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ВЗАИМОСВЯЗЬ ПЕРВИЧНЫХ ГИДРООПТИЧЕСКИХ ХАРАКТЕРИСТИК НА 650 НМ С ГЛУБИНОЙ ВИДИМОСТИ ДИСКА СЕККИ И КОНЦЕНТРАЦИЕЙ СИНЕ-ЗЕЛЕНЫХ ВОДОРОСЛЕЙ В ГОРЬКОВСКОМ ВОДОХРАНИЛИЩЕ

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Настоящая работа направлена на исследование гидрооптического режима озерной части Горьковского водохранилища, основанного на судовых и лабораторных измерениях характеристик оптически активных компонентов воды и первичных гидрооптических характеристик, выполненных в 2016 г. Проанализирован массив данных, собранных в период с 27 апреля по 24 октября с 97 станций, покрывающих более половины площади озерной части водохранилища (на участке от дамбы до с. Сокольское). Обнаружено доминирующие влияние сине-зеленых водорослей на прозрачность водной толщи при квазиоднородном пространственно-временном распределении растворенного органического вещества на уровне 11—12 мг/л и пренебрежимо малой концентрации минеральной взвеси. Установлен диапазон изменчивости глубины видимости диска Секки от 0.2 м до 3.5 м при вариации численности сине-зеленых водорослей от 500 до 100 000 клеток/мл соответственно. Для этого диапазона изменчивости найдены регрессии между некоторыми первичными гидрооптическими характеристиками (показателем ослабления и поглощения на длине волны 650 нм) и численностью сине-зеленых водорослей, а также получены простые формулы оценки показателя ослабления и альбедо однократного рассеяния по измерениям глубины видимости диска Секки.

Ключевые слова: Горьковское водохранилище, эвтрофный водоем, первичные гидрооптические характеристики, диск Секки, фитопланктон.

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ON CORRELATION BETWEEN INHERENT OPTICAL PROPERTIES AT 650 NM, SECCHI DEPTH AND BLUE-GREEN ALGAL ABUNDANCE FOR THE GORKY RESERVOIR

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The present work is devoted to the investigation of the hydro-optical regime of the Gorky reservoir, based on shipboard and laboratory measurements of the characteristics of optically active components and inherent optical properties in 2016 year. The data collected at 97 stations covering more than half the area of the lake part of the reservoir are analyzed. The dominant influence of blue-green algae on the transparency of the water column was observed under the quasi-constant spatio-temporal distribution of dissolved organic matter at the level of 11—12 mg/l and the negligible presence of a mineral suspension. The limits of the Secchi depth variability from 0.2 to 3.5 m respectively algal abundance from 500 to 100 000 cells/ml are established. For this ranges regressions between some inherent optical properties and blue-green algal abundance were constructed as well as formulas for estimating attenuation coefficient and the single scattering albedo by Secchi depth were obtained.

Key words: Gorky reservoir, eutrophic basin, inherent optical properties, Secchi depth, phytoplankton.

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Introduction. Measurement of optical properties of various reservoirs is a classical and still problematic task in ocean optics. The peak of its solution fells in the second half of the last century and the results for different oceans and seas were published in appropriate atlases and hydro-optics literature. Under these circumstances the least demanded and studied by oceanologists were turbid waters of inland basins which characterized by high spatial and temporal variability due to the influence of meteorological, hydrological, biogenic and anthropogenic factors. With the introduction of new optical devices for water monitoring, like satellite image radiometer, LiDAR, and fluorescence sonde, interest to such basins increased. For example, development of bio-optical algorithms for monitoring inland water bodies using their satellite images is being conducted in many countries of the world [1—3] and requires knowledge on hydro- and bio-optical characteristics of water. At the same time, LiDAR methods are actively developing too [4—5], but with reference to waters with intensive algal bloom require the refinement of algorithms for determining the suspension by echo-signals in view of the appearance of significant fluctuations in it caused by fluctuations in the optical characteristics of water [6]. The solution of this problem proves to be successful in the case of using real distributions of the optical characteristics of water and hydrosol that can be individual for some internal reservoir. This information for many lakes and reservoirs of Europe and Asia can be found in the newer literature (for example, [7]) and in digital databases ([8]). Simultaneously, the large inland water bodies of the Russian Federation are well illuminated from the hydrological side and weakly from the hydro-optical one. A concrete example of this imbalance is the Gorky reservoir, which is an example of the eutrophic reservoir and located at a distance that is accessible for organizing its regular monitoring. The information on the current hydrological regime and long-term changes can be summarized from these sources [9, 10] and cited therein. To obtain the information about hydro-optical characteristics measurements are required. In this regard an attempt to simultaneously measure some inherent optical properties (IOP) with suspended and dissolved matter characteristics of the Gorky reservoir water in order to accumulate information on the hydro-optical regime of the reservoir, to establish the range of variability of measured quantities and the factors determining their variability was made.

Data and methods. Gorky reservoir enters into the cascade of 9 reservoirs on the Volga river which is the main waterway of the central part of Russia. The reservoir was filled in 1955—1957. Its area is 1590 km^2, the volume — 8.71 km^3, the average depth — 3.65 m, the maximum depth — 27 m, the full length is 427 km, the height above sea level — 84 m. The last 85 km of the reservoir length form a lake part with medium width is about 10 km. Fig. 1 demonstrates the map of the lake part and the experimental area where the black gradient shows the distribution of depths, the double continuous line marked the Volga river channel, the arrow marks flow direction, shaded areas define areas with intensive algal bloom. List of cities and main inflows are listed on the map too. Excepting estuaries estuaries of the Ungja and the Nemda rivers, which are open to the spread of algae from it and downward to the reservoir by the dominant winds of the northern direction and the channel flow (shown by the arrow lines in fig. 1), the other areas (shaded areas on fig. 1) are usually enclosed on top by foreland that deflects the channel flow and forms zones of weak currents and higher temperatures. In addition, vortex structures that concentrate algae were many times recorded in these areas with the help of the Doppler current meter (for details see [11]). Spatial distribution of algae was not stationary [12]: with the prolonged action of winds with velocities from 6 m/s and above shifting of algal bloom areas to significant distances, up to the opposite shore for several days, was observed. As an example, fig. 2 shows three MODIS images for 29.07.16—01.08.16 including our experimental area, which clearly demonstrates this situation. However, the algal shifting effect was not important for the present study because of it was important to find places with both small and large concentrations of algae in order to capture the largest range of their variability. This was not a problem for us, as we were not limited in time or route.

According to fig. 1, hydro-optical and accompanying measurements were carried out from the south side of the lake part in the period from 27 April to 24 October of 2016 year on the experimental area from the dam to Sokolskoe with size is about 55 km x 10 km. Works performed with the help of the expedition vessel «Geoscientist» (fig. 2), equipped by radio physical complex for measuring the characteristics of the water column and near-water wind (fig. 3). It consisted of: the turbid meter Turbido-1M of the original design by Institute of Applied Physics to measure the absorption and attenuation coefficients at 650 nm, sonde YSI 6600 v2 to measure the turbidity of water and blue-green algal abundance, Doppler current velocity meter ADCP Workhorse Sentinel 600 kHz, digital ultrasonic wind speed meter WindSonic, echo-sounder with GPS-tracking

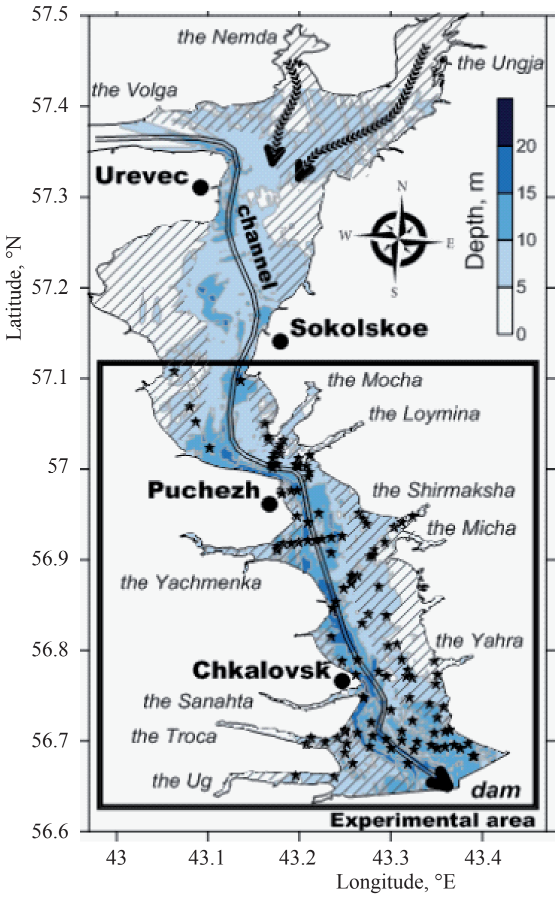

Fig. 1. Lake part of the Gorky reservoir: double continuous line marks the Volga river channel, shaded areas are areas with intensive algal bloom, stars are stations.

Рис. 1. Озерная часть Горьковского водохранилища: двойной линией отмечено русло реки Волга, заштрихованной области соответствуют области интенсивного цветения, звездочками обозначены станции.

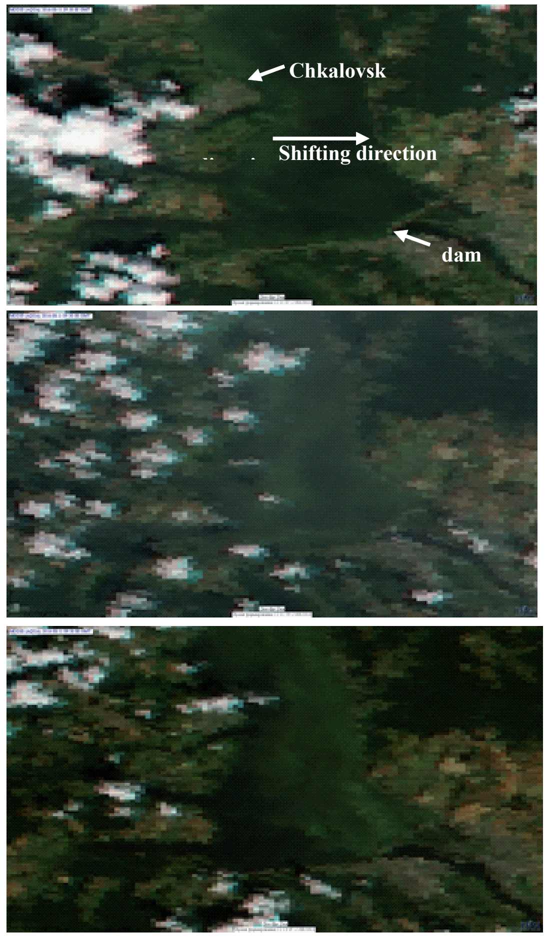

Fig. 2. MODIS image of Gorky reservoir illustrating the process of transferring the algal bloom area: 29.07.16 (top), 30.07.16 (center), 01.08.16 (bottom).

Рис. 2. MODIS изображения Горьковского водохранилища, иллюстрирующие перенос зоны цветения: 29.07.16 (верхний), 30.07.16 (средний), 01.08.16 (нижний).

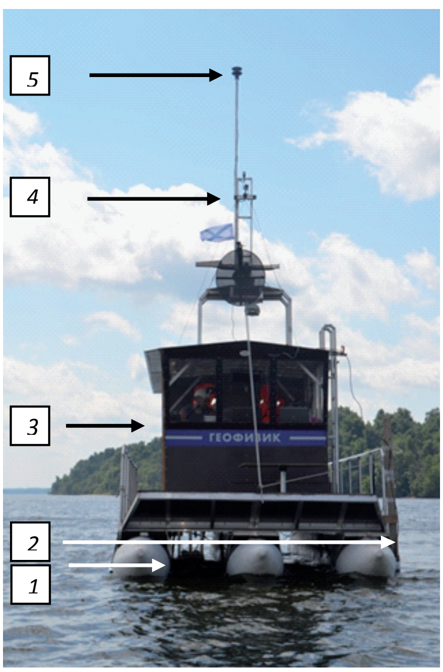

Fig. 3. Scheme of equipment on expedition vessel "Geoscientist": *1* — Doppler current velocity meter; *2* — sonde; *3* — echo-sounder; *4* — optical vision system; *5* — digital ultrasonic wind speed meter.

Рис. 3. Схема размещения оборудования на судне «Геофизик»: *1* — доплеровский измеритель скорости течений; *2* — погружной зонд; *3* — картплоттер; *4* — оптическая регистрирующая система; *5* — цифровой ультразвуковой измеритель скорости ветра.

function Garmin EchoMap 51s, depth and water temperature, and Secchi disk. All listed devices are serial devices of well-known brands, except Turbido-1M, which requires an explanation of the operational principles and technical characteristics. This device a modified version of the Turbido-1 [13] due to the introduction of the second base to measure irradiance from wide-angle light source from two distances. In this case attachment to reference medium sample is reduced. The instrument is tested at depths up to 30 m in waters with attenuation coefficient up to 10 inverse meters. The accuracy of the measurement does not exceed 20 %. The device has a digital output, which allows recording the characteristics of the medium in a continuous mode.

On the entire route of the vessel sonde was fixed at the broadside at the depth is 0.2 m and operated in continuous mode (together with Doppler current velocity meter, echo-sounder and wind speed meter). This made it possible to obtain primary information of algal abundance. On the basis of these data the coordinates of the points in which measurements would ensure the greatest variations of measured characteristics were uniquely determined. At these points we carried out contact measurements by turbid meter on depths 0.2 m (for some minutes) and Secchi disk, and took from the depths 0.1 m water samples for laboratory analysis on determination algal groups, their biomass and abundance and also to restore the concentrations of optically important components such as chlorophyll-*a*, total organic carbon (TOC) and total suspended matter (TSM). Collected water samples were placed in the refrigerator and delivered to the laboratory next morning, where analysis was conducted according to the common methods. In particular, the algal groups were determined by Microscope Meiji with 400-1000 times increasing, the Nageotte camera was used to calculate its total abundance in accordance with GOST 17713.07-32. Estimation of chlorophyll-a concentration was performed by spectrophotometric method in accordance with GOST 17.1.4.02-90, suspended in water substance (dry residue) — by gravimetric method in accordance with GOST 18164-72 and TOC estimation - in accordance with GOST 52991-2008 using modern automated TOC-analyzer «TOCOR» by oxidation of carbon compounds at 850 °C in the presence of an oxygen-containing gas and a catalyst to carbon dioxide (IV).

We collected data from 97 stations (marked by stars in fig. 1) of which for 24 stations data of the concentration of chlorophyll-a and TSM were obtained, for 30 stations — data of algal groups and abundance, for 33 stations - data of TOC concentrations, for 43 stations — data of absorption and attenuation coefficients, for 62 stations — data of Secchi depth. Data on flow, wind speed and blue-green algal abundance were obtained for all 97 stations. Thus, it was possible to collect a complete set of data covering data from direct measurement and laboratory analysis results for less than 30 stations. There are several reasons for it: a limited budget for the performance of laboratory analyzes, developed wind waves and strong ship's motions as a result, lack of sunlight, itself failures and breakdowns of the equipment. In conclusion, it should be noted that wind and current data were not used in the present study, but it were used in the study of signal fluctuations from optical sensors of turbidity and blue-green algal abundance as well as absorption and attenuation coefficients (results of this study go beyond this paper).

Results. The presented below results are based on the analysis of 97 measurements at various points of the Gorky reservoir located in channel way of Volga river, shallow coastal zones and estuaries of the flowing rivers.

Algal groups. The algae bloom in summer on the Gorky reservoir when the water warms up more than 16 degrees is a regular occurrence as well as on many other basins. Fig. 4 shows the seasonal distribution of abundance and biomass of the main algal groups observed in the reservoir: green, blue-green, cryptophytes, diatoms, euglenoids and golden algae. It can be seen from the figure that in the beginning and at the end of summer when the water is cold diatoms algae prevails in the water by biomass only while in the middle of summer blue-green algae comes to the fore by biomass and abundance both. It is important to note that the background abundance of blue-green algae at the beginning and at the end of the warm season equals approximately 500 cells/ml while at the peak of bloom their abundance will increase 200 times. The composition of blue-green algae is represented by the following species: *Aphanizomenon flos-aquae* (L.) Ralfs ex Born. et Flah., *Anabaena* sp., *Anabaena flos-aquae* Bréb. ex Born. et Flah., *Merismopedia tenuissima* Lemm., *Microcystis aeruginosa* (Kütz.) Kütz., *Microcystis wesenbergii* (Kom.) Kom. In general laboratory analysis of water samples showed that in warm water there are about 40 species of algal forming mentioned above algae groups. In particular the largest number of species (25—40) was observed near the estuaries of the flowing rivers and 20—30 species on the channel of the Volga river.

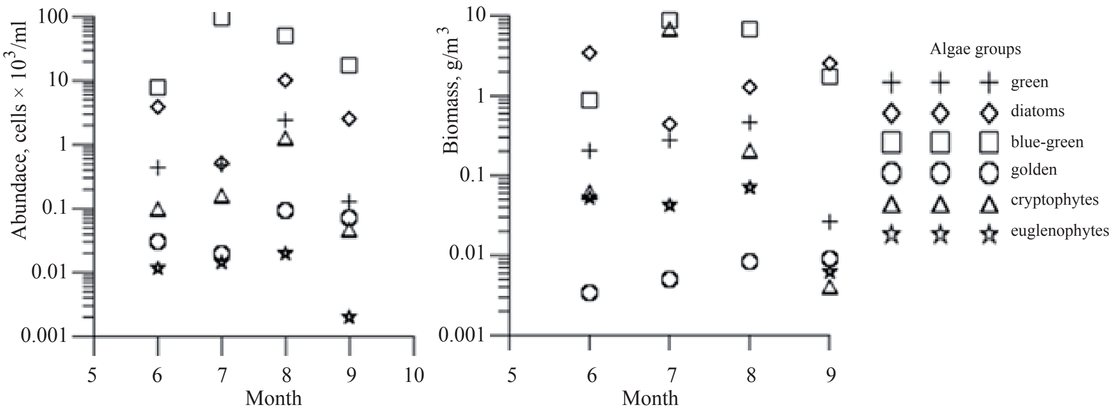

Fig. 4. The seasonal distribution of algal abundance and their biomass in the waters of the Gorky reservoir.

Рис. 4. Сезонное распределение численности водорослей и их биомассы в водах Горьковского водохранилища.

Thus the most toxic blue-green algae are dominant during all summer. These algae usually can be observed on the surface in the form of various colonies with different sizes (fig. 5).

Chlorophyll-a. Usually the bloom of blue-green algae is characterized by concentration of chlorophyll-*a*. At the end of the expedition it became clear that we have only 24 points in which there are results of laboratory analysis for chlorophyll-*a* and more than 70 points where there is data on abundance and biomass of blue-green algae. Moreover we had a big massive of data from sonde which operated continuously during vessel track. Due to more biomass samples it was decided to calibrate sonde by laboratory results and to establish a relationship between abundance and biomass. With the help of regression analysis we did it:

$$B = (C - 4374)/8195, \quad r = 0.96, \quad n = 97, \tag{1}$$

where C [cells/ml] is abundance of blue-green algae and B [mg/l] is their biomass, r — Pearson's correlation coefficient, n — quantity of measurements. This expression can be used when blue-green algal abundance above 5 000 cells/ml. Subsequent substitution of (1) into the regression ratio of Mineeva [14]

$$C_{Chl} \approx 3.23B, \quad r = 0.73, \quad n = 97 \tag{2}$$

obtained from long-term observations on the Gorky reservoir. This allows to rewrite the formula (2) in desired concentration of chlorophyll-*a* C_{Chl} [μg/l]:

$$C_{Chl} \approx 3.94 \cdot 10^{-4} (C - 4374), \quad r = 0.73, \quad n = 97. \tag{3}$$

Fig. 5. Various structures of blue-green algae on the water surface of the Gorky reservoir.

Рис. 5. Различные структуры сине-зеленых водорослей на поверхности Горьковского водохранилища.

As it follows from fig. 4 and equation (3) chlorophyll-*a* concentration was observed in the range from 1 μg/l to 40 μg/l in the summer at the Gorky reservoir. The indicated range of seasonal variability of chlorophyll-*a* concentration is in accordance with the data of long-term measurements by Mineeva [14].

Total organic carbon. One of the most important differences between inland fresh water bodies from ocean waters is the high content of colored dissolved organic matter (CDOM). In inland waters due to the huge variety of organic substances it is more correct to talk about the total organic matter (TOM). In practice the total organic carbon (TOC) is often chosen as the TOM indicator because of poor knowledge on nature of its components (more than 60 % of the composition has an indeterminate nature). Results of laboratory analysis of water samples showed that TOC concentration in the Gorky reservoir varies in the range of 11.2—12.2 mg/l. Such a small range of variability allowed us to consider the CDOM concentration to be constant, and the change in the depth of visibility of the Secchi disk depends only on the intensity of the algal bloom. Only on this assumption below presented formulas for estimating the attenuation coefficient and the single scattering albedo by Secchi depth are constructed. In fairness, it should be noted that in later measurements of 2017 and 2018 years we observed higher concentrations of TOC up to 16—23 mg/l (usually after heavy rains) for which the below formulas (4)—(7) may be incorrect.

Total suspended matter. According to the results of the laboratory analysis wide variations of total suspended matter were found. In particular in the channel way of Volga the concentrations of TSM is about 3—6 mg/l and up to 15 mg/l in the estuaries of the small flowing rivers during long-standing weather without rainfall. Rainfall results in a spatial averaging of the concentration with an average value 3 mg/l due to mixing of reservoir waters with clear rain water. According to the data of additional laboratory analysis on dry and fixed residue for five samples collected at the channel, at the Troca estuary and in shallow water near the opposite shore showed that concentration of mineral suspension in the water was negligible. This fact confirms the possibility of using the below presented formulas for estimating the attenuation coefficient and the single scattering albedo by Secchi depth for mentioned above CDOM concentration.

Secchi disk depth. Analysis of the obtained data showed that the dominant algal groups is the most toxic blue-green algal abundance of which varies from 500 cells/ml in spring and autumn to more than 100 000 cells/ml at the peak of bloom at the end of July-beginning of August. In the absence of roughness the most volume of the algae is observed near the water surface severely limiting the penetration depth of solar radiation and visibility of underwater objects such as Secchi disk. In this case its depth can decrease to 0.2 m. The developed roughness at winds exceeding 6 m/s leads to mixing of algae and as a result to a relative improvement of the water transparency to 1.0—2.0 m. However the maximum of the Secchi depth is equal to 3.5 m was recorded in spring after ice drift (27th April) and in autumn (24th October) when the water temperature was below 5 degrees and blue-green algal abundance is close to the background value and the algae sink to the bottom. In this case, the depth of visibility of the Secchi disk is determined by the concentration of organic matter (see the section Total organic carbon).

Inherent optical properties. Typical values of the attenuation and absorption coefficients as a function of the Secchi depth Z_S and the abundance of blue-green algae C are shown in fig. 6. The solid line indicates linear regressions

$$c_{650} = 4.497 \cdot 10^{-5} \cdot C + 2.345 \text{, [m}^{-1}\text{]}, \ r = 0.34 \text{, } n = 43 \text{,} \tag{4}$$

$$a_{650} = 3.648 \cdot 10^{-5} \cdot C + 1.118 \text{, [m}^{-1}\text{]}, \ r = 0.59 \text{, } n = 43 \text{.} \tag{5}$$

Formulas (4) and (5), if necessary, can be rewritten through the chlorophyll-*a* concentration using expression (3), but their accuracy will be lower.

In practice it may be useful to estimate the attenuation coefficient by the Secchi disk depth

$$c_{650} Z_S = 4 \text{, } r = 0.37 \text{, } n = 39 \tag{6}$$

and the single scattering albedo

$$\Lambda = 1 - a_{650} / c_{650} = 0.41 \text{, } r = 0.14 \text{, } n = 39 \tag{7}$$

which follow from fig. 7 with the exception of the outermost points.

Summary. The results of field measurements aimed on studies of the bio-optical water properties of the Gorky reservoir are presented. The results obtained in the work indicate that the Gorky reservoir is a vivid example of eutrophic reservoir with high spatiotemporal variations of blue-green algal abundance (500—

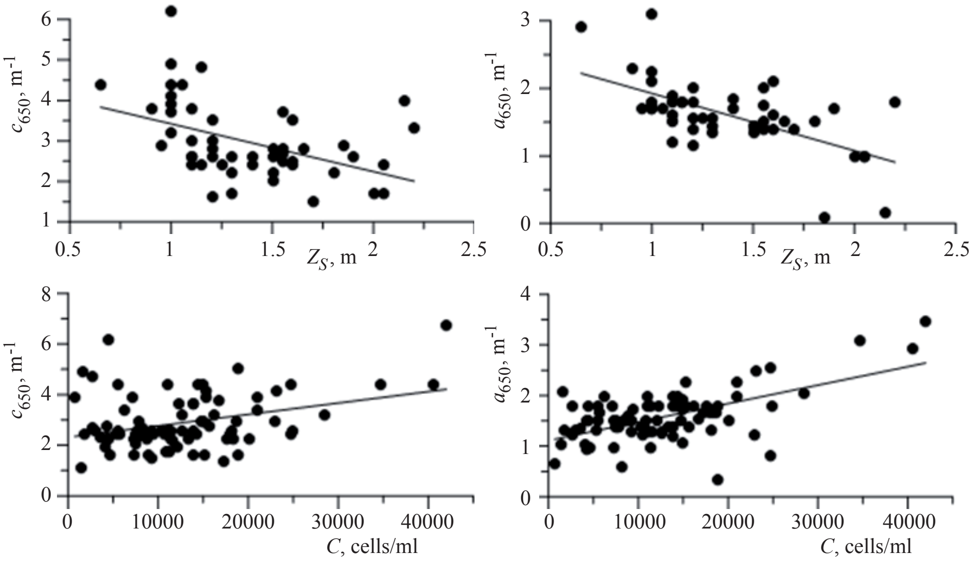

Fig. 6. Attenuation (*left*) and absorption (*right*) coefficients as a functions
of the Secchi depth (*top row*) and blue-green algal abundance (*bottom row*).

Рис. 6. Коэффициенты ослабления (левый столбец) и поглощения (правый столбец) как функции глубины видимости диска Секки (верхняя строка) и численности сине-зеленых водорослей (нижняя строка).

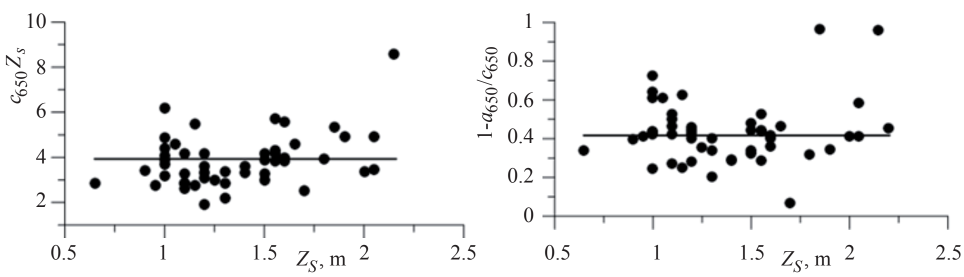

Fig. 7. Optical depth (*left*) and the single scattering albedo (*right*) as a functions of the Secchi depth.

Рис. 7. Оптическая глубина и альбедо однократного рассеяния как функции глубины видимости диска Секки.

100 000 cells/ml). According to the data obtained in the hottest weather algae accumulate at the surface in huge concentration which has a harmful effect on the reservoir life. The concentration of chlorophyll-a reaches up to 40 μg/l and status of the reservoir changes on hypertrophic. Once again it should be emphasized that the obtained formulas for estimation of IOP through the abundance of blue-green algae, as well as the Secchi depth, are obtained under the condition of a weak variability in the concentration of dissolved organic matter and the absence of mineral suspensions, which took place in the summer of 2016. Our conclusions may be incorrect in case of violation of these conditions, but to say how much we can not, because we do not have statistics for other years.

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