Detecting biogenic pollution in Rybinsk Reservoir from satellite data and contact measurements

Olga Yu. Lavrova[*a], Ludmila G. Korneva[b], Victoria D. Shendrick[c],
Dmitry M. Soloviev[d], Alexey Ya. Strochkov[a]

[a]Space Research Institute of RAS, 84/32 Profsoyuznaya str., Moscow, Russia;
[b]I.D. Papanin Inland Water Biology Institute of RAS , Borok, Russia;
[c]Dubna International University for Nature, Society and Man, 19 University str., Dubna, Russia
[d]Marine Hydrophysical Institute, 2, Kapitanskaya, Sevastopol, Crimea

ABSTRACT

The problem of excessive algae bloom in Volga River and adjacent reservoirs has long been acknowledged. Massive algae bloom causes serious economic damage and represents a threat to water inhabitants as well as man's life and health. From ecological point of view, cyanobacteria are the most dangerous algae type.

The detection of areas most affected by algae bloom using remote sensing instruments was performed on the basis of data obtained from the following sensors: TM Landsat-5; ETM+ Landsat-7; OLI Landsat-8; Envisat MERIS and ASAR. Landsat data were used to compile color composites and select bands, the combination of which provides the best detection results. Visible satellite data were found to better manifest eutrophication zones with predomination of cyanobacteria. Envisat MERIS was used to compile suspended matter concentration charts providing rough estimates of algae content. Envisat ASAR data were compared with quasi-simultaneous visible range data.

In-situ measurements of algae properties in Rybinsk Reservoir have been performed for many years by researchers of the I.D. Papanin Inland Water Biology Institute located on its coast. They regularly perform cruises to collect water samples and determine phytoplankton content. Joint analysis of Landsat-7/8 and contact data resulted in good correlation of both bloom areas of diatoms, which predominated in June 2013, and those of cyanobacteria, the lifecycle peak of which was recorded in late August – early September.

Keywords: Harmful algae bloom, cyanobacteria, diatoms, satellite observations, radar remote sensing, the Rybinsk Reservoir, the Baltic Sea, Landsat, Envisat.

1. INTRODUCTION

Studying water "blooming" is one of the crucial tasks in hydrobiology for the moment. Algal bloom occurs both in fresh and sea water. Foremost it is observed in water reservoirs with feeble currents; and first of all – in basins with nonmoving fresh water. Water blooming is recognized to be the mass development of either one or 2-3 phytoplankton species, resulting in significant deterioration of water quality. It poses a hazard to human and animal health, and makes it difficult to use water bodies for recreational and industrial purposes. In fresh water reservoirs in summer water blooming is more often caused by blue-green (cyanobacteria) and dinophytes algae; in spring and autumn – diatomic ones. Less frequently water blooming is due to green and yellow-green algae. Water color varies with phytoplankton species and may change from blue-green, bright green and gray to yellow-green, chestnut-brown or rich red, brick-red, fallow-red and brown. Bright green blooms result from cyanobacteria growth (colloquially known as blue-green algae). When fresh water reservoirs are "blooming", algae biomass amounts to $1.5 – 2.0$ kg/m^3, and in the sites of algae concentration – to 5-7 kg/m^3. Under the calm and waveless conditions algae are accumulated in surface waters and form "blooming" spots or so called mats, floating on water surface, where its biomass riches 40-50 kg/m^3. Changes in water color and turbidity induced by intensive algal bloom open up a wide set of opportunities for satellite monitoring of water reservoirs

---

[*] olavrova@iki.rssi.ru; phone +7 495 333-4256; fax +7 495 333-1056

environment, and primarily it could be done with the use of optical sensors providing information in visible and infrared (IR) microwave ranges of electromagnetic spectrum.

Since 2002 Swedish Meteorological and Hydrological Institute (SMHI) has been running the "Baltic Algal Watch System", which is a satellite-based observation system for blue-green (cyanobacteria) algal blooms in the Baltic Sea[1]. The Baltic Sea is known to be subject to intensive blooming of cyanobacteria, almost in all its aquatic area. Analyzed satellite images, providing graphical presentation of algae development throughout the summer are available via the Internet from smhi.se. Moreover, harmful algal blooms are also increasing in volume and frequency in western Lake Erie[2,3]. Scientists from The NOAA Great Lakes Environmental Research Laboratory not only regularly record the situation with harmful algal bloom, but also make everyday forecasts of contamination spread in the lake.

In Russia strong algae bloom occurs in many inland water bodies, first of all in water storage reservoirs on rivers Volga, Dnepr, Don as well as the Azov Sea and bays of the Baltic Sea. Over the last years water quality and off-shore strip condition of the Black Sea and Barents Sea have been degrading[4]. It is worth mentioning that regular satellite monitoring of algae bloom in the largest water reservoirs of Russia is not performed. Russian scientists have been carrying on serious investigation of this problem and a lot of practical materials obtained by means of in-situ measurements have been compiled.

This article deals with the results of satellite monitoring of Rybinsk Reservoir starting from the year 1999 and provides the comparative analysis results between the data received from satellite sensors and the data obtained through in-situ measurements. Such indicators as cyanobacteria population and biomass were determined by two listed above methods at 6 observation points for the periods of June and August 2013.

2. STUDY AREA

By the present moment a cascade of nine water storage reservoirs has been constructed on the largest river in Europe – the Volga River, which starches in north-south direction. Rybinsk Reservoir is the biggest water storage basin on the river that is located in its northern part, being the third element of the cascade.

Water surface area of Rybinsk Reservoir makes up 4580 km^2, its length – 150 km, the maximum width – 70 km, the average depth – 5.6 m, the maximum depth – 30.4 m. Rybinsk Reservoir was created in 1941 after the construction of dams on rivers Volga and its tributaries Sheksna and Mologa near Rybinsk city. Five thousand square kilometers of land were drowned in order to create this reservoir; Mologa town with more than 860 years history along with 663 villages completely disappeared under water. Vast forest territories (3645 sq. km) and fertile lands had to be drowned to create Rybinsk Reservoir. The huge amount of nutrients contained in the soil of flooded area was processed by water microorganisms, which led to enhanced water mineralization and contributed to water enrichment with peat-like organic matter. After the damming of the Volga River the closed cycle of elements circulation formed in the water reservoir that was characterized by low water exchange, intensified accumulation and sedimentation processes, extra enrichment with mineral and organic substances, changes in temperature and hydrologic behavior. Construction of this water storage body resulted in formation of shallow waters and areas with fluctuating water level, reduced oxygen concentration in water column. Transformation of water environment promoted changes favorable for increased growth and development of phytoplankton.

According to depth distribution and morphological characteristics of reservoir bed the 4 main reaches of the river in this place can be distinguished: Volga, Mologa, Sheksna, Main (Glavniy) (Fig. 1). The first three reaches are located in valleys of similarly-named rivers and look like elongated quite narrow water zones. Shallow waters with 2 m depth occupy about 21% of the total reservoir area, with the depth to 6 m – more than a half, 8 m and deeper – 27%. The depth along the flooded riverbeds of Volga, Mologa and Sheksna varies within the interval 11–30 m.

Spatial algae distribution in Rybinsk Reservoir depends chiefly on the power and direction of wind and water circulation. Prevailing winds blow south and west, however, in years with meridian flow dominance the role of northern winds noticeably increases. The average wind speed over the water surface reaches 4.2-4.5 m/sec, which is 20-30% higher compared to the coastal area[5]. In spring mostly north-western winds blow with the speed of 6 m/sec and form the system of 9 cyclonic and anticyclonic circulations, the size of which fluctuates from 10 to 60 km and which occupy the area up to 1600 km^2. When the wind speed rises and amounts to the stormy level the number of circulations keeps constant, only the intensity of water-mass transportation increases between vortexes and occupied area slightly grows. In summer water

circulation is principally influenced by south-western winds and represented by 5 cyclonic and anticyclonic vortexes[6], their size along the axis varies within the interval 5-90 km and the total occupied area makes up 2100 km^2.
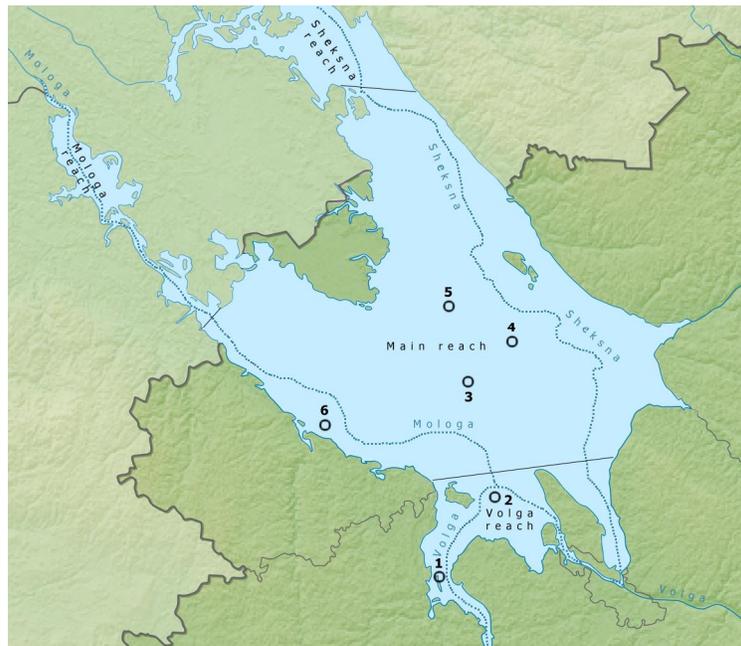

Figure 1. Subdivision of Rybinsk Reservoir. Numbers mark the location of the in-situ observation stations: 1 – Koprino, 2 – Mologa, 3 – Navolok, 4 – Izmaylovo, 5 – Sredniy Dvor, 6 – Breitovo.

Predominant phytoplankton species inhabiting Rybinsk Reservoir are the following:

1. Diatomic algae – *Melosira* and *Stephanodiscus*.

2. Blue-green algae – *Aphanizomenon flos-aquae*, *Microcystis aeruginosa*, *Microcystis viridis*, *Anabaena spiroides*.

3. Green algae – *Pediastrum boryanum*, *Mougeotia elegantula*.

Seasonal dynamics of phytoplankton development in the water reservoir is characterized by 3 waves of biomass growth: in spring, in summer and in autumn, timing and magnitude of the growth varying with weather conditions and location. The four main stages can be pointed out in the seasonal dynamics of phytoplankton biomass in Rybinsk Reservoir:

1. spring biomass increase that is due to diatomic algae development;

2. «summer depression» – clean water stage;

3. the most significant summer biomass increase caused by blue-green and diatomic algae development;

4. Autumn rise – not always can be observed and usually it is related to heavy growth of diatomic algae with substantial contribution of blue-green ones.

In autumn more frequently there is observed gradual reduction of biomass due to the growth recession of diatomic and blue-green summer species. Starting from 1981 up to the present moment the summer maximum has exceeded the spring one because of more intensive cyanobacteria development.

Systematic studies of phytoplankton in Rybinsk Reservoir have been pursued by the Papanin I.D. Institute of the Biology of Inland Waters since 1950-s. Annually in summer period researchers of the Institute carry out measurements of biological, chemical and physical water indicators at standard sampling stations. In June and August of 2013 one of this article authors – Shendrick Viktoriya – took an active part in such measurements and the results are discussed below.

Rybinsk Reservoir was chosen as an object of research for the following reasons:

• intensive algae bloom in this reservoir, especially it concerns blue-green and diatomic algae, is quite similar to the blooming in the Baltic Sea and the other water bodies of Volzhskiy basin. This fact makes it possible to compare observation results obtained by other scientists[7,8,9].

•   the huge size of the reservoir allows performing monitoring by means of satellite sensors providing information with moderate spatial resolution (150 m for ASAR and 260 m for Meris Envisat);

•   the presence of constant cyclonic and anticyclonic vortexes give an opportunity to study their influence on biogenic pollution distribution.

3.   SATELLITE-BASED MONITORING OF ALGAL BLOOM IN RYBINSK RESERVOIR

The research on dynamics of spatial and temporal distribution of "blooming" spots on the surface of Rybinsk Reservoir was conducted on the basis of satellite data obtained from the following sensors: TM Landsat-5, ETM+ Landsat-7, OLI Landsat-8, MERIS Envisat and ASAR Envisat. Data from sensors installed at Landsat satellites were downloaded from the archive available for free on the website glovis.usgs.gov. On the basis of this information color-synthesized images were developed with 30 m spatial resolution. Data from sensors MERIS and ASAR at Envisat satellite were provided by European Space Agency in the framework of several scientific projects. Spatial resolution for radar images was 150 m, and for color-synthesized images MERIS – 260 m.

Color-synthesized images in visible range are the best to be used for detection of areas with blooming cyanobacteria. During the long periods when the weather is warm, sunny and windless cyanobacteria assemble in aggregates, which come closer to the surface and form surface or subsurface accumulations. In satellite images cyanobacteria appear either as bright thread-like stripes or as massive clusters. Besides, the color of such spots depends on algae development stage and varies from bright green to reddish-brown.

The authors of the article have analyzed all available archive data received from Landsat in days when the weather was fair with some cloud or cloudless for the period from 1999 to the present day. The analysis has revealed that blue-green algae bloom was observed annually with the most intensive period in late July – mid August. However, blooming intensity manifested in satellite images in visible range varied both in years and location. According to Landsat data the most intensive cyanobacteria blooming was recorded in August 2000. In the image obtained in August 12, 2000 (Fig. 2) it can be clearly seen, that algal bloom spread almost over the entire water body. The area covered by algae was more than 4 thousands km^2. Less intensive algal bloom was noticed in the northern part of Mologa reach and in the area where the Volga River falls into the reservoir.

According to ETM+ Landsat-7 data, by the end of the month algae occupied area insignificantly diminished. Main and Sheksna reaches are known to be the regions where blue-green algae bloom was annually observed in satellite images. The main sources of pollution in Sheksninskiy reach are the objects near Cherepovets city, they are: municipal sewage discharged into stream bed part of the river reach via the deep water outlet; waste waters discharged by Cherepovets metallurgical complex; waste waters discharged by nitrogen and mercury industrial enterprises.

The river Main reach unlike the rest looks like a lake. It has deep-water zone, shallow coastal waters and inflow from rivers Sit', Sogozha and Ukhra. The large portion of nitrogen in relation to phosphorus is contained in water of the reach, this nitrogen-to-phosphorus balance is a key factor regulating the development of phytoplankton on the whole area of Main reach. Remarkable fluctuations of nutrients content in the period from summer to autumn result from frequent disturbance of bottom sediments due to the wind and discharge currents.

Diatomic algae typical of spring bloom are manifested in images of visible range in basically different manner (Fig. 3). They are depicted as fields of paler color compared to surrounding water. However, to distinguish diatomic algae in color-synthesized images is a considerably more difficult task as far as the similar manifestations could result from not only algal bloom, but, for example, be related to the inflow of muddy waters from small rivers running into Rybinsk Reservoir.
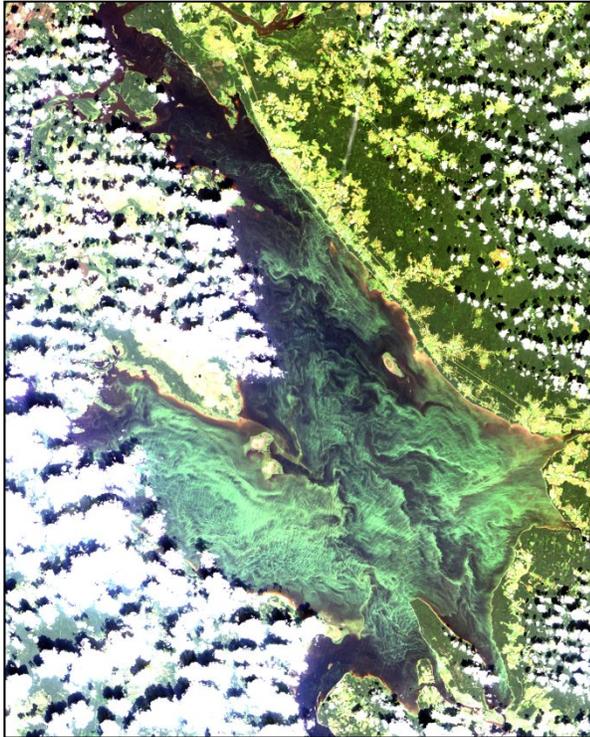
Figure 2. Most intensive cyanobacteria blooming in the Rybinsk reservoir, 12.08.2000. Fragment of ETM+ Landsat-7 image (3-2-1 bands).

Figure 3. Manifestation of diatomic algae bloom on OLI Landsat-8 (4-3-2 bands), 05.06.2013. Arrows point at the areas of intensive diatom blooming.

Color-synthesized images from Landsat and MERIS Envisat allow only the qualitative assessment of blooming intensity. In order to estimate quantitative parameters on the basis of MERIS Envisat data, there were made special maps describing concentration of chlorophyll-a (Chl-a) and of total suspended matter (Fig. 4). Chlorophyll-a concentration appeared to be not informative indicator for the purpose of revealing the fields with intensive algal bloom as it is increased almost in all areas of water reservoir. At the same time on the maps of total suspended matter it is possible not only to reveal localization of algal bloom, which corresponds well with areas characterized by the increase of this indicator values, but also to determine quite accurately phytoplankton biomass. This fact was confirmed by collecting samples and in-situ measurements.

Unfortunately the use of optical data is very limited because of quite frequent cloudiness and in July-August, 2010 and apart from clouds it was hindered by smog derived from forest fires. Moreover, in Landsat archive for the period 1999-2007 the data covering Rybinsk Reservoir territory are lacking. Only 78 Landsat images suitable for revelation of intensive algal bloom areas were received, processed and analyzed.

Radar images permit to acquire information about water surface under any meteorological conditions. We attempted to conduct simultaneous analysis of both data obtained in visual range of electromagnetic spectrum and radar data compiled for Rybinsk Reservoir as it was previously performed by the example of the Baltic Sea[10].

We possessed 5 ASAR Envisat images obtained on: 15.06, 18.07, 19.07, 26.07, 14.08 2011; and 3 SAR ERS-2 images, obtained on 03.07, 19.07 2009, and 18.06 2010. The analysis showed that in radar images best of all one could distinguish areas with intensive diatomic algal bloom, which look like spots with reduced dispersion of reflected radar signal.
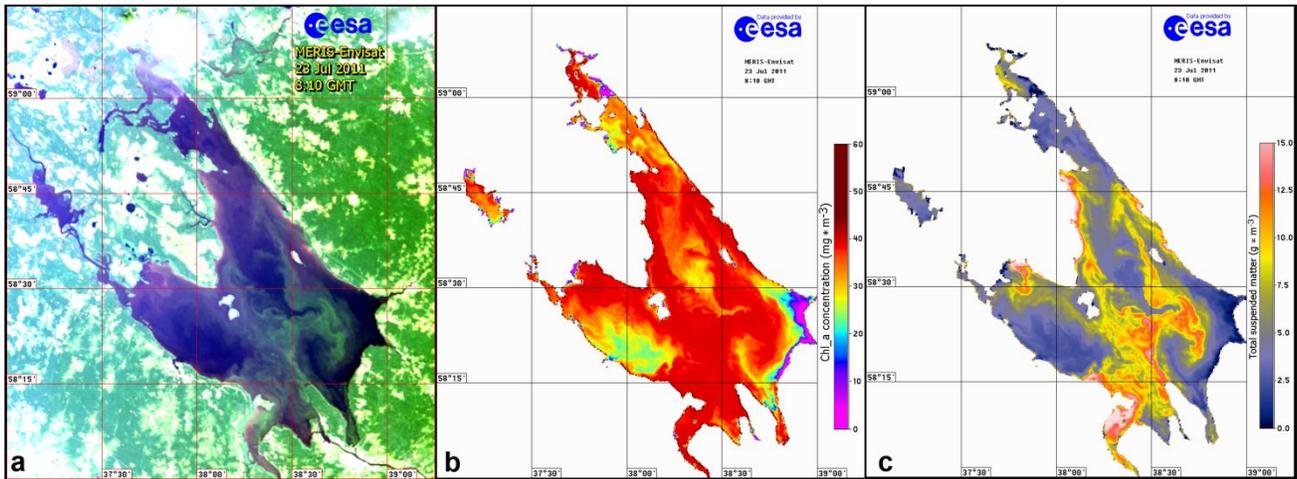
Figure 4. Manifestation of cyanobacteria bloom on MERIS Envisat, 23.07.2011: *a* – true color image (7-5-2 bands); *b* – chlorophyll-a concentration map; *c* – total suspended matter map.

It is most likely to be due to algal aggregation into so-called mats (Fig. 5a), which almost completely damp out ripples and smoothed water surface. When blue-green algae are blooming the typical slicks are observed in radar images (Fig. 5b). The small amount of available radar data of moderate resolution does not allow us to draw unmistakable conclusions on applicability of satellite radar data for algal bloom detection.
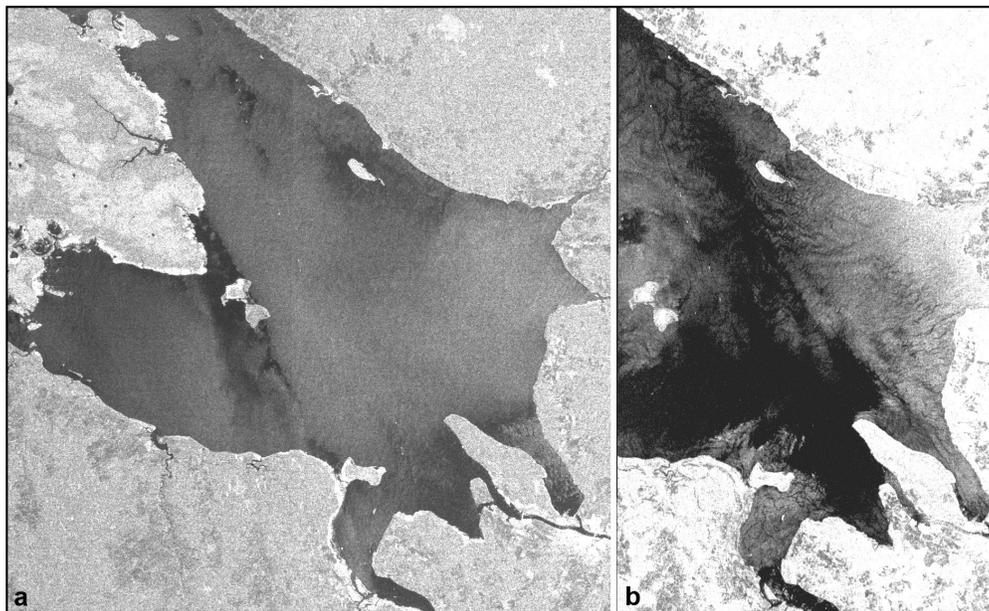

Figure 5. Manifestation of algae bloom on radar images: *a* – dark spots correspond to diatomic algal bloom (ASAR Envisat, 15.06.2011); *b* – slicks generated by cyanobacteria blooming (SAR ERS-2, 19.07.2009).

4. GROUND-TRUTH OBSERVATIONS OF ALGAL BLOOM IN RYBINSK RESERVOIR

Taxonomic composition estimation of blue-green algae (cyanobacteria) in Rybinsk Reservoir was performed by collecting water samples at 6 observation stations during regular cruises in June 15, 2010; August 10, 2010; June 24, 2013 and August 20, 2013. It is worth mentioning that experiments were focused on blue-green algae in particular.

Diatomic ones were not considered. Stations are arranged as follows: in Main reach – Navolok, Izmaylovo, Sredniy Dvor, Breitovo; in Volga reach - Koprino, Mologa. Observation stations layout is given in Fig. 1.

In order to carry out quantitative analysis of cyanobacteria, surface water samples were collected at the depth fluctuating from 0 to 2 m. The standard technique developed in Papanin I.D. Institute of the Biology of Inland Waters was used for quantitative phytoplankton measurements. Evaluation of cyanobacteria biomass was conducted by the standard volume-weight method.

In the process of analysis of water samples from 6 stations in Rybinsk Reservoir the following dominant cyanobacteria species can be distinguished for the monitoring period: *Aphanizomenon flos-aquae*; *Anabaena flos-aquae*; *Microsystes aureginosa*; *Microsystes wesenbergii*.

The obtained results make it possible to perform quantitative evaluation of blue-green algae biomass, comparative study of species composition and development level of blue-green algae in various areas of Rybinsk Reservoir both during the period of phytoplankton biomass reduction ("clean water" stage) in June of years 2010 and 2013 and during the period of its maximal development in August of 2010 and 2013.

The data analysis demonstrates that number and biomass of cyanobacteria on 15.06.2010 was not large at all observation stations. Taxonomic composition of cyanobacteria for that period turned out to be quite poor and at all stations was mostly represented by two species: *Aphanizomenon flos-aquae* and *Anabaena*. At Navolok station not any species of blue-green algae was revealed.

On August 10, 2010 a significant increase in number and consequently in biomass of cyanobacteria was recorded. The highest cyanobacteria number was noted at Navolok station and reached 265 900 thousand cells in 1 litre, while the biomass respectively amounted to 13.5 mg/l.

Taxonomic composition of blue-green algae in August rather expanded in contrast to June and was represented by six predominant species: *Aphanizomenon flos-aquae*, *Microcystis aeruginosa*, *Microcystis viridis*, *Anabaena spiroides*, *Microcystis holsatica*, *Aphanizomenon elenkinii*.

Cyanobacteria species composition on June 24, 2013 was found to be much more diversified compared to the one observed on June 15, 2010. The six prevailing species of blue-green algae were the following: *Aphanizomenon flos-aquae*, *Microcystis aeruginosa*, *Microcystis wesenberge*, *Anabaena spiroides*, *Anabaena flos-aquae*, *Anabaena sheremetieva*.

The maximum number of blue-green algae was revealed on that day at stations Breitovo (6787 thousand cells per litre), Sredniy Dvor (3363 thousand cells per litre), Mologa (2887 thousand cells per litre), Koprino (2040 thousand cells per litre). Furthermore, cyanobacteria biomass values at all observation stations exceeded the ones recorded on June 15, 2010.

The results of examination of water samples collected in Rybinsk Reservoir on August 20, 2013 demonstrate that in comparison with June 24, 2013 the larger number of cyanobacteria and its biomass were observed at all stations. Besides, the maximum cyanobacteria number and biomass were noted at stations Sredniy Dvor, Navolok as well as at near-shore stations – Breitovo and Izmaylovo. In August, prevailing species of blue-green algae were *Aphanizomenon flos-aquae*, *Microcystis aeruginosa*, *Microcystis wesenberge*. It is these dominating species of blue-green algae which cause water blooming in Rybinsk Reservoir in summer time.

Some graphic materials are given below (Fig. 6), they describe the development level of blue-green algae at 6 stations in June and August of 2010 and 2013 and allow conducting comparative analysis.

In Russia summer of 2010 is known to be characterized by extended period of abnormally hot weather (last decade of June – first half of August). Water temperature in Rybinsk Reservoir increased to 26∘C, which promoted intensive cyanobacteria bloom. In August 2010 the maximum amount of blue-green algae was registered at Navolok station. In Fig. 6d it is graphically shown how cyanobacteria biomass was distributed in June and August of 2010 and 2013 at 6 observation stations. According to this diagram, it can be concluded, that maximum cyanobacteria biomass was revealed at Navolok station (about 14 mg/l) on August 10, 2010 and at Sredniy Dvor station (near 6 mg/l) on August 20, 2013.
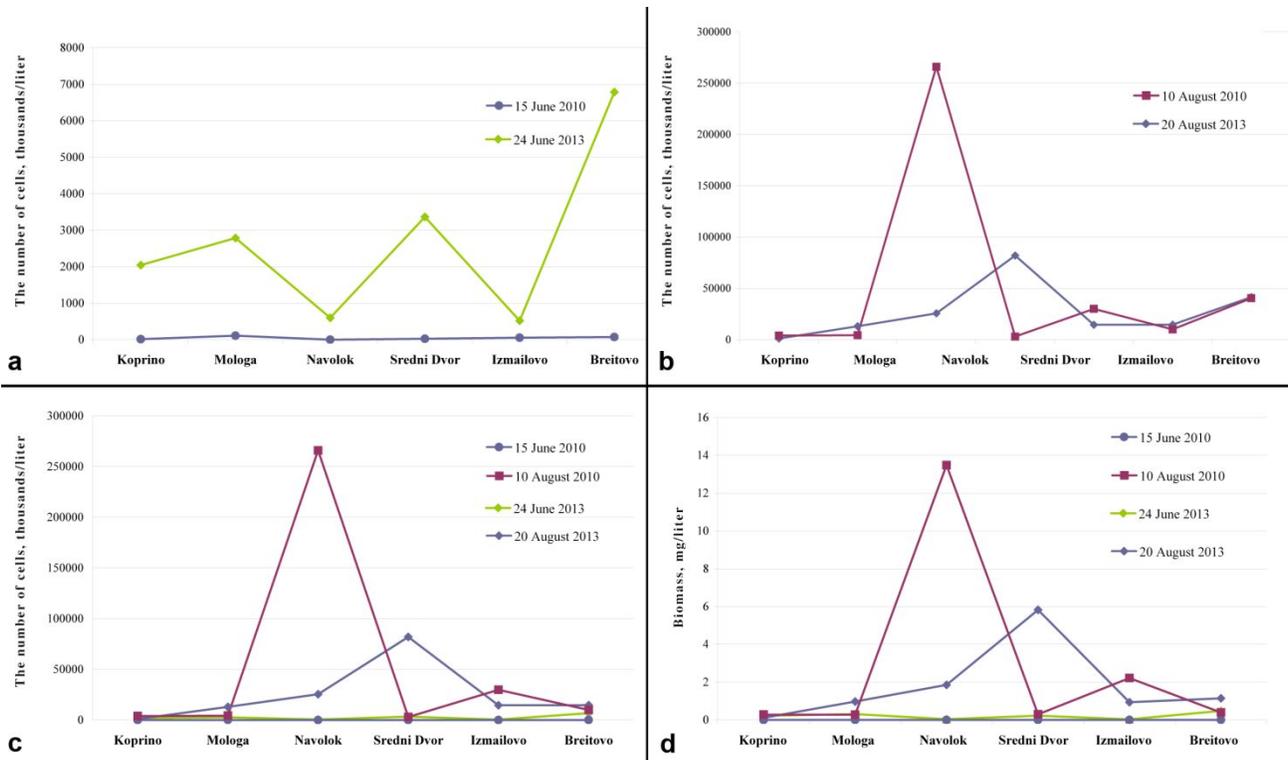
Figure 6. Quantitative characteristics of cyanobacteria in Rybinsk Reservoir measured at 6 stations. The number of cells: *a* – June 2010 and 2013; *b* – August 2010 and 2013; *c* – June, August 2010 and 2013; *d* - The biomass of cyanobacteria June, August 2010 and 2013.

5. COMPARISON OF SATELLITE OBSERVATION RESULTS AND IN-SITU MEASUREMENTS DATA

In order to perform combined analysis of satellite data and results of in-situ measurements the six Landsat images were selected, being obtained close together in time and when the weather was mainly clear. The results of in-situ measurements were compared to satellite data:

- measurements on 15.06.2010 compared to image ETM+ Landsat-7 on 21.06.2010;
- measurements on 10.08.2010 compared to image TM Landsat-5 on 31.07.2010;
- measurements on 24.06.2013 compared to images OLI Landsat-8 on 05.06.2013 and ETM+ Landsat-7 on 29.06.2013 (there were no other images that would be closer in time and taken in cloudless weather)
- measurements on 20.08.2013 compared to images OLI Landsat-8 on 08.08.2013 and OLI Landsat-8 on 09.09.2013.

The analysis shows that in June 2010 and 2013 blue-green algae bloom was very feeble, though varied with years of research (Fig. 6a). Moreover, in photos taken from the board of the scientific ship at observation stations Breitovo and Navolok one can see that water is intensively "blooming" (Fig. 7a). Qualitative research of water "blooming" fulfilled at Mologa station in June 2013 by means of plankton sampler provides evidence of considerable amount of diatomic algae content in water samples.

Let's take a good look at images received on 05.06.2013 from OLI Landsat-8 and on 29.06.1013 from ETM+ Landsat-7 and compare them to the data obtained from the scientific ship on 24.06.2013. Typical bright-green filaments, which are usually indicative of blue - green algae presence in water, cannot be distinguished in the first image (Fig. 3). In the second image, taken close in time to the moment of in-situ measurements, it is already possible to notice discrete signs of blue-green algae, however, near the sampling stations they are still indiscernible (Fig. 7b). Negligibly small amount of cyanobacteria is evidenced by field measurements as well. Lighter spots along the shore in Fig. 3 and Fig. 7b correspond to the areas of diatomic algae bloom.
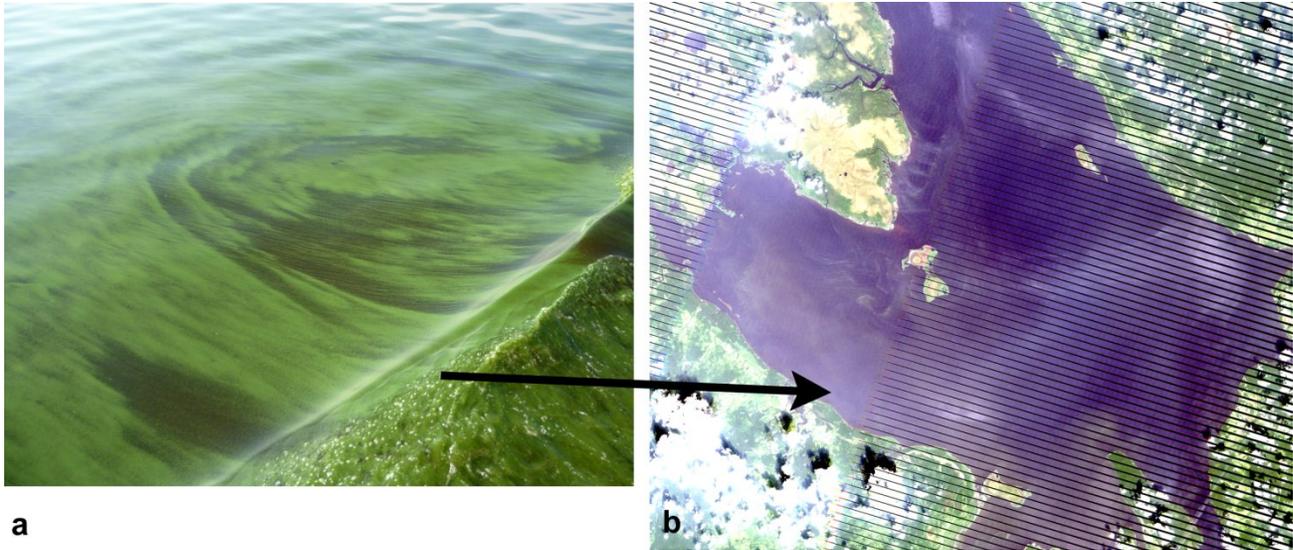
Figure 7. Algae bloom in June, 2013: *a* - the picture taken on June 24, 2013 from the board of the scientific ship at observation station Breitovo (Photo V. Shendrick); *b* – ETM+ Landsat-7 image (3-2-1 bands), 29.06.1013.
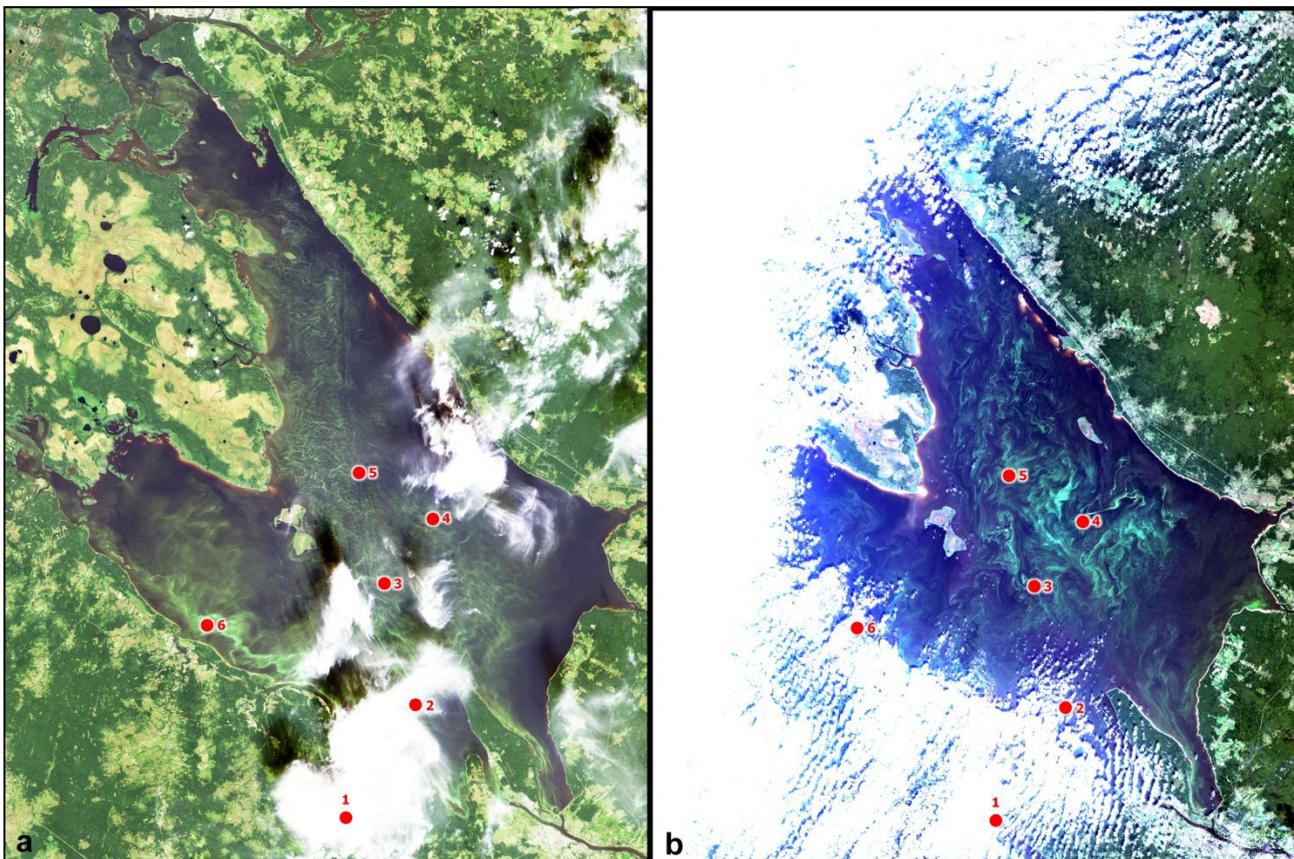

Figure 8. Algae bloom manifestations on OLI Landsat-8 images: *a* - 08.08.2013; *b* - 09.09.2013. Numbers mark the location of the in-situ observation stations: 1 – Koprino, 2 – Mologa, 3 – Navolok, 4 – Izmaylovo, 5 – Sredniy Dvor, 6 – Breitovo.

When comparing the measured indicators of cyanobacteria in water samples collected on 20.08.2013 with OLI Landsat-8 color-synthesized images on 08.08.2013 and 09.09.2013 (as there were no other images that would be closer in time and taken in cloudless weather) qualitative correspondence can be observed (Fig. 8). The areas with bright-green filaments, related to the intensive bloom of blue-green algae, cover almost the entire central part of Main reach where such stations as Navolok, Sredniy Dvor and Izmaylovo are located and where the increased cyanobacteria biomass was registered (Fig. 6d). Unfortunately more accurate comparison was impossible to perform because of presence of clouds in satellite images made in August and significant time gap between the moment of satellite monitoring and in-situ measurements.

6. CONCLUSION

Long-term satellite monitoring of Rybinsk Reservoir waters showed that biogenic contamination resulting in intensive algal bloom is observed each year. The most intensive diatomic algae bloom occurs along the shore, the peak of activity being registered in the end of May – first half of June. Main reach is the most susceptible area to blue-green algae bloom especially in its central part. In addition, there are noticed year-to-year variations of cyanobacteria blooming intensity, however, the direct correlation with air temperature was not traced. This is because blooming intensity depends on many circumstances and not only on water warming.

Satellite sensors data from Landsat and especially from OLI Landsat-8 are the most adequate for detecting blooming areas and for qualitative evaluation of blooming intensity. In order to obtain quantitative characteristics based on satellite remote sensing data, it is necessary to develop regional algorithms since standard algorithms are not always applicable for inland fresh water reservoirs.

In radar images of Rybinsk Reservoir, accumulations of diatomic algae are seen best of all and look like dark spots of reduced dispersion. Excessive cyanobacteria bloom is manifested in radar images as numerous slicks resulting from biogenic films developed on water surface.

The attempt to compare in-situ measurements with satellite remote sensing data revealed that in-situ measurements should be performed simultaneously with satellite monitoring. Furthermore, it is advisable to expand measurement network and to conduct complementary measurements in areas, where excessive algal bloom is observed according to satellite data.

The authors express their hope that further collaborative work, the initial results of which are given in this article, will allow receiving some new interesting results.

ACKNOWLEDGMENTS

REFERENCES

[1] Hansson, M. and Hakansson, B., "The Baltic Algae Watch System - a remote sensing application for monitoring cyanobacterial blooms in the Baltic Sea," Journal of Applied Remote Sensing. 1(1), 1-10 (2007).
[2] Ouellette, A., Handy, S. and Wilhelm, S., "Toxic microcystis is widespread in Lake Erie: PCR detection of toxin genes and molecular characterization of associated cyanobacterial communities," Microb. Ecol. 51(2), 154–165 (2006).
[3] Rogalus, M. and Watzin, M., "Evaluation of sampling and screening techniques for tiered monitoring of toxic cyanobacteria in Lakes," Harmful Algae. 7(4), 504–514 (2008).
[4] Lavrova, O. Yu., Kostyanoi, A. G., Lebedev, S. A., Mityagina, M. I., Ginzburg, A. I. and Sheremet, N. A., [Complex satellite monitoring of the Russian Seas], Moscow: IKI RAN, 1-470 (2011).
[5] Korneva, L.G., Mineeva, N.M., Elizarova, V.A., et al., [Phytoplankton ecology of the Rybinsk Reservoir], Tol'jatti, 1-264 (1999).
[6] Poddubnyi, S. A., "Hydrological conditions of hydrobiont distribution in reservoirs," Izvestiya Akademii Nauk, Seriya Geograficheskaya. 2, 33-41 (2002).

[7] Kahru, M., Savchuk, O. P. and Elmgren, R., "Satellite measurements of cyanobacterial bloom frequency in the Baltic Sea: interannual and spatial variability," Marine Ecology-Progress Series. 343, 15-23 (2007).

[8] Reinart, A. and Kutser, T., "Comparison of different satellite sensors in detecting cyanobacterial bloom events in the Baltic Sea," Remote Sensing of Environment. 102(1), 74–85 (2006).

[9] Ermakov, S. A., Kapustin, I. A., Lazareva, T. N., Sergievskaya, I. A. and Andriyanova, N. V., "On the possibilities of radar probing of eutrophication zones in water reservoirs," Izvestiya - Atmospheric and Ocean Physics. 49(3), 307-314 (2013).

[10] Karimova, S. S., Lavrova, O. Y. and Soloviev, D. M., "Observation of eddy structures in the Baltic Sea with the use of radiolocation and radiometric satellite data," Izvestiya - Atmospheric and Oceanic Physics. 48(9), 1006-1013 (2012).