Mathematical modelling of spatial-temporal variability of phosphorus content and phytoplankton development in the Kuibyshev reservoir

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Abstract. The article is dedicated to simulation of phytoplankton biomass growth dynamics amidst flow control in one of the biggest flowing water reservoirs in the world – the Kuibyshev Reservoir. Uniqueness of this natural-technical water body with such large area is pre-defined by significant spatiotemporal changes in physical, chemical and biological parameters, specifying quality and ecological condition of aquatic environment. Studies are conducted using materials of full-scale hydro-ecological observations in the reservoir within vegetation period, in 2016. Some simulation exercises were performed on the model. The model is developed based on hydro- thermodynamics equations and empirical dependences of phosphorous limitation of phytoplanktonic community biomass growth, which is implemented in VOLNA authorial software envelope. The calculation was performed on rectangular spatial grid with spacing of 200 m and timed discretization of 1 day. Within full-scale observations, initial information is acquired, model parameters are calibrated and quality of performed calculations is assessed. Simulation modelling of seasonal phytoplankton field dynamics in Kuibyshev reservoir were analysed using 2D-model of phyto- phosphorous system and results were represented. According to calculations data, phytoplankton biomass growth along reservoir length from headstream to Zhigulevsk HPP dam is observed, as well as intense water blooming locations were detected in estuarial areas and shallow-water parts of the reservoir.

1. Introduction

In the modern context of business activity growth and splitting intensification of anthropogenic impact onto the quality of surface waters, the eutrophication problem of low water-exchange reservoirs becomes extremely important. Big reservoirs creation and excessive ingress of biogenic substances, primarily, phosphor, from water collection area, led to phenomena of uncontrolled massive planktonic algae “blooming”, with ensuring ecological effects [1-3]. Kuibyshev reservoir relates to eutrophic water types and, therefore, studies of spatial non-uniformity and seasonal phytoplankton development dynamics seems actual for this, as it is connected to manifestation of negative effects of anthropogenic reservoir eutrophication.

The purpose of this work is the development of spatial model for seasonal phytoplankton development in Kuibyshev reservoir, considering phosphorous limitation and detection of phytoplanktonic biomass distribution non-uniformities, as affected by hydro- physical factors in vegetation period.
2. Materials and methods

Kuybyshev Reservoir is formed by two biggest waterways, Volga and Kama, and is the biggest valley reservoir in Europe. Being elongated longitudinally, Kuybyshev Reservoir outspreads from forestry landscaping area in the north and crosses the whole forestry-stepped area [4].

Kuybyshev Reservoir has complicated configuration of 2,500-km long shoreline and the series of dub extensions alternating with sharp narrowing. 2D-model, implemented in VOLNA software envelope, was developed to study seasonal phytoplankton development in Kuybyshev Reservoir [5]. The model consists of 143562 nodes of spatial rectangular grid with 200-m interval and is based on “shallow-water” hydro-dynamics set of equations, heat-transfer equations, eddy transfer and phytoplankton cells growth equations, and equations of convectional diffusion transfer and transformation of phosphor dissolved in water [6-9].

Mineral phosphor ($P_{\text{min}}$), dissolved in water, was used in presented calculation model as limiting biogenic substance significantly impacting to phytoplankton development in the reservoir. Seasonal progress of phytoplanktonic biomass dynamics and phosphor transformation was calculated using known dependencies [10, 11].

Water temperature fields, phytoplanktonic biomass and mineral phosphor concentrations were calculated for vegetation period from 1 May to 7 November 2016 within unstable hydro-dynamical regime, when specifying average daily flows in Volga and Kama branches of the reservoir. Onshore reservoir boundary, seasonal trend of water consumption was specified in the points of Kazanka, Mesha, Sheshma, Cheremshan and USA tributaries confluence.

3. Results and discussion

Amidst joint action of hydro-physical factor of aquatic environment, current velocity, water temperature and concentration of $P_{\text{min}}$, dissolved in water, exert a strong impact to dynamics of phytoplankton development in Kuybyshev reservoir. For low-water period 2016, current velocity in different parts of Kuybyshev Reservoir is 0.02-0.07 m/s in all dub-shaped and lake-like expansions and shallow-water bays and reaches 0.15-0.25 m/s in Volga and Kama branches, as well as in reservoir narrowing places only. The highest water temperature (27-28°C) is observed in left-shore littoral area of all dubs, except for Priplotinniy, as well as in large Cheremshansk and Usinsk bays. On hydrodynamically active fluvial sections of Volga and Kama dubs, along the whole deepwater right shore and in Priplotinniy water area, water temperature is significantly lower and reaches 20-23°C.

Calculations show that Kuybyshev reservoir is featured by high non-uniformity of phytoplanktonic biomass distribution that reaches 0.5 to 10 g/m$^3$ (figure 1a) in different sections.

Active phytoplankton biomass growth (0.5-1.0 g/m$^3$) starts from the first decade of June, when spring flood disgorges. During the first summer month, in open part of the reservoir, phytoplankton biomass concentration reaches 2.0-3.5 g/m$^3$ in average. Max. phytoplankton concentration is observed in the end of July and coincides with max, reservoir heating phase. In this time, phytoplankton biomass concentration reaches 2.6-3.2 g/m$^3$; 3.5-4.0 g/m$^3$ in the dubs of Volga and Kama; 4.0-4.5 g/m$^3$ in the dubs of Tetyushy and Ulyanovsk; and 4.5-5.0 g/m$^3$ in Undory, Novodevichiy and Priplotinniy dubs. Max. phytoplankton concentration is formed in the bays of Mesha, Cheremshan and USA Rivers along the right shore of Priplotinniy dub and reaches 6.9-9.4 g/m$^3$. In the end of August – beginning of September, phytoplankton concentration starts decreasing from 3.5 to 2.1 g/m$^3$ and reaches minimal values in September-October (table 1).

The value of variation factor ($C_v$), featuring spatial non-uniformity of phytoplanktonic biomass distribution along water area of the reservoir is 23-29 %. Within massive summer phytoplanktonic development, $C_v$ factor increases to 38-40 %. Extremely ununiform phytoplankton distribution falls for the end of summer -beginning of autumn and reaches 59-70 %.

$P_{\text{min}}$, as well as phytoplankton distribution in different parts of Kuybyshev reservoir is not uniform (table 1). The biggest $P_{\text{min}}$ values are typical for the areas with least blooming of algae, i.e. upper part of the reservoir (Volga and Kama dubs), as well as bays, wherein rivers bring the biggest volumes of $P_{\text{min}}$. For central and dam part of the reservoir, the least $P_{\text{min}}$ content is typical; here, high
phytoplankton concentration is observed (Fig. 1b). In spring flood period, $P_{\text{min}}$ concentration is maximal and reaches 0.050-0.130 g/m$^3$. When phytoplankton biomass starts growing in the reservoir, $P_{\text{min}}$ concentration decreases and reaches 0.001-0.014 g/m$^3$, and even zero values until massive algae blooming in summer.

Spatial non-uniformity of $P_{\text{min}}$ in the reservoir is high and connected to phytoplankton development dynamics. In the end of spring – beginning of summer, variation factor $C_v$ is 38%, reaches 64% in mid-summer and reaches 92% in autumn.

**Figure 1.** Calculation of the spatial distribution of phytoplankton biomass (a) and mineral phosphorus (b) during the summer heating of the Kuibyshev Reservoir in 2016.

Model calculations show that following the results of massive phytoplankton blooming along main axis of the reservoir from headstream to dam dub, average water temperature increase by 1.3°C, phytoplankton biomass increase by 2.6 g/m$^3$ and phosphate concentration decrease by 0.010 g/m$^3$ is observed. Accordingly, as compared to upper incoming sections, only at the expense of water temperature increase and outflow deceleration in open part of the reservoir, phytoplankton biomass increases twice, and 3.6 times in shallow-water bays.

Numerical simulation results were compared with full-scale data measured on 15 stations from 7 to 31 July, 2016. Validity of developed model was assessed against Theil’s criterion ($T$) [12]. Model calculations are considered satisfactory, if $T < 0.4$ and demonstrate acceptable convergence of
calculations and observations for phytoplankton ($T=0.27$) and mineral phosphor ($T=0.37$) for this criterion.

Table 1. Model calculation of the seasonal variation of phytoplankton biomass and mineral phosphorus in the reaches of the Kuibyshev reservoir in 2016.

| Water areas          | Mineral phosphorus, g/m³ | Phytoplankton biomass, g/m³ |
|----------------------|--------------------------|-----------------------------|
|                      | V  | VI | VII | VIII | IX  | X   | XI  |
| Volzhsky reach       | 0.048 | 0.055 | 0.019 | 0.013 | 0.024 | 0.068 | 0.088 |
| Kamsky reach         | 0.056 | 0.041 | 0.020 | 0.014 | 0.018 | 0.033 | 0.040 |
| Volzhsko-Kamsky reach| 0.058 | 0.036 | 0.009 | 0.011 | 0.014 | 0.023 | 0.029 |
| Tetyushinsky reach   | 0.059 | 0.040 | 0.010 | 0.009 | 0.014 | 0.034 | 0.052 |
| Ulyanovsk reach      | 0.069 | 0.039 | 0.006 | 0.003 | 0.009 | 0.017 | 0.023 |
| Novodevichy reach    | 0.086 | 0.053 | 0.005 | 0.001 | 0.002 | 0.007 | 0.010 |
| Pryplotinny reach    | 0.090 | 0.067 | 0.008 | 0.001 | 0.001 | 0.002 | 0.004 |
| Cheremshansky bay    | 0.129 | 0.125 | 0.045 | 0.011 | 0.009 | 0.010 | 0.010 |
| Usinsky bay          | 0.091 | 0.085 | 0.017 | 0.004 | 0.003 | 0.003 | 0.002 |

4. Conclusion
Based on the results of model calculation, top significance of water temperature and dissolved mineral phosphor content in phytoplankton fields formation is confirmed. It is found that within summer low waters, phytoplanktonic biomass doubles and dissolved mineral phosphor concentration decreases to extremely low values along main axis of the reservoir with gradual water temperature increase from headstream to dam dub of the reservoir. The highest intensity of phytoplanktonic community development is observed in shallow waters and fluvial areas of Mesha, Cheremshan and Usa Rivers. Spatiotemporal pattern of phytoplankton distribution in Kuibyshev Reservoir is connected to vast “blooming” areas and, therefore, pre-defines trends in spatial non-uniformity of mineral phosphor content.

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