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© *А. А. Мольков*[1]*, *В. В. Пелевин*[2], *Е. Н. Корчемкина*[3]

[1]Институт прикладной физики РАН, 603950, ул. Ульянова, д. 46, г. Нижний Новгород, Россия
[2]Институт океанологии им. П.П. Ширшова РАН, 117997, Нахимовский пр., д. 36, г. Москва, Россия
[3]Морской гидрофизический институт РАН, 299011, Капитанская ул., д. 2, г. Севастополь, Россия
*e-mail: a.molkov@inbox.ru

ОРИГИНАЛЬНАЯ МЕТОДИКА ВАЛИДАЦИИ СПУТНИКОВЫХ ДАННЫХ В УСЛОВИЯХ СИЛЬНОЙ ПРОСТРАНСТВЕННО-ВРЕМЕННОЙ ИЗМЕНЧИВОСТИ ОПТИЧЕСКИХ СВОЙСТВ ВОДЫ ВНУТРЕННИХ ЭВТРОФНЫХ ВОДОЕМОВ

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Региональные биооптические модели восстановления концентраций оптически активных компонентов воды для внутренних водоемов строятся по всему миру. Эта задача оказывается особенно трудной в условиях сильной пространственно-временной изменчивости оптических свойств воды вследствие регулярных неоднородных течений, ветрового форсинга и плюмов впадающих рек. В этом случае результаты традиционных подспутниковых измерений на станциях для описания сезонного состояния водоема или для валидации спутниковых данных теряют информативность, а иногда и рациональность. В качестве альтернативы нами был предложен оригинальный подход, заключающийся в непрерывной синхронной регистрации яркости воды портативным спектрометром и концентраций ее оптически активных компонентов флуоресцентным лидаром с борта скоростного судна. Такой подход обеспечил возможность сбора данных с высоким пространственным и временным разрешениями (8 м и 1 Гц соответственно) с больших площадей за короткий промежуток времени, внутри которого можно считать, что пространственное распределение биооптических характеристик воды остается неизменным. Одновременно с этим эффективность метода не падает и при полевых работах в условиях разрывной облачности. В результате он был успешно применен для создания статистически достоверных моделей восстановления концентраций хлорофилла-*а* и общей взвеси по спутниковым изображениям высокого разрешения Sentinel-2 и Sentinel-3 применительно к водам Горьковского водохранилища как примера эвтрофного динамичного водоема.

Ключевые слова: внутренние водоемы, дистанционное зондирование, цвет моря, Sentinel, фотометрические измерения, изображения высокого разрешения, лидар УФЛ-9, хлорофилл-*а*, взвесь, Горьковское водохранилище

© *A. A. Molkov*[1]*, *V. V. Pelevin*[2], *E. N. Korchemkina*[3]

[1]Institute of Applied Physics RAS, 603950, Ulyanova Str., 46, Nizhny Novgorod, Russia
[2]Shirshov Institute of Oceanology RAS, 117997, Nahimovsky Prospekt, 36, Moscow, Russia
[3]Marine Hydrophysical Institute RAS, 299011, Kapitanskaya Str., 2, Sevastopol, Russia
*e-mail: a.molkov@inbox.ru

APPROACH OF NON-STATION-BASED IN SITU MEASUREMENTS FOR HIGH RESOLUTION SATELLITE REMOTE SENSING OF PRODUCTIVE AND HIGHLY CHANGEABLE INLAND WATERS

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Regional bio-optical models of water constituent retrieval for lakes and reservoirs are developed all over the world. It is especially difficult for reservoirs with high spatio-temporal variability of the water optical properties due to heterogeneous currents, plumes and irregular wind forcing. In this case, the usage of the traditional station-based sampling to describe the seasonal state of the reservoir or to validate satellite data may be uninformative or even irrational for a variety of reasons. As an alternative, an original approach based on simultaneous in situ measurements of the remote sensing reflectance by a spectrometer and concentration of water constituents by an ultraviolet fluorescence LiDAR from a high-speed gliding motorboat was proposed. This approach

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provides fast data collection with high spatial and temporal resolutions, i. e. 8 m and 1 Hz, respectively, from a large area in a short time interval within the spatial distribution of the hydro-optical characteristics do not change. Besides, the presented approach remains efficient in condition of broken cloud coverage. It was successfully applied for develop high-resolution and statistically reliable *Chl-a* and TSM models by Sentinel-2 and Sentinel-3 images of the Gorky Reservoir as an example of eutrophic productive and highly changeable inland waters.

Key words: inland water, remote sensing, ocean color, Sentinel, radiometric measurements, high-resolution imagery, LiDAR UFL-9, chlorophyll-*a*, TSM, Gorky reservoir

1. Introduction

Inland waters are known as an object difficult to study using satellite imagery. In eutrophic basins the spatial distribution of optically active components of water can be sharply heterogeneous with strong temporal variability due to presence of channel current, wind forcing, and intense plumes of inflows [1]. In such conditions, the results of station-based *in situ* measurements at time moment remote from satellite overpass do not correspond to results retrieved by the satellite image. Additionally, at broken cloud coverage, certain stations performed before the satellite overpass may appear under the cloud in the satellite image and *vice versa*. As a result, such *in situ* data becomes useless. In these conditions, traditional station-based measurements in productive and highly changeable inland waters are not rational [2]. Therefore, applicable methods and tools must significantly differ from the required ones in manuals on validating satellite data for marine and ocean waters [3].

One possible approach was presented in [4]. Its was successfully applied for design high-resolution and statistically reliable *Chl-a* and TSM models by Sentinel-2 and Sentinel-3 images of the Gorky Reservoir as an example of eutrophic productive and highly changeable inland waters [5]. The details and features of the presented approach are shown in this paper.

2. Study area

The Gorky Reservoir (56.65–58.08°N, 38.83–43.37°E) based on the Volga has 427 km of length and covers 1590 km² (fig. 1, *a*; see Insert). The last 100 km forms a lake part with an average and maximum depths are of 3.65 m and 26.6 m, respectively (fig. 1, *b*; see Insert). Its waters are eutrophic in average for a season but can be considered as hypertrophic in some regions in the hottest days of summer (fig. 1, *c*; see Insert). Measured concentrations of water constituents typically are 0.5–460 mg/m^3 for chlorophyll-*a* (*Chl-a*), 9–21 mg/l for total organic carbon (TOC), and 5–20 mg/l for total suspended matter (TSM). The Secchi depth varies from 0.2 to 3.5 m, and the euphotic zone — from 1.0 to 4.1 m [6, 7].

The lake part of the reservoir ends by a hydroelectric gravity dam (fig. 1, *b*). Water discharge through the dam has a significant effect on the current structure in the reservoir [8]. At discharge of 1000 m^3/s, the average velocity of current along the Volga channel is about 3–6 cm/s, and it increases up to 10–15 cm/s in narrowing places of the reservoir. At discharge of 1300 m^3/s, the current velocity reaches to 25 cm/s in front of the dam. The mentioned water discharges are typical for summer, but they can increase several times after intense rains significantly changing the currents structure in the reservoir and forming spatially heterogeneous distributions of phytoplankton and suspended matter over the reservoir. In addition, there are a lot of areas with reverse currents near shoreline leading to the occurrence of vortex structure and frontal zones with the highest water constituent concentration. Their dimensions vary from tens of meters to several kilometers and depend on water discharge as well as their location.

Obviously, that in such a hydrological situation usage of low-resolution satellite sensors will produce underestimated *Chl-a* values due to spatial averaging over a large pixel. To restore the *Chl-a* distribution with high resolution and realistic values of its concentration, it is necessary to use high-resolution sensors, such as Sentinel-2 (fig. 1, *d*; see Insert). For 20 m resolution and listed above current velocities we can get the following estimates of the time within a random point on the water surface will shift by pixel size: 12 minutes at current velocity of 3 cm/s, 6 minutes — at velocity of 6 cm/s, 1.5 min — at velocity of 25 cm/s. Allowing the protocols of validating satellite data for the marine waters and oceans, let's assume that time difference T between *in situ* measurements in time moment T_1 and satellite overpass in time moment T_2 equals 3 hours. During this time mentioned above point of water surface will shift by 300 m (15 pixels) at a current velocity of 3 cm/s, 600 m (30 pixels) — at a velocity of 6 cm/s, and at 2.4 km (120 pixels) — at a velocity of 25 cm/s. On the example of fig. 1, *e* (see Insert), it becomes obvious that the concentration of *Chl-a* obtained from a water sample will not coincide with the concentration of *Chl-a* recovered from the pixel corresponding to the sampling place after a reasonable time interval T. In practice, most researchers of inland waters use data obtained during one day, or even several days that completely unacceptable for inland waters like the Gorky reservoir.

Along with water discharge, wind forcing has a significant effect on the redistribution of phytoplankton too [9]. According to long-term measurements, the north winds coincidental with the reservoir extensiveness are considered as the most regular winds. They increase the upper water layer velocity up to 3 % of the wind speed and lead to phytoplankton vertical mixing. At the same time, wind forcing of other directions have an impact on the redistribution of phytoplankton from low-current shallow areas with well-heated water and intensive algal bloom throughout the reservoir.

3. Approach Description

Overview. According to [5], in conditions of strong spatio-temporal variability of the water optical properties, the *in situ* simultaneous radiometric and water constituent measurements from a high-speed gliding motorboat may be considered as the most promising tool. Our motorboat had 9 m of length that several times exceeded the length of dominant long waves. Therefore, movement was stable, noticeable pitching and rolling absent. Motorboat position and speed were registered by onboard Chartplotter Garmin EchoMap 721. The cruise speed was 8 m/s.

Continuous measurements were carried out on the south side of the reservoir (fig. 2) from 8:00 to 9:00 UTC on September 21, 2018 and September 22, 2018 under Sentinel-2 and Sentinel-3 overpasses at 9:34 UTC, respectively. The sky was clear, the weather was sunny.

Wind waves were smooth (height was about 0.3–0.5 m) according to WMO Sea State Code on the first day and calm on the second one. During measurements, the Sun azimuth angles and solar elevations varied within 162.8–180.8° and 33.3–34.5°, respectively (fig. 2). The motorboat route began at the Start point, passed along 4 tracks and ended at the Finish point, which coincides with the Start point. Each track was about 6–8 km and took about 10–15 minutes, meanwhile, the Sun position changed by azimuth and elevation on 4.5° and 0.3°, respectively.

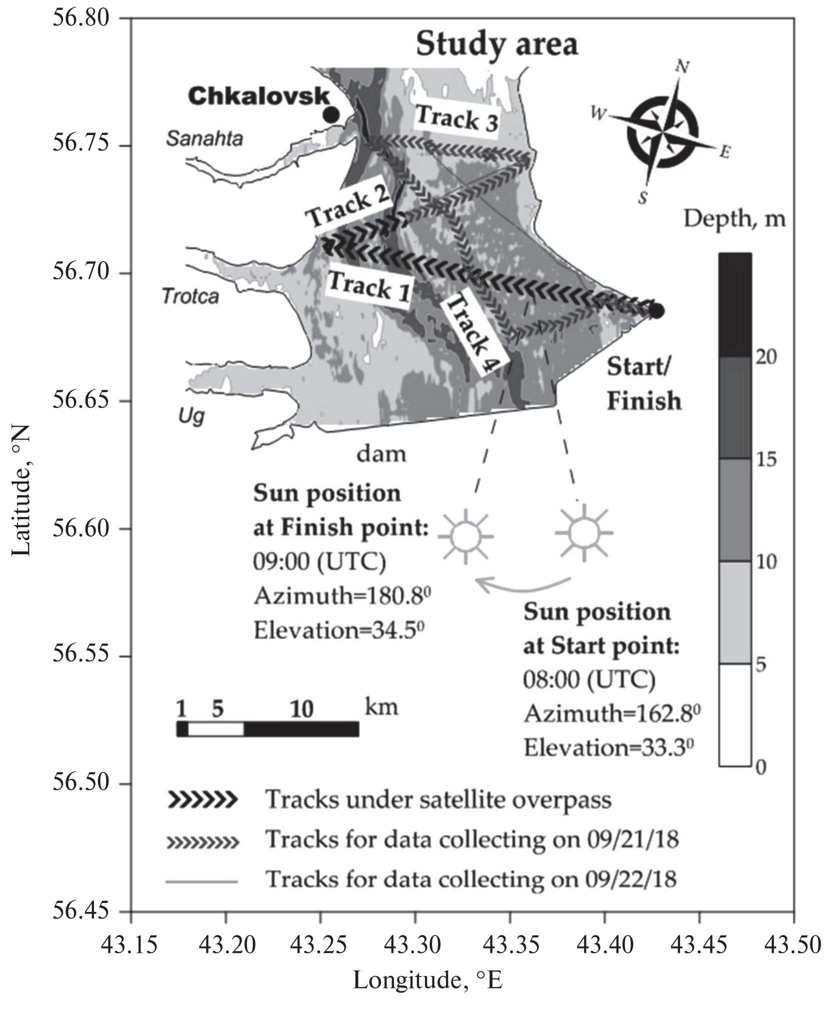

Fig. 2. Motorboat route relative to Sun position for September 21–22, 2018.

Two mentioned above optical devices were installed on the bow deck. First of them was spectrometer Ocean Optics USB2000 + for lighting measurements and the second one was ultraviolet fluorescent LiDAR UFL-9 [10] to assess *Chl-a* concentration. The spectrometer with field-of-view (FOV) of 20° was installed on the bow railing in the center of the motorboat at the zenith angle of 30°. Its azimuth angle was set up to 90° from the Sun before the first track and it was changed mechanically to keep the angle of 90° to the Sun when motorboat changed its track to the next one. Errors within ±8° were associated with inaccuracies in the manual orientation of the spectrometer and boat course fluctuations. This observation geometry satisfied the requirements of the NASA protocols [3]. The second optical instrument LiDAR UFL-9 with FOV of 1° was also installed on the bow, slightly behind the spectrometer. It was oriented at an angle of 30° to the zenith and at an angle of 45° to the motion direction. Such position of both optical devices was necessary to perform passive optical observations and active laser sensing of the unperturbed water surface in front of the motorboat and minimized falling of splashes and sun glints to FOV. As a result, on the move we continuously registered upwelling radiance with frequencies of 1 Hz by the spectrometer as well as *Chl-a* and TSM concentration with frequencies of 2 Hz by the LiDAR. So, the spatial data resolutions were equal to 8 m and 4 m respectively.

Radiometric measurements. Continuous radiometric measurements from a moving vessel satisfying the NASA protocol are not traditional tasks of water remote sensing. Therefore, the necessary protocols are not presented in the literature. In this regard, we proposed one of the possible approaches for performing continuous radiometric measurements.

Obviously, when the vessel is moving, it is extremely difficult to make continuous measurements of water-leaving radiance from underwater as it required the NASA protocols [3]. Only above water surface measurements can be carried out most correctly. Usually, three intercalibrated spectrometers are used for this [11], but there are a lot of investigations (for example, [12]), where only two spectrometers were applied. However, at small time intervals, when the lighting conditions are quasi-constant, water-leaving radiance can be obtained with only one spectrometer using a variation of the method [13]. Initially, this method consists in sequential measurement of total upwelling radiance L_u above the water surface and upwelling radiance L_{cuv} above water-filled cuvette that has walls and bottom absorbing 98 % of the incident light. In this case, upwelling underwater radiance in cuvette is considered to be zero, so we have only radiance of light reflected by the water surface L_r, $L_{cuv} \approx L_r$. After that, the water-leaving radiance L_w can be obtained as a difference $L_w = L_u - L_{ur}$ and recalculated in the remote sensing reflectance R_{rs} using the downwelling irradiance E_d measured by additional spectrometer [14]:

$$R_{\text{rs}} = \frac{L_u - L_r}{E_d}. \quad (1)$$

As a result, the considered method allows to eliminate the contribution of a randomly rough air-water interface without using empirical estimates based on wind speed. It was used in the presented form at ship stops and from a stationary oceanographic platform. But to carry out continuous measurements from a moving vessel, this method was modified. For the cloudless day we considered light conditions by a constant along one track, i. e. for 10–15 minutes. Based on this assumption, the total upwelling radiance L_u was continuously measured along the track, but the required reflected radiance L_r and the downwelling irradiance E_d were measured only at the start and finish points of each track. Here it is necessary to clarify that due to the lack of an additional spectrometer, the downwelling irradiance E_d was calculated through the radiance L_p of a horizontal plaque with a known reflection coefficient R_p close to Spectralon reflectance standard. This approach is allowed by the NASA protocol [3]. The measurements L_r and L_p were carried out sequentially (by replacing a cuvette to a plaque) for 1 minute for each one. Later, their time records were smoothed by the median filter and averaged between values at start and finish point of each track. Resulted values $\bar{L}_r$ and $\bar{L}_p$ with time record of L_u along the track were used to calculate the remote sensing reflectance R_{rs} by equation:

$$R_{\text{rs}} = \frac{L_u - \bar{L}_r}{\bar{E}_d}, \quad (2)$$

where $\bar{E}_d = \pi \bar{L}_p / R_p$. All radiometric measurements were performed in the spectral range of 378–760 nm with a resolution of 1 nm, integration time of each measurement of 1 s and average error of 3 % [15].

Water sample. To recalculate fluorescence lidar signals to *Chl-a* and TSM concentration, surface water samples were collected from different stations of study area regardless to time of satellite overpass. Sampling was performed along the route in those places where there was a visual difference in the algal bloom intensity from previous regions accompanied by significant changes in lidar fluorescence signals. At each station, water sample was taken from a depth of 0–30 cm using clear polyethylene bottles. These bottles were delivered to the shore within 1–2 hours in a refrigerator at a temperature of –4 °C. On the shore filtration was realized immediately using 47 mm Whatman GF/F fiberglass filters with a pore size of 0.7 µm with a low vacuum (~0.2 bar). The filtered volume was 2 liters. Filters were frozen at −16 °C and stored under dark conditions for 1 week. In the laboratory, *Chl-a* concentration was determined using the spectrophotometric method [16] and calculated according to the equation for mixed phytoplankton [17]. Chlorophyll was extracted in 10 ml of 90 % aqua acetone solution twice an hour. The extracts were clarified twice by centrifugation for 10 min at 8000 r/min speed. *Chl-a* concentration was measured by SF-14 spectrophotometer (Russia), previously calibrated using pure chlorophyll (Sigma) as a standard. Despite the fact, that the spectrophotometric method does not satisfy with the NASA protocols [18], it is often used to retrieve the concentration of *Chl-a* as the most accessible method providing reliable accuracy (for example [1, 16]). Intercomparison of the spectrophotometric method with two others valid by the NASA protocols, fluorometric and high-performance liquid chromatography method, was performed, for example, in [19].

TSM concentrations were determined gravimetrically by weight following the drying of filtered samples of known volume on pre-dried and weighed GF/F filters (pore size 0.7 μm). Wherein, the organic and mineral suspended matter concentrations were obtained by their spectral absorption in accordance with the procedure described in [20].

LiDAR measurements. Fluorescence LiDAR UFL-9 has been involved in field measurements worldwide: in the Atlantic Ocean, in the Black, the Kara, the Aral, the Caspian, the Baltic, the South China, the Barents, the North and the Mediterranean Seas, on the Lakes Balaton and Issyk-Kul, in the Ikshinsky and the Gorky Reservoirs. Recently, it was used on the Lake Balaton in Hungary, whose geometric dimensions, shape and the water optical properties are similar to the Gorky Reservoir. As a result, high-quality ground-truth LiDAR data were obtained and used for calibration L2 MODIS data [21]. The high quality of the LiDAR data is reached due to its physical principles and technical characteristics. The ultraviolet fluorescence LiDAR UFL-9 analyses returned signal from dual excitation (355 and 532 nm) Nd: YAG laser pulses emitted at 2 Hz with the energy of 2 mJ. Detection is carried out consistently across 11 bands (355, 385, 404, 424, 440, 460, 499, 532, 620, 651, and 685 nm) on stations simultaneously with water sampling for the instrument calibration, and across four bands (355, 404, 440, and 685 nm) simultaneously in transect mode while motorboat moves. Fluorescence intensities at 440 nm (CDOM) and 685 nm (*Chl-a*) and backscattering signal at 355 nm (TSM) are normalized to the Raman scattering at 404 nm and then calibrated using a set of laboratory-measured concentrations of *Chl-a*, CDOM, and TSM. In general, LiDAR allows measuring bio-optical properties with high accuracy for non-contact and express methods. According to [8], the total relative measurement error of UFL-9 is 10 % for TSM and CDOM and 16 % for *Chl-a*. LiDAR signal processing and its calibration are exhaustively described in [22].

4. Results and Discussion

In situ measurements under the satellite overpass in accordance with the proposed method allowed to collect data from an area of more than 100 km^2 in 1 hour with a spatial resolution of 8 m and a time resolution of 1 s. After filtering, a joint dataset including more than twenty thousand counts was formed. Each count containing R_{rs}, *Chl-a* and TSM concentration was equivalent to measurements at one station. One part of the array was aimed at choosing the optimal R_{rs} model and atmospheric correction algorithm, while another part, including data of a 10-minute interval near satellite overpass, was used to validate satellite data with the subsequent development of a regional algorithm for retrieval of *Chl-a* and TSM concentration by the Sentinel-2 and Sentinel-3 images. Here it is important to note, that the selected time interval falls into the estimated above one for typical current velocities of 3–6 cm/s within the aquatic environment can be considered as “frozen” (unchangeable). So, the obtained models are enough reliable but for short period of season. To expand the models for the entire season, it is necessary to carry out additional measurements covering the seasonal features of the reservoir. At the same time, the amount of obtained data is so large that the time interval can be narrowed in case of huge current velocity without loss of reliability of the developed models. Concurrently, it allows both building and validating these models in a wide range of concentrations of optically active components. Experience has shown that in this case, the standard deviation of an arbitrary medium characteristic (*Chl-a* or TSM) reconstructed from the image and measured by lidar is higher than for station-based measurements with subsequent laboratory processing. But station number does not exceed 100 measurements usually even for a series of expeditions during the season, while in our case the result is statistically reasonable, covering the widest range of optical properties of water.

More details on the application of the obtained data can be found in [5].

5. Conclusion

This paper proposed an original approach of non-station-based *in situ* measurements for high-resolution satellite remote sensing of productive and highly changeable inland waters. The presented approach consists in simultaneous *in situ* measurements of the remote sensing reflectance by a spectrometer and concentration of water constituents by an ultraviolet fluorescence LiDAR from a high-speed gliding motorboat.

It is an intentional rejection of the traditional method of performing *in situ* measurements at stations under satellite overpass. We realized that in this case, our priority was to measure a smaller number of hydro-optical characteristics (remote sensing reflectance, *Chl-a*, and TSM concentration) but to obtain a huge dataset with high spatial resolution. On the example of measurements on September 21, such dataset including 6020 combined measurements (one measurement corresponded to one pixel) were collected. This volume makes it possible to use one part for choosing the optimal R_{rs} model and atmospheric correction algorithm, while another part, including data of certain time interval near satellite overpass, to validate satellite data with the subsequent development of a regional algorithm for retrieval of *Chl-a* and TSM concentration by the Sentinel-2 and Sentinel-3 images.

It is obvious that the obtained dataset allows to develop only empirical but statistically valid models of remote sensing reflectance. In addition, these models may become seasonal after applying the results of *in situ* measurements during the season.

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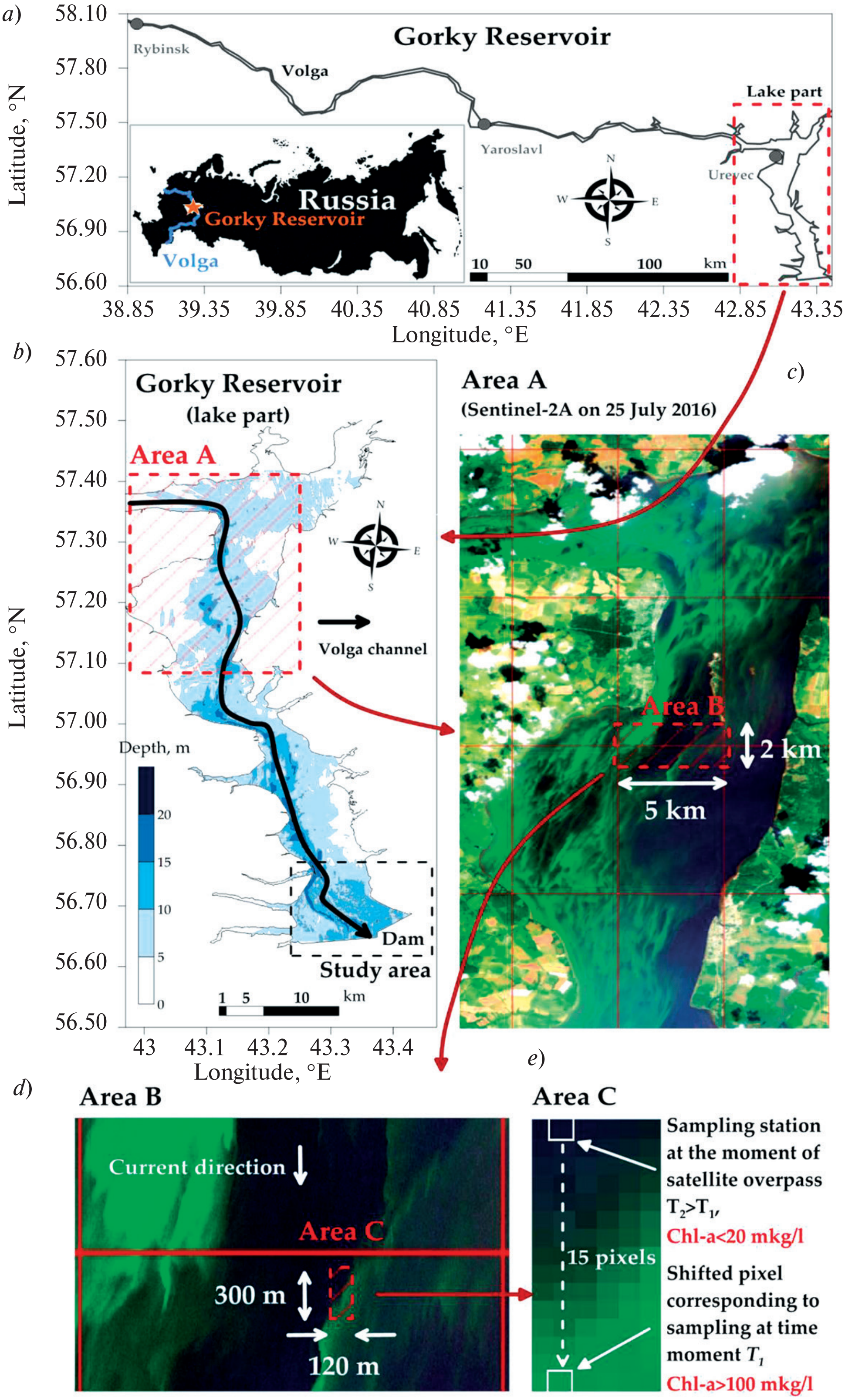

Fig. 1. Map of the Gorky Reservoir (*a*) and its lake part (*b*), an example of intensive heterogeneous cyanobacteria bloom in the northern side of the lake part, area A (*c*), a close-up view of area B corresponding to strong heterogeneous structure of cyanobacteria bloom (*d*), a zoomed-in view of area C explaining potential error in Chl-a estimation by sampling and satellite image remote in time (*e*).