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Oil Products in Lake Baikal and Its Tributaries

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Abstract—The results of studying present-day oil product concentrations in water of Baikal and its tributaries are given. The highest concentrations of oil products have been identified in the Southern Baikal. Seasonal and year-to-year dynamics of oil product concentrations in lake tributaries was determined. The level of water pollution by hydrocarbons was evaluated in accordance the sanitary-hygienic standards for water bodies used for fishery. The inflow of oil products from Baikal through the Angara River was calculated, and their approximate budget in the lake was compiled.

Keywords: oil products, Baikal, pollution, lake tributaries, water runoff, export

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INTRODUCTION

Oil products (OP) are ecotoxicants most widespread and hazardous for the functioning of aquatic ecosystems. In freshwater hydrochemistry, OP are regarded as a complex and diverse mixture of substances consisting of nonpolar and low-polarity aliphatic, aromatic, and alicyclic hydrocarbons, which account for the most common part of oil and its components [1, 3].

The natural sources of OP for water bodies are mostly oil seeps from the bed. The known natural oil seeps have a total discharge rate of ~4 t per year [17, 19, 23].

The anthropogenic sources are more diverse, including water and railroad transport, wastewater, industrial emissions, drainage waters at oil field development, etc. The pollution by oil products causes changes in the chemical, physical, and biological processes in water bodies. Toxic pollutants in OP composition (in particular, polycyclic aromatic hydrocarbons (PAH)), cause cancer, as well as cardiovascular and other deceases. Covering water surface as a film, oil disturbs the oxygen and carbon-dioxide exchange, reduces light penetration, hampers photosynthesis, and suppresses the activity of production–destruction processes, thus producing an adverse effect on the flora and fauna [4, 8, 9, 22, 25].

OP enter Baikal mostly with waters of tributaries. In the recent 20–30 years, increased OP pollution has been observed in the coastal part of the lake, maybe due to the increased number of tourists. Tourist camps on the lake coast are being operated without treatment facilities, and wastewater from them enters the lake with groundwater or small watercourses. Considerable amounts of oil-containing pollutants enter the lake from water transport. According to the data of the State Inspection of small-size vessels, ~300 large-size and 5.5 thousand small-size vessels are now in operation in Baikal.

Considerable amounts of OP arrive in the region with atmospheric precipitation, especially, in the areas near the East-Siberian and Baikal-Amur Mainlines, as can be seen from the accumulation of hydrocarbons in snow cover near the railroads [14].

The focus of the study is the present-day concentrations of OP in the water of Baikal and its tributaries and their export with Angara water.

MATERIALS AND METHODS

OP concentrations in Lake Baikal were studied in 2017–2020. Water samples were taken at 47 coastal and 4 deep-water stations. The coastal stations were located along lake perimeter at a distance of ~100 m from its shoreline and far from populated localities (Fig. 1). At coastal stations, water samples for OP were taken by bathometers from two horizons: 1 m from the surface and 2–3 m from the bed. At deep-water stations in the northern, middle, and southern depressions of the lake ~3 km from the shore, water samples were taken from the surface and from the depth of 50 m. An additional deep-water station was used near the natural oil release at Gorevoi Utes Cape near Barguzinskii Bay (Middle Caucasus).

In the tributaries of the lake, water samples were taken in different hydrological seasons (March, May,

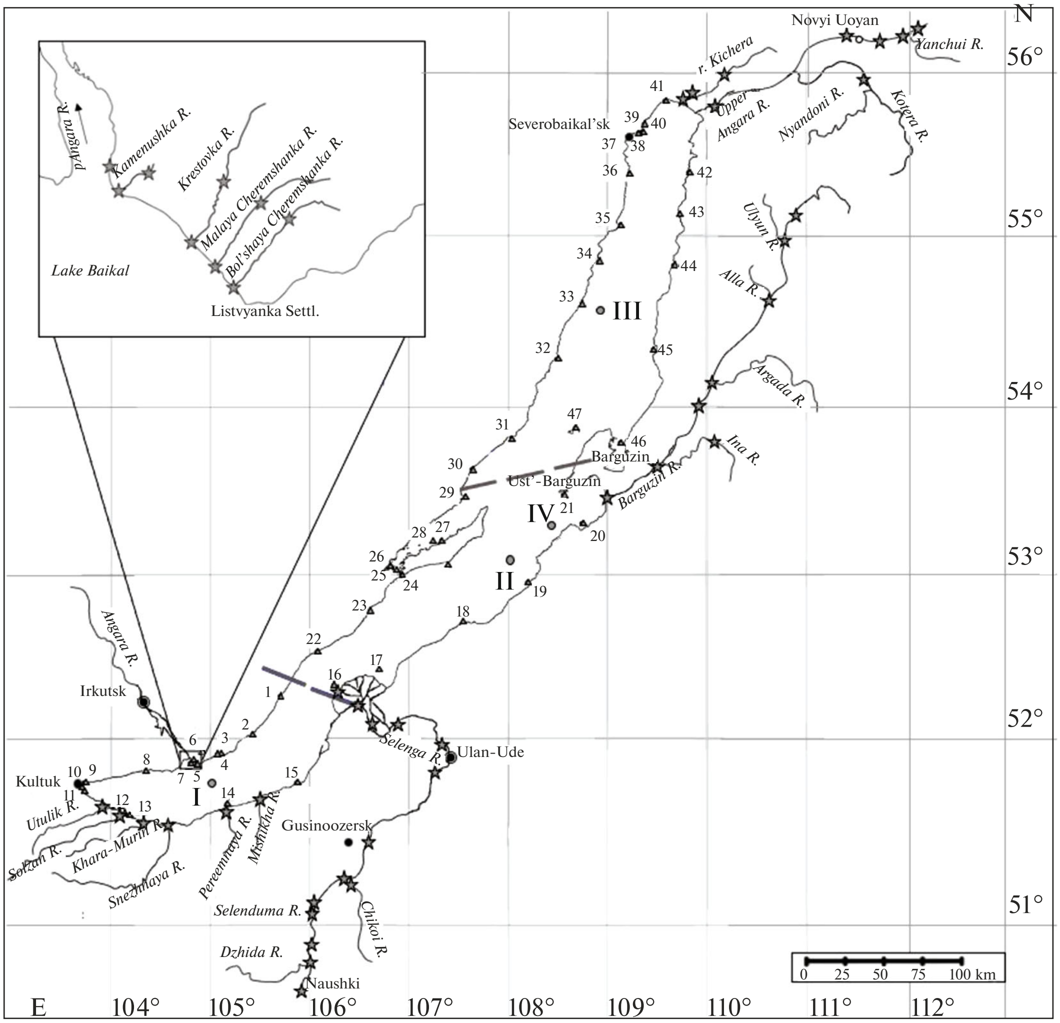

Fig. 1. Schematic map of water sampling sites in Lake Baikal and its tributaries. Triangles with Arabic numerals are coastal stations on Lake Baikal; circles with roman figures are deep-water stations; asterisks are stations on rivers; dashed lines are boundaries between lake depressions.

July, September) of 2010–2020. The study embraced 13 rivers with the total catchment area of 496 164 km^2, which amounts to 92% of lake basin area. First of all, the largest rivers were studied (the Selenga, Upper Angara, and Barguzin) with several stations (gages) installed on the rivers (Fig. 1). In the tributaries of the Southern Baikal, flowing from the northwestern slope of the Khamar-Daban Ridge, the samples were taken at river mouths beyond the zone of influence of Baikal.

Considering the high touristic load and OP pollution in the coastal areas at the southwestern part of the Southern Baikal, small watercourses were studied near Listvyanka Settl. (Fig. 1). Water samples at these rivers were taken on the monthly basis at two sections: upstream of the settlement (background section) and in the mouth zone. Also, samples were taken on the monthly basis at the Angara source to evaluate OP export from Baikal.

Water for determining OP was sampled into dark bottles and delivered for the analysis in thermos–containers into a laboratory of the Limnological Institute, Siberian Branch, Russian Academy of Sciences. The samples were taken either from the research vessel or in Irkutsk. In total, 450 samples of lake water and >2 thousand samples of river water were taken for OP analysis.

OP was determined by fluorimetric method [15] on Flyuorat-02 analyzer. The range of mass concentration of OP, measured by the chosen procedure was from 5 to 50 000 μg/dm^3. In this case, the accuracy of measurement results decreases with decreasing OP concentration. In accordance with the procedure, the determination error (the uncertainty) for different concentration ranges varied from 5 to 10 (55%), from 10 to 500 (35%), and from 500 to 50 000 μg/dm^3 (25%).

Table 1. Oil products in water of Baikal tributaries in different seasons of 2010–2020 and their input into the lake (a dash means no data available)

Rivers	Concentration variation range, μg/dm^3					Water runoff, km^3/year	OP export, t/year
	Mar.–May	June–Aug.	Sep.–Nov.	Dec.–Jan.	mean		
Selenga	5–78	9–30	7–10	7–19	9	23.2	209
Upper Angara	7–18	5–11	6–11	–	6	8.48	68
Barguzin	8–26	<5	<5	–	7	3.39	20
Utulik	13–40	<5–130	<5–29	8–46	18	0.47	8
Solzan	6–12	<5–9	<5–16	<5–26	9	0.12	1
Khara-Murin	11–52	<5–68	<5–16	<5–19	12	0.68	8
Snezhnaya	6–49	<5–9	<5–16	6–23	9	1.42	13
Pereemnaya	<5–7	<5–12	<5–14	5–9	7	0.45	3
Mishikha	<5–11	<5–16	<5–9	<5–12	7	0.60	4
Bol'shaya Cheremshanka	5–780	<5–17	5–16	<5–150	54	0.0003	0.016
Malaya Cheremshanka	6–790	<5–12	5–20	6–59	30	0.0003	0.009
Krestovka	<5–32	<5–5	<5–8	<5–100	8	0.006	0.045
Kamenushka	11–220	<5–9	<5–10	5–27	18	0.00015	0.003
Total					10.5	38.2	408

OP export by rivers was evaluated by the mean OP concentrations over 2010–2020 and the volume of water runoff. The data on river runoff were taken from reports of Roshydromet and Register and Cadaster.

The level of water pollution by OP was evaluated relative to their MAC for water bodies used for fishery (MAC_{fish}), which is 50 μg/dm^3 [18].

RESULTS AND DISCUSSION

Main Tributaries

The highest OP concentrations in the examined rivers were recorded in the water of the main tributary, the Selenga, the basin of which contains many populated localities, as well as industrial and agricultural enterprises of Mongolia and Russia. OP concentration in the Selenga water varied from <5 to 78 μg/dm^3, which is 1.5 times as large as the MAC_{fish}. In the Upper Angara, because of the low economic development of its basin, this characteristic varied from 5 to 18 μg/dm^3, and that for the Barguzin Rivera, from <5 to 26 μg/dm^3 (Table 1). The analysis of the obtained results shows that the seasonal dynamics of OP concentration in the rivers is determined by variations of water flow. During spring flood, their concentration mostly increases due to the export of pollutants from the drainage area with snowmelt water. The lowest concentrations were recorded in winter, when there is no pollutant input from the catchment.

Higher OP concentrations in the Selenga and Barguzin rivers are commonly recorded downstream of large populated localities (Ulan-Ude, Selenginsk, Kabansk, and Ust'-Barguzin), as can be also seen from earlier studies [2, 12, 21]. Thus, in the 1990s, maximal OP concentrations in the Selenga River at a level of 200–300 μg/dm^3 were recorded downstream of wastewater discharges from Ulan-Ude City and the Selenginskii Pulp and Cardboard Mill (TsPCM). The annual OP input to the Selenga from Ulan-Ude industry in this period varied from 32 to 35 t, and that from the Selenginskii TsPCM, from 0.43 to 1.0 t [21]. High OP concentrations were recorded in the Selenga at the boundary with Mongolia near Naushki Settl., where they were 2–5 times the MAC [21]. Selenga water pollution by OP and high OP concentrations were recorded throughout its Russian segment: they reached 230–750 near Naushki Settl. and 680 μg/dm^3 downstream of Ulan-Ude City [2].

Later (in 2001–2010), according to data of state surface water monitoring, carried out by the Hydrochemical Institute, OP concentration in the Selenga decreased: it varied within 20–420 at Naushki Settl., 10–190 downstream of Ulan-Ude C., and 18–200 μg/dm^3 downstream of the Selenginskii TsCM [24]. The results of the authors' studies in 2010–2020 also show a decrease in OP concentration in the water of the major tributaries of Lake Baikal (the Selenga, Upper Angara, and Barguzin) compared with data collected 30 years ago. The maximal OP concentration in these watercourses is ≤78 μg/dm^3 (Table 1).

In the tributaries on the southeastern coast of the Southern Baikal (Utulic, Solzan, Khara-Murin, Snezhnaya, Pereemnaya, Mishikha), OP concentrations vary, on the average, from 7 to 18 μg/dm^3 (Table 1). The input of wastewater being low, the major pollution of these rivers enters it through the atmosphere [20].

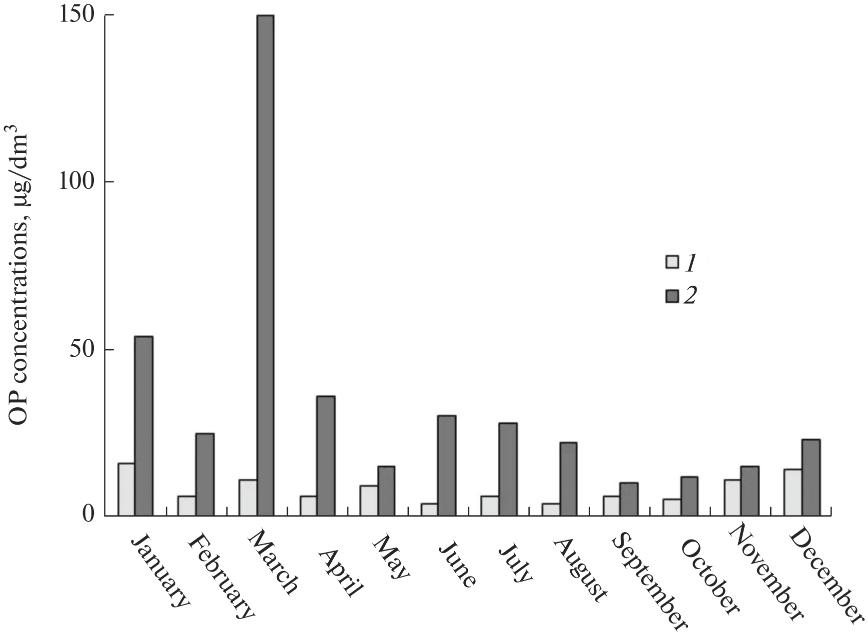

Fig. 2. Annual variations in OP concentrations in water of the Bol'shaya Cheremshanka R. (*1*) Background section, (*2*) mouth.

Hydrocarbons accumulate in snow cover [13, 14] and, during snow melting, they enter streams [11, 13]. Snow pollution is facilitated by Trans-Siberian Railroad and a motor road running along lake shore and crossing the near-mouth reaches of rivers, as well as by TPPs and boiler houses of the towns of Baikal'sk and Slyudyanka, as well as holiday camps on the coast [16]. Spring flood period is the time when OP concentrations in the water of these rivers exceeds the MAC_{fish} (Table 1) by factors of 2.6 and 1.4 in the rivers of Utulik and Khara-Murin, respectively.

Small Streams in Listvyanka Settlment

The examined streams in the southwestern coast of the Southern Baikal (Krestovka, Bol'shaya Cheremshanka, Malaya Cheremshanka, and Kamenushka), flowing through Listvyanka Settl., experience the highest anthropogenic load [10] because of the large motor traffic. OP concentration in these rivers is generally higher than in other tributaries of Baikal (Table 1). The maximal concentrations here are also recorded during spring flood, thus demonstrating once again that snow cover is the medium that accumulates pollutants [14].

Concentrations of OP in excess of MAC_{fish} were recorded in this period at the mouths of the Malaya Cheremshanka (by factors 2.2–15.6), Bol'shaya Cheremshanka (14.2–15.8), and Kamenushki (1.8–4.4). In this case, OP concentrations in the upper reaches of the rivers (upstream of Listvyanka Settl.) are always lower than at their mouths (Fig. 2). At the beginning of the summer tourist season with an increase in motor traffic, an increase in OP concentrations takes place at the mouths of the Bol'shaya Cheremshanka and Malaya Cheremshanka rivers, the basins of which in their lower reaches contain many tourist camps, hotels with parking areas and with no treatment facilities. The inflow of domestic wastewaters into river water causes its pollution by nutrients, sulfates, pathogenic microflora, as well as OP [6, 10].

Lake Baikal

OP concentrations in Baikal water varied within a wide range (Fig. 3; Table 2). In lake pelagic zone, higher OP concentrations were recorded in the Southern Baikal, and minimal, in the Middle Baikal, except for the area at Gorevoi Utes Cape with a natural oil manifestation. In the coastal zone, OP concentration varied mostly within <5–56 μg/dm^3. In all three depressions, higher OP concentrations were recorded at the eastern shore, subject to higher anthropogenic effect due to the trans-Siberian Railroad and Baikal motor road. From the eastern shore, the lake receives its major tributaries (the Selenga and Barguzin), the basins of which contain the majority of settlements of Buryatia and Mongolia.

The obtained results showed that OP concentrations in the surface layer of the lake are mostly higher than those in the bottom layer (Table 2). At the year-to-year scale, the highest OP concentrations were recorded in May 2017, when a research vessel moved into the northern part of the lake, following ice melting and recording high OP concentrations due to pollutants accumulated in ice and snow in winter. The

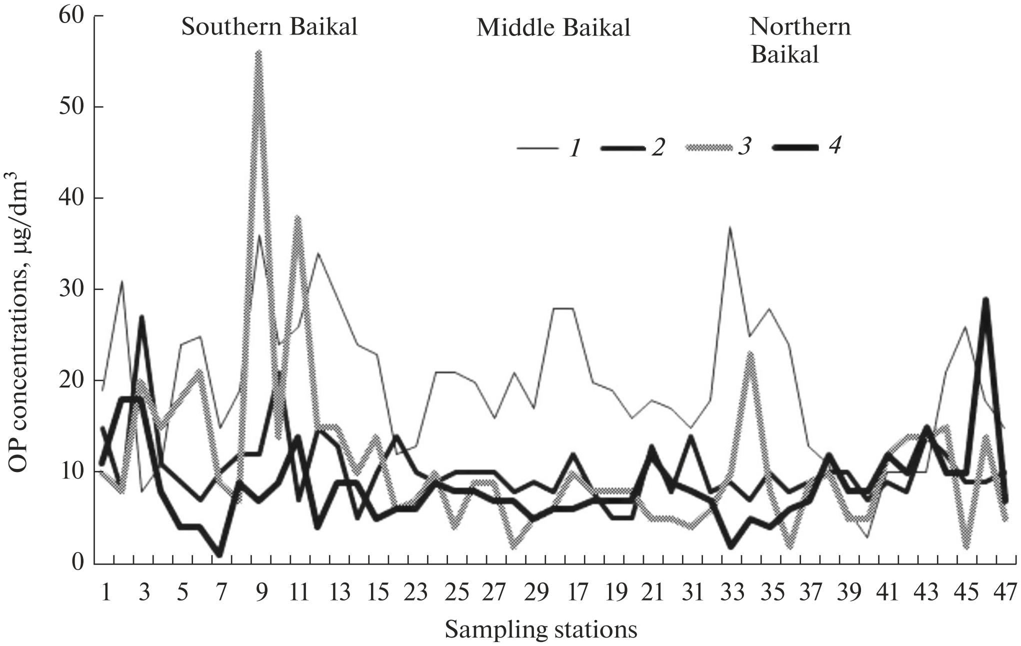

Fig. 3. OP concentrations in Baikal surface layer in different years in June. (*1*) 2017; (*2*) 2018; (*3*) 2019; (*4*) 2020.

local sources of pollutants in winter are ice motor roads on the lake, which run along the shore between populated localities and to the sites of winter fishery. The surface ice layer near motor roads shows extremely high accumulation of pollutants, which is hundreds of times higher than their concentration in under-ice water [13]. In the following 2018–2020, spring studies were carried out later, after the lake had become free of ice, and OP concentrations in lake water were appreciably lower than they were in 2017.

The analysis of the results of long-term measurements shows that higher OP concentrations in lake water mass are mostly recorded in the coastal zone and near the areas of high economic activity. In the area in the Southern Baikal where industrial and domestic wastewaters from Slyudyanka and Baikal'sk towns, Baikal Port, and Listvyanka Settl. enter lake water, OP concentration mostly varied within the range of 8–36 μg/dm^3. Concentrations 1.1 times the MAC_{fish} were recorded near Kultuk Settl. in the surface layer at the pier in May 2019. The variation range of OP concentrations in the Middle Baikal is somewhat narrower (5–21 μg/dm^3), than it is in the Southern Baikal (Table 2). In the Northern Baikal, they varied from 7 to 37 μg/dm^3 with an increase at Severobaikal'sk Town at the mouth of the Tyya R., into which municipal wastewaters are discharged. Here concentrations in excess of MAC_{fish} are recorded from time to time.

Studies near the natural oil show at Gorevoi Utes Cape found that OP concentration in the surface layer in such places reaches extremely high values of 300–1200 μg/dm^3. The maximum recorded in this region is 13000 μg/dm^3 [5]. OP concentration abruptly decreases with the distance from the boundaries of oil spills on water surface (Table 2), but it is higher than the mean concentration over lake water area. The area of oil spills is ≤1 km^2 and it remains relatively stable since 2005. In lake pelagic area beyond the zone of influence of the oil spill, OP concentration in the surface layer is ≤10 μg/dm^3 in the water mass and 5–7 μg/dm^3 in the bottom layer [5]. Lighter oil fractions migrate toward the surface, where they suffer biodegradation, while heavy fractions stay on lake bed where they form asphalt towers [23]. In the zone near oil spills, intense development of microorganisms was found to take place, which use petroleum hydrocarbons as the only source of nourishment, thus contributing to water purification [17].

The Angara River

OP concentrations at the Angara R. source are mostly determined by their concentration in the Southern Baikal. Additional water pollution is due to OP inflow with wastewater from Listvyanka Settl. (from the right bank), Baikal port (from the left bank), and the operation of a ferry between these points. In winter, the pollution due to the ferry increases because of the operation of a service boat which breaks ice along the crossing route. OP concentration in the Angara in the observation period varied within <5–28 μg/dm^3. Their concentration is minimal from July to September (Fig. 4a), which may be due to the higher river flow and the summer intensification of oil-destroying bacteria in Baikal. The increase in the

Table 2. OP concentrations in the surface (above the line) and bottom (below the line) water in Lake Baikal pelagic zone in different years, μg/dm^3 (0, 10–15, 50 m are depths; given in parentheses are mean values)

Sampling station		2017	2018	2019	2020
Coastal stations					
Southern Baikal	Western shore: 0 m	15–36 (21)	7–27 (13)	7–56 (18)	<5–18 (8)
	10–15 m	7–25 (16)	5–20 (10)	<5–30 (12)	<5–17 (6)
	Eastern shore: 0 m	23–34 (27)	5–15 (10)	10–36 (18)	<5–14 (8)
	10–15 m	16–27 (23)	5–11 (7)	<5 (<5)	<5–7 (5)
Middle Baikal	Western shore: 0 m	12–21 (17)	8–14 (10)	5–10 (6)	5–11 (8)
	10–15 m	12–21 (16)	6–10 (8)	<5 (<5)	<5–14 (8)
	Eastern shore: 0 m	16–28 (22)	5–13 (8)	<5–10 (7)	6–12 (8)
	10–15 m	15–22 (17)	<5–7 (6)	<5–5 (<5)	<5–5 (<5)
Northern Baikal	Western shore: 0 m	6–37 (17)	7–14(9)	<5–23 (8)	<5–12 (7)
	10–15 m	6–21 (15)	<5 (<5)	<5–16 (6)	<5–15 (8)
	Eastern shore: 0 m	10–26 (19)	8–14 (11)	<5–15 (11)	7–29 (14)
	10–15 m	11–21 (16)	6–10 (8)	<5–10 (7)	<5–15 (8)
Deep-water stations					
Southern Baikal,	0 m	12	<5	20	7
st. I	50 m	9	5	9	<5
Middle Baikal,	0 m	15	7	10	<5
st. II	50 m	13	<5	6	<5
Northern Baikal,	0 m	27	<5	6	<5
st. III	50 m	11	<5	<5	<5
Middle Baikal, st. IV,	0 m (in the center and on the margins of the spot)	–	300–1200	–	–
Gorevoi Utes Cape	0 m (200 m from the spot)	–	30	–	–

concentrations in May is clearly due to the input of pollutants, which have accumulated in ice and snow during winter. However, the highest OP concentrations are mostly observed from November to March, when their biodegradation slows down.

OP export by the Angara is mostly governed by the dynamics of its water flow and, as mentioned above, oil concentration in the Southern basin of the lake. In 2016–2018, water flow from Baikal was low, while the following two years showed medium water abundance, which could be seen in the year-to-year variations of OP runoff from the lake, which varied from 450 to 970 t/year (Fig. 4b). One can see that OP export in 2020 was appreciably lesser, most likely, because of a decrease in the number of tourists visiting Baikal and the lesser traffic of water transport because of restrictions due to COVID-19 epidemic. The mean OP runoff from the lake in 2016–2020 was 643 t/year.

The Budget of Oil Products

The obtained results make it possible to approximately estimate the total OP inflow into Lake Baikal and their export through the Angara R. As shown above, the water of the rivers under study brings on the average ~408 t OP/year. Its inflow through other rivers with the total water flow of 17.1 km^3/year at OP concentration taken equal to the average in the examined streams is 179 t/year. Therefore, the total inflow of oil into the lake with surface water is 587 t/year. Taking into account other significant sources of OP inflow into Baikal, given in [7, 19] (Table 3), that is, atmospheric deposition (with precipitation and dry fallout), the pollution from water transport, and release from the bed, we can approximately evaluate the total current OP input into the lake at ~1040 t/year. This is about one-third less than the estimate made ten years ago [7]; this fact can be a demonstration of either the general improvement of the environmental situation in the region (the closing down of Baikal Pulp-and-

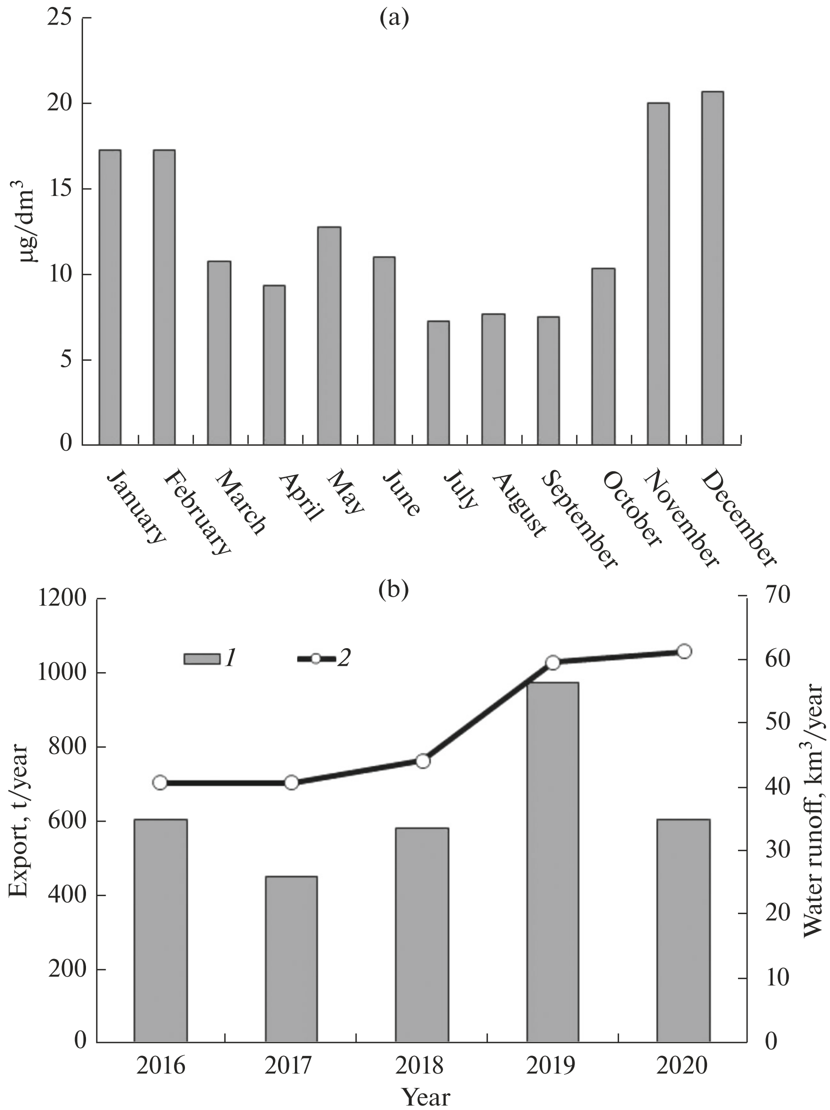

Fig. 4. (a) Seasonal variations of OP concentrations in Angara water and (b) year-to-year variations of their export from the lake. (*1*) OP runoff, (*2*) water flow.

Paper Plant and a decrease in atmospheric emissions), or the complexity of the examined problems because of errors in determining OP concentrations, the high space and time variations of their concentrations in river water and the atmosphere, which reduce the accuracy of such estimates.

Out of the total amount of OP that enters the lake, a major portion (61.9%) is carried out by the Angara, while the 396 t that remain in the water body (Table 3) are utilized by oil-oxidizing bacteria. The relative stability of OP concentration in Baikal suggests the high oil-removal potential of the Baikal microbial community, which is confirmed by the high concentration of oil-destroying microorganisms in the area of natural oil manifestations in the lake [19].

CONCLUSIONS

The studies carried out suggest the conclusion that more than half (56%) of OP enters Lake Baikal with the water of inflowing rivers. OP concentration in the water of major tributaries varies from 18 to 78 μg/dm^3, reaching its maximum in the Selenga R. in which an increase to 2.6 MAC_{fish} was recorded. The load is highest in the case of small streams within the boundaries of Listvyanka Settl. in the Southern Baikal, where OP concentration increases to 15.8 MAC_{fish}. The oil pollution is least in the rivers of the southeastern coast of the lake, though an increase up to 2.6 MAC_{fish} was recorded in some years in the Utulik River. Seasonally, the maximal OP concentrations were recorded in the period of spring snow melting.

Table 3. OP balance in Lake Baikal

Input/output items	t/year	%
Input		
Examined rivers	408	39.3
Other streams	179	17.2
Navigation [7]	250	24.1
Precipitation [7]	198	19.0
From the bed [19]	4	0.4
Total	1039	100
Discharge		
Export through the Angara	643	61.9
Utilized in the lake	396	38.1
Total	1039	100

In Baikal, higher OP concentrations were recorded in surface water in the coastal zone of the southern depression. An increase in OP concentration to 1.1 MAC_{fish} was recorded at Kultuk Settl. in June 2019. Elevated concentrations are recorded from time to time in the bottom water at Severobaikal'sk City near the Tyya R. mouth (Northern Baikal). OP concentration in lake pelagic zone is much lower. In the surface layer, it is ≤10, and in the bottom layer, 6 μg/dm^3, which is comparable with the data obtained earlier. The only exception is the area of oil show at Gorevoi Utes Cape, where OP concentration in the surface layer reaches extremely high values (300–1200 μg/dm^3). OP concentration in water decreases by 10–40 times with the distance from the oil spill.

The total current input of OP into the lake, taking into account atmospheric precipitation, natural oil releases, and pollution by water transport, averages ~1040 t/year, of which 640 t is delivered by the Angara and ~400 t remains in the lake and biodegrades.

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