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Notes

Nearshore benthic blooms of filamentous green algae in Lake Baikal

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ABSTRACT

For the first time, species of the genus *Spirogyra*, non-typical of the open nearshore waters of Lake Baikal, formed algal mats with *Ulothrix zonata*, *Ulothrix tenerrima*, and *Ulothrix tenuissima* near the village of Listvyanka, Russia. Normally widely distributed in the 0- to 1.5-m depth range, the growth of *U. zonata* was now evident and dominant (63% of the biomass) in the 2- to 5-m depth range. The overgrowth of the lake bottom by filamentous green algae, changes in distributional boundaries, the emergence and mass development of species of the genus *Spirogyra*, the presence of the eutrophic diatom indicator *Fragilaria capucina* var. *vaucheriae*, elevated abundances of coliform bacteria, and elevated levels of nutrients suggest an early stage of cultural eutrophication in the nearshore of Lake Baikal near Listvyanka, a popular tourist destination. The unusual abundance of *Fragilaria* associated with the filamentous green algae consisted of long-ribbon colonies of *F. capucina* var. *vaucheriae*, a eutrophic species, wound around the filamentous green algae, enhancing the dense algae mats. Historically dominant species, such as *Didymosphenia geminata*, *Tetraspora cylindrica* var. *bullosa*, and *Draparnaldioides baicalensis* typically observed at deeper depths of Lake Baikal, are now subdominants or minor species in the nearshore along the shoreline near Listvyanka.

Introduction

Vegetation plays an important role in functioning and self-purification of aquatic environments, determines trophic status, and serves as an indicator of anthropogenic effect (Pourriot et al., 1995; Smith et al., 2006). Intense economic activity is often associated with an increase in "nutrient pollution", and particularly phosphorus load, to freshwater aquatic ecosystems and contributes to a gradual disturbance of both structural and functional organizations of ecosystems (Puzachenko, 1989; Vinberg, 1960). As a result of nutrient pollution in freshwater and marine environments (Auer et al., 2010; Depew et al., 2011; Higgins et al., 2005; Nozaki et al., 2003; Ostendorp et al., 2004; Pokrovskaya et al., 1983; Smith et al., 2006), a succession of plant communities and blooms of green algae may occur.

Unlike the European lakes and North American Great Lakes, the anthropogenic or cultural eutrophication of the waters of Lake Baikal, Russia, is a recent phenomenon associated with the development of the tourism industry. Over the past century in Lake Baikal, there have been no recorded occurrences of benthic mats of filamentous green algae (Dorogostaisky, 1906; Izhboldina, 1990; Meier, 1930; Skabichevsky, 1934) until the summer of 2011 near the village of Listvyanka. The village of Listvyanka with a population of about 2000 people is located on the shore of Lake Baikal, Russia. With over 350,000 tourists annually visiting the village surroundings in recent years, recreational use of the shoreline and of the nearshore areas of the lake has increased. Unfortunately, the village and numerous small-boat marinas do not have a centralized wastewater treatment plant. It is now apparent that the existence of a primitive wastewater treatment infrastructure has likely negatively affected the coastal zone of Lake Baikal.

The aim of this study was to evaluate the current benthic plant communities of the Lake Baikal nearshore zone in areas where elevated nutrient loads occurred and to determine the distribution and boundary of the overgrowth of filamentous benthic green algae.

Material and methods

Field studies

In July–August of 2011, a reconnaissance survey of benthic plant communities in the nearshore zone of Listvennichny Bay, Lake Baikal, was undertaken (Fig. 1A). Samples were taken along 100-m transects perpendicular to the lake-bottom contours to a depth of 10 m. Transect

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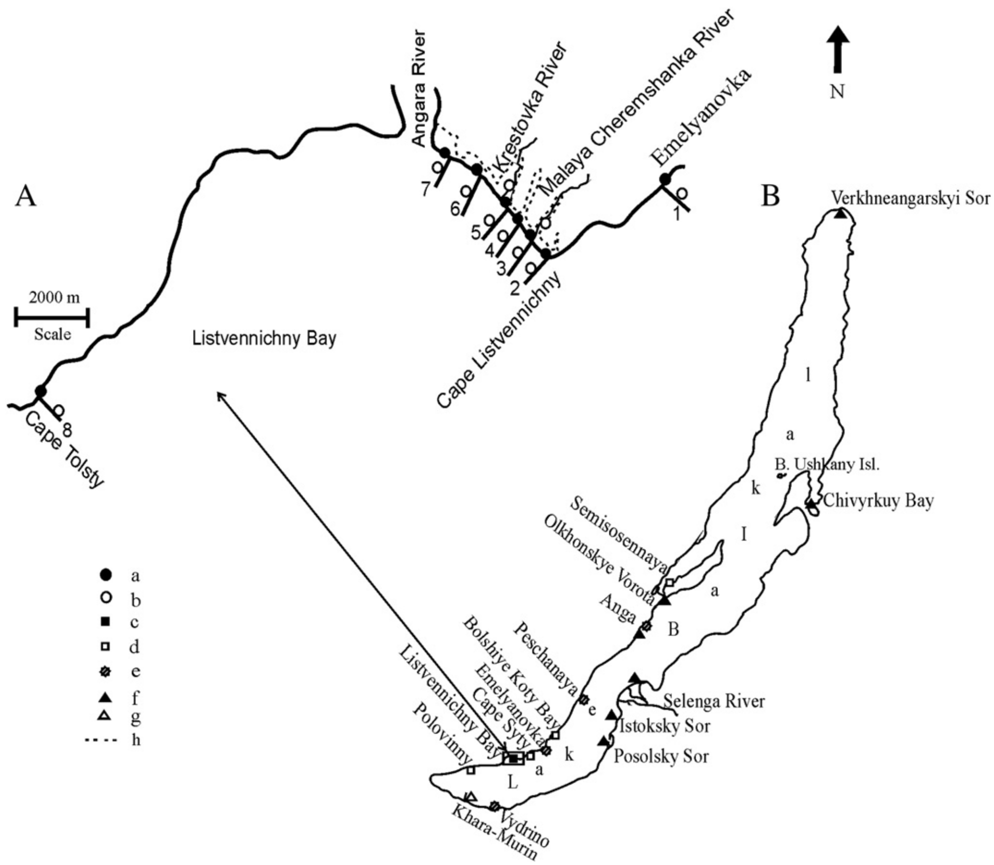

Fig. 1. Map of Listvennichny Bay (A) and the nearshore zone of Lake Baikal (B) showing sampling sites and locations where *Spirogyra* was observed. Survey transects are labeled 1 to 8. Symbols on map are explained by legend at lower left: a = shallow groundwater sample sites. b = water sample sites: Krestovka and Malaya Cheremshanka Rivers, near-bottom layers (3-m depth), and the lake surface (0 m). c = blooms of *Spirogyra*. d = filaments of *Spirogyra* not found. e = singular filaments of *Spirogyra* occurrence in Lake Baikal in 2011. f = occurrence of *Spirogyra* in Lake Baikal (from 1925 to 1990 by Izhboldina, 2007). g = absence of *Spirogyra* in 1975–1988 (Izhboldina's unpublished data on monitoring of benthic flora at site Khara-Murin). Dashed line (h) is the boundary of Listvyanka village.

1 (Emelyanovka) was 5 km to the northeast of Cape Listvennichny. Transects 2 to 7 were in the nearshore adjacent to the village of Listvyanka. Transect 5 was near the mouth of the Krestovka River which flows through the densely populated Listvyanka (Fig. 1A). Transect 8 was at Cape Tolsty west of Listvyanka (Fig. 1A). The bottom in this area was covered with boulders and sand.

Water sampling

To evaluate anthropogenic effects on Lake Baikal, water was sampled with 50-mL and 500-mL syringes for nutrients and bacteria. River water was sampled 100 m upstream from the mouths of the Krestovka and Malaya Cheremshanka Rivers while lacustrine near-bottom (at a depth of 3 m) and surface water samples (0 m) were collected at eight sites (Fig. 1A) 70 m off the lake shore. Shallow groundwater samples were taken from 30- to 50 cm holes dug in the ground 1.5 to 2 m inland from the water edge above the shoreline at each location (Fig. 1A). Only one sampling and analysis were performed at each site because of financial constraints.

Mapping of vegetation

To identify distribution boundaries of filamentous benthic green algae, scuba divers estimated vegetation abundance (semi-quantitative estimates) visually along Transects 1–8 every 10 m on the 100-m transect using a six-point scale (Abakumov, 1983):

a. 6 points — very abundant species, cover > 90%;
b. 5 points — abundant, 70–90% cover;
c. 4 points — many individuals, 50–70% cover;
d. 3 points — 30 to 40% cover;
e. 2 points — individuals small in number, 10–30% cover; and
f. 1 point — very few individuals, up to 10% cover.

Qualitative sampling of vegetation

Qualitative samples (8) were collected by scuba divers from each transect in Listvennichny Bay to characterize diversity of benthic flora. In addition, 16 qualitative samples were collected in September in the nearshore zone of the southern and central basins of Lake Baikal (Fig. 1B).

Quantitative sampling of vegetation

Quantitative benthic samples were collected at the reference site near Emelyanovka (Transect 1) and at the site of high anthropogenic activity located near the mouth of the Krestovka River (Transect 5) in Listvennichny Bay (Fig. 1A). Replicate vegetation (meio- and macro-algae and submerged macrophytes) samples (0.16 m^2 frame, $n = 3$) were collected by scuba divers from two depth zones (from rocky and sandy substrates between 0 to 1.5 m and between 2 to 5 m), placed in bags, and on the shore placed into flat-bottomed containers ($30 \times 50 \times 10$ cm). Submerged macrophytes (higher vascular plants) were cleaned from epiphytes by brushing, dried on filter paper, and placed in the herbarium for further identification in the laboratory. Meio-algae (>0.5 mm and <2 mm) and macro-algae (>2 mm) were also removed from stone surfaces by brushing and placed evenly onto the bottom of the large containers. One eighth of the sample was poured through a sweep net (gauze sieve 35), placed into 500-mL bottles, and fixed in 4% formalin. Microalgae (<0.5 mm) were also collected with a piston cylinder (4 cm in diameter and 5 cm long) at the same sites where meio- and macro-algae were collected. On the shore, the samples with microalgae were placed into 50-mL bottles and fixed in 4% formalin.

Laboratory analysis

Nutrients (PO_4^{3-}-P, NH_4^+-N, NO_2^--N) and Si were determined using colorimetric methods (Boeva, 2009; Fomin, 2000), while NO_3^--N was determined by high performance liquid chromatography via direct UV detection (Vereshchagin et al., 2000). Standard nutrient solutions were obtained from the Canto Chemical Company (Japan). Total microbial count (TMC) in CFU mL^{-1} (colony forming units per 1 mL), the amount of total coliform bacteria (TCB), and thermotolerant coliforms (TC) in CFU 100 mL^{-1} (colony forming bacteria per 100 mL) were estimated using standard procedures (MRR, 2004; SRSR, 2000).

Meio- and macro-algae were sorted under an MBS 9 microscope at 8 and 16× magnifications and identified to species with an Amplival microscope at 480×. To determine wet weight (w.w.) of each species, meio- and macro-algae were dried on the filter paper and weighed on a torsion balance (WT, Poland) (precision ± 1 mg).

Microalgal samples ($n = 20$) were brushed off the rocks and remains of submerged macrophytes into Petri dishes and rinsed with a fixative. The water volume plus fixative was measured, poured into a bottle, mixed, and 0.1 mL of it was placed into a counting Nageotte Chamber where microalgae were counted ($n = 3$) with a Axiovert-200 light microscope. Diatom valves were cleaned with hydrogen peroxide to eliminate organic matter and identified with a scanning electron microscope (Philips 525M).

Data analysis

Redundancy analysis (RDA) (ter Braak and Šmilauer, 2002) implemented in the R statistics package was used to evaluate correspondence between filamentous green algal abundance and microbiological characteristics on nutrient concentrations at a depth of 3 m in study area of Lake Baikal. Explanatory variables X (PO_4^{3-}-P, NH_4^+-N, NO_2^--N, NO_3^--N L^{-1}, and Si) and response variables Y (TC, TCB, TMC and Alg) were transformed [$\log(A + 1)$, where $X \in A$ and $Y \in A$]. Alg is a semi-quantitative estimate of filamentous green algae based on a six-point scale.

Similarity of floristic composition between Transects 1 and 5 in 2011 and 1987 was estimated from the Sørensen coefficient (Odum, 1971), $S = 2c / a + b$, where S is a coefficient of floristic similarity (%), c is the number of the same species of submerged macrophytes as well as meio- and macro-algae at Transects 1 and 5, and a and b are the total numbers of submerged macrophytes and meio- and macro-algae at Transects 1 and 5, respectively.

Plant communities of meio- and macro-algae were identified according to the species biomass [g Wet Weight (w.w.) m^{-2}]. At first, dominant species in each sample were determined by the ranking of their share in total biomass. Samples with the same dominant species, which usually had the maximal percentage of biomass, were grouped and associated with depth. Such groups, i.e. plant communities, were named by dominant species. Species with a biomass higher than 1% were treated as subdominant communities, but species with biomass lower than 1% were considered as rare and were not taken into account.

Unpublished data of L.A. Izhboldina were used for comparative estimation of quantitative growth of meio- and macro-algae, which were collected at Transect 1 (Emelyanovka) and Transect 5 (Listvennichny Bay) in 1987 and in other areas of Lake Baikal (Khara-Murin, 1975–1988; Fig. 1B) using the same sampling methods. We analyzed 145 quantitative samples (n) of meio- and macro-algae. All quantitative parameters of vegetation (meio-, macro-, and microalgae) were expressed in units per m^2 of the lake bottom.

Results

Water quality and spatial distribution of vegetation

Water temperature and pH in July and August ranged from 7 to 10 °C and 7.4 to 7.8, respectively. At Transect 5, maximum concentrations of PO_4^{3-}-P (423 μg L^{-1}) and NH_4^+-N (1898 μg L^{-1}) were exceptionally high in the near-bottom water layers and similar to shoreline groundwater samples. High Si concentrations were observed in streams (5270 to 5790 μg L^{-1}) (Table 1).

The microbiological parameters of TC (components of the fresh fecal water), TCB, and TMC exceeded the Sanitary Regulations and Standards of Russia (2000) along the lake shoreline near Listvyanka (Table 1). Total coliform bacteria should not exceed 500 CFU 100 mL^{-1} in water for recreational use and TC should be no higher than 100 CFU 100 mL^{-1} (SRSR, 2000). Outside the village of Listvyanka at Transects 1 and 8, TC and TCB of water (except shallow groundwater) did not exceed the Sanitary Regulations and Standards of Russia.

Up to a depth of 1.5 m, rocks were covered with *Ulothrix* Kütz. having 3–5 cm long thalli at all transects (1 to 8). From 3 to 10 m, algal mats were observed near Listvyanka at Transects 2 to 7. These algal mats (25–30 cm thick, 50 to 70 cm filamentous strands) were dense clumps of *Ulothrix* Link and *Spirogyra* Link (cover > 70–90% or 5–6 points according to the Abakumov (1983) scale). Filamentous green algae grew intensely all along the 4-km shoreline from Cape Listvennichny to the outlet of the Angara River (Fig. 1A).

Tetraspora Link., *Didymosphenia* M. Schmidt, and *Draparnaldioides* C. Meyer et Skabitsch. were sparsely distributed among filamentous green algae on rocky substrates near Listvyanka (Transects 2 to 6). The maximum cover of *Tetraspora* (30%) was observed at Transect 1 at a depth of 2.5 m, whereas only a single specimen was found at other transects. Transect 7 was inhabited by *Didymosphenia* (40% cover) at a depth of 1.8 to 3 m while at other transects it was up to 10% cover. The abundance of *Draparnaldioides* was observed at a depth of 3 to 5 m at Transects 1, 8 (70% cover), and 7 (40% cover), while at Transects 2–6 the abundance was low (<10% cover).

Submerged macrophytes *Elodea* Mich., *Myriophyllum* L., *Potamogeton* L., and *Ranunculus* L. were often found on the sandy substrate at Transect 5. *Elodea* and *Myriophyllum* (10–30% cover) were observed at Transects 2–5 at a depth of 3 m, while *Potamogeton* L. and *Ranunculus* L. were detected at Transect 2.

Floristic composition (submerged macrophytes, meio- and macro-algae) at the reference site Emelyanovka (Transect 1) differed from that at Transect 5. The Sørensen coefficient of floristic similarity between sites was slightly lower (57%) in 2011 than in 1987 (62%). In 2011, besides the typical inhabitant *Myriophyllum spicatum* L. of the sandy-silt substrates, submerged macrophytes of the genera *Potamogeton* L. and *Ranunculus* L., as well as moss and an invasive species *Elodea canadensis* Mich., were observed at the site near Listvyanka but were absent from the reference site Emelyanovka.

Ordination analysis indicated that Transects 1 (Emelyanovka) and 8 (Cape Tolsty) outside the village of Listvyanka were distinct from Transects 2–7 located along the shoreline near Listvyanka (Fig. 2). At Transects 1 and 8, mats of filamentous green algae at 3 m were not observed, nutrients in the Baikal water were low, TC were not found, and TCB were lower than Russian Sanitary standards (Table 1). High TMC values and high concentrations of algal mats and almost all nutrients, except NO_3^--N, were recorded at Transects 5 and 6 which are closely associated on the RDA ordination diagram. Transects 2, 3, 4, and 7 were grouped on the RDA ordination diagram and appeared to be associated with thermotolerant coliforms of fresh fecal origin and elevated NO_3^--N.

Table 1
Nearshore nutrient chemistry and bacteria abundance (n = 1) in the nearshore zone (Fig. 1) of Lake Baikal (July 21–22 and August 3–5 of 2011). Thermotolerant coliforms = TC. Total coliform bacteria = TCB. Total microbial count = TMC. ND = no data. MC River = Malaya Cheremshanka River. CFU = Colony Forming Units. Concentrations exceeding standard values (in bold) (SRSR, 2000) which state that TC and TCB in 100 mL should not exceed 100 CFU and 500 CFU respectively.

Sampling areas	Transect	PO_4^{3-}	NH^{4+}	NO_3-	NO_2-	Si	TC	TCB	TMC
		(µg P/L)	(µg N/L)	(µg N/L)	(µg N/L)	(µg/L)	CFU/100 ml		
Krestovka River		5	132	39	3	5270	78	**5500**	8220
MC River		36	1890	549	2	5790	0	**6540**	2800
Shallow groundwater	1	6	ND	23	2	620	**1280**	**7500**	2280
(1.5 to 2 m, inland from water edge)	2	4	ND	25	ND	680	**1000**	**11,000**	780
	3	35	23	675	6	2290	**1000**	**19,800**	6000
	4	157	70	709	36	3010	0	**23,000**	5800
	5	135	2333	425	104	1090	90	**27,500**	4800
	6	45	257	99	19	600	80	**5480**	5670
	7	168	31	262	898	1900	**980**	**15,000**	9540
	8	91	54	41	66	590	**820**	**4620**	340
Nearshore surface water	1	1	171	23	4	570	0	12	2
(0 m)	2	45	233	203	164	1360	8	8	4
	7	1	124	18	9	680	30	270	8
	8	2	ND	16	3	700	56	240	90
Nearshore water	1	5	31	115	2	580	0	12	2
(3 m depth)	2	31	171	156	40	1280	64	**3500**	2440
	3	15	54	90	42	800	**130**	**5600**	3600
	4	13	54	65	14	800	75	**7200**	6800
	5	423	1898	29	75	2760	4	**3200**	12190
	6	64	257	9	26	1610	0	**12,000**	12,500
	7	7	16	14	4	690	**320**	**13,500**	2000
	8	4	0	11	3	660	0	64	8

Plant community structure of meio- and macro-algae

Reference sites at Emelyanovka and Khara-Murin

In 2011 at Emelyanovka, plant communities were dominated by *Ulothrix zonata* (Web. & Mohr.) Kütz. from 0 to 1.5 m. Besides *U. zonata*, the singular filaments of green algae *Ulothrix tenerrima* Kütz., *Ulothrix tenuissima* Kütz., and *Spirogyra* sp. (up to 300 µm long) were detected in this community. *U. zonata* was the most abundant filamentous species, accounting for 99% of the total meio- and macro-algal biomass (175 g w.w. m^{-2}) (Fig. 3). In 1987, the same plant community with the *U. zonata* prevalence was recorded at this depth, but its biomass was low (9 g w.w. m^{-2}); singular filaments of *Spirogyra* sp. were absent in this community (Fig. 3). Average long-term biomass of *U. zonata* at the Khara-Murin transect, a long term reference site on the southeastern coast of Lake Baikal (Fig. 1), was 89 ± 18 g w.w. m^{-2} (range = 1 to 300 g w.w. m^{-2}, n = 46) (Fig. 5A). Total average meio- and macro-algal biomass at a depth of 0 to 1.5 m was higher in 2011 than in 1987 as well as being higher than the average long-term biomass (1975–1988) at the Khara-Murin transect: 122 ± 18 g w.w. m^{-2} (range = 22 to 333 g w.w. m^{-2}, n = 46) (Fig. 5A).

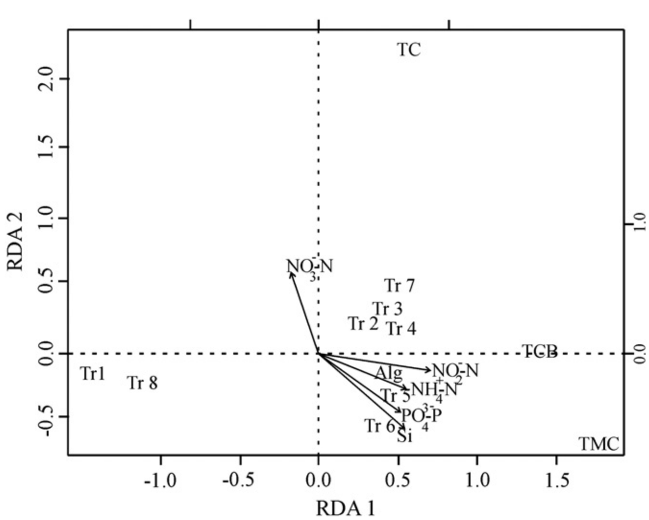

Fig. 2. Redundancy ordination (RDA) diagram of axis 1 and 2 of the sites, filamentous green algae, bacterial microflora, and nutrient variables in the nearshore (3-m depth) waters of Lake Baikal. Tr = transects 1 to 8. Alg = semi-quantitative estimates of filamentous green algae according to the six-point scale. TMC = total microbial count, TCB = total coliform bacteria, and TC = thermotolerant coliforms. PO_4^{3-}-P = phosphate phosphorus, NH_4^+-N = ammonium nitrogen, NO_2^--N = nitrite nitrogen, NO_3^--N = nitrate nitrogen, and Si = silica.

In 2011 at a depth of 2 to 5 m, plant communities were dominated by *Draparnaldioides baicalensis* C. Meyer & Skabich., as in 1987, and accounted for 74% of total meio- and macro-algal biomass (812 g w.w. m^{-2}). In 1987, besides this community, another community of *Chaetocladiella pumila* (C. Meyer) C. Meyer & Skabich. was found. It was established that filamentous green algae were absent in the composition of both communities (Fig. 3). At a depth of 2 to 5 m, the biomass of *D. baicalensis* was higher in 2011 (597 g w.w. m^{-2}) than in 1987 (81 g w.w. m^{-2}) and higher than the average long-term (1975–1988) biomass of *Draparnaldioides* [125 ± 48 g w.w. m^{-2-} (range = 3 to 1385 g w.w. m^{-2}, n = 56)] at the Khara-Murin transect (Fig. 5B). The average of total meio- and macro-algal biomass at Emelyanovka (Transect 1) was higher at the 2- to 5-m depth in 2011 (812 g w.w. m^{-2}) than in 1987 (130 g w.w. m^{-2}) and higher than the average long-term (1975–1988) biomass at the Khara-Murin transect (309 ± 60 g w.w. m^{-2}, n = 56).

The average abundance of microalgae was 140 × 10^6 cells m^{-2} at a depth of up to 1.5 m. A colonial alga *Hannaea baicalensis* Genkal, Popovsk. et Kulikovskiy, a typical representative of the nearshore zone, dominated the microphytobenthos, accounting for 50% of the total microalgal abundance. Species of the genera *Cocconeis* Ehr., *Cymbella* Ag., *Encyonema* Krammer, *Navicula* Bory., *Gomphonema* Ehrenberg., and *Fragilaria* Lyngh., all typical of the open coast of Lake Baikal, were numerous at the 2- to 5-m depth (average abundance = 215 × 10^6 cells m^{-2}). Cell sizes of *Fragilaria capucina* var. *vaucheriae* (Kützing) Lange–Bertalot detected at the reference site were 32 µm in length, and their ribbon-like colonies did not exceed 100 µm in length with its abundance of 19 × 10^6 cells m^{-2}. A solitary planktonic diatom *Ulnaria acus* (Kütz.) Aboal. was also found in the samples.

The site of high anthropogenic activity near the village of Listvyanka

At the 0- to 1.5-m depth zone in 2011, *U. zonata* was the most abundant (59 g w.w. m^{-2}) filamentous species of algae, accounting for 98% of total meio- and macro-algal biomass of plant community,

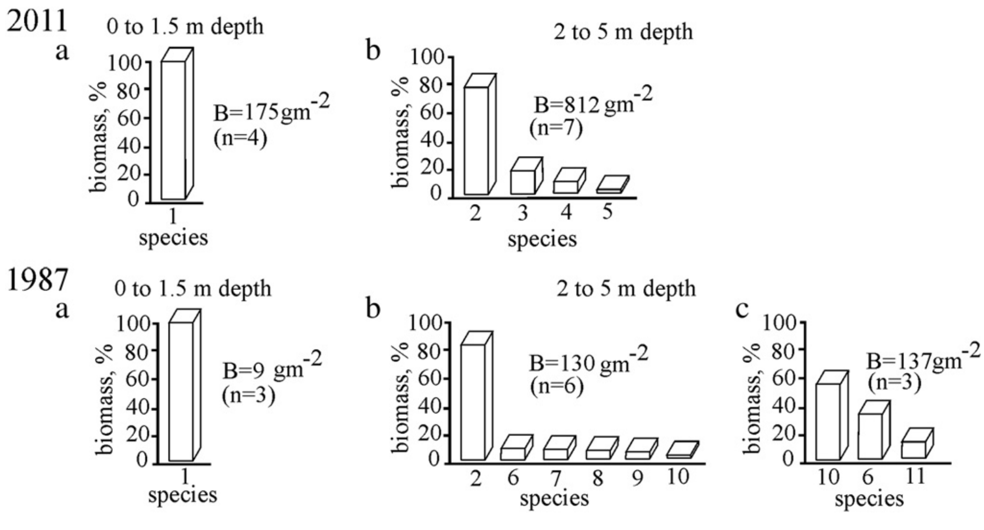

Fig. 3. Nearshore plant community structure of meio- and macro-algae of two depth zones of Lake Baikal at the reference Emelyanovka site (Transect 1) in 2011 (top panel) and 1987 (bottom panel). Letters by individual graphs indicate dominant algal communities: *a*, *b*, and *c* — algal communities: *a* — *Ulothrix zonata*, *b* — *Draparnaldioides baicalensis*, and *c* — *Chaetocladiella pumila*. The x-axis is the position of dominant species in accordance with biomass decrease. Numbers below x-axis indicates species: 1 — *Ulothrix zonata* (Web. & Mohr.) Kütz, 2 — *Draparnaldioides baicalensis* C. Meyer & Skabich., 3 — *Draparnaldioides arenaria* C. Meyer & Skabich., 4 — *Tetraspora cylindrica* (Wahlenb.) Ag.var. *bullosa* C. Meyer, 5 — *Draparnaldioides baicalensis* f. sp., 6 — *Schizothrix* sp., 7 — *Cladophora floccosa* C. Meyer, 8 — *Cladophora kursanovii* Skabich., 9 — *Cladophora compacta* (C. Meyer) C. Meyer, 10 — *Chaetocladiella pumila* (C. Meyer) C. Meyer & Skabich., and 11 — *Tolypothrix distorta* (Fl. Dan.) Kütz.

and was similar to the 1987 biomass and to the average long-term biomass (89 g w.w. m^{-2}) at the Khara-Murin transect (1975–1988, n = 46) (Fig. 5A). In 2011 at this site, the occurrence of *U. tenerrima* and *U. tenuissima* as well as filamentous green algae of the genus *Spirogyra* increased. Species of the genus *Spirogyra* were not numerous in the summer, and their large mat-like patches were often observed in late September. Three morphotypes (with 1–3 chloroplasts) differing in filament width (from 40.5 μm to 60.7 μm) were represented in the mats. The average total meio- and macro-algal biomass was almost identical in 2011 and 1987 within the same depth range (Fig. 5A).

In 2011 at the 2- to 5-m depth range, and for the first time in Lake Baikal, intense growth of *U. zonata* was observed, comprising 63% of the biomass (Fig. 5B) while average biomass of *Draparnaldioides* in 2011(<1 g w.w. m^{-2}) was low. In 1987, biomass of *Draparnaldioides* accounted for 3 g w.w. m^{-2}, and the plant communities were represented by *Didymosphenia geminata* (Lyngb.) M. Schmidt, *Dermatochrysis reticulata* (C. Meyer) Entw. & R.A.Anders., and *Nitella flexilis* (L.) Ag. (Fig. 4). The average total meio- and macro-algal biomass in this depth zone was higher (385 g w.w. m^{-2}) in 2011 than in 1987 (87 g w.w. m^{-2}), and it was similar to long-term (1975–1988) biomass at the Khara-Murin transect (309 ± 60 g w.w. m^{-2} n = 56) (Fig. 5B).

The average abundance of microalgae at Transect 5 was 130 × 10^6 cells m^{-2} at a depth of up to 1.5 m. Singular cells of *H. baicalensis* were recorded up to a depth of 1.5 m. Average abundance of microalgae was 184 × 10^6 cells m^{-2} within the 2- to 5-m depth range. Representatives of the genera *Fragilaria*, *Cymbella*, *Encyonema*, *Cocconeis*, and *Nitzschia* Hass. dominated at this depth. The genus *Fragilaria* had the highest abundance (maximum = 570 × 10^6 cells m^{-2}) with a smaller diatom *F. capucina* var. *vaucheriae* (the most frequent size was 15 μm and the least 30 μm) being dominant. The latter

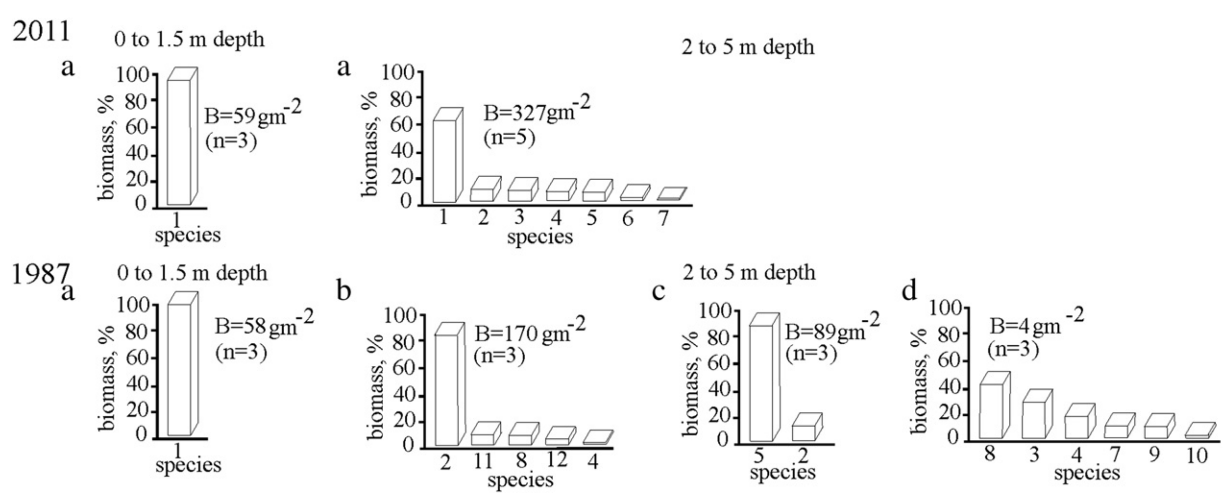

Fig. 4. Nearshore plant community structure of meio- and macro-algae of two depth zones of Lake Baikal at the site of high anthropogenic activity near the village of Listvyanka (Transect 5) in 2011 (top panel) and 1987 (bottom panel). Letters by individual graphs indicate dominant algal communities:. *a*, *b*, *c*, and *d* — algal communities: *a* — *Ulothrix zonata*, *b* — *Didymosphenia geminata*, *c* — *Nitella flexilis*, and *d* — *Dermatochrysis reticulata*. The x-axis is the position of dominant species in accordance with biomass decrease. Numbers below x-axis indicates species: 1 — *Ulothrix zonata* (Web. & Mohr.) Kütz., 2 — *Didymosphenia geminata* (Lyngb.) M. Schmidt., 3 — *Tetraspora cylindrica* (Wahlenb.) Ag.var. *bullosa* C. Meyer, 4 — *Nostoc verrucosum* Vaucher ex Bornet & Flahault, 5 — *Nitella flexilis* (L.) Ag., 6 — *Spirogyra* sp., 7 — *Cladophora compacta*, 8 — *Dermatochrysis reticulata* (K.I.Meyer) Entwisle & R.A.Andersen, 9 — *Draparnaldioides simplex* C. Meyer & Skabich., 10 — *Chaetocladiella pumila* (C. Meyer) C. Meyer & Skabich., 11 — *Dermatochrysis* sp., and 12 — *Tolypothrix distorta* (Fl. Dan.) Kütz.

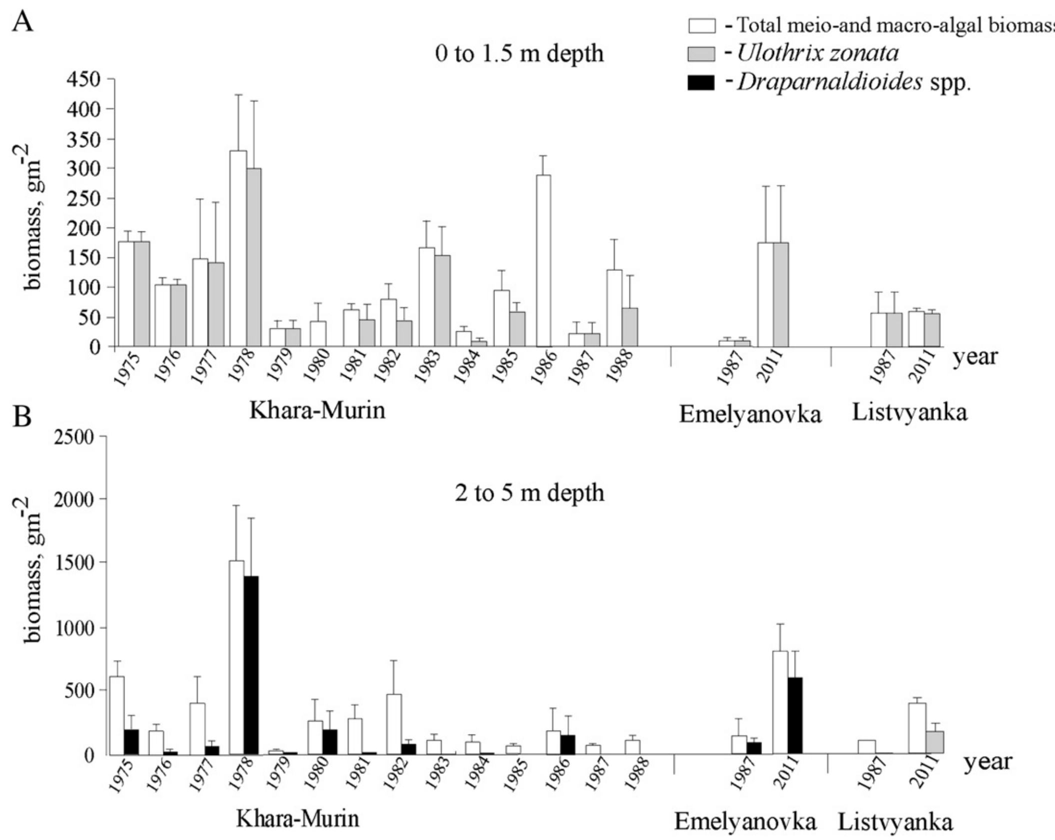

Fig. 5. Biomass (mean ± S.E.) of meio- and macro-algae at (A) 0- to 1.5-m and (B) 2- to 5-m depths in the coastal zone of Lake Baikal at Khara-Murin, Emelyanovka (Transect 1), and Listvennichny Bay (Transect 5) (Fig. 1).

formed ribbon colonies longer than 300 μm. The abundance of *Cymbella ventricosa* Kütz., *Nitzschia dissipata* (Kütz.) Grun, and *N. fonticola* Grun. was 130 $\times 10^6$ cells m^{-2}. A planktonic diatom *U. acus*, abundant in the lake pelagic area in autumn, had settled and made up 396 $\times$ 10^3 cell m^{-2} of the phytobenthos.

Altogether, benthic flora in the studied areas were represented by 109 taxa, 34 of them were meio- and macro-algae, five submerged macrophytes, and 70 microalgae. Of special attention were green algae of the genus *Spirogyra*, non-typical of the historic aquatic plant communities on the open coast of Lake Baikal. Their singular filaments were observed for the first time in 2011 on the western shore at Emelyanovka, in Peschanaya Bay, and on the eastern shore near the village of Vydrino. However, they were not found at other sites under study (Cape Polovinny, Cape Syty, and Bolshiye Koty and Semisosennaya Bays) nor during long-term monitoring of benthic flora (from 1975 to 1988) at the Khara-Murin site (Fig. 1B).

Discussion

Lake Baikal aquatic vegetation is very diverse. Eighty-six species of bryophytic and submerged macrophytes (Azovsky and Chepinoga, 2007), 137 species and varieties of meio- and macro-algae (Izhboldina, 2007), and 444 species of diatoms/microalgae (Pomazkina and Rodionova, 2004) are known to exist. Typically, along the open shoreline of the lake, a zonal distribution of benthic vegetation is evident with substitution of dominant species with depth. *U. zonata* is the dominant in the first zone from 0 to 1.5 m deep, while *Tetraspora cylindrica* (Wahlenb.) Ag. *bullosa* C. Meyer and *D. geminata* form the second belt in water 1.5 to 2.5 m deep. In water deeper than 2.5 m (up to 12 to 20 m), the endemic genus *Draparnaldioides* C. Meyer & Skabich. forms a third zone or belt. These species have a short vegetation period and a major growth spurt seasonally (Izhboldina, 2007; Meier, 1930; Skabichevsky, 1934).

In 2011 at the reference site Emelyanovka (Transect 1) (Fig. 1A), the vertical spatial distribution of meio- and macro-algae, such as *U. zonata* and *D. baicalensis*, was similar to historical zonal distributions in Lake Baikal. Biomass was relatively high but was within the historical variation observed in Lake Baikal. For example, the maximum biomass (100 to 400 g m^{-2}) of *U. zonata* was at the 0- to 1.5-m depth range on the western coast of Lake Baikal in Bolshiye Koty Bay in late June–early July. Biomass of *Draparnaldioides spp.* varied from 50 to 1200 g m^{-2} (Izhboldina, 2007) at a depth of 2 to 5 m in spring through autumn. On the eastern shore near the long term reference site at Khara–Murin, the average long-term biomass and annual variability of *U. zonata* and *Draparnaldioides* were similar to those of Bolshiye Koty Bay (Fig. 5).

Listvennichny Bay

Generally along the open coastline of Lake Baikal (Izhboldina, 1990; Meier, 1930) and in other lakes (e.g., Lake Erie, Stewart and Lowe, 2008), the habitat of *U. zonata* typically is confined to the surf zone, usually not exceeding depths of 1.5 m. However an atypical zonal distribution of meio- and macro-algae was observed in 2011 near Listvyanka (Transect 5). *U. zonata* was widely distributed and was the dominant species at depths greater than 1.5 m. *D. geminata*, *T. cylindrica* var. *bullosa* and *D. baicalensis*, the historically dominant species at the 2- to 5-m depth, are now subdominants or minor species (Fig. 4). However, despite the overgrowth of the bottom by filamentous green algae at the site of high anthropogenic activity near the village of Listvyanka (Transect 5), total algal biomass measured in the 0 to 1.5-m and 2- to 5-m zones were actually lower than those at the reference site Emelyanovka (Transect 1) (Fig. 5).

Possible causes of the species composition changes observed along the nearshore around the village of Listvyanka include, but are not limited to, acid precipitation, changes in grazing pressure, wave action, and nutrient enrichment. Acid precipitation is not an issue in this region because of the huge water volume of Lake Baikal and intense water mixing (Domysheva et al., 2009), while changes in grazing pressure are not likely as there are no consumers in Lake Baikal which graze macrophytes intensively (Kozhova and Izmestyeva, 1998). The growth of benthic algae may be modified by wave action and mixing of water (Nozaki et al., 2003; Reiter, 1986). The most extensive algal growth in the nearshore was observed at the bottom near Listvyanka at water depths deeper than 1.5 m, that is below the zone of strong wave action. In this area of weakened hydrodynamic effect, benthic algal mats of *U. zonata*, *U. tenerrima*, *U. tenuissima* and *Spirogyra* were observed from 3 to 10 m depth. Long strands of filamentous green algae were observed not only on rocks but also on the sandy bottom where the submerged macrophytes *M. spicatum* and *E. canadensis* and other meio- and macro-algae serve as a substrata for attachment. Filamentous algae forming dense mats may also reduce light penetration to the bottom and may explain the depressed state of *C. pumila*, an endemic species, at the sites covered with algal mats but do not explain the increase in abundance of *Ulothrix* spp. or *Spirogyra* observed. Changes in benthic plant communities rather than in the pelagic communities have served as an indicator of local eutrophication effect on the nearshore zone. In the Laurentian Great Lakes, nearshore blooms of benthic algae have also been observed while the pelagic phytoplankton community is indicative of oligotrophic conditions (Makarewicz and Howell, 2012).

In the area near the village of Listvyanka, an area impacted by the growing tourist industry and located along the shoreline (Transects 2 to 7), poorly treated wastewaters are evident and are a likely groundwater and surface source of inorganic phosphorus and nitrogen. For example, sewage pollution in ground water, in the Krestovka River, and in the nearshore bottom water is evident as Total Coliform bacteria (TCB) abundance exceed the Russian Sanitary Code of 500 CFU 100 mL^{-1} in recreational waters in Russia (SRSR, 2000) (Table 1). Associated with wastewater pollution is nutrient pollution. Nutrients can be transported via surface and shallow groundwater flows, as well as via streams flowing through the densely populated creek valleys (Table 1) into the nearshore lake waters. Meio- and macro-algae, which grow along the coasts, are known to take up nutrients originated from the catchment area and near-bottom layer of coastal waters (Puzachenko, 1989). We suggest that the luxurious growth of *Spirogyra* and the non-typical mass growth and depth distribution of *U. zonata* are responses to a high content of nutrients in Lake Baikal near Listvyanka. There is some preliminary data to support this hypothesis.

Generally, phosphorus and nitrogen are major elements controlling the growth of vegetation in freshwater ecosystems (Pourriot et al., 1995; Smith et al., 2006; Stevenson et al., 1996). Anthropogenic activities near the village of Listvyanka appear to be elevating nutrient concentrations in the coastal near-bottom waters but not in the coastal surface waters. Coastal surface water concentrations [(1–2 μg PO_4^{3-}-P L^{-1}) and (16–23 μg NO_3^--N L^{-1}); Table 1] near Listvyanka are within the range of pelagic offshore water (1–5 μg PO_4^{3-}-P L^{-1}; 1–80 μg NO_3^--N L^{-1}; Domysheva, unpublished data), with the exception of Transect 2 where active mixing is hampered by Cape Listvennichny. However, the P concentrations (423 and 64 μg PO_4^{3-}-P L^{-1}, respectively) in the near bottom layer at Transects 5 and 6 (village of Listvyanka), where the newly discovered benthic blooms were observed, were elevated compared to surface waters (1 to 2 μg PO_4^{3-}-P L^{-1}; Table 1). In addition, at Transects 5 and 6 NH_4 levels were high compared to other nearshore sites. Shallow groundwater samples taken near the village of Listvyanka contained high levels of nitrogen (e.g., 898 μg NO_2^--N L^{-1}, 2333 μg NH_4^+-N L^{-1}, and 709 μg NO_3^--N L^{-1}) compared to other sites in the study area (Transects 1 and 8) and in the northern basin of Lake Baikal [in Chivyrkuy Bay — village of Monakhovo and Bolshoy Uskany Island (nitrite range = 6 to 41 μg NO_2^--N L^{-1}; ammonium range =40–1170 μg NH_4^+-N L^{-1}; nitrate = 100–300 μg NO_3^--N L^{-1}); Tomberg et al., 2012]. Nutrient enrichment of shallow groundwater is likely influencing nearshore water quality. Our data are not conclusive as the preliminary nutrient sampling regime has to be expanded to encompass more than one sampling date to confirm this hypothesis.

Furthermore, the emergence of three morphotypes of *Spirogyra*, non-typical of open coasts of Lake Baikal but common freshwater species (Cambra and Aboal, 1992; Jain and Srivastava, 2008; Rosenberger et al., 2008; Zarina et al., 2009) near Listvyanka, supports the hypothesis that elevated nutrient loads in the coastal zone near Listvyanka are causative. Algal assemblages dominated by *Spirogyra* sp. (80–99%) are typically formed when total phosphorus content is ≥10 μg L $-^1$ (McCormick and O'Dell, 1996). Historically (from 1925 to 1990), singular filaments of *Spirogyra* were recorded mainly in bays and sandbars (aquatic areas separated from the lake by a ridge of sand) in the central and northern basins of Lake Baikal (Fig. 1B) and often occurred in streams (Izhboldina, 2007; Kozhova and Izhboldina, 1994). Our results indicate that the species population boundary of *Spirogyra* has now expanded to the southern basin of Lake Baikal where even singular filaments were absent from 1975 to 1988 along the eastern shore (Khara-Murin site). In 2011, however, *Spirogyra* were recorded not far from the transect in Vydrino, as well as on the western shore in Peschanaya Bay, in Emelyanovka, and in Listvennichny Bay (Fig. 1B), making up 3% of the algal biomass of plant community at Transect 5 (Fig. 4). Because unfavorable conditions for *Spirogyra* growth occur in the open coastal lake (low temperature, low content of PO_4^{3-}-P, pH), *Spirogyra* blooms in Listvennichny Bay are being transported from the bay by wave action and alongshore currents due to cyclonic and acyclonic circulations in Lake Baikal during periods of open water. *Spirogyra* was not observed in other areas of the lake.

Blooms of filamentous green algae also affect bacterial and diatom microflora distribution. Occupying benthic areas, algal mats act as a platform onto which bacterial microflora as well as planktonic diatoms *U. acus* settle from the water column, extending their life cycle. It is likely that algal mats of filamentous green algae accumulating bacterial microflora of fecal origin in the near-bottom water layers contribute to the increase of bacterial abundance (Table 1) and, as a result, deterioration of water quality near Listvyanka. Moreover, the dominance of smaller species of *Fragilaria* is characteristic of anthropogenic eutrophication of aquatic ecosystems (Trifonova, 2007). In the coastal area of Lake Baikal, species of *Fragilaria* are typical, but their maximal abundance in the entire lake is low and does not exceed 3×10^5 cells m^{-2} (Flower et al., 2004). However, *Fragilaria* abundance at the nearshore Listvyanka site is unusually higher (570×10^6 cells m^{-2}) than at the reference site Transect 1 (19×10^6 cells m^{-2}). Here the long-ribbon colonies of the smaller *F. capucina* var. *vaucheriae* wound around the filamentous green algae enhancing the dense algae mats. This species is characterized by a high degree of morphological variability (Metzeltin et al., 2005) and is the first record of such long colonies in Lake Baikal. The dominance of *Fragilaria* and of other indicative species from the genera *Nitzschia*, *Cocconeis*, and *Cymbella* is characteristic of eutrophic ecosystems (Hellawell, 1986). At present, although microalgal abundance in the study area at Transect 1 (184×10^6 cells m^{-2}) and Transect 5 (215×10^6 cells m^{-2}) is almost identical, the algal assemblage composition is significantly different.

Conclusions

Overgrowth of the lake bottom by filamentous green algae; changes in distributional boundaries and the structure of benthic plant communities, such as the expansion of *U. zonata* dominance to depths of 2 to 5 m; the emergence and mass development of species of the genus *Spirogyra*, a species non-typical of Lake Baikal; diatom assemblages characteristic of eutrophic ecosystems in oligotrophic Lake Baikal; elevated abundances of coliform bacteria; and elevated levels of nutrients are attributed to anthropogenic eutrophication and are likely at an early stage of development. Strategies to reduce eutrophication based on scientific studies, including monitoring and recommendations, are required to reduce the anthropogenic effects on the Lake Baikal ecosystem. Special attention should be given to filamentous green algae as indicators of nutrient load in this aquatic ecosystem. To prevent further eutrophication of the nearshore zone of Lake Baikal, a UNESCO World Heritage Site, elimination of sources of nutrient and coliform bacteria inputs to the coastal area is necessary through the construction of a centralized sewage treatment that treats wastewater from the village and from the numerous tourist centers on the lake shore.

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