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Lacustrine, wastewater, interstitial and fluvial water quality in the Southern Lake Baikal region

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ABSTRACT

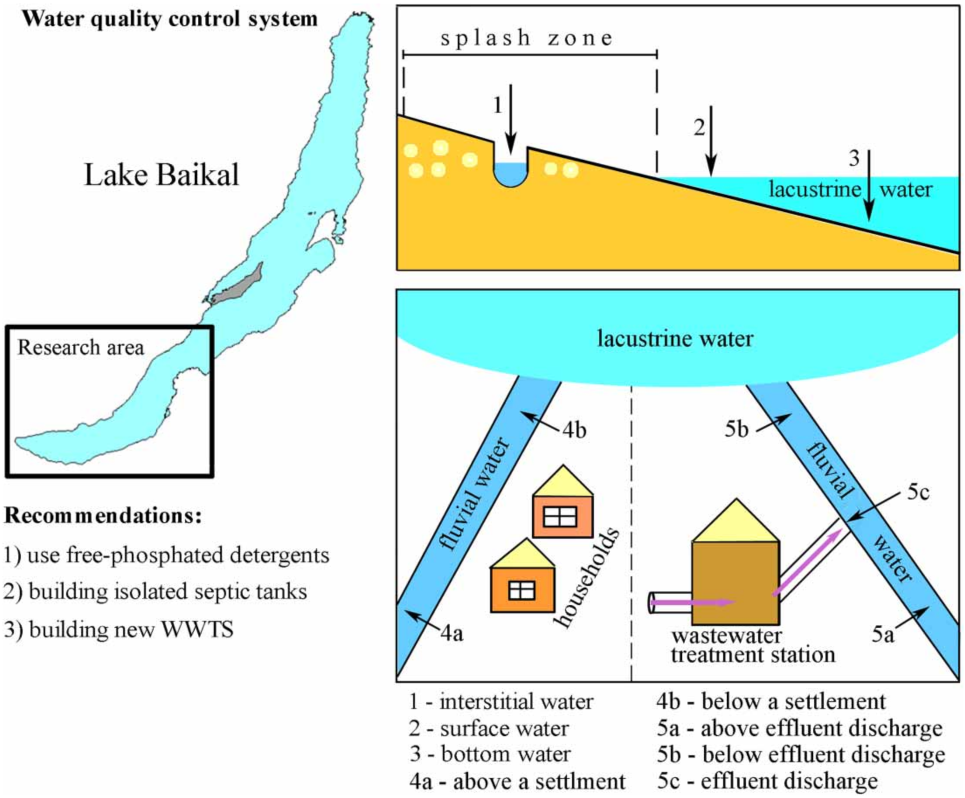
The coastal area of the southern Lake Baikal with the population over 35,000 people remains an attractive spot for both tourists and local residents. Despite high anthropogenic impact, a detailed assessment of water quality in this area has not been performed so far. Here, we performed a comprehensive evaluation of the quality of the surface, bottom and interstitial water in rivers, lacustrine water and wastewater in the southern Lake Baikal region. We analyzed 37 samples for the presence of fecal enterococci, *Escherichia coli* and assessed their hydrochemical parameters: concentrations of nutrients (nitrate-N, nitrite-N, ammonium-N and phosphate-P), dissolved oxygen and amount of ions ($HCO_3^- + SO_4^{2-} + Cl^- + Ca^{2+} + Mg^{2+} + Na^+ + K^+$). In addition, the temperature, pH and electrical conductivity were also measured. We found that multiple areas around South Baikal suffer from microbiological and hydrochemical pollution. We conclude that ecological situation in this area requires immediate attention from local authorities, more efficient wastewater management systems should be constructed in the settlements. We also conclude that interstitial waters from the lake's splash zone represent an effective and sensitive indicator of sanitary-microbiological and hydrochemical pollution and their analysis can be included in the standard protocol of water quality assessment for all types of water bodies.

Key words: anthropogenic impact, fecal indicator bacteria (FIB), Lake Baikal, nutrients, wastewater management

HIGHLIGHTS

- Water quality analysis of the South Lake Baikal area is presented.
- Concentration of fecal bacteria in the rivers near settlements is significantly higher than that of the protected areas.
- Concentration of nutrients in the interstitial water in Listvyanka settlement is significantly higher than that of lake water.
- The splash zone represents an effective indicator of pollution in the coastal areas of Lake Baikal.

GRAPHICAL ABSTRACT



INTRODUCTION

The quality of surface water is an important and urgent environmental issue (Babić *et al.* 2019). Coastal water resources are habitually exposed to indiscriminate anthropogenic pollution (Adeniji *et al.* 2019). Due to their negative consequences to the public health, recreational waters require continuous monitoring for disease-causing organisms. As the human population and associated coastal development continue to grow, monitoring water quality for sewage pollution is essential (Abaya *et al.* 2018). With such an intense release of human waste into water bodies, it is not surprising that global models of wastewater pollution predict large-scale contamination of surface waters (Font *et al.* 2019). Whereas the idea of a threat of a sanitary crisis to human population has been well established, until recently, the impact of various types of pollution on ecosystems themselves has not been sufficiently addressed by ecologists (Wear *et al.* 2021).

The genus *Enterococcus* is in the intertidal interstitial water in concentrations that could affect water quality and public health (Sanchez Dominguez *et al.* 2015). It is, therefore, recommended that interstitial water monitoring should be included as a measure of predictive microbiological safety of recreational water on sandy beaches. The safety of recreational waters is an important and timely issue specially when dealing with public health and sustainable water management, particularly in a context of climate changes. The number of hazardous microorganisms and forms present in recreational waters is large and the regulatory agencies approach is guided by fecal contamination events. The limitation of traditional FIB, the regulatory approach and the potential effects of climate change on pathogenic organisms and human infectious diseases need an improvement of the indicator systems (Rodrigues & Cunha 2017). In addition to classical filtration and cultivation methods to detect FIB, marker genes have also been used to determine the source of fecal contamination in water bodies (Brooks *et al.* 2020; Sangkaew *et al.* 2021).

Pollution of surface waters with nutrients is a widespread problem, calling for regional assessments of water quality conditions (Clune *et al.* 2020). The global character of this problem is underlined by recent reports on quality of water in many areas around the world (Kucuksezgin *et al.* 2019; Shi *et al.* 2020; Dantas *et al.* 2021; Wang *et al.* 2021). For instance, a recent analysis of the ecological state of the coastal zone of Izmir Bay in Turkey (Kucuksezgin *et al.* 2019) reports on microbial pollution (enterococci and *E. coli*) in the bay area and the impact of human waste from the coastal population on the quality of water in the rivers flowing into the bay. Another example is ecological survey of water quality in the water bodies located within an urbanized area in the Velhas River basin in Brazil (Dantas *et al.* 2021) which shows the presence of nutrients and coliforms in the water samples due to inefficient treatment of wastewater.

The term 'splash zone', which is commonly used in the scientific literature on marine coastal zoning, refers to the part of the littoral zone that is subject to wetting by breaking waves (Lincoln *et al.* 1982). Such a zone, with distinct gradients in abiotic conditions, permanently exists in Lake Baikal and occupies the area from the shoreline to the slope base. The splash zone (as part of the near-shore zone) of most Eurasian lakes has not been extensively studied until recently and remains a white spot for limnologists (Zohary & Gasith 2014; Timoshkin 2018). However, it was demonstrated that this zone is a rapid and reliable environmental indicator capable of reflecting the responses of ecosystems to anthropogenic stress (Timoshkin *et al.* 2012a).

Several studies reported massive overgrowth of filamentous algae in the southern basin of Lake Baikal (Kravtsova *et al.* 2014; Timoshkin *et al.* 2016, 2018). This outgrowth is believed to result from the constant supply of phosphates and nitrates to the ecosystem and may indicate the pollution of the lake. Recent reports also show an elevated amount of nutrients and FIB in the coastal water of the Listvyanka settlement (Malnik *et al.* 2019a) as well as the presence of sanitary-indicative bacteria in interstitial water. Detailed studies of this problem have been carried out in the southern basin of Lake Baikal (Gorshkova *et al.* 2020). The outstanding questions are (i) to determine the specific places on the coast of Lake Baikal that are subject to pollution and (ii) to find the solution that will stop pollution of these places on the coast of the southern basin of the lake.

The main aim of this study was to perform a comprehensive evaluation of the quality of the surface, bottom and interstitial water in rivers, lacustrine water and wastewater in the Southern Lake Baikal region. Another aim of the study was to assess 'the quality of the interstitial waters' of the lake's splash zone.[1] This zone is prone to fecal and hydrochemical contamination and therefore represents a sensitive and effective indicator of pollution of coastal areas.

MATERIALS AND METHODS

Sampling sites and procedures

Lake Baikal, in the northeastern part of Eurasia, comprises one of the most unique freshwater ecosystems on Earth (Figure 1(a)). Estimated to be over 25 million years old, Lake Baikal is the world's deepest (maximum depth of 1,637 m) and largest freshwater basin, and it contains up to 20% of all freshwater globally (Galaziy 1993).

Settlements in the southern Lake Baikal area with populations of ~20,000 people were chosen as sampling sites (Figure 1). Settlements that possessed centralized wastewater purification systems (i.e., Sludyanka and Baikalsk) and those lacking such systems (i.e., Bolshoe Goloustnoe and Listvyanka) were included in the survey. In some of these settlements, there has been a significant increase in the recreational load during summer, mainly due to tourism. The Listvyanka settlement is a tourist destination located within Listvennichnyi Bay on the western shore of southern Lake Baikal, and it lies to the east of the Angara River head (Figure 1). The settlement stretches from the Rogatka Cape to the Listvennichnyi Cape over 5 km (Suturin *et al.* 2016). The coastal zone of the open Listvennichnyi Bay is characterized by rocky beaches. There are a total of six streams and rivers in the valleys of Listvyanka, and among these, the Krestovka River has the highest water levels. The other tributaries include the Bolshaya Cheremshanka, Malaya Cheremshanka, Kamenushka, and Sennaya rivers, and the Bannyi stream. Water from the Bolshaya Cheremshanka, Malaya Cheremshanka, Kamenushka and Krestovka rivers was subjected for sanitary-microbiological (definition of *E. coli*, fecal enterococci) and chemical analyses (definition of nutrients) (Figure 1(d); Table 1).

To detect pollution (or its absence), water samples collected upstream of the settlements (about 2 km from the mouth) as well as in the mouths of the rivers were analyzed (e.g., the Listvyanka and Bolshoe Goloustnoe settlements, and Sludyanka).

Samples of surface water ($n = 22$), interstitial water (holes were made in the swash zone about 1 m above the water's edge; $n = 9$) and bottom water ($n = 4$) from the coastal zone of the lake, as well as wastewater samples ($n = 2$), were collected. For sampling, sterile 150 mL Janet syringes were used. Water samples were taken as described previously (Water. Sampling for Microbiological Analysis 2012). Briefly, samples of surface water were taken from a depth of 10–30 cm from the water surface, whereas samples of bottom water were taken from a depth of 30–50 cm from the bottom. For bottom water sampling, the

[1] There is no generally accepted standard on the quality of interstitial waters.

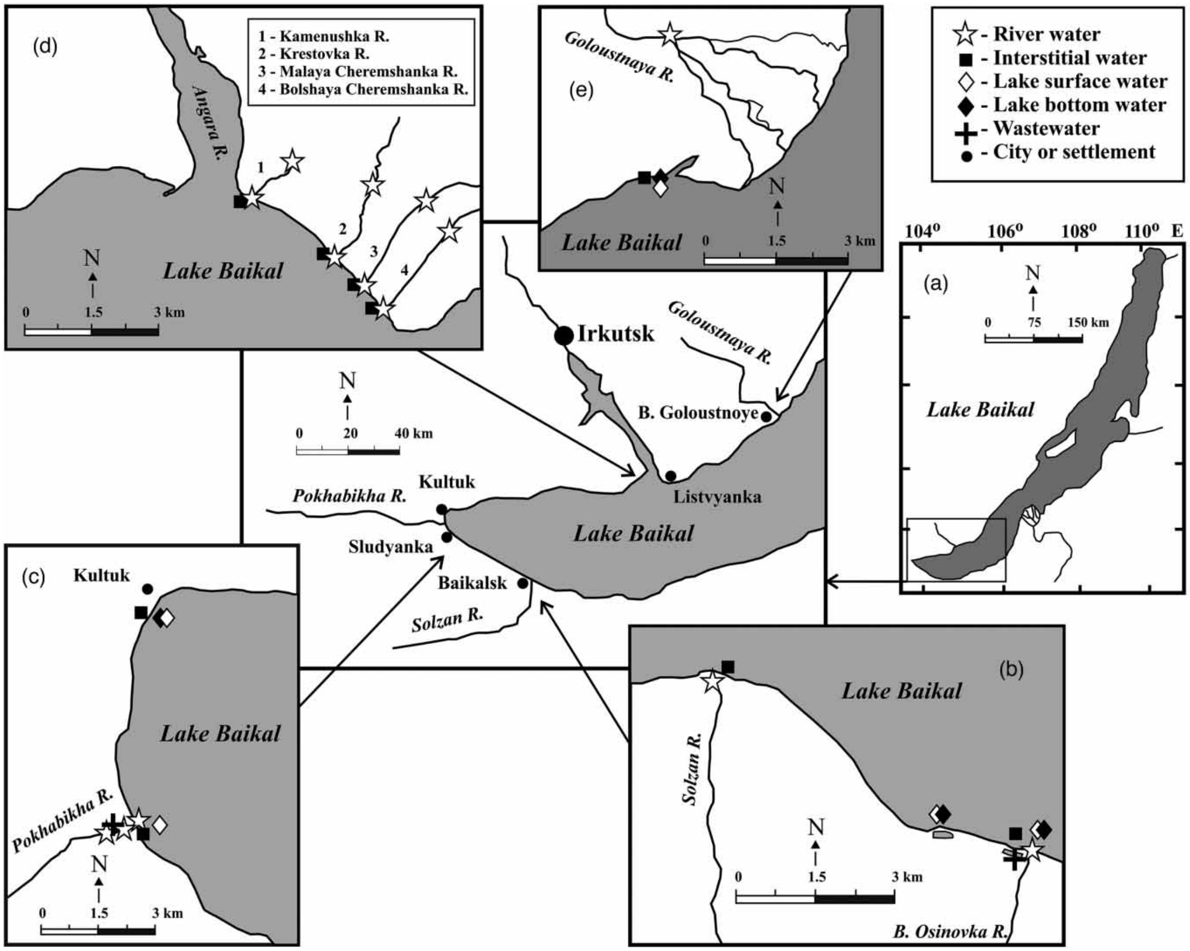


Figure 1 | Sampling points in the southern Lake Baikal area, river water (white star), interstitial water (black square), lake surface water (white diamond), lake bottom water (black diamond) and wastewater (black cross), city or settlement (black circle).

syringes were attached to a long stick. The samples were then poured into sterile glass 250 mL vials, which were placed into a cooler bag with ice packs and analyzed in the chemical and microbiological laboratories of LIN SB RAS (Irkutsk, Russia). A detailed description of the term 'swash zone' is given by Timoshkin *et al.* (2012a). In general, detritus-free areas were chosen on the shores for the purpose of collecting samples. Interstitial water samples for microbiological and hydrochemical analyses were collected from the same hole (hole depth varied from 0.15 to 0.7 m) immediately after the holes were made by sterile stainless-steel shovel. This is mainly lake water that has passed through the soil, to a lesser extent this is river water flowing through the soil, finally, this can also be moisture accumulated in the ground after rain, which was not able to penetrate deeper to the groundwater level. The samples of the waste water upon treatment were obtained from the outlet pipe of the water treatment facility in Sludyanka town. Sterile gloves and sterile bottles were used for sampling.

All microbiological assays were performed in two replicates. Chemical analyses were performed once, but in every location, the standard analytical error was taken into account. All sampling and analyses were performed in June of 2016 (from 10th to 14th) and in August of 2016 (23th).

Microbiological analyses

Detection and counting of the study groups of bacteria (*E. coli* and fecal enterococci) and interpretation of the results were conducted according to the 2012 standards published by the United States Environmental Protection Agency (Recreational Water Quality Criteria 2012). The following sample volumes were used for filtration: 50–100 mL for surface samples, 50 mL for bottom samples and 5–20 mL for both wastewater and interstitial samples. Filtration was performed by using 0.45 μm nitrocellulose filters.

Table 1 | Description of main sampling points

Sampling location number	Description	Land use	Coordinates
1	Kamenushka River, above a settlement	Property of public law entities	N 51°52′24.70″ E 104°50′41.85″
2	Kamenushka River mouth	Property of public law entities	N 51°52′02.81″ E 104°49′58.80″
3	Near the Kamenushka River mouth, hole (interstitial water)	Property of public law entities	N 51°52′01.76″ E 104°49′57.73″
4	Krestovka River, above a settlement	Settlement lands	N 51°51′55.10″ E 104°52′10.91″
5	Krestovka River mouth	Settlement lands	N 51°51′19.45″ E 104°51′36.43″
6	Near the Krestovka River mouth, hole (interstitial water)	Settlement lands	N 51°51′19.71″ E 104°51′35.64″
7	Malaya Cheremshanka River, above a settlement	Specially protected areas, National Park	N 51°51′44.4″ E 104°52′52.2″
8	Malaya Cheremshanka River mouth	Settlement lands	N 51°50′58.7″ E 104°52′09.6″
9	Near the Malaya Cheremshanka River mouth, hole (interstitial water)	Settlement lands	N 51°50′58.9″ E 104°52′09.1″
10	Lake Baikal, offshore from the Malaya Cheremshanka River mouth	–	N 51°50′58.9″ E 104°52′09.1″
11	Bolshaya Cheremshanka River, above a settlement	Specially protected areas, National Park	N 51°51′30.7″ E 104°53′40.7″
12	Bolshaya Cheremshanka River mouth	Settlement lands	N 51°50′41.8″ E 104°52′33.0″
13	Near the Bolshaya Cheremshanka River mouth, hole (interstitial water)	Settlement lands	N 51°50′41.9″ E 104°52′32.4″
14	Lake Baikal, offshore from the Bolshaya Cheremshanka River mouth	–	N 51°50′41.9″ E 104°52′32.4″
15	Pokhabikha River, 100 m above effluent discharge	Settlement lands	N 51°40′14.41″ E 103°42′04.06″
16	Pokhabikha River, at the site of effluent discharge	Settlement lands	N 51°40′15.11″ E 103°42′09.71″
17	Pokhabikha River, 100 m below effluent discharge	Settlement lands	N 51°40′15.73″ E 103°42′15.19″
18	Sewage water from Sludyanka	Settlement lands	N 51°40′15.11″ E 103°42′09.71″
19	Pokhabikha River mouth	Settlement lands	N 51°40′19.52″ E 103°42′31.82″
20	Lake Baikal, offshore from the Pokhabikha River mouth	–	N 51°40′19.92″ E 103°42′35.11″
21	Near the Pokhabikha River mouth, hole (interstitial water)	Settlement lands	N 51°40′19.92″ E 103°42′35.11″
37	An effluent pond sample	Property of public law entities	N 51°30′00.2″ E 104°14′09.6″

E. coli were identified following filtration and sample incubation at 44 °C for 24 h using the selective agar HiCrome (Himedia production, No. M1571). Fecal enterococci were determined by membrane filtration and sample concentration using Slanetz and Bartley Medium (Himedia production, No. M612) incubated at 37 °C for 24 h, as well as Bile Esculine Azide

Agar (Himedia production, No. M493) incubated at 44 °C for 2 h (Murray 2003). Colonies that acquired a black color were counted as fecal enterococci (*Enterococcus faecius* and *E. fecalis*).

Chemical analyses

For chemical analyses, the water samples were filtered through acetate cellulose membrane filters with a pore diameter of 0.45 μm. Cations were determined by atomic absorption spectroscopy (calcium [Ca^{2+}] and magnesium [Mg^{2+}]) and the flame emission method (sodium [Na^{+}] and potassium [K^{+}]) on an Atomic Absorption Spectrophotometer 30 (AAS-30; Carl Zeiss Jena, Germany) with 5–7% error (Fomin 2000). Anion concentrations (bicarbonate [HCO_3^-], chloride [Cl^-], sulfate [SO_4^{2-}] and nitrate [NO_3^-]) were measured by high-performance liquid chromatography on a chromatograph Milichrom A-02 (EcoNova, Russia) with 7–10% error (Khodzher *et al.* 2016). The sum of ions ($\sum i$) was calculated as $HCO_3^- + SO_4^{2-} + Cl^- + Ca^{2+} + Mg^{2+} + Na^+ + K^+$. Dissolved oxygen (DO) concentrations were measured on site (*in situ*) by the Winkler test with 3% error. Nutrient analyses (phosphate-P, ammonium-N and nitrite-N) were performed with a spectrophotometer KFK-3 (Zagorsky Optical-Mechanical Plant, Russia) with 10–20% error. Mineral phosphorus concentrations (soluble reactive phosphate) were estimated with ammonium molybdate, ammonium nitrogen concentrations were measured with indofenol, and nitrite concentrations were estimated with the Griess reagent (Boeva 2009).

The temperature and conductivity at the sampling sites were measured with the use of a portable device (Horiba, Japan) and the pH was measured with the use of pH meter (Hanna, Germany).

Statistics

Confidence intervals (95%) for the average values in microbiological and chemical parameters were estimated using the bootstrap method (1,000 replicas) (Davison & Hinkley 1997). The results of bootstrap statistics were used to determine the significance of differences between the average values of parameters in sampling points of different zones (ecotopes). The calculations were performed using the «boot» (Canty & Ripley 2017) and «sfsmisc» (Maechler 2017) packages for the R programming language.

The principal component analysis (PCA) method was used to determine the similarities and differences between the samples based on the summation of microbiological and chemical parameters. Before PCA analysis all data were transformed by logarithmic scaling (natural logarithm) to eliminate the physical dimensions. PCA results were visualized using the «gplot2» package (Wickham 2009).

Pairwise correlations between all microbiological and chemical parameters were estimated with Spearman's r correlation coefficient. P-values for the correlation coefficients were calculated using Spearman's «W» statistics and corrected for the false discovery rate in multiple comparisons using the Benjamini–Hochberg equation.

RESULTS AND DISCUSSION

Microbiological data

At the mouths of the rivers flowing into Lake Baikal near Listvyanka, such as Bolshaya Cheremshanka, Malaya Cheremshanka and Kamenushka, the counts of *E. coli* (Figure 2(a)) were 12, 35 and 24 times higher than the US EPA recommended standard (235 colony forming units (CFUs) per 100 mL), respectively (Recreational Water Quality Criteria 2012). Similarly, enterococci counts (Figure 2(a)) were 16, 64 and 47 times higher than the standard value (61 CFU/100 mL) in the Bolshaya Cheremshanka, Malaya Cheremshanka and Kamenushka rivers, respectively (Recreational Water Quality Criteria 2012; Figure 2(a)). In the wastewater discharged into the Pokhabikha River, the *E. coli* and enterococci counts exceeded the standard values by 26 and 31 times, respectively (Figure 2(a)).

In the other rivers flowing into the southern part of the lake (i.e., the Bolshaya Goloustnaya, Solzan and Bolshaya Osinovka), the indicator microorganism concentrations were within the sanitary standards (Figure 1(b) and 1(e); Table 2). At the sampling site in Lake Baikal near the mouth of the Malaya Cheremshanka River, the number of enterococci exceeded the US EPA recommended standard (Recreational Water Quality Criteria 2012) by 12 times, and the number of *E. coli* exceeded the standard by 9 times (Figure 2(a)).

Analysis of interstitial water revealed abundant FIB in the samples collected in the holes near the mouths of the Krestovka River (*E. coli* = 3,800 CFU/100 mL; enterococci = 25 CFU/100 mL) and the Bolshaya Cheremshanka River (*E. coli* = 2,120 CFU/100 mL; enterococci = 800 CFU/100 mL) (Figure 2(a)). We also found high amounts of FIB near the Kultuk settlement, at the mouth of the Solzan River, and near the Bolshoe Goloustnoe settlement (Table 2). Interestingly, the

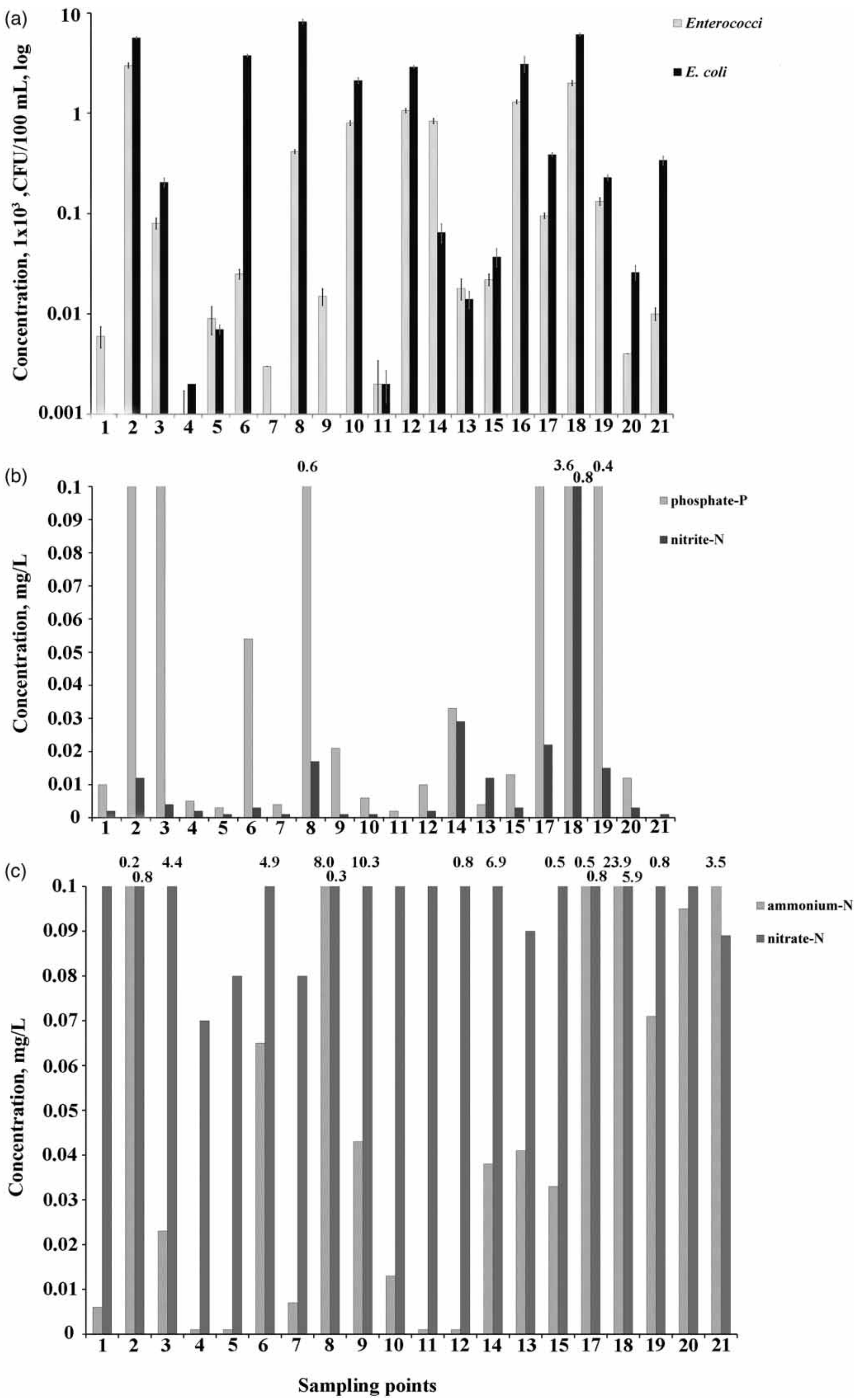


Figure 2 | Concentrations of (a) FIB and (b,c) nutrients at different sampling points. Sampling sites: 1 – Kamenushka River, above a settlement, 2 – Kamenushka River mouth, 3 – Near the Kamenushka River mouth, hole (interstitial water), 4 – Krestovka River, above a settlement, 5 – Krestovka River mouth, 6 – Near the Krestovka River mouth, hole (interstitial water), 7 – Malaya Cheremshanka River, above a settlement, 8 – Malaya Cheremshanka River mouth, 9 – Near the Malaya Cheremshanka River mouth, hole (interstitial water), 10 – Lake Baikal, offshore from the Malaya Cheremshanka River mouth, 11 – Bolshaya Cheremshanka River, above a settlement, 12 – Bolshaya Cheremshanka River mouth, 13 – Near the Bolshaya Cheremshanka River mouth, hole (interstitial water), 14 – Lake Baikal, offshore from the Bolshaya Cheremshanka River mouth, 15 – Pokhabikha River, 100 m above effluent discharge, 16 – Pokhabikha River, at the site of effluent discharge, 17 – Pokhabikha River, 100 m below effluent discharge, 18 – Sewage water from Sludyanka, 19 – Pokhabikha River mouth, 20 – Lake Baikal, offshore from the Pokhabikha River mouth, 21 – Near the Pokhabikha River mouth, hole (interstitial water).

Table 2 | Concentrations of FIB and nutrients in the water of southern Baikal tributaries, interstitial waters and Lake Baikal

		Microbiological data[a]		Hydrochemical data				
Sampling points		*E. coli*, CFU/100 mL	Enterococci, CFU/100 mL	NH_4^+, mg N/L	NO_2^-, mg N/L	NO_3^-, mg N/L	PO_4^{3-}, mg P/L	Sum of ions, mg/L
Rivers	Solzan Bolshaya Osinovka	0 ± 0	2 ± 1	<0.005	<0.002	0.19 ± 0.02	0.002 ± 0.0004	51.2
		2 ± 1	2 ± 1	<0.005	<0.002	0.24 ± 0.02	0.003 ± 0.0006	36.0
	Goloustnaya	91 ± 9	29 ± 3	0.013 ± 0.001	<0.002	0.05 ± 0.005	0.001 ± 0.0002	126.4
Interstitial water	Baikalsk town, near an effluent pond	35 ± 4	0 ± 0	<0.005	<0.002	0.27 ± 0.03	0.005 ± 0.001	469,1
	Baikalsk town, standard point	350 ± 24	75 ± 3	0.026 ± 0.003	0.002 ± 0.0004	1.10 ± 0.08	0.009 ± 0.002	142.6
	Bolshoe Goloustnoe settlement	992 ± 16	48 ± 8	<0.005	0.005 ± 0.001	0.14 ± 0.01	0.017 ± 0.003	108.2
	Kultuk settlement	16,300 ± 600	9,300 ± 440	0.310 ± 0.030	0.076 ± 0.008	0.40 ± 0.04	0.002 ± 0.0004	182.3
Surface Baikal water	Baikalsk town, near an effluent pond	6 ± 2	5 ± 2	0,002	0	0,51	0.002	171
	Baikalsk town, standard point	9 ± 3	3 ± 1	0.006 ± 0.001	<0.002	0.03 ± 0.003	0.004 ± 0.001	104.7
	Bolshoe Goloustnoye settlement	2 ± 1	2 ± 1	<0.005	<0.002	0.07 ± 0.01	0.001 ± 0.0002	106.9
	Kultuk settlement	350 ± 28	132 ± 18	0.006 ± 0.001	<0.002	0.08 ± 0.01	0.002 ± 0.0004	98.7
Bottom Baikal water	Kultuk settlement	94 ± 6	52 ± 6	0.013 ± 0.002	<0.002	0.03 ± 0.003	<0.001	94.4
	Baikalsk town, near an effluent pond	22 ± 4	8 ± 2	0	0,001	0,03	0,006	109.5
	Baikalsk town, standard point	4 ± 1	0 ± 0	<0.005	0.002 ± 0.0004	0.02 ± 0.002	0.007 ± 0.001	933.4
	Bolshoe Goloustnoe settlement	8 ± 2	2 ± 1	0.005 ± 0.001	0.002 ± 0.0004	0.02 ± 0.002	0.010 ± 0.002	104.7

[a]CFU, colony forming units; ± standard error of the mean for microbiological data, standard analytical error for chemical data.

obtained data are consistent with the results of the water quality analysis that was carried out on the southern coast of Lake Michigan (Nevers *et al.* 2020). The authors showed that the concentration of *E. coli* in interstitial water samples was significantly higher when compared to that of sediment and overlying water samples. The similarity of these data might indicate a common pattern in how these territories are affected by anthropogenic activities.

Analysis of the near-bottom water revealed that FIB concentration near the Kultuk settlement, Bolshoe Goloustnoe settlement and Baikalsk town met the US EPA standards (Recreational Water Quality Criteria 2012; Table 2). Analysis of the surface water revealed that FIB concentrations near the Kultuk settlement exceeded both national and international standards (Inspection 2000; Recreational Water Quality Criteria 2012). The quality of surface water near the Solzan, Baikalsk and Bolshoe Goloustnoye settlements complied with existing standards (Inspection 2000; Recreational Water Quality Criteria 2012; Table 2).

In addition, the sample from an effluent pond in Baikalsk also contained FIB (*E. coli* = 222 CFU/100 mL; enterococci = 72 CFU/100 mL). The concentration of enterococci in the water sample obtained in the river part upstream of the settlement differed significantly from those obtained in the estuaries and interstitial water in the lower parts of the rivers ($P = 0.005$ and 0.007, respectively; Table 3). Even greater difference ($P = 0.002$ and 0.003, respectively) was observed for the concentration of *E. coli* in the parts of the rivers upstream and downstream of the settlements. At the same time, we observed no significant difference between concentrations of *E. coli* in the sample of water obtained in the lake and those obtained in the river part upstream of the settlement, downstream of the settlement and interstitial water ($P = 0.07$, 0.091 and 0.17, respectively). Likewise, no significant difference was observed in the concentration of enterococci for the aforementioned sampling sites ($P = 0.08$, 0.22 and 0.195, respectively).

Hydrochemical data

Chemical analyses of the samples from the four rivers connected to the Listvyanka settlement area revealed that the water samples collected upstream of the settlement had low concentrations of salts ($\sum_i$ – 50–150 mg/L) and nutrients. The quantity and composition of nutrients carried by rivers play an important role in maintaining the ecosystem of downstream rivers and marginal seas (Wang 2020). Water mineralization (sum of major ions) in the mouths of the Krestovka and Kamenushka rivers were not different from the upstream sites (Table 3). By the sum of ions, the maximum differences were found between samples taken from (i) the river upstream of the settlement and interstitial waters ($P = 0.001$), (ii) the estuarine river and interstitial waters ($P = 0.003$) and (iii) lake and interstitial waters ($P = 0$). The largest sum of ions was observed in interstitial water in comparison with lake and river waters (Table 3). The chlorine concentration in samples taken above the settlement was significantly lower than in samples taken at river mouths, interstitial and lake water (Table 3). In our opinion, this is due to the influence of anthropogenic activity. K^+ ions concentration in the sample of water taken upstream of the settlement was significantly lower than those taken in lake and interstitial waters (Table 3). In our opinion, this is also associated with the influence of anthropogenic activities.

It is generally known that phosphate-P and nitrate-N, even at low, but constant concentrations, can stimulate the growth of aquatic vegetation (e.g., genus *Spirogyra*) which is atypical for this habitat (Timoshkin *et al.* 2016). High concentrations of chloride ion and ammonium-N may indicate their anthropogenic input, since chlorine and ammonium are contained in human waste products, such as urine (Alemayehu *et al.* 2020). Therefore, the determination of the concentration of these ions is very important.

The concentrations of phosphate-P and ammonium-N were elevated in the river mouths compared with areas upstream of the settlements, whereas the concentrations of nitrate-N and nitrite-N did not significantly differ (Table 3). Phosphate-P concentrations in water samples obtained upstream of the settlement and lake were significantly lower than those in the sample of interstitial water as well as samples taken at the estuary ($P = 0.05$ and 0.009, respectively). The concentration of ammonium-N in water samples taken upstream of the settlement was significantly lower than in those taken at the river mouths and interstitial samples ($P = 0.015$ and 0.028, respectively). Interestingly, similar results were previously obtained for four rivers in Listvyanka settlement (Onischuk *et al.* 2019). The ammonium-N levels in the parts of the rivers located upstream of the residential buildings differed from those in the downstream parts of the rivers downstream. The authors linked this observation with the flow of municipal washing water into the rivers.

For all the samples tested, the highest nitrate-N concentration was found in interstitial water. The concentration of nitrite-N in samples taken upstream of the settlement was significantly lower than in that of interstitial water ($P = 0.019$). Concentrations of nutrients in the rivers that flow through other settlements in the southern part of Lake Baikal were within

Table 3 | Analysis of hydrochemical and microbiological indicators in the sampling zones

					P-value* of validation test for the reliability of differences in average values of the indicators in pairwise comparison of sampling zones			
Name of the indicator	**Name of sampling zone**	**Average value, mg/L**	**Minimal boarder of 95% confidence interval**	**Maximal boarder of 95% confidence interval**	**Fluvial water, above settlement**	**Fluvial water, mouth**	**Interstitial water**	**Lacustrine water**
Enterococci	Fluvial water, above settlement	0.007	0.002	0.016	1*	**0.005***	**0.007**	0.08
	Fluvial water, mouth	0.582	0.129	1.95	**0.005**	1	0.482	0.22
	Interstitial water	1.139	0.045	5.268	**0.007**	0.482	1	0.195
	Lacustrine water	0.094	0.015	0.405	0.08	0.22	0.195	1
E. coli	Fluvial water, above settlement	0.008	0.001	0.023	1	**0.002**	**0.003**	0.07
	Fluvial water, mouth	2.193	0.426	4.868	**0.002**	1	0.746	0.091
	Interstitial water	2.468	0.453	8.408	**0.003**	0.746	1	0.17
	Lacustrine water	0.241	0.027	1.001	0.07	0.091	0.17	1
Phosphate-P	Fluvial water, above settlement	0.007	0.003	0.01	1	**0.009**	**0.05**	0.53
	Fluvial water, mouth	0.148	0.021	0.354	**0.009**	1	0.138	**0.005**
	Interstitial water	0.03	0.013	0.076	**0.050**	0.138	1	**0.015**
	Lacustrine water	0.005	0.003	0.007	0.53	**0.005**	**0.015**	1
Ammonium-N	Fluvial water, above settlement	0.009	0.002	0.022	1	**0.015**	**0.028**	0.587
	Fluvial water, mouth	1.007	0.031	5.007	**0.015**	1	0.485	**0.029**
	Interstitial water	0.451	0.044	2.027	**0.028**	0.485	1	**0.05**
	Lacustrine water	0.016	0.006	0.046	0.587	**0.029**	**0.05**	1
Nitrate-N	Fluvial water, above settlement	0.169	0.088	0.386	1	0.189	**0.004**	0.505
	Fluvial water, mouth	0.411	0.205	0.646	0.189	1	**0.014**	**0.05**
	Interstitial water	3.167	1.336	6.188	**0.004**	**0.014**	1	**0.002**
	Lacustrine water	0.102	0.054	0.261	0.505	**0.05**	**0.002**	1
Nitrite-N	Fluvial water, above settlement	0.002	0	0.002	1	0.172	**0.019**	0.624
	Fluvial water, mouth	0.006	0.002	0.011	0.172	1	0.291	0.328
	Interstitial water	0.013	0.003	0.041	**0.019**	0.291	1	0.08
	Lacustrine water	0.002	0.001	0.005	0.624	0.328	0.08	1
K^+	Fluvial water, above settlement	0.643	0.398	0.992	1	0.144	**0**	**0.023**
	Fluvial water, mouth	1.312	0.791	1.942	0.144	1	**0**	0.286
	Interstitial water	3.957	3.166	5.075	**0**	**0**	1	**0**
	Lacustrine water	1.107	1.002	1.223	**0.023**	0.286	**0**	1
Cl^-	Fluvial water, above settlement	0.261	0.182	0.351	1	**0.025**	**0**	**0**
	Fluvial water, mouth	2.667	0.642	6.928	**0.025**	1	**0.02**	0.168
	Interstitial water	17.304	9.243	27.906	**0**	**0.02**	1	**0**
	Lacustrine water	0.831	0.626	1.473	**0**	0.168	**0**	1
Sum of ions	Fluvial water, above settlement	111.982	70.064	145.936	1	0.963	**0.001**	0.432
	Fluvial water, mouth	111.402	74.294	149.168	0.963	1	**0.003**	0.45
	Interstitial water	270.789	203.754	345.087	**0.001**	**0.003**	1	**0**
	Lacustrine water	107.91	100.732	129.888	0.432	0.45	**0**	1

**P*-values ($P > 0.05$) indicate no difference in the compared mean values; *P*-values highlighted in bold ($P < 0.05$) indicate a difference in the compared mean values.

standard values (Table 2). Importantly, our data are in agreement with the results of the recent report on ecological status of the tributaries and shores of Lake Baikal (Gagarinova *et al.* 2021). The authors show that the maximal values of phosphate-P, nitrate-N, ammonium-N and nitrite-N in the Goloustnaya River for the study period from 2015 to 2019 were 0.009, 0.200, 0.250 and 0.084, respectively. We also found high chloride concentrations (22–44 mg/L) in the samples of interstitial water taken from the holes located near rivers. These values considerably exceeded those obtained in the rivers of the Listvyanka settlement (<12.6 mg/L) or the coastal waters of the lake in this area (<0.6 mg/L).

In the Pokhabikha River, water in the area that is downstream of the point where the effluent from Sludyanka is discharged upon treatment is of poor quality (Figures 2 and 3). High concentrations of ammonium-N (up to 0.43 mg/L) and nitrate-N (up to 0.82 mg/L) levels were detected in the area of the river upstream of the river mouth. This may be due to (i) dense development near the river in the area upstream of the discharge site, as well as (ii) excessive grazing in that area. The concentration of ammonium-N levels in interstitial water near the mouth of the Pokhabikha River was significantly higher than those in the samples of lake water as well as samples taken upstream of the sewage discharge site (Table 3). The shore in this area is mostly sandy, but it also contains organic material deposited by the river. The concentration of DO in the interstitial water sample was below 1 mg/L. A plausible explanation for the high ammonium-N concentration in the interstitial water is its accumulation in the coastal soil where it may remain unoxidized for a long time, due to the high density of the sandy soil (Wang & Alva 2000; Sieczka & Koda 2016).

A high concentration of ammonium-N (0.31 mg/L) and low amount of DO (3 mg/L) were also detected in the interstitial water sample obtained from the sandy beach next to the Kultuk settlement which might indicate the presence of the buried vegetation in the coastal zone. The ammonium which is formed during the decomposition of vegetation can persist for a long

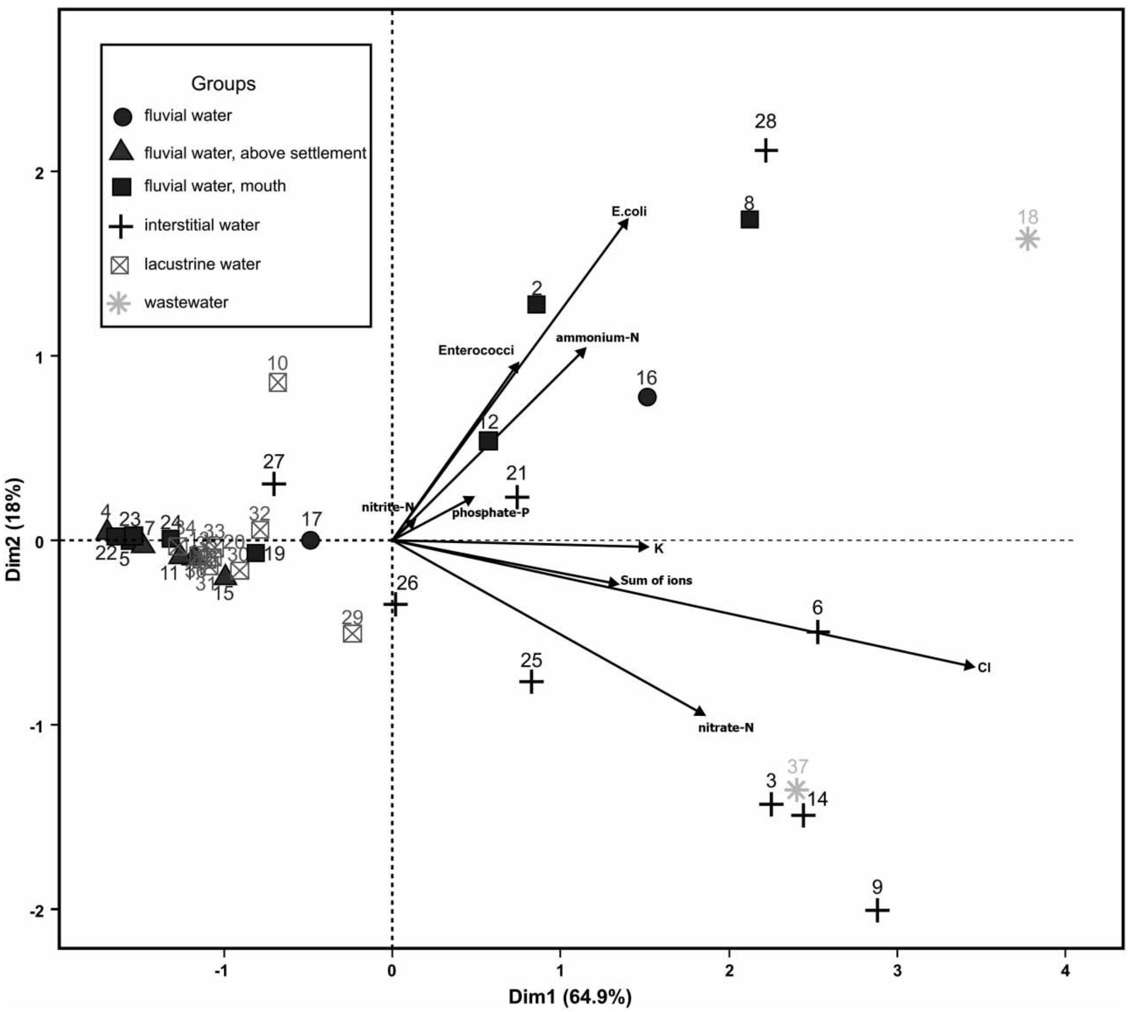


Figure 3 | The principal component analysis (PCA) of microbiological and chemical parameters of water in different sampling points. The vectors show gradient changes of parameters. Sampling points are labeled as shown in the figure.

time under low oxygen conditions (Garcia-Robledo *et al.* 2008; Tomberg *et al.* 2012). High concentrations of nitrate-N and phosphate-P (up to 5 and 1.13 mg/L, respectively) were observed in (i) an effluent pond in Baikalsk, which is likely associated with the oxidation of ammonium to nitrate and with an excess of phosphate in municipal wastewater and (ii) the interstitial water sample obtained on the lakeshore in the area that is influenced by pond drainage (Table 2), which may be associated with seepage of wastewater through interstitial and groundwater.

Low concentration of nutrients was detected in the bottom water samples. Concentrations of nitrite-N did not exceed 0.002 mg/L, those of nitrate-N were below 0.03 mg/L and those of ammonium-N and phosphate-P were below 0.01 mg/L (Table 2). Such low values can be explained by (i) dilution of nutrients in Baikal water and (ii) consumption of the nutrients by aquatic vegetation (Afanasiev & Verbolov 1977; Kreiling *et al.* 2011; Kulikova *et al.* 2018, 2021).

Despite the inflow of contamination with the waters of the tributaries and interstitial waters, we did not detect high concentrations of chemical elements in the samples of surface water. The concentration of ammonium-N, phosphate-P and nitrate-N in interstitial water and river mouth was significantly higher than in lake water (Table 3), which can be associated with geochemical barriers in the form of soils and alluvial deposits. In addition, we measured several abiotic parameters (pH, T) of the water samples (Supplementary Material, Table S4).

Timoshkin *et al.* (2018) reported on the poor water quality (i.e., fecal contamination and high nutrient concentrations) of the coastal zone of the southern Baikal region. Several studies have previously addressed the presence of nutrients and FIB in the stream waters entering Lake Baikal, as well as in the splash zone of the lake (Kravtsova *et al.* 2014; Suturin *et al.* 2016; Malnik *et al.* 2019a; Onischuk *et al.* 2019). However, there is a lack of current comprehensive data on the sanitary bacteriological and hydrochemical conditions of the tributaries and coastal zone of the southern part of Lake Baikal. The results of this study were compared with published bacteriological and hydrochemical data from Lake Baikal to detail the changes in lake water quality between 2011 and 2016 (Kravtsova *et al.* 2014). In a number of countries, similar studies have also been carried out (Jiang *et al.* 2016; Jin *et al.* 2017; Vadde *et al.* 2018). Long-term changes (2003–2014) of the water temperature, dissolved oxygen (DO), pH, total nitrogen (TN), ammonium-N, total phosphorous (TP) and chemical oxygen demand (COD_{Mn}, where Mn refers to the chemiluminescence method for COD analysis) were examined at eight sampling stations along the Liujiang River (Jiang *et al.* 2016). Water quality parameters showed considerable spatial and temporal variability. Pollution levels were generally higher in the lower Liujiang than in the upper and middle parts of the river because of the impacts of urban sewage.

We can associate the changes in the coastal water quality of Lake Baikal with the increased concentrations of FIB and nutrients observed in the rivers flowing into the lake. Two model areas of the southern Baikal region, namely the Listvyanka settlement (west-facing coast) and the town of Sludyanka (east-facing coast), were chosen to test this hypothesis.

Our data show that the samples with elevated concentrations of *E. coli* and enterococci also contain elevated concentrations of nutrients such as phosphate-P, ammonium-N and nitrite-N (Figure 2). We can, therefore, assume that pollution by non-oxidized organic compounds takes place in these sampling sites. Nitrate-N commonly appears when organics are completely oxidized (Xia *et al.* 2018). For example, ammonium-N at sampling point 37 was oxidized to nitrate-N in a pond aerator (Figure 3), which indicates that the organic oxidation process has passed. Most of the points on the resulting graph are located closely to each other, which indicate the proximity of the values of certain concentrations. Samples with a high concentration of the determined parameters are located at points to the right of the central axis. A group of points with a high sum of ions, chlorine, nitrate-N is located in the lower right rectangular region, whereas points with high concentrations of FIB, ammonium-N and phosphate-P can be seen in the upper right rectangular region. The potassium concentration was high in all the samples located to the right of the central axis. The graph shows that samples 5, 19, 22, 23 and 24 from river estuaries did not differ much from lake water samples. And some of the estuarine river samples 2, 12 and 8 were close to the wastewater sample in Sludyanka No. 18. Samples 3, 9, 14, 25 and 26 in their characteristics are similar to that of the sample from the pond aerator No. 37 (originally untreated municipal wastewater). In general, in the sampling points with interstitial water, we can observe a large spread in their position on the graph. We also performed a correlation analysis of the studied indicators and found that the concentration of enterococci and *Escherichia coli* correlates well with each other (Table 4). The concentration of enterococci correlates well with those of phosphate-P, nitrate-N, nitrite-N, ammonium-N and chlorine, whereas the concentration of *E. coli* correlates well with those of ammonium-N, nitrite-N, potassium and chlorine. Interestingly, a similar correlation of FIB with ammonium-N and nitrite-N concentrations was described in the recent water quality analysis of the samples obtained from four rivers and a lake in the Wujiang District in China (Sekar *et al.* 2021). We speculate as well that the strong correlation between concentrations of FIB and chlorides is due to

Table 4 | Results of correlation analysis

	Enterococci	*E. coli*	Phosphate-P	Ammonium-N	Nitrate-N	Nitrite-N	K^+	Cl^-
Enterococci	–	**0.84**	**0.47**	**0.65**	**0.57**	**0.62**	0.00	**0.54**
E. coli	**0.84**	–	0.00	**0.60**	0.00	**0.61**	**0.50**	**0.58**
Phosphate-P	**0.47**	0.00	–	**0.51**	**0.67**	**0.75**	0.00	**0.46**
Ammonium-N	**0.65**	**0.60**	**0.51**	–	**0.55**	**0.66**	0.00	**0.56**
Nitrate-N	**0.57**	0.00	**0.67**	**0.55**	–	**0.55**	**0.62**	**0.64**
Nitrite-N	**0.62**	**0.61**	**0.75**	**0.66**	**0.55**	–	0.00	0.00
K^+	0.00	**0.50**	0.00	0.00	**0.62**	0.00	–	**0.85**
Cl^-	**0.54**	**0.58**	**0.46**	**0.56**	**0.64**	0.00	**0.85**	–
Sum of ions	0.00	**0.47**	0.00	**0.54**	**0.63**	0.00	**0.72**	**0.80**

The values Spearman's rank correlation coefficients are given for the pairwise comparison of the studied indicators.
Reliable values of the correlation coefficients are highlighted in bold. Not significant values of correlation coefficients are replaced by 0 (P-value $>$ 0.05).

anthropogenic influence on sampling sites, since chlorides are contained in biological fluids excreted from the body (e.g., urine). The concentration of phosphate-P correlates well with those of ammonium-N, nitrate-N, nitrite-N and chlorine. Ammonium-N concentration correlates well with those of nitrate-N and nitrite-N and chlorine. Furthermore, nitrate-N concentration shows correlation with that of nitrite-N, potassium and chlorine. Finally, the concentration of potassium correlates well with that of chlorine (Table 4).

Many households in the Listvyanka settlement lack connections to centralized sewage facilities. Most of the local population use on-plot latrines in their yards, while hotels have cesspits that often leak. The settlement is located in the water protection zone, in which wastewater discharge is supposed to meet specific requirements stipulated by Sanitary Rules and Regulations 2.1.5.980-00 (Inspection 2000). According to these requirements, urban wastewater must not be discharged within settlements. A small portion of the urban wastewater is drawn aside from the Listvyanka settlement to the Angara riverhead, and the rest of the sewage is passively filtered through the soil, where it then appears in the coastal zone of Lake Baikal or flows there via tributary waters. The paradox is that urban wastewater, which is a minor component of all local wastewater, is drawn aside from the settlement, and there are no other treatment facilities. Therefore, no one is penalized for improperly discharging wastewater because there is no pipe and sewage is not discharged directly into the lake. Domestic wastewater penetrates into the soil and into the groundwater. It then gets transported into the tributaries or coastal zone of Lake Baikal. A peak in the wastewater load occurs during winter and early spring, when small rivers are only supplied by groundwater.

Investigations on Lake Baikal tributaries in the Listvyanka settlement revealed the following water quality patterns: (i) upper parts of the rivers (outside of the settlements) are clean and (ii) water quality in the lower parts of the rivers (including river mouths) is poor (Figure 2). Water quality of other analyzed tributaries (i.e., Bolshaya Osinovka, Solzan and the Goloustnaya rivers) met both the national and the US EPA standards (Table 2).

High concentrations of FIB and nutrients were detected in the interstitial waters of the splash zone near the river mouths in Listvyanka settlement (Figure 2(a)–2(c)) and in Sludyanka town (Figure 2(a)–2(c)). FIB were also detected in the surface water of Lake Baikal near the river mouths (Figure 2(a)). Furthermore, microbiological analyses revealed persistent fecal pollution of the interstitial and surface waters of Lake Baikal around coastal settlements (i.e., Listvyanka settlement and Sludyanka). Neither national nor international water quality standards were met when the samples of the 'purified' wastewater from Sludyanka were analyzed (Figure 2). Thus, the sewage and wastewater treatment facilities in Sludyanka do not seem to adequately filter wastewater contaminants, which results in the discharge of wastewater enriched in nutrients and FIB into the coastal zone of Lake Baikal. A unified concept of the elaboration of a water disposal system has been developed stage-by-stage for a large area in the central ecological zone of Baikal region with the use of a program–goal-oriented method (Pupyrev *et al.* 2020). The authors propose to construct (i) wastewater treatment facilities in the Kultuk settlement; (ii) a pipeline system for transport of wastewater from nearby settlements around Lake Baikal to the treatment facilities and (iii) a pipeline system to transport the treated wastewater to Bystraya river which flows directly into Irkut river and thereby bypasses Lake Baikal. Undoubtedly, this idea is quite interesting and if it is implemented into reality, the ecological situation in the region of the southern basin of the lake might improve.

The interstitial water in Bolshoe Goloustniy is contaminated by FIB, which may be related to the building out of the coastal territory of the lake with hotels and cottages without a wastewater treatment system, as well as to the grazing of large livestock in the coastal zone of the lake. However, the quality of surface and bottom water in the settlement met US EPA standards, which may indicate a good buffering capacity of this type of soil in the splash zone.

The quality of all three types of water in Baikalsk and Solzan settlements was good (with the exception of interstitial water in Solzan), which may be related to the small number of tourists in the area, as well as to the cessation of the Baikalsk pulp and paper mill. All three types of water are polluted in Kultuk, where significant anthropogenic loading occurs.

Previous studies of the Listvyanka area have shown that the concentration of *E. coli* in the water of the inflow tributaries (in their lower reaches) and interstitial waters reached up to 8,300 CFU/100 mL and 1,280 CFU/100 mL, respectively (Kravtsova *et al.* 2014; Suturin *et al.* 2016). In the present study, these areas had *E. coli* counts of up to 8,200 CFU/100 mL in the water of inflowing tributaries and 3,770 CFU/100 mL in interstitial waters (Figure 2(a)). The difference in bacterial counts between these studies may have been due to the different sampling times as the samples from the earlier study (Kravtsova *et al.* 2014) were collected in August of 2011, whereas our samples were obtained in June of 2016. We speculate that the ecological situation in this region has deteriorated over this period of time.

A similar study was conducted in the lacustrine environment of Lake Wigry, one of the largest and deepest lakes in Poland (Aleksander-Kwaterczak & Zdechlik 2016). Elevated amounts of the trace metals and nutrients were detected in the sample of the sediment and interstitial water obtained in the Czarna Han'cza River estuary and are believed to be the result from increasing industrial wastewater, domestic sewage discharge and runoff from agricultural soil. The presence of nutrients in the water of inflow tributaries (in their lower reaches) and in the interstitial waters in the Listvyanka settlement area has been previously reported (Kravtsova *et al.* 2014). Another study has shown that when passing through the settlements, the rivers are more or less enriched with all chemical elements. The greatest enrichment was observed for chlorine – an average of 7 times (Suturin *et al.* 2016). Our studies showed that chlorine concentrations in B. and M. Cheremshanka differed by 10 and 50 times, respectively. This may indicate that anthropogenic chlorine is being introduced into the rivers. These data also indicate that the river and lake waters around Listvyanka settlement are subjected to continuous fecal and hydrochemical pollution. Taken together, these data reveal that the concentrations of FIB and chemical compounds in the waters of the lower reaches of many tributaries, interstitial waters and anthropogenic wastewater are very high in comparison with the normative standards of Russia and the US EPA (Inspection 2000; Recreational Water Quality Criteria 2012).

Counts of FIB in interstitial waters of the splash zone in the southern Baikal region were performed in 2010–2011 (Timoshkin *et al.* 2012b) and again in 2016 (Suturin *et al.* 2016). The concentrations of thermotolerant coliform bacteria ranged from 0 to 4,950 CFU/100 mL in these studies. These data are not consistent with our observations on the pollution of interstitial waters of Lake Baikal at points with high anthropogenic loads. The concentrations of *E. coli* in our research ranged from 0 to 16,300 CFU/100 mL. First, this may be related to the use of different sampling points, and second, to the increase in anthropogenic loading on coastal areas over the last 6 years (Suturin *et al.* 2016; Malnik *et al.* 2019a). Sampling procedures used in these studies were similar. At the Pokhabikha River, the wastewater was neither disinfected (microbiological data) nor devoid of macronutrients, such as nitrate-N, nitrite-N, ammonium-N and phosphate-P, after purification. This situation is very problematic in that the river water contains *E. coli* in the areas where it flows into Lake Baikal, and in the lake, such contamination can be found at distances of 1.5–2 km from the Pokhabikha River mouth (Figure 2(a)). Therefore, recreation in this area has become unsafe, and the risk of intestinal infections to those coming into contact with the contaminated water, especially children, is very high. Additionally, the increased concentrations of macronutrients, especially nitrogen and phosphorus, discharged into the lake can trigger an increase in the algal biomass, including *Spirogyra* sp., which is atypical for Lake Baikal and can result in the replacement of endemic algae species (Kravtsova *et al.* 2014; Timoshkin *et al.* 2015a, 2016; Kobanova *et al.* 2016). These new algae can accumulate at the bottom of the lake, and storms may then transport the algae to the shoreline, where it rots, as has happened in northern Lake Baikal (Timoshkin *et al.* 2015b).

The situation in Listvyanka is similar to that found in the Pokhabikha River. High phosphorus and nitrogen concentrations in the rivers of the settlement can be associated with the increase in tourists during summer and consequential increase in the wastewater sewage discharged from hotels and other activities such as washing clothes and dishes and bathing (Malnik *et al.* 2019b). The enormous exceedance of the standards in rivers for FIB increases the risk of intestinal infections in people present on the shore of Lake Baikal. This problem is compounded because the popular beaches for locals and tourists occur near the mouths of the contaminated rivers, especially near the mouth of the Bolshaya Cheremshanka River. The increase in the number of tourists and residents in the southern Baikal region has led to an increase of human waste products, which are mostly disposed through on-plot latrines. Such human waste likely contaminates ground water and penetrates into Lake Baikal as interstitial water. To demonstrate the possibility of human waste contamination through interstitial water, we measured FIB not only in the rivers but also in the interstitial waters of the lake. The analyses of the interstitial water samples obtained on the beaches of the Listvyanka settlement near to the river mouths revealed the accumulation of chemical compounds (phosphate-P, ammonium-N, nitrite-N and nitrate-N) at high concentrations. Nitrification processes in such conditions are very unlikely to occur, which implies that water enriched with ammonium-N flows directly into the lake.

Interstitial waters near the mouths of the Krestovka and Bolshaya Cheremshanka rivers are also contaminated with FIB (Figure 2(a)) derived from the toilets of hotels and private households. However, during the tourist season, the natural purifying system cannot cope with the huge anthropogenic loads. As a result, the concentrations of FIB fail to meet the US EPA standards (Recreational Water Quality Criteria 2012; Figure 2(a)).

There are many articles about eutrophication (Longley *et al.* 2019; Vincone-Leite & Casenave 2019; Wang *et al.* 2019) and lake pollution (El-Rayis *et al.* 2019; Egessa *et al.* 2020; Akiner & Akiner 2021). Lake Baikal is such a huge lacustrine system that human settlements seem to represent an insignificant influence, but as our study has shown these settlements do have significant effects on the littoral zone of the lake.

We propose to take the following measures to reduce and prevent further pollution of the coastal and splash zones of Lake Baikal: (i) construction of the effective water treatment facilities, where appropriate (e.g., Kultuk, Sludyanka and Listvyanka settlements); (ii) use and construction of isolated septic tanks in the settlements around Lake Baikal and (iii) use of phosphate-free washing powders and detergents in the area around Lake Baikal.

CONCLUSION

The study has shown that contaminants in river waters flowing into Lake Baikal, which were derived from the surrounding residential areas, have negatively affected the water quality of the lake. Samples from areas located upstream of the Listvyanka settlement were uncontaminated, while in the river mouths within the boundaries of a built-up area, pollutant levels were very high. Interstitial waters were also found to be contaminated near the lakeshore. The possibility of human waste contamination through the interstitial water pathway has been demonstrated.

The data from the Pokhabikha River (Sludyanka town area) also revealed fecal and nutrient contamination, despite the presence of a centralized sewage system, which suggests that the current system does not purify wastewater well as the river waters contain very high levels of phosphate-P, nitrate-N, ammonium-N and FIB (Supplementary Material, Table S3).

The ecological conditions around southern Lake Baikal should be recognized as critical, and actions should be taken to remediate the influence of untreated wastewater contamination. First, the wastewater treatment situation in Sludyanka must be improved. An efficient wastewater system should also be constructed in Listvyanka as the influx of tourists has increased from year-to-year (Kobanova *et al.* 2016), and the ecological state of the coastal zone near the settlement is very poor (Kravtsova *et al.* 2014; Timoshkin *et al.* 2016). This is, in part, due to the mass proliferation of non-typical for Baikal *Spirogyra* algae and subsequent degradation of water quality in the lake. Additionally, our findings suggest that the coastal zone of Lake Baikal is under the persistent threat of eutrophication. The results of this study demonstrate that eutrophication should be considered the main driver of the ecological crisis, which is currently taking place in the shallow waters of Lake Baikal.

A comprehensive data analysis, including information on the splash zone (along with the analysis of interstitial water) contributes to a more accurate assessment of the ecological situation around Lake Baikal. In particular, it allows us to determine the quality of coastal or river water in any specific location around Lake Baikal. Thus, the applicability of the splash zone for assessing the state of the ecosystem of the coastal zone of the lake within its southern basin seems both necessary and appropriate. Based on the obtained data, we conclude that the sanitary-microbiological and hydrochemical indicators of the quality of interstitial waters should be included in the standard monitoring procedures for large lakes around the world.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Abaya, L. M., Wiegner, T. N., Colbert, S. L., Beets, J. P., Carlson, M., Lindsey Kramer, K. & Couch, C. S. 2018 A multi-indicator approach for identifying shoreline sewage pollution hotspots adjacent to coral reefs. *Marine Pollution Bulletin* **129**, 70–80. https://doi.org/10.1016/j.marpolbul.2018.02.005.

Adeniji, O. O., Sibanda, T. & Okoh, A. I. 2019 Recreational water quality status of the Kidd's Beach as determined by its physicochemical and bacteriological quality parameters. *Heliyon* **5** (6), 1–7. https://doi.org/10.1016/j.heliyon.2019.e01893.

Afanasiev, A. N. & Verbolov, V. I. 1977 *Currents in Lake Baikal*. Nauka, Novosibirsk.

Akiner, M. E. & Akiner, I. 2021 Water quality analysis of drinking water resource Lake Sapanca and suggestions for the solution of the pollution problem in the context of sustainable environment approach. *Sustainability* **13**, 1–13. https://doi.org/10.3390/su13073917.

Aleksander-Kwaterczak, U. & Zdechlik, R. 2016 Hydrogeochemical characteristics of interstitial water and overlying water in the lacustrine environment. *Environmental Earth Sciences* **75**, 1352. https://doi.org/10.1007/s12665-016-6146-8.

Alemayehu, Y. A., Asfaw, S. L. & Terfie, T. A. 2020 Nutrient recovery options from human urine: a choice for large scale application. *Sustainable Production and Consumption* **24**, 219–231. https://doi.org/10.1016/j.spc.2020.06.016.

Babić, G., Vuković, M., Voza, D., Takić, L. & Mladenović-Ranisavljević, I. 2019 Assessing surface water quality in the Serbian part of the Tisa River basin. *Polish Journal of Environmental Studies* **28** (6), 4073–4085. https://doi.org/10.15244/pjoes/95184.

Boeva, L. 2009 *Manual for Chemical Analysis of Surface Water*. RosHydromet, Rostov-on-Don.

Brooks, Y. M., Spirito, C. M., Bae, J. S., Hong, A., Mosier, E. M., Sausele, D. J., Fernandez-Baka, C. P., Epstein, J. L., Shapley, D. J., Goodman, L. B., Andersen, R. R., Glaser, A. L. & Richardson, R. E. 2020 Fecal indicator bacteria, fecal source tracking markers, and pathogens detected in two Hudson River tributaries. *Water Research* **171**, 1–9. 1https://doi.org/10.1016/j.watres.2019.115342.

Canty, A. & Ripley, B. 2017 *boot: Bootstrap R (S-Plus) functions.* R package version, 1.

Clune, J. W., Crawford, J. K., Chappell, W. T. & Boyer, E. W. 2020 Differential effects of land use on nutrient concentrations in streams of Pennsylvania. *Environmental Research Communications* **2**, 1–15. http://doi.org/10.1088/2515-7620/abc97a.

Dantas, M. S., Barroso, G. R. & Oliveira, S. C. 2021 Performance of sewage treatment plants and impact of effluent discharge on receiving water quality within an urbanized area. *Environmental Monitoring and Assessment* **193**. Article number 289. https://doi.org/10.1007/s10661-021-09075-1.

Davison, A. & Hinkley, D. 1997 In: *Bootstrap Methods and Their Application* (Gill, R. & Ripley, B., eds). Cambridge University Press, London.

Egessa, R., Nankabirwa, A., Ocaya, H. & Pabire, W. G. 2020 Microplastic pollution in surface water of Lake Victoria. *Science of the Total Environment* **741** (1), 1–9. https://doi.org/10.1016/j.scitotenv.2020.140201.

El-Rayis, O. A., Hemeda, E. I. & Shaaban, N. A. 2019 Steps for rehabilitation of a Lake suffering from intensive pollution; Lake Mariut as a case study. *Egyptian Journal of Aquatic Biology & Fisheries* **23** (2), 331–345. doi:10.21608/EJABF.2019.31838.

Fomin, G. 2000 *Water – Inspection of Chemical, Bacteriological and Radiation Safety According to International Standards (Third)*. Protector, Moscow.

Font, C., Bregoli, F., Acuna, V., Sabater, S. & Marce, R. 2019 *GLOBAL-FATE (Version 1.0.0): A Geographical Information System (GIS)-Based Model for Assessing Contaminants Fate in the Global River Network*.

Gagarinova, O. V., Belozertseva, I. A., Vorobyeva, I. B., Vlasova, N. V., Emelyanova, N. V. & Sorokovoi, A. A. 2021 Anthropogenic transformations in the mouth area of tributaries as factors of negative impact on Lake Baikal. *Water* **13** (9), 1–14. https://doi.org/10.3390/w13091295.

Galaziy, G. I. 1993 *Lake Baikal: Atlas*. Publishing House of the Federal Service of Geodesy and Cartography of Russia, Moscow.

Garcia-Robledo, E., Corzo, A., Garcia de Lomas, J. & van Bergeijk, S. A. 2008 Biogeochemical effects of macroalgal decomposition on intertidal microbenthos: a microcosm experiment. *Marine Ecology Progress Series* **356**, 139–151. doi:10.3354/meps07287.

Gorshkova, A. S., Malnik, V. V., Kostornova, T. Y., Potapskaya, N. V. & Timoshkin, O. A. 2020 Distribution of bacteria as the pollution indicators in the splash zone of Lake Baikal. *Geography and Natural Resources* **2**, 90–98. https://doi.org/10.21782/GIPR0206-1619-2020-2(90-98).

Inspection, T. M. of H. of R. F. C. of S. Sanitary Rules and Regulations. *Hygienic Requirements for Surface Water Protection* 2000. Moscow.

Jiang, B., Chen, J., Luo, Q., Lai, J., Xu, H., Wang, Y. & Yu, K. 2016 Long-term changes in water quality and eutrophication of China's Liujiang River. *Polish Journal of Environmental Studies* **25** (3), 1033–1043. https://doi.org/10.15244/pjoes/61819.

Jin, Z., Zhang, X., Li, J., Yang, F., Kong, D., Wei, R., Huang, K. & Zhou, B. 2017 Impact of wastewater treatment plant effluent on an urban river. *Journal of Freshwater Ecology* **32** (1), 697–710. https://doi.org/10.1080/02705060.2017.1394917.

Khodzher, T., Domysheva, V. M., Sorokovikova, L. M. & Golobokova, L. P. 2016 Methods for monitoring the chemical composition of Lake Baikal Water. In: *Novel Methods for Monitoring and Managing Land and Water Resources in Siberia*, 1st edn. (Mueller, L., Sheudshen, A. K. & Eulenstein, F., eds). Springer Water, Switzerland, pp. 113–132.

Kobanova, G. I., Takhteev, V. V., Rusanovskaya, O. O. & Timofeyev, M. A. 2016 Lake Baikal ecosystem faces the threat of eutrophication. *International Journal of Ecology* **2016**, 1–7. https://doi.org/10.1155/2016/6058082.

Kravtsova, L. S., Izhboldina, L. A., Khanaev, I. V., Pomazkina, G. V., Rodionova, E. V., Domysheva, V. M., Sakirko, M. V., Tomberg, I. V., Kostornova, T. Y., Kravchenko, O. S. & Kupchinsky, A. B. 2014 Nearshore benthic blooms of filamentous Green algae in Lake Baikal. *Journal of Great Lakes Research* **40**, 441–448. https://doi.org/10.1016/j.jglr.2014.02.019.

Kreiling, R. M., Richardson, W. B., Cawanaugh, J. C. & Bartsch, L. A. 2011 Summer nitrate uptake and denitrification in an upper Mississippi River backwater lake: the role of rooted aquatic vegetation. *Biogeochemistry* **104**, 309–324. doi:10.1007/s10533-010-9503-9.

Kucuksezgin, F., Gonul, L. T., Pazi, I. & Kacar, A. 2019 Assessment of seasonal and spatial variation of surface water quality: recognition of environmental variables and fecal indicator bacteria of the coastal zones of Izmir Bay, Eastern Aegean. *Regional Studies in Marine Science* **28**, 1–11. https://doi.org/10.1016/j.rsma.2019.100554.

Kulikova, N. N., Volkova, E. A., Bondarenko, N. A., Chebykin, E. P., Saibatalova, E. V., Timoshkin, O. A. & Suturin, A. N. 2018 Element composition and biogeochemical functions of algae *Ulothrix zonata* (F. Weber et Mohr) Kützing in the coastal zone of the Southern Baikal. *Water Resources* **45** (6), 908–919. doi:10.1134/S032105961806010X.

Kulikova, N. N., Chebykin, E. P., Volkova, E. A., Bondarenko, N. A., Zhuchenko, N. A., Timoshkin, O. A. & Suturin, A. N. 2021 Elemental composition of algae of the genus *Spirogira* as the indicator of pollution of the Baikal near-shore zone with domestic sewage. *Geography and Natural Resources* **2**, 79–91. doi:10.15372/GIPR2021-0209.

Lincoln, R., Boxshell, G. & Clark, P. 1982 *A Dictionary of Ecology Evolution and Systematics*. Cambridge University Press, London.

Longley, K. R., Huang, W., Clark, C. & Johnson, E. 2019 Effects of nutrient load from St. Jones River on water quality and eutrophication in Lake George, Florida. *Limnologica* **77**, 1–13. https://doi.org/10.1016/j.limno.2019.125687.

Maechler, M. 2017 *Package 'Sfsmisc' Title Utilities From 'Seminar Fuer Statistik' ETH Zurich*.

Malnik, V. V., Shtykova, Y. R., Suturin, A. N. & Timoshkin, O. A. 2019a Influence of settlements on sanitary-microbiological status of small tributaries and coastal waters as exemplified by Listvennichnyi Bay (South Baikal). *Geography and Natural Resources* **4**, 84–92. https://doi.org/10.21782/GIPR0206-1619-2019-4(84-92).

Malnik, V. V., Timoshkin, O. A., Suturin, A. N., Onishchuk, N. A., Sakirko, M. V., Tomberg, I. V., Gorshkova, A. S. & Zabanova, N. S. 2019b Anthropogenic changes in the hydrochemical and sanitary-microbiological characteristics of water quality in Southern Baikal tributaries: Listvennichnyi Bay. *Water Resources* **46** (5), 748–758. https://doi.org/10.1134/S0097807819050154.

Murray, P. 2003 *Manual of Clinical Microbiology*, 8th edn. ASM Press, Washington.

Nevers, M. B., Byappanahalli, M. N., Nakatsu, C. H., Kinzelman, J. L., Phanikumar, M. S., Shively, D. A. & Spoljarich, A. M. 2020 Interaction of bacterial communities and indicators of water quality in shoreline sand, sediment, and water of Lake Michigan. *Water Research* **178**, 1–11. https://doi.org/10.1016/j.watres.2020.115671.

Onischuk, N. A., Netsvetaeva, O. G., Tomberg, I. V., Sakirko, M. V., Domysheva, V. M., Golobokova, L. P. & Khodzher, T. V. 2019 Seasonal dynamics of mineral forms of nitrogen in the rivers, snow cover and precipitation at the southwest coast of the Southern Baikal. *Limnology and Freshwater Biology* **3**, 245–252. doi:10.31951/2658-3518-2019-A-3-245.

Pupyrev, E. I., Chupin, R. V., Gogina, E. S., Makisha, N. A., Nechaev, I. A. & Pukemo, M. M. 2020 Elaboration of a regional concept for developing a water disposal system for the Central Ecological Zone of the Baikal Natural Territory. *Water Resources* **47** (4), 663–671. doi:10.1134/S0097807820040144.

Recreational Water Quality Criteria 2012. United States Environmental Protection Agency/Office of Water 820F-12-058, Washington, DC, USA.

Rodrigues, C. & Cunha, M. Â. 2017 Assessment of the microbiological quality of recreational waters: indicators and methods. *Euro-Mediterranean Journal for Environmental Integration* **2** (25), 1–18. https://doi.org/10.1007/s41207-017-0035-8.

Sanchez Dominguez, B., Grandos-Barba, A., Castaneda-Chavez, M. & Bernal-Ramirez, R. G. 2015 Enterococci presence in interstitial water in intertidal areas of sandy beaches from Veracruz-Boca del Rio, Gulf of Mexico. *Global Journal of Biology, Agriculture and Health Sciences* **4** (1), 28–31.

Sangkaew, W., Kongprajug, A., Chyerochana, N., Ahmed, W., Rattanakul, S., Denpetkul, T., Mongkolsuk, S. & Serikanchana, K. 2021 Performance of viral and bacterial genetic markers for sewage pollution tracking in tropical Thailand. *Water Research* **190**, 1–11. https://doi.org/10.1016/j.watres.2020.116706.

Sekar, R., Jin, X., Liu, S., Lu, J., Shen, J., Zhou, Y., Gong, Z., Feng, X., Guo, S. & Li, W. 2021 Fecal contamination and high nutrient levels pollute the watersheds of Wujiang, China. *Water* **13**, 1–20. https://doi.org/10.3390/w13040457.

Shi, R., Zhao, J., Shi, W., Song, S. & Wang, C. 2020 Comprehensive assessment of water quality and pollution source apportionment in Wuliangsuhai Lake, Inner Mongolia, China. *International Journal of Environmental Research and Public Health* **17** (14), 1–12. https://doi.org/10.3390/ijerph17145054.

Sieczka, A. & Koda, E. 2016 Kinetic and equilibrium studies of sorption of ammonium in the soil-water environment in agricultural areas of Central Poland. *Applied Sciences* **6** (10), 1–14. https://doi.org/10.3390/app6100269.

Suturin, A., Chebykin, E., Malnik, V., Khanaev, I., Minaev, A. & Minaev, V. 2016 The role of anthropogenic factors in the development of ecological stress in Lake Baikal littoral (The Listvyanka settlement lakescape). *Geography and Natural Resources* **6**, 43–54. https://doi.org/10.21782/GIPR0206-1619-2016-6(43-54).

Timoshkin, O. A. 2018 Coastal zone of the world's great lakes as a target field for interdisciplinary research and ecosystem monitoring: Lake Baikal (East Siberia). *Limnology and Freshwater Biology* **1**, 81–97. https://doi.org/10.31951/2658-3518-2018-A-1-81.

Timoshkin, O. A., Suturin, A. N., Bondarenko, N. A., Kulikova, N. N., Rozhkova, N. A., Sheveleva, N. G., Obolkina, L. A., Domysheva, V. M., Zaytseva, E. P., Malnik, V. V., Maximova, M. V., Tomberg, I. V., Nepokrytykh, A. V., Shirokaya, A. A., Lukhnev, A. G., Popova, O. V., Potapskaya, N. V., Vishnyakov, V. S., Volkova, E. A., Zvereva, Y., Logacheva, M., Sakirko, N. F., Kostornova, M. V. & Ya, T. 2012a Introduction into biology of the coastal zone of Lake Baikal. 1. Splash zone: first results of interdisciplinary investigations and its role for the lake ecosystem monitoring. *The Bulletin of Irkutsk State University. Series Biology.* Ecology **5** (3), 33–46.

Timoshkin, O. A., Tomberg, I. V., Kulikova, N. N., Popova, O. V., Malnik, V. V., Kostornova, T. Y., Lukhnev, A. G., Zaytseva, E. P., Shirokaya, A. A., Potapskaya, N. V., Zvereva, Y., Bondarenko, M., Rozhkova, N. A., Obolkina, N. A., Sheveleva, L. A., Suturin, N. G., Saybatalova, A. N., Ye, V., Nepokrytykh, A. V., Vishnyakov, V. S., Volkova, E. A. & Logacheva, N. F. 2012b Biology of the coastal zone of Lake Baikal. 3. Seasonal dynamics of the infauna of onshore accumulated material, hydrochemical and microbiological analyses of interstitial water in the splash zone. *The Bulletin of Irkutsk State University. Series Biology.* Ecology **5** (3), 33–46.

Timoshkin, O. A., Bondarenko, N. A., Volkova, Y. A., Tomberg, I. V., Vishnyakov, V. S. & Malnik, V. V. 2015a Mass development of green filamentous algae of the genera *Spirogyra* and *Stigeoclonium* (Chlorophyta) in the littoral zone of the southern part of Lake Baikal. *Hydrobiological Journal* **51** (1), 13–23.

Timoshkin, O. A., Malnik, V. V., Sakirko, M. V. & Boedeker, C. 2015b Ecological crisis on Lake Baikal: diagnosed by scientists. *Science First Hand* **41** (2), 25–41.

Timoshkin, O. A., Samsonov, D. P., Yamamuro, M., Moore, M. V., Belykh, O. I., Malnik, V. V., Sakirko, M. V., Shirokaya, A. A., Bondarenko, N. A., Domysheva, V. M., Fedorova, G. A., Kochetkov, A. I., Kuzmin, A. V., Lukhnev, A. G., Medvezhonkova, O. V., Nepokrytykh, A. V., Pasynkova, E. M., Poberezhnaya, A. E., Potapskaya, N. V., Rozhkova, N. A., Sheveleva, N. G., Tikhonova, I. V., Timoshkina, E. M., Tomberg, I. V., Volkova, E. A., Zaitseva, E. P., Zvereva, Yu. M., Kupchinsky, A. B. & Bukshuk, N. A. 2016 Rapid ecological change in the coastal zone of Lake Baikal (East Siberia): is the site of the world's greatest freshwater biodiversity in danger? *Journal of Great Lakes Research* **42**, 487–497. http://dx.doi.org/10.1016/j.jglr.2016.02.011.

Timoshkin, O. A., Moore, M. V., Kulikova, N. N., Tomberg, I. V., Malnik, V. V., Shimaraev, M. N., Troitskaya, E. S., Shirokaya, A. A., Synyukovich, V. N., Zaitseva, E. P., Domysheva, V. M., Yamamuro, M., Poberezhnaya, A. E. & Timoshkina, E. M. 2018 Groundwater contamination by sewage causes benthic algal outbreaks in the littoral zone of Lake Baikal (East Siberia). *Journal of Great Lakes Research* **44**, 230–244. https://doi.org/10.1016/j.jglr.2018.01.008.

Tomberg, I. V., Sakirko, M. V., Domysheva, V. M., Sez'ko, N. P., Lopatina, I. P., Bashenkhaeva, N. V., Filevich, E. A., Kulikova, N. N., Popova, O. V., Malnik, V. V., Lucknev, A. G., Zaitseva, E. P., Potapskaya, N. V., Zvereva, Yu. M. & Timoshkin, O. A. 2012 First data on the chemical composition of interstitial waters in the splash zone of Lake Baikal. *The Bulletin of Irkutsk State University. Series Biology. Ecology* **5** (3), 64–74.

Vadde, K., Wang, J., Cao, L., Yuan, T., McCarthy, A. & Sekar, R. 2018 Assessment of water quality and identification of pollution risk locations in Tiaoxi River (Taihu Watershed), China. *Water* **10** (2), 183. https://doi.org/10.3390/w10020183.

Vincone-Leite, B. & Casenave, C. 2019 Modelling eutrophication in lake ecosystems: a review. *Science of the Total Environment* **651** (2), 2985–3001. https://doi.org/10.1016/j.scitotenv.2018.09.320.

Wang, F. 2020 Impact of a large sub-tropical reservoir on the cycling of nutrients in a river. *Water Research* **186**, 1–11. https://doi.org/10.1016/j.watres.2020.116363.

Wang, F. L. & Alva, A. K. 2000 Ammonium adsorption and desorption in sandy soils. *Soil Science Society of America Journal* **64** (5), 1669–1674. https://doi.org/10.2136/sssaj2000.6451669x.

Wang, J., Fu, Z., Qiao, H. & Liu, F. 2019 Assessment of eutrophication and water quality in the estuarine area of Lake Wuli, Lake Taihu, China. *Science of the Total Environment* **650** (1), 1392–1402. https://doi.org/10.1016/j.scitotenv.2018.09.137.

Wang, J., Li, C., Xu, Y., Li, S., Du, J., Han, Y. & Hu, H. 2021 Identifying major contributors to algal blooms in Lake Dianchi by analyzing river-lake water quality correlations in the watershed. *Journal of Cleaner Production* **315**, 1–12. https://doi.org/10.1016/j.jclepro.2021.128144.

Water. Sampling for Microbiological Analyses. GOST 31942-2012, Moscow.

Wear, S. L., Acuna, V., McDonald, R. & Font, C. 2021 Sewage pollution, declining ecosystem health, and cross-sector collaboration. *Biological Conservation* **255**, 1–9. https://doi.org/10.1016/j.biocon.2021.109010.

Wickham, H. 2009 *Ggplot2. Elegant Graphics for Data Analysis*, 2nd edn. Springer, New York. https://doi.org/10.1007/978-0-387-98141-3.

Xia, X., Zhang, S., Li, S., Zhang, L., Wang, G., Zhang, L., Wang, J. & Li, Z. 2018 The cycle of nitrogen in river systems: sources, transformation, and flux. *Environmental Science: Processes and Impacts* **20**, 863–891. https://doi.org/10.1039/c8em00042e.

Zohary, T. & Gasith, A. 2014 The littoral zone. *Aquatic Ecology Series* **6**, 517–532. doi:10.1007/978-94-017-8944-8_29.

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