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Mass Development of Green Filamentous Algae of the Genera *Spirogyra* and *Stigeoclonium* (Chlorophyta) in the Littoral Zone of the Southern Part of Lake Baikal[†]

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As a result of long-term studies (2008–2013) of macroalgae of the littoral zone of the western bank of the southern part of Lake Baikal (the reaches of the Angara River – Listvennichny Bay), it has been found that species of the genus *Spirogyra* Link. dominate at the depths of 0.3–3.0 m in late summer and autumn. Previously species of this genus were not found in Lake Baikal. The study of the biology of the algae both under natural and under laboratory conditions made it possible to identify one of the dominant species as *S. fluviatilis* Hilse. Mass development of *Stigeoclonium tenue* (C. Agardh) Kütz. was registered for the first time in November 2012 near the water edge in Bolshiye Koty Bay. The intensity of development of the species of the genus *Spirogyra* was assessed in the region of investigations. It has been shown that during the period of mass development (November) the phytomass of the algae can attain $317 \pm 143 \text{ g/m}^2$. In this case, projective cover of bottom sediments represented by stones can be 100%.

KEYWORDS: littoral zone, green filamentous algae, mass development, *Spirogyra*, *Stigeoclonium tenue*, Lake Baikal.

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Introduction

Macroalgae are among the main components of primary trophic link of the littoral zone of lakes and reservoirs. They influence oxygen and nutrients regime. In addition, they are used as food and habitats by invertebrates. It has been known that changes in the trophic state of water bodies (in response to anthropogenic load) can result in mass development of foreign species of macroalgae (atypical to this water body), in changes in the composition of aboriginal dominant species, or to the deterioration in their natural distribution [15, 23, 31, 34]. The Great Lakes are an example of mass development of green filamentous algae in response to the increase in the content of nutrients [16, 26–29, 38]. Plant remnants accumulated in littoral zones can exert an adverse effect on water quality and result in secondary contamination of water bodies by organic matter and heavy metals responsible for fish kills [24, 35, 36]. In addition, pathogenic microorganisms can use algal mats as substratum [21, 25].

Previously it has been shown [5, 6, 9] that macroalgae are of considerable importance in the functioning of littoral communities of Lake Baikal [5, 6, 9]. Their taxonomic composition and peculiarities of biology, and also the quantitative indices of macroalgae development, are clearly understood [3, 5, 8, 11].

In Lake Baikal, the annual dynamics of benthic macroalgae development are characterized by summer peak. During this period, algae species occurring the year round are accompanied by the species with a short vegetation period. In summertime, all five zones of vegetation typical to Lake Baikal are well defined [5, 8, 11]. Recent publications are indicative of the deterioration in the distribution of macroalgae in the lake. In particular, in summer 2011 in Listvennichny Bay endemic species of the genus *Draparnaldioides* dominating in the third plant zone gave way to the filamentous alga *Spirogyra* sp. In 2012 mass development of species of the genus *Spirogyra* attached to stones was observed in this bay at the depths of 0.3–0.5 m (in the composition of the first plant zone) [3, 7]. Previously in the open part of Lake Baikal, the filaments of *Spirogyra* sp. were not registered at all [5]. Mass development of the green alga *Stigeoclonium tenue* (C. Agardh) Kütz. was observed in late autumn 2011 near the water edge in Bolshiye Koty Bay [3]. In Listvennichny Bay, intensive development of this alga was registered on stones near the water edge, and also in the shallow water zone. Prior to our investigations, mass development of species of the genus *Stigeoclonium* and the absence of typical species of the genus *Ulothrix* near the water edge in Lake Baikal were not observed. In Lake Baikal, *Stigeoclonium tenue* is registered along the whole northwestern coast of its southern part. In August – September, it occurs on stones at the depths of 1.0–2.5 m. During this period, mass development of this species is observed in the Bolshaya Kotinka River flowing into Bolshiye Koty Bay [5].

The objective of the present work was to give brief characteristics of a new phenomenon registered in the littoral zone of Lake Baikal consisting in changes in the complex of dominant species (on the example of Bolshiye Koty Bay and Listvennichny Bay), to analyze data on the ecology of representatives of the genera *Spirogyra* Link. and *Stigeoclonium* Kütz., and also to identify dominant species of the genus *Spirogyra*.

Material and Methods**

The material obtained in 2008–2013 both under natural and under laboratory conditions was used in the paper. The obtained results were compared to those collected in 2003 near the Berezovy testing ground at the depths of 1.2–4.2 m. The samples are stored at the Laboratory of Biology of Aquatic Invertebrates of the Limnological Institute of the Siberian Department of the Russian Academy of Sciences.

Long-term investigations were carried out near the western coast of the southern part of the lake, in Bolshiye Koty Bay, from the Chernaya River to the Varnachka village (4–5 km), and also in the reaches of the Angara River.

The distribution of macrophytes was studied along transects located perpendicularly to the coast line. For the most part standard transects were not less than 50–70 m long. Within the first two zones of vegetation, the peculiarities of vegetation of macroalgae of both genera were studied along the transects 10–20 m long to the depths of 1.7–2.0 m. The samples were taken by divers or using special bottom samplers according to the scheme. It included 1) video profile of the transect, 2) sampling within each plant zone, 3) macrophotographs of landscapes and sections of the bottom using the frame (0.25 m²) or scale rule (for determining projective cover), 4) collection of quantitative samples by the stone-unit method [17].

The scale rule was used in determining the area of projective cover of not less than three stones with the fouling taken from each depth and station. The area was determined in terms of macrophotographs using the original program *Sponge area****. Characteristics of this method were given previously [33].

Biomass was measured using the Iuchi Sefi (IB-200H) (Japan) and the Adventurer Ohaus AR 2140 (China) balance. Fouling was separated from stones, rinsed with water, and separated from the mixtures. Prior to weighing, macroalgae were slightly dried using filter paper. In determining dry weight, algae were dried at 105°C for three hours.

Special preparations from two–three points on the surface of each stone (“stone-unit”) were used in calculating algae frequency of occurrence. On the whole, 25–30 microphotographs (magnification $\times 200$ to $\times 400$) corresponded to each sampling place and date. Each microphotograph was considered as one sample. The number of *Stigeoclonium* and *Spirogyra* filaments and their relative content (% of the total number of macroalgae) were calculated in some samples (microphotographs). Microphotographs were obtained using the Olympus CX 21 and Meiji Techno microscopes with the magnification from $\times 40$ to $\times 400$ and the Olympus C-3040 photo-apparatus with the NY 2000S 01705 and SONY Cyber-shot photo-extension. On the whole, 135 samples and more than 2000 microphotographs were analyzed.

Algae were cultivated in the Petri dishes at natural illumination and room temperature. At first, algae were placed into the Petri dishes with lake water. The Z-8 nutrient medium [30] was added at a

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***The program was elaborated by K.P. Bukshuk.

later time. In this case, the values of pH corresponded to those in the initial water. Such mixed cultures were used in studies of the life cycle of algae for their identification.

The samples for hydrochemical analysis were taken from the surface and near bottom layers of water. Hydrochemical analysis was carried out following standard procedures [10, 12]. The samples of water were filtered through the membranous (polycarbonate) filters with the openings of 0.45 μm in diameter.

Results and Discussion

In 2009 species of the genus *Spirogyra* were found in benthic algae cenoses in Bolshiye Koty Bay and in its tributaries. At a later time, they were identified as *S. varians* (Hass.) Kütz. (Fig. 1, *d, e, f*) occurring in the Bolshaya Kotinka and Chernaya rivers and *S. porticalis* (O. Müll.) Cleve occurring in the estuary of the Malaya Kotinka River. Sterile filaments of *Spirogyra* closely similar to *S. varians* in their morphology were found in the Zhilishche River.

In summer and autumn 2011–2012, mass vegetation of foreign species of the genus *Spirogyra* was observed along the whole shallow water zone of Bolshiye Koty Bay. Their intensive development was observed in summer at the temperature of water of more than 10°C, whereas their maximal biomass was registered in November at 4°C. In wintertime ($t \sim 0^\circ\text{C}$), *Spirogyra* also occurred, but it was not abundant. The same pattern was observed in the shallow water zone of Listvennichny Bay during the period of the open water in 2012. In autumn, the biomass of *Spirogyra* was closely similar to the maximal biomass of *Ulothrix zonata* (210 g/m²) typical to Lake Baikal (Table 1).

The study of the life cycle of algae under cultural conditions has shown that *Spirogyra fluviatilis* Hilse [37] dominated along the whole littoral zone (Fig. 1, *g, h, i*). Previously this species was found neither in the lake, nor in the tributaries of Bolshiye Koty Bay.

It has been known that *Spirogyra fluviatilis* is the widely distributed alga occurring during the warm period in lakes, rivers, and streams [18, 32]. Rather often mass development of representatives of the genus *Spirogyra* exerts an adverse effect on water quality [1, 14, etc.]. For example, the increase in the biomass of green algae of the genera *Spirogyra* and *Zygnema* Ag. in the littoral zone of Lake Conesus (the USA) resulted in changes in the ecological state of this zone [14]. From the point of view of the authors, this phenomenon was conditioned by the influx of large amounts of the dissolved forms of phosphorus and nitrogen.

It has been found that intensive development of *S. fluviatilis* is registered in summer in the waters with a high content of nitrogen and phosphorus. In this case, moderate water velocity (from 12 to 15 cm/sec) is favorable to the uptake of nutrients, and also to the intensity of photosynthesis [18, 19].

In Lake Baikal, sterile filaments of *Spirogyra* were found by many authors [5, 6, 8, etc.]. However, previously their mass development was not observed. In 2003, only individual sterile filaments of *Spirogyra* sp. were found in the lake. In 2008 the filaments of *Spirogyra* sp. were registered in the reaches of the Angara River. However, they were not abundant. These facts suggest that mass development of *Spirogyra* sp. in the littoral zone of Lake Baikal is observed only in recent years.

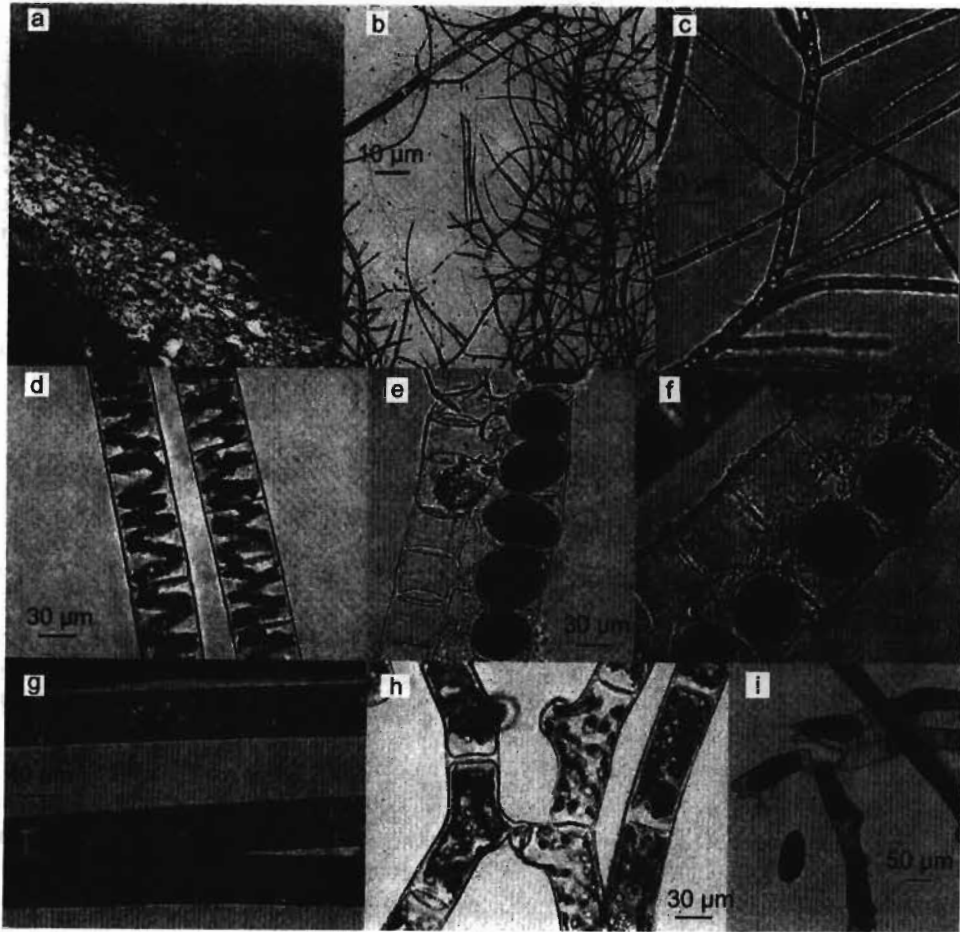


Fig. 1. Photograph of the littoral zone of the lake and microphotographs of the algae: *a* – the zone formed by *Stigeoclonium tenue* (arrows) in the littoral zone of Lake Baikal and in Bolshiye Koty Bay; *b, c* – *S. tenue*, $\times 100$, $\times 400$; *d, e* – *Spirogyra varians* from the Bolshaya Kotinka River: vegetative filaments (*d*), conjugation with zygospores (*e*), $\times 400$; *f* – *S. varians* from the Chernaya River: conjugation with zygospores, $\times 400$; *g, h, i* – *S. fluviatilis* from Bolshiye Koty Bay: vegetative filaments (*g*), conjugating filaments (*h*), $\times 400$, conjugation with zygospores (*i*), $\times 100$.

In November 2011 in the Zhilishche village (Bolshiye Koty Bay), the stones located near the water edge were totally covered by brightly green fouling (100% projective cover) [3]. This zone was at least superficially similar to the I-zone typical to Lake Baikal (Fig. 1, *a*). However, the detailed microscopic analysis has shown that the fouling represents the filaments of the green alga identified as *Stigeoclonium tenue* (Fig. 1, *b, c*).

In November 2012, similar investigations were carried out in the southern part of Lake Baikal, including Bolshiye Koty Bay. It has been found that the stones located near the water edge were

Table 1

Area of projective cover and mass of *Spirogyra fluviatilis* (autumn 2012)

Date	Sampling site	Projective cover, %	Net mass, g/m ²	Dry mass, g/m ²
18 September	Bolshiye Koty Bay, in front of the biostation, depths 1.0–1.5 m	53 ± 13.5	190 ± 70	33.90 ± 12.65
9 November	Bolshiye Koty Bay, in front of the laboratory, depths 1.0–1.5 m	72 ± 27.5	176 ± 91	31.45 ± 18.44
26 November	Listvennichny Bay, in front of the museum, depths 1.0–1.5 m	89 ± 23.6	317 ± 143	56.62 ± 22.67

covered by green filamentous algae of the genus *Stigeoclonium* (90–100%), and also by the algae of the genus *Ulothrix* (10%). In this case, the average net mass of *Stigeoclonium* sp. accounted for 322 ± 58 g/m². In 2013 in Bolshiye Koty Bay, the filaments of *Stigeoclonium* sp. were also found in abundance.

Thus, it is possible to conclude that in late autumn in 2011–2013 in the first plant zone of the open part of Lake Baikal *Ulothrix zonata* gave way to species of the genera *Spirogyra* and *Stigeoclonium*. The records of *Stigeoclonium* sp. in Listvennichny Bay, near the western coast of the Maloye More, and in the northern part of Lake Baikal are indicative of the increase in the area of distribution of these algae.

What are the reasons of this phenomenon in Lake Baikal? It is likely that previously investigations were not carried out in late autumn. In addition, it is not inconceivable that species of the genera *Spirogyra* and *Stigeoclonium* were taken as *Ulothrix* sp.

Another reason of this phenomenon is the increase in the intensity of anthropogenic load. From the point of view of the authors [7], the records of species of the genera *Spirogyra* and *Stigeoclonium* in Listvennichny Bay were conditioned by the increase in the content of nutrients. However, the performed hydrochemical investigations have shown that the concentration of nutrients remained almost unchanged as compared to the 1950s and 1960s [4, 13]. In the littoral waters of the lake and 100 m away from the coast, the content of phosphate phosphorus accounted for 1–6 µg/L [13] and only in the water of Listvennichny Bay it increased up to 10.5 µg P/L.

Hydrochemical analysis has shown that in summertime in the littoral zone of Bolshiye Koty Bay the concentration of mineral phosphorus decreased to zero, whereas its maximal content (11 µg P/L) was observed in autumn (Table 2).

In summer in the littoral zone of Listvennichny Bay, the concentration of phosphate was not less than 2 µg P/L, whereas in autumn it was not more than 10 µg P/L. In this case, the content of

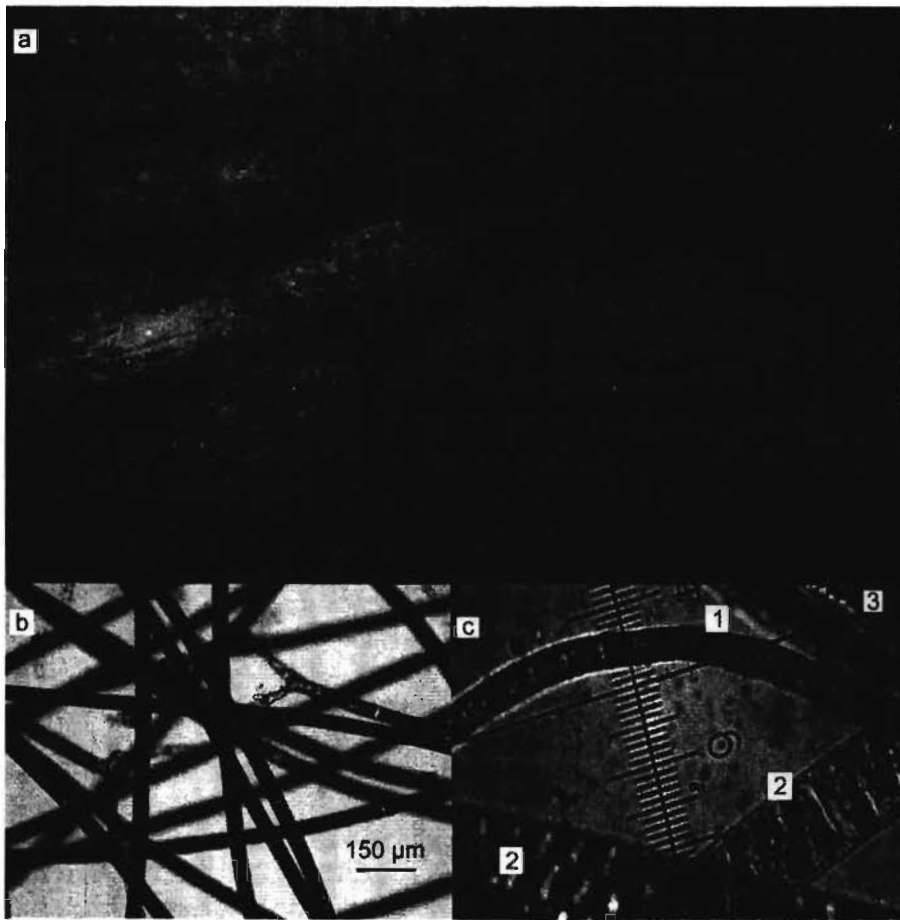


Fig. 2. Photographs made under the water and microphotographs of benthic algae: *a* – mass development of *Spirogyra* on stony substratum in Bolshiye Koty Bay, November 2012, at the depths of 1.0–1.5 m; *b*, *c* – examples of microphotographs differing in relative abundance of algae: *b* – filamentous algae of the genus *Spirogyra*, *c* – mixed fouling: 1 – *Ulothrix zonata*; 2 – *Spirogyra* sp.; 3 – *Fragilaria* sp.

mineral nitrogen was 2–8 times higher than that in the bay. In Listvennichny Bay, the contribution of nitrate was 70–95% of the total nitrogen content, whereas in Bolshiye Koty Bay this form prevailed only in summertime. In early June and in September – November in the littoral zone of Bolshiye Koty Bay, the contribution of ammonium increased up to 60% of the total content of mineral nitrogen. In summer and autumn in the littoral zone of the bays, the content of organic matter was not more than 2 mg O/L (in terms of permanganate oxidizability). However, in autumn during the process of macroalgae decomposition in the near bottom layer of water this index increased up to 4.6 mg O/L, whereas the content of mineral nitrogen – to 0.62 mg N/L.

The regions with stable water flow are observed near the western coast from Peschanaya Bay to Listvennichny Bay. Under the ice, water velocity accounts for 9–10 cm/sec, whereas during the pe-

Table 2

Concentration of chemical components in the littoral zone (1 m away from the bank) of Listvennichny Bay and Bolshiye Koty Bay

Date	Bolshiye Koty Bay			Listvennichny Bay		
	P _{min} , μg/L	Sum N _{min} , mg/L	PO, mg O/L	P _{min} , μg/L	Sum N _{min} , mg/L	PO, mg O/L
2011						
June	0-4	0.01-0.01	0.93-0.94	×	×	×
August	0-4	0.03-0.08	0.63-1.1	×	×	×
September	1-7	0.01-0.05	1.01	10	0.10-0.11	1.24-1.86
November	4-8	0.04	0.92	8	0.12	0.92
2012						
June	3-7	0.03-0.07	0.92-1.77	×	×	×
July	1-7	0.04-0.1	0.69-1.58	5	0.13	0.85
September	0-7	0.02-0.04	0.69-1.27	2-5	0.17-0.32	1.7-1.9
7 November	6-11	0.03-0.1	0.69-1.27	10	0.14-0.16	0.88-1.00
26 November	×	×	×	8-10	0.09-0.18	0.69-2.00
26 November*	×	×	×	4-10	0.08-0.62	1.33-4.61

Note. PO – permanganate oxidizability; × – not investigated; * the near-bottom samples of water were taken by syringes near the stones with fouling.

riod of the open water it is one order of magnitude higher [2], that is it is higher than the velocity optimal for the development of algae (from 12 to 15 cm/sec). Nevertheless, intensive vegetation of *S. fluviatilis* was observed in the southern part of Lake Baikal. In the bays, water velocity is lower, whereas the zone occupied by *S. fluviatilis* was 20–30 m wide.

At the present time, the reasons of the phenomenon observed in the littoral zone of Lake Baikal are difficult to explain and predict. It is likely that mass development of foreign species of filamentous algae in the lake is conditioned by two main reasons. Firstly, it can be conditioned by natural cycles of algae development under the influence of global factors, including climatic ones. Secondly, mass development of *Spirogyra* sp. is often registered in the places with a rather high concentration of nutrients conditioned, in particular, by the spill of insufficiently purified sewage [20, 22]. For the most part household sewage incoming from the residential areas located on the banks of Lake Baikal are not subjected to central purification. In recent years, the number of private hotels significantly increased. The soils of the splash over zone serve as a filter protecting the lake. However, their capability for filtering is limited. It is likely that in Listvennichny Bay this limit is exceeded. Based on our data in summer 2010–2013, the traces of fecal contamination conditioned

primarily by insufficient filtration of sewage incoming from villages were observed in the pore waters of the splash over zone, and also in the samples of the near bottom water taken from the shallow water zone of Bolshiye Koty Bay and Listvennichny Bay. For example, in November 2012 on the beach of the Listvyanka village, the numbers of thermotolerant coliform bacteria and enterococci were very high (15 000 and 3700 CFU/100 ml, respectively). During the same period, high numbers of the total coliform bacteria, thermotolerant coliform bacteria, and enterococci were observed in the samples of near bottom water – 210, 80, and 66 CFU/100 ml, respectively.

Conclusion

Long-term (2003, 2008–2013) investigations of the structure and quantitative characteristics of macroalgae occurring in the littoral zone of the western coast of the southern part of Lake Baikal have shown that foreign species of the genus *Spirogyra* dominated at the depths of 0.3–3.0 m (and more) in late summer and autumn. The study of algae biology both under natural and under laboratory conditions made it possible to identify one of the dominant species as *Spirogyra fluviatilis* Hilse. This species is new for the flora of the lake. In tributaries of the studied region, it was not found yet. During the period of mass development (November), algae biomass can attain $317 \pm 148 \text{ g/m}^2$ with 100% projective cover of the stony substratum of the bottom. Mass development of *Stigeoclonium tenue* (C. Agardh) Kütz. was observed in the splash over zone in Bolshiye Koty Bay and in Listvennichny Bay. Previously this alga was observed in the lake at the depths of 1–2.5 m. In abundance it occurred only in the Bolshaya Kotinka River. In autumn during the period of macroalgae decomposition, the content of organic matter in the near bottom layer of water significantly increased (by a factor of 2.0–2.5). The obtained results along with literature data are indicative of the increase in the intensity of eutrophication in the littoral zone of Lake Baikal located near residential areas.

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