lack starts limiting algae growth. Mineral nitrogen concentration in the reservoir in vegetation period remains high enough and cannot act as limiting factor for phytoplankton development.
**Figure 4.** The relationship between Chl $a$ and phytoplankton biomass in the Kuibyshev reservoir

**Figure 5.** The relationship between Chl $a$ and the rate of photosynthesis of phytoplankton in the Kuibyshev reservoir
Phytoplankton development parameters in the Kuybyshev reservoir are represented by values typical for low-eutrophic and eutrophic waters [2, 15]. Behind well heating of the reservoir in 2016, average Chl a values amounted to 3.44-37.31 mg m⁻³ over field studies period, 3.32-9.23 mg m⁻³ in 2015; photosynthetic rates were 1.54-6.52 g m⁻³ and 0.84-2.01 g m⁻³, respectively; destruction 0.66-2.80 g m⁻³ and 0.26-0.0 g m⁻³; integral primary production 2.62-6.84 gO₂ m⁻² day and 0.75-3.93 gO₂ m⁻² day and integral destruction 4.21-28.95 gO₂ m⁻² day and 2.12-6.16 gO₂ m⁻² day. Average spatial variation factor of trophic profile varied from 4.0 to 40.6 % in 2015 and from 3.2 to 70.7 % in 2016 (table 3).

The studies have shown that intensive phytoplankton development and expressed spatial non-uniformity were observed in 2016. It has its own specific in shallow-water and deep-water section in each individual broad and it was connected to an extent and direction of runoff and drift currents. In 2016, increase in all phytoplankton parameters observed from north to south along the whole length of the reservoir, while in 2015, such dependence was not found. The most intensive photosynthesis was attributed to the reaches in the middle and lower parts of the reservoir: Undory and Novodevichiy and, to lesser extent Kama, Tetyush and Priplotinny. The lowest photosynthetic activity was observed in upper broads, Volga and Volga-Kama. Kama broad is an exception, wherein phytoplankton abundance parameters are higher due to the impact of Vyatka waters and other inflows.

As it was noted earlier, more than 80% of the Kuybyshev reservoir inflow falls to afflux from the Volga and Kama branches of the reservoir, with which allochthonic OM enters. According to our observations in July 2016, average value of reservoir primary production amounted to 5.1 gO₂ m⁻² day or, in terms of organic carbon content, 1.62 gC m⁻² day that matches with background additions of 10,100 tC day of unstable autochthonous OM due to blooming. Evaluation of OM ingress with Volga and Kama influx in summer low-waters shows that total organic carbon content in inflow is 5,314 tC day and 1,152 tC day in its unstable part. As regards to common daily OM ingress, primary production of Kuybyshev reservoir approx. 2 times exceeds total OM ingress from Cheboksary and Nizhnekamsk reservoirs, Vyatka River and 9 times exceeds the same for its unstable part. Therefore, it can be seen that primary production contributes the most in OM stock formation in Kuybyshev reservoir. 

ΣA/ΣR ratio, featuring organic matter balance in water layer is an important criterion of ecosystem condition of the reservoir. In some sections, these values vary from 0.1 to 1.35 in average; for the whole water area of the Kuybyshev reservoir, it is less than 1 (table 3). In deep-water broads, ΣA/ΣR<1 and reflects heterotrophic trend in plankton community functioning. In shallow-water Kama and Volga-Kama broads, ΣA/ΣR>1 balance is equal to 1.14 and 1.35 that is indicative of autotrophic behavior of intrabasin processes.

4. Conclusion

Studies, conducted in 2015-2016, have shown that areas with different hydro-chemical non-uniformity and primary productivity are formed in Kuybyshev reservoir waters. For the same low-water periods with different water content, BM and OM concentrations, as well as phytoplankton development profile can differ several times. However, despite of the differences in annual runoff, low phytoplankton biomass and primary products values in low-water 2015, first of all, are due to weak water heating, as compared to high-water 2016. Substantially, phytoplankton development intensity in open water period depends on water temperature and not only on water content of the year, but on runoff distribution within a year. Some hydro-chemical and trophic profiles of spatial non-uniformity of Kuybyshev reservoir waters in high-water year were more significant than in low-water one. In the period of water “blooming” in 2016, the highest biomass and primary phytoplankton production values were observed in lower and central parts of the reservoir, while the upper part is featured by lower values of photosynthesis. As compared to allochthonic OM, primary products of the Kuybyshev reservoir contribute the most in OM stock formation in Kuybyshev reservoir. In summer period, daily primary production of the reservoir approx. 2 times exceeds total OM ingress from the Cheboksary and Nizhnekamsk reservoirs, the Vyatka River. Negative tendency in OM balance (ΣA/ΣR<1) in
summer period shows heterotrophic trend in plankton community functioning and is indicative of good ability of the Kuibyshev reservoir waters self-purification.

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