УДК 556.5/502.05

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БИОГЕННАЯ НАГРУЗКА С РОССИЙСКОЙ ТЕРРИТОРИИ НА ФИНСКИЙ ЗАЛИВ

Статья поступила в редакцию 28.10.2018, после доработки 07.02.2019

Установление целевых показателей сокращения биогенной нагрузки на Балтийское море и мониторинг выполнения этих целей требует достоверной информации о количестве биогенных веществ, поступающих с территории всех стран Финского залива. Целью исследования было оценить поступление общего азота и общего фосфора с российской территории в Финский залив – один из самых эвтрофированных подбассейнов Балтийского моря. Оценка биогенной нагрузки проводилась на основе доступных данных наблюдений и статистических данных, данных математического моделирования и данных дополнительного мониторинга в ранее неконтролируемых областях. Представлены и проанализированы новые данные о поступлении биогенных веществ на небольших неконтролируемых притоках Финского залива. Показано, что для выполнения рекомендаций по снижению уровня питательных веществ согласно Плану действий ХЕЛКОМ по Балтийскому морю для Финского залива необходимо дальнейшее сокращение поступления общего азота на 2084 т/год и общего фосфора на 202 т/год со стороны России. Представлены предложения по улучшению российской системы мониторинга.

Ключевые слова: Финский залив, мониторинг, неконтролируемый водосбор, общий азот, общий фосфор, биогенная нагрузка, моделирование.

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NUTRIENT LOAD FROM THE RUSSIAN TERRITORY ON THE GULF OF FINLAND

Received 28.10.2018, in final form 07.02.2019

Setting nutrient load reduction targets for the Baltic Sea, and monitoring whether these targets have been met, calls for reliable information on the nutrient load from all the surrounding countries. The objective of this study was to estimate the loading of N_{tot} and P_{tot} from the Russian territory on the Gulf of Finland, one of the most eutrophied sub-basins of the Baltic Sea. The nutrient load assessment was based on available monitoring data and statistics, mathematical modelling and additional sampling in the previously unmonitored areas. New data on nutrient loads at the small unmonitored rivers of the Gulf of Finland immediate catchment are presented and discussed. The data compilation showed that in order to fulfil the nutrient abatement recommendations of the HELCOM Baltic Sea Action Plan for the Gulf of Finland, a further reduction of 2084 t of N/a and 202 t of P/a from Russia is needed. Suggestions to improve Russian load monitoring system are given.

Keywords: Gulf of Finland, monitoring, unmonitored catchment, total nitrogen, total phosphorus, nutrient load, model.

Ссылка для цитирования: *Кондратьев С.А., Ершова А.А., Экхольм П., Викторова Н.В.* Биогенная нагрузка с российской территории на Финский залив // Фундаментальная и прикладная гидрофизика. 2019. Т. 12, № 2. С. 77–87.

For citation: *Kondratyev S.A., Ershova A.A., Ekholm P., Victorova N.V.* Nutrient Load from the Russian Territory on the Gulf of Finland. *Fundamentalnaya i Prikladnaya Gidrofizika*. 2019, 12, 2, 77–87.

DOI: 10.7868/S2073667319020096

Introduction

The Gulf of Finland is considered as one of the most eutrophied sub-basins of the Baltic Sea [1]. Its catchment area covers 422 580 km^2, of which 67.6% is situated in Russia, 25.3% in Finland, 6.2% in Estonia and 0.9% in Latvia [2]. This semi-enclosed water body is heavily influenced by nutrient loading from the surrounding agricultural and urban areas, with significant part of the loading entering the gulf via the River Neva [3–5], despite the drastic reductions in point-source loading after the recent introduction of new water treatment plants and improvement of wastewater treatment technologies in St.-Petersburg.

The Baltic Sea Action Plan (BSAP) [6, 7], adopted at the sessions of Helsinki Commission as a long-term strategy of improving the Baltic Sea health, aims at achieving a set of indicators of "good environmental status" of the sea by 2021. However, there are still gaps in knowledge on the amount of nutrients coming from some parts of the catchment. In this view it is important to close the existing data gaps to ensure the accurate and reliable estimation of nutrient load reduction goals. The BSAP goals include country-allocated nutrient reductions to alleviate the symptoms of eutrophication. According to the HELCOM recommendations [7, 8] Russia should reduce its waterborne nutrient input to the Gulf of Finland by 7683 t of N/a and 3277 t of P/a in respect to the level of 1997–2003, i.e. 68 653 t of N/a and 6169 t of P/a [4]. Thus, the waterborne nutrient load from the Russian territory on the Gulf of Finland should not exceed 60 970 t of N/a and 2892 t of P/a. For the moment, Russia contributes 84% of N_{tot} load and 71% of P_{tot} load on the Gulf of Finland out of the total load from Russia, Estonia and Finland, with this percentage being nearly constant for the last 20 years [4].

The problems of formation of nutrient load on the Gulf of Finland have been studied for many years by many researchers in Finland, Estonia and Russia. The estimates of 1996 showed that while in late 1980s the load from the Russian part of the catchment was as high as 8200 t of P/a and 123 000 t/a N, in 1992–1994 it decreased to 6800 t/a P/ and 94 000 t/a N, and in 1995 it made 5950 t/a P and 80 900 t/a N [9].

The disadvantage of the HELCOM estimates is that since mid-1990s no regular measurements of nutrient load has been carried out at the Russian unmonitored catchments. While these catchments account only 3.2% of the total Russian catchment of the Gulf of Finland, their potential significance in the load formation may be higher, because they contain no larger lakes and thus retention of nutrients is low. An experimental assessment of N_{tot} and P_{tot} input from the small tributaries of the Russian part of the Gulf of Finland was carried out for the first time in frames of the project "Gulf of Finland Year – 2014". Therefore, the objective of this study was to combine available knowledge on Russian sources of nutrients in the Gulf of Finland region and to estimate the loading of N_{tot} and P_{tot} from the Russian part of the catchment on the basis of monitoring data and statistical reports, results of special monitoring campaigns and making use of mathematical modelling.

MATERIALS AND METHODS

The nutrient load from the Russian part of the Gulf of Finland catchment consists of loads from its sub-catchments and separate major sources like the city of St.-Petersburg (fig. 1, see insert). In this study the total load was calculated as a sum of inputs of N_{tot} and P_{tot} (in unfiltered water) from all these sources for the period of 2012–2013. Some of the data was taken from previous studies and the remaining gaps were covered by the field investigations described below (immediate catchment of the Gulf of Finland) to account for the entire catchment.

Components of total nutrient load on the Russian part of the Gulf of Finland

Lake Ladoga. Approximately 77% of the studied area (Russian part of the Gulf of Finland catchment) consists of the catchment of Lake Ladoga, situated on the territory of three countries: Russia (80% of total area), Finland (19.9%) and Belarus (0.1%). Lake Ladoga is the largest freshwater reservoir in Europe with an area of 17870 km^2 and water volume of 838 km^3, and currently, it is in a stable mesotrophic state [2]. The long-term research [2, 10] shows that since the end of 1990s the annual mean concentrations of N_{tot} and P_{tot} at the head of the Neva River have been ≈0.6 and 0.011 mg/l, respectively.

River Neva. The Neva is the largest river discharging into the Gulf of Finland, linking the Baltic Sea with Lake Ladoga, and the largest nutrient source from the Russian territory (due to its high water discharge). The river is 74 km long with the average annual water discharge of 2510 m^3/s and river bed slope of 0.053 m/km. The area of the immediate catchment of the River Neva is 5180 km^2 (4800 km^2 without Saint-Petersburg), accounting only for 2% of the total area of the basin (281 000 km^2). However, the contribution of the immediate catchment of the river to the total amount of riverine nutrient input to the Gulf of Finland can be marked due to pressures from a high population, large animal breeding units and industries in this region.

The load from this territory was estimated separately (due to the low availability and irregularity of monitoring data on runoff and nutrient concentrations in the Neva) using the mathematical model of nutrient load ILLM (Institute of Limnology Load Model) [11, 12]. The model was developed on the basis of existing models of runoff and removal of nutrients from the catchment areas and nutrient inputs into the water bodies and is described in detail in [10–13]. The model is designed to solve problems associated with the quantification of nutrient load formed by point and diffuse sources of pollution in conditions of scarce data, and allows predicting the load changes under the influence of anthropogenic and climatic changes. The model incorporates the existing capabilities of data input from the Russian State Monitoring of water bodies, as well as of materials of state statistical reporting on wastewater discharges and agricultural activities in the catchment. It also allows calculating nutrient export from the catchment with the account of hydrological factors and retention of nutrients by the catchment and hydrographic net. The final result of the model is an evaluation of the nutrient load and its components on the water body from the catchment.

River Narva. The Narva is a transboundary river between Russia and Estonia linking the Gulf of Finland with Lake Peipsi (Chudskoe). The river is 77 km long with an average annual water discharge of 321 m^3/s and river bed slope of 0.39 m/km. The area of the immediate catchment of the Narva is 14.6% of the total area of the basin (56 200 km^2)· Nutrient content of the Narva flow (similarly to the River Neva case) is mainly driven by the amount of nutrients in the lake that it starts from Lake Chudskoye/Peipsi where nutrient concentrations do not vary much throughout the years [14]. It was shown by Rumyancev et al. [15] that nutrient load on the lake is distributed between Russia and Estonia proportionally to the areas of national catchments. Thus, the present study assumes that Russia is responsible for about 2/3 of nutrient export by the River Narva that flows out of Lake Chudskoye/Peipsi.

River Luga. The Luga is the third largest tributary of the Russian part of the Gulf of Finland with the catchment area of 14 010 km^2. The river is 353 km long with the average annual water discharge of 95 m^3/s and river bed slope of 0.15 m/km. In 2008–2010 an extremely high load of P_{tot} was registered in this river (over 1000 t/a) that was associated with unauthorized industrial wastewater discharges [16]. However, in the present time this problem has been solved and the River Luga nutrient load remains at the level of the beginning of 2000s according to the data of the Russian State Monitoring of Roshydromet Service.

St.-Petersburg. Information on nutrient discharges with treated and untreated sewage of the city of St.-Petersburg was taken from the official website of the municipal water disposal company "Vodokanal of St. Petersburg" [17], responsible for the entire city water supply and sewage treatment. The wastewater treatment plants in St.-Petersburg, processing over 98.5% of all city wastewaters, remain the largest point-source of nutrient pollution in the Gulf of Finland area. Yet, SUE "Vodokanal of St.-Petersburg" provides the constant and significant reduction of nutrient load from this source through the improvement of wastewater treatment technologies, modernization of treatment plants and inclusion of new territories to the city sewer system.

Atmospheric input. The long-term studies have shown that the P load from atmospheric depositions in this area range from 0.002 to 0.005 t/km^2 per year [18]. So, in this study the atmospheric input of P_{tot} was taken as a constant value (0.005 t/km^2/a for the period of the present study) that was incorporated in the model. The atmospheric N input can be quite high. Over 50% of its input and output components are atmospheric precipitation, biological fixation, denitrification and volatilization [19]. The problem of estimation of biological fixation and N volatilization is especially complex for large river catchments characterized by a non-uniform landscape structure and agricultural land-use. So, for the atmospheric N load an assumption was made that it equals to zero based on an extensive study of German researchers [20, 21] where they showed that N deposition from the atmosphere (loss with precipitation + biological fixation) can be compensated by the amount of N removed by denitrification.

The previously unmonitored *immediate catchment of the Gulf of Finland* (its Russian part) included the tributaries discharging directly into the gulf from an area of about 9200 km^2. In 2013, an assessment of nutrient load from this area was carried out for the first time. In total, 17 small tributaries in the immediate catchment of the Gulf of Finland were investigated (fig. 2, see insert).

There are about 400 000 inhabitants in the area, living in rural and urban areas. In addition, the area is home to 31 large cattle farms, 9 pig farms and 11 poultry factories. The average amount of application of chemical fertilizers is 72 kg/ha/a N and 7.7 kg/ha/a P; this amount of fertilizers would be sufficient only for 25 to 40% of total field area, suggesting that crop production in the area is not very intensive [22]. Total catchment area of the studied 17 rivers is about 4300 km^2,which is 47% of the unmonitored immediate catchment of the gulf. The catchments of the northern coast (from the Finnish border to St. Petersburg, fig. 2, *a*) are located in the area of the Baltic Crystalline Shield and most of the rivers flow into the Vyborg Gulf. The maximum elevation of the catchments is 110 m above sea level. Forests cover ca. 62%, agricultural areas about 3% and urban areas 3% of the northern catchment area, the remaining area being mainly peatland. The southern coastal catchment area extends from St.-Petersburg to the Luga River (fig. 2, *b*). The rivers here flow from the Izhora highland (maximum elevation 160 m). Forests cover ca. 55%, agricultural areas about 13% and urban areas 5% of the southern catchment.

Assessment of the nutrient export from unmonitored territories included the determination of the river runoff and nutrient concentrations.

The sampling dates were selected according to the hydrological seasons: sampling in March represented the winter low-flow period, April the spring flood, June the summer low-flow period and September the early autumn. During each of these four periods water flow parameters (depth and current velocity) and concentrations of N_{tot} and P_{tot} were measured (in the vicinity of mouths of the rivers and passable roads).

Total water volume for month and year for the studied small rivers was calculated as $W = q \times F \times t \times 10^{-3}$, where: q — monthly and annual specific runoff (l/s × km^2); F — catchment area, km^2; t — calculation time. Due to the absence of regular measurements on the studied rivers the flow rate was determined using the method of hydrological analogy, when the rivers-analogs with regular flow observations are selected that are situated in similar physical and geographical conditions as the studied river. Hydrological characteristics of the selected rivers are then applied to the unmonitored rivers. The rivers-analogs were selected based on a comparison of measured flows on unmonitored rivers with data for rivers from the regular Roshydromet Service monitoring network. The measured water flow rates and calculated river runoff for the newly monitored rivers for the considered period are presented and discussed in the Results section.

N_{tot} and P_{tot} concentration in river waters was determined in accordance with the current Russian State Monitoring System recommendations [23, 24]. Concentrations of nutrients were measured at each hydrological season, that is four measurements during the year in total. The load L was calculated as: $L = W \times C$, where W is monthly water volume, C the nutrient concentration. Monthly water volume was calculated for each month as described above to make the total annual sum. Concentrations of N_{tot} and P_{tot} for each season (winter, spring, summer and autumn) were taken equal to the concentrations measured for each of the rivers in one of the months of the season. The result was the total nutrient load in tonnes per year.

The relationships between nutrient concentrations and catchment characteristics were analysed using a linear regression analysis. The explaining variables included the percentages of forested area f_{for}, marsh area f_{sw}, lake area f_{lake}, agricultural area f_{agr} and urban area f_{urb}. These data were based on geographical maps. The regressions between the concentrations of P_{tot} and N_{tot} and the catchment characteristics were calculated for all the rivers and separately for the four seasons.

Nutrient load from the part of immediate catchment of the Gulf of Finland that was not covered by field measurements was calculated using the mathematical model of nutrient load ILLM described above for calculations of the River Neva load. Various sources of initial data for model experiments were used: data on agricultural activities at the investigated area (application of organic and mineral fertilizers, type of crops, their nutrient value, as well as areas of crops and their yield, data on animal farming, etc.) were obtained from the available geographic information system of the area, the Forms of State Statistical Reporting 2-TP Vodkhoz and information from the Federal Service of State Statistics available at the official website [25]. Also, the results of estimation of some components of nutrient load on the Gulf of Finland catchment area obtained during numerous previous research projects were introduced in this work [9, 10, 12, 13, 22].

RESULTS AND DISCUSSION

Previously unmonitored rivers

Reliable estimation of the diffuse and point-source loading carried by rivers calls for a sampling strategy that captures both high- and low-flow events. In small catchments that contain few lakes, such as the 17 rivers studied here, the flow variations are typically high and the flow peaks are easily missed by the sampling. Therefore, sampling only four times a year can only give a tentative estimate of the riverine loads. Hydrological characteristics of 17 newly monitored rivers are presented in table 1.

An analysis of variance showed that the measured water flows differed significantly between the seasons ($p < 0.001$), the spring discharges being some ten times as high as those in other seasons. This finding indicates

Table 1

Measured water flow rates (m^3/s) and estimated river run-off volume in 17 small tributaries of the Russian part of the Gulf of Finland in 2013

Измеренные значения расходов воды ($м^3/с$) и рассчитанные объемы речного стока в 17 малых притоках российской части Финского залива в 2013 г.

River	Catchment area, km²	Measured water flow rates (m³/s)				River run-off volume	
		11.03.2013	25.04.2013	29.06.2013	04.09.2013	Specific runoff *q*, l/s/km²	Run-off volume *W*, mln m³/a
Peschanaya	121	0.3	8.4	0.07	0.083	8.99	34.3
Velikaya	80	1.1	17.7	0.5	0.525	8.99	22.7
Chulkovka	71.8	0.04	6	0.1	0.099	8.99	20.4
Polevaya	104	0.68	8.6	0.8	0.815	8.99	29.5
Drema	45.7	0.41	2.6	0.2	0.144	10.4	14.9
Matrosovka	55.2	0.17	1.1	0.8	0.89	10.4	18.0
Gororkhovka	731	–	22.2	2.2	2.45	10.4	238.7
Chernaya I	668	7.5	37.4	1.5	1.71	11.7	247.4
Strelka	155	0.79	7.39	1.9	1.9	15.2	74.2
Shingarka	121	0.28	1.3	0.8	0.9	15.2	57.9
Karasta	55.8	0.08	1.6	0.06	0.06	15.2	26.7
Chernaya II	96.2	0.96	7.39	0.17	0.18	7.76	23.5
Lebyazhye	101	0.5	3.64	0.02	0.01	7.76	24.7
Kovashi	612	4.0	13.4	3.8	3.6	7.76	149.8
Voronka	286	–	9.6	1.7	1.7	7.76	70.0
Sista	672	9.6	44.5	5.2	5.4	11.4	242.6
Khabolovka	330	1.44	2.88	0.1	0.1	11.4	119.2

that the sampling in April has successfully coincided with the snow-melt period. On the other hand, the low water flows in September show that the typical wet autumn period has been missed.

Concentrations of P_{tot} and N_{tot} in the 17 tributaries are presented in table 2 and their spatial distribution is consecutively shown on fig. 3 and 4, see insert. An analysis of variance indicated that for both nutrient concentrations there was a significant ($p < 0.001$) difference between the seasons but not between the northern and southern coastal areas.

The variation in the concentrations of P_{tot} in the rivers of the *northern coast* during the winter low-water period was low: mean value was 0.07 mg/l (range 0.05–0.08 mg/l). In the spring, the mean concentration decreased to 0.05 mg/l (range 0.04–0.12 mg/l), possibly due to a dilution effect caused by the melting snow. The highest concentrations of P_{tot} were observed in the summer (mean 0.13 mg/l, range 0.06–0.25 mg/l) and in the autumn (mean 0.13 mg/l, range 0.1–0.2 mg/l). For the *southern tributaries* there was a slightly different pattern of P_{tot}: as in the northern coast, the minimum concentrations were observed at winter low-water period (mean 0.08 mg/l, range 0.05–0.12 mg/l). However, during the spring high-water period there was no decrease in P_{tot} concentrations (mean 0.09 mg/l, range 0.04–0.14 mg/l) and in some rivers P_{tot} concentration were at the highest, up to 0.15 mg/l. In the summer, the concentrations ranged from 0.05 to 0.27 mg/l. Mean P_{tot} concentration in autumn in the southern coast was 0.12 mg/l (range 0.09–0.13 mg/l). In neither region, there were statistically significant correlations between the flow and P_{tot} concentrations. There was a significant, but weak correlation between P_{tot} and N_{tot} concentrations.

Table 2

Results of field measurements (concentrations in unfiltered water) in 2013 for studied tributaries of non-monitored catchment of the Gulf of Finland and calculated nutrient loads (4 samplings within a year)

Результаты полевых измерений в 2013 г. для изученных притоков на неконтролируемой части водосбора Финского залива и рассчитанные значения биогенной нагрузки (4 отбора проб в год)

	River	Catchment area, km^2	P_{tot} conc., mg/l mean (max/min)	N_{tot} conc., mg/l mean (max/min)	P_{tot} load		N_{tot} load	
					t/a	kg/km^2/a	t/a	kg/km^2/a
1	Peschanaya*	121.0	0.107 (0.20/0.04)	1.95 (2.50/1.50)	3.1	25.6	70.5	582.6
2	Velikaya*	80.0	0.062 (0.10/0.04)	1.72 (2.30/0.80)	1.3	16.3	45.0	562.5
3	Chulkovka	71.8	0.102 (0.15/0.04)	2.35 (3.10/1.20)	1.2	16.9	46.4	653.5
4	Polevaya*	104.0	0.072 (0.11/0.05)	2.28 (2.50/1.10)	1.3	12.5	63.1	606.7
5	Drema	45.7	0.068 (0.10/0.04)	1.92 (3.10/0.70)	0.9	20.0	23.9	531.1
6	Matrosovka	55.2	0.118 (0.25/0.05)	1.68 (1.90/1.10)	1.5	27.3	29.7	540.0
7	Gororkhovka	731.0	0.108 (0.15/0.06)	1.78 (2.50/1.10)	20.3	27.8	374.7	512.6
8	Chernaya I	668.0	0.142 (0.18/0.12)	2.30 (2.80/2.00)	30.0	45.0	479.6	719.0
9	Strelka	155.0	0.108 (0.13/0.08)	3.50 (6.70/1.30)	8.2	52.9	291.2	1878.7
10	Shingarka	121.0	0.065 (0.12/0.04)	2.10 (3.00/0.90)	3.3	27.3	126.3	1043.8
11	Karasta	55.8	0.130 (0.27/0.06)	1.98 (2.60/1.70)	3.2	58.2	55.6	1010.9
12	Chernaya II	96.2	0.100 (0.13/0.08)	2.08 (3.10/1.30)	2.3	24.0	45.2	470.8
13	Lebyazhye	101.0	0.120 (0.22/0.05)	2.25 (3.40/0.70)	2.4	23.8	52.4	518.8
14	Kovashi	612.0	0.085 (0.11/0.07)	1.95 (2.90/1.00)	12.2	20.0	265.2	434.0
15	Voronka	286.0	0.108 (0.14/0.07)	2.45 (3.40/1.70)	8.3	29.0	159.2	556.6
16	Sista	672.0	0.085 (0.13/0.06)	2.52 (3.60/1.60)	23.3	34.7	554.2	825.9
17	Khabolovka	330.0	0.098 (0.17/0.05)	1.82 (2.80/0.70)	10.2	30.9	197.8	599.4
	Total	4300.0			133.0		2880.0	

* Nutrient load was assessed only for the Russian part of these catchments

As for N_{tot} concentrations, the concentrations in the *northern* coast ranged from 1.16 mg/l in the winter to 2.5–3.0 mg/l in the autumn. In the *southern* coast, N_{tot} concentrations ranged from 1.29 mg/l in the winter to 2.9 mg/l in the autumn. There was a characteristic upward trend in N_{tot} concentrations for all the tributaries by the end of the hydrological year (September). Four rivers (the Karasta, the Matrosovka, the Shingarka, the Strelka) showed a positive correlation between N_{tot} concentrations and the flow.

In the entire data set, there was no statistically significant relationships between nutrient concentrations and catchment characteristics, except for the weak positive relationship between N_{tot} and f_{urb} ($N_{tot} = 1.8 + 0.1\,f_{urb}$, $p < 0.01$, $r^2 = 0.11$). The fact that the percentage of agricultural land did not emerge as an explaining factor, unlike in many other studies (e.g. [26]), suggests that agricultural practices in the area are not very intensive. The seasonal analysis showed that in April there were significant inverse relationships between N_{tot} and f_{for} ($N_{tot} = 6.6–0.07\,f_{for}$, $p < 0.001$, $r^2 = 0.59$) and between N_{tot} and f_{sw} ($N_{tot} = 3.8–0.13\,f_{sw}$, $p < 0.05$, $r^2 = 0.36$). In addition, N_{tot} showed a positive relationship with f_{urb} in April ($N_{tot} = 1.4 + 0.3\,f_{urb}$, $p < 0.01$, $r^2 = 0.65$) and in June ($N_{tot} = 2.0 + 0.07\,f_{urb}$, $p < 0.05$, $r^2 = 0.31$). It should be noted that the results from the regression analysis should be taken with caution due to the severe multicollinearity of the explaining factors, the highest correlation being between f_{for} and f_{urb} ($r = –0.75$).

Measured values of water flows and concentrations of P_{tot} and N_{tot} in the Gulf of Finland tributaries allowed to approximately estimate the nutrient load on the Gulf of Finland formed on the 17 small rivers' catchments: 133 t of *P/a* and 2880 t of *N/a*.

As discussed above, visiting the rivers only for 4 times a year makes the results rather uncertain. Yet, comparison to Finnish, more frequent upstream measurements in three transboundary rivers (the Peschanaya, Velikaya, Polevaya) showed no major discrepancies: typically the values in the Finnish part of the catchment were about 50% lower (see table 3). Differences in the concentrations of Russian and Finnish data can be explained by the fact that the Russian parts of the catchment were measured only in 2013, while the Finnish data represents a longer period (table 3). In addition, there can be the differences in chemical methods of P_{tot} and N_{tot} determination.

Table 3

Upstream nutrient concentrations for the Finnish parts of the catchments of studied small tributaries of the Gulf of Finland [26]

Концентрации биогенных веществ вверх по течению рек на финской территории водосборов изученных малых рек Финского залива [26]

	River	Catchment area (km^2)	Finnish site	Sampling period	P_{tot} conc., mg/l mean (max/min)	N_{tot} conc., mg/l mean (max/min)
1	Peschanaya (Kaltonjoki)	187 (35% in Russia)	Kaltonjoki 002 (almost at the border)	2000–2014 (n = 18)	0.024 (0.05/0.015)	0.85 (1.5/0.48)
2	Velikaya (Vilajoki)	344 (27% in Russia)	Leino (almost at the border)	1998–2000 (n = 8)	0.029 (0.046/0.022)	0.66 (0.82/0.5)
3	Polevaya (Tervajoki)	204 (47% in Russia)	almost at the border	2000–2014 (n = 16)	0.030 (0.087/0.017)	0.95 (2.0/0.71)

The loading formed on the area not covered by measurements was estimated using the mathematical model ILLM [10, 12]. The initial data for the model were taken from different sources of information, as listed above. Besides, the model was calibrated on the data of field observations carried out on studied small tributaries of the gulf. As a result, the nutrient load on the Gulf of Finland from the unstudied area was estimated at 152 t/a *P* and 1890 t/a *N*. So, it was then possible to calculate the total value of nutrient load on the Gulf of Finland from the northern and southern parts of immediate catchment in 2013: 363 t/a *P* and 5059 t/a *N*.

Total nutrient load from the Russian catchment of the Gulf of Finland

Table 4 shows the combined data on nutrient loading on the Gulf of Finland from the Russian territory for the period of 2012–2013 based on the results of field measurements and mathematical modelling, as well as on the published results of previous studies.

The main sources of nutrient load in the Russian part of the Gulf of Finland catchment are Lake Ladoga catchment, the Neva River immediate catchment and the city of St.-Petersburg. However, the unmonitored coastal areas, covering only 1.8% of the total catchment area, account for a disproportionate high share (7.5% for N_{tot}, 9.0% for P_{tot}) of the total nutrient load on the Gulf of Finland from the Russian side. Natural (background) load on the Gulf of Finland immediate catchment from unmonitored rivers makes just 23% for P_{tot}, while it is over 70% for N_{tot}. This shows the clear domination of anthropogenic sources of *P* in this territory (manure, fertilizers, insufficient municipal wastewater treatment, and vast recreational area).

Table 4 also contains the estimated specific loads illustrating the export of N_{tot} and P_{tot} per unit catchment area. Obviously, the maximum values of specific loads are found for the area of St.-Petersburg (312.4 kg/km^2/a *P*, 6701.8 kg/km^2/a *N*) and can be explained by the high loading from the city of nearly 5.2 million people and with a high amount of industrial enterprises. Specific load in the River Neva immediate catchment, in northern and southern coastal areas, is also high due to a number of large settlements and towns in the suburbs of St.-Petersburg, as well as large industrial and agricultural enterprises and recreational areas. The value of specific load for the River Luga catchment can be taken as a representative figure for Russian catchments of average level of agricultural activities in Leningradskaya, Pskovskaya and Novgorodskaya Oblasts (24.1 kg/km^2/a *P*,

Table 4

Assessment of the nutrient load on the Gulf of Finland from the Russian territory in 2012–2013 based on published data, data of field monitoring and mathematical modelling: annual total and specific loads of total phosphorus and total nitrogen

Оценка биогенной нагрузки на Финский залив с российской территории в период 2012–2013 гг. на основе опубликованных данных, данных полевых исследований и математического моделирования: среднегодовые значения биогенной нагрузки и удельная нагрузка для общего азота и общего фосфора

Source	Catchment area	Land area in the catchment	P_{tot}		N_{tot}	
	km^2		t/a	kg/km^2/a	t/a	kg/km^2/a
Lake Ladoga[a] [2, 13]	220000	183300	951	5.2	34747	189.6
River Neva immediate catchment [11, 12]	4800	4770	790	165.6	3830	802.9
River Narva [10]	36130	33640	217	6.5	5703	169.5
River Luga [10, 16]	14010	13740	331	24.1	4252	309.5
Small tributaries of the Gulf of Finland						
– monitored territory	4300	4170	133	31.9	2880	690.6
– unmonitored territory (modeled)	4900	4800	152	31.7	1890	393.8
– direct discharges			78		269	
St.-Petersburg [17]	1440	1415	442	312.4	9483	6701.8
Total[a]	**285580**	**245835**	**3094**	**12.6**	**63054**	**256.5**
Maximum Allowable Inputs from Russia			2892		60970	
Reduction needed			**202**		**2084**	

[a] The load originating from the Russian part of the Lake Ladoga catchment is obtained by subtracting the load originating from the Finnish territory (56 200 km^2, 49 t/a *P*, 5353 t/a *N*, HELCOM 2015) from the total estimated load for Lake Ladoga (1000 t/a *P*, 40 100 t/a *N*) [2].

309.5 kg/km^2/a *N*). The values of specific load in table 4 for catchments of Lake Ladoga and the River Narva are not representative indicators of nutrient export from these areas; they merely reflect the high nutrient retention capacity of great lakes in the area (Ladoga, Onega, Il'men, Peipsi – Chudskoye).

The HELCOM BSAP [7, 8] recommends the modern waterborne nutrient load on the Gulf of Finland not to exceed 2892 t/a *P* and 60 970 t/a *N*. The calculations, model experiments and field research results described in this paper showed that for 2012–2013 nutrient load on the Gulf of Finland from the territory of Russia exceeds the recommended values by 202 t/a for *P* and 2084 t/a for *N* (table 4).

One can ask whether the reduction is achievable in the near future? What should be done to reach the BSAP targets? To answer these questions a thorough analysis of a realistic load reduction is needed. First of all, we must note that over 88% of the Russian territory of the Gulf of Finland consists of catchment areas of such great lakes as Ladoga, Onega, Il'men and Peipsi – Chudskoye). According to the study carried out in frames of the project RusNIP II [27], these lakes retain 76%, 76%, 53% and 56%, respectively, of the incoming *P*. Thus, these major lakes play a great role in acting as geochemical barriers during the transport of nutrients from the upper parts of the catchment area to the sea. For example, only 5% of *P* load formed in the territory of Lake Onega catchment will finally reach the Gulf of Finland. This shows that, on the one hand, lake barriers protect the Gulf of Finland from the high nutrient input from such a vast territory. On the other hand, any abatement measures undertaken at the upper parts of the catchment area will have mainly local effect with minimum impact on the marine ecosystem. Therefore, the main attention must be paid on the perspectives of load reduction in the sub-catchments that export nutrients directly to the Gulf of Finland. These are the immediate catchment of the Gulf of Finland, the Luga River catchment, the immediate catchment of the Neva River and St.-Petersburg area.

At the same time, the authors' preliminary assessment of load reduction measures shows that the reduction discussed above is realistic in near future [28]. The reduction consists of two components: 1) fulfilling the HELCOM standards at wastewater treatment facilities of enterprises in the catchment and 2) reduction of nutrient load from agricultural enterprises situated in the catchment area as a result of application of the Best Available Techniques – BAT [29]. However, this estimate must be further improved e.g. by taking into account the atmospheric deposition estimates, as well as load flow normalization, improvement of land-based monitoring system.

Conclusions

For the first time in 20 years the estimate of the total nutrient loads to the Gulf of Finland from the Russian part of its immediate catchment was obtained (363 t/a of *P* and 5059 t/a of *N*, 2013) and from the entire Russian territory (3094 t/a of *P* and 63054 t/a of *N*, 2012–2013). The Russian load to the Gulf of Finland exceeds the HELCOM recommendations by 202 t/a in the case of *P* and 2084 t/a in the case of *N*.

The remaining load reduction can be achieved, provided that best available agricultural practices will be introduced in the North-West of Russia and that the wastewater treatment of industrial and municipal enterprises will be improved according to HELCOM standards. At the same time, the dominant geochemical role of great lakes in the catchment must be taken into account, that is, only the reduction measures performed downstream of the lakes will have an evident effect on the load entering the Gulf of Finland.

To further improve the estimates of nutrient load on the Gulf of Finland, the monitoring system of the Russian State Monitoring Programme should be developed. Reliable estimation of riverine nutrient loads calls for accurate information of the concentrations and flows, and the use of a proper load calculation method. For example, HELCOM suggests that at least 12 samples be taken annually to estimate riverine nutrient fluxes. According to statistical analyses, such a relatively sparse sampling may allow estimating a longer term load (for example, several years) reasonably well, if there is information on daily flow and the flow can be used as a covariate in load estimation [26, 30].

The precision of the load estimates would be greatly increased, if a set of representative rivers should be equipped with continuous flow measurement facilities and intensively monitored for water quality. Ideally, the rivers should be sampled as often as weekly or twice a month to estimate the true variation in nutrient concentrations and to analyse the relationship between concentrations and flow. For some water quality variables (e.g. nitrate, particulate phosphorus), online sensors would give highly useful data, provided that the maintenance of sensors is taken care of. After such an initial investment in sampling, a lower sampling frequency could then be established for basic monitoring. The nutrient losses found on a few representative catchments should be related to their catchment characteristics (e.g. field percentage, population outside sewer systems), which would make it possible to estimate the losses from neighbouring, less monitored catchments. Yet, occasional snapshot campaigns on such less monitored areas are recommended to pinpoint potential future risk sites.

Acknowledgements

The research was partly funded by the Neva-Ladoga Water Administration in frames of the project "The Gulf of Finland Year 2014" and in the study № 0154-2019-0001 of the State research plan for the Institute of Limnology RAS.

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К статье *Кондратьев С. А.* и др. Биогенная нагрузка...

Kondratyev S. A. et al. Nutrient Load...

Fig. 1. Catchment of the Gulf of Finland with its sub-catchments located in Russia:
1 — catchment of Lake Ladoga, 2 — immediate catchment of the River Neva, 3 — Russian catchment of the Narva River and Lake Chudskoye (Peipsi), 4 — River Luga catchment, 5 — immediate catchment of the Gulf of Finland [10].

Рис. 1. Водосборная территория Финского залива и его частные водосборы, расположенные в России:
1 — водосбор Ладожского озера, 2 — частный водосбор р. Нева, 3 — водосбор Псковско-Чудского озера, 4 — водосбор р. Луга, 5 — частный водосбор Финского залива.

К статье *Кондратьев С. А.* и др. Биогенная нагрузка...

Kondratyev S. A. et al. Nutrient Load...

a *a*

b *б*

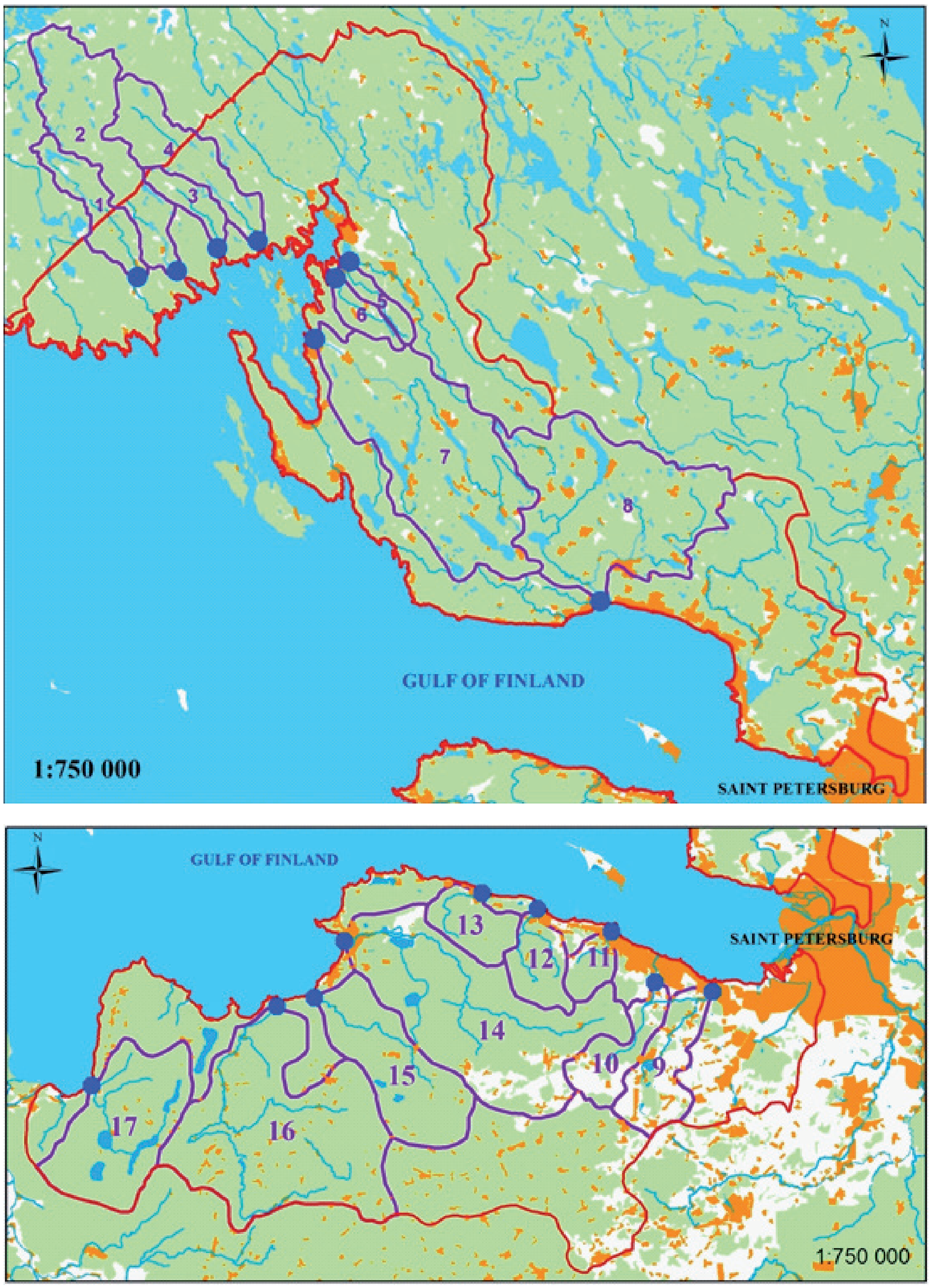

Fig. 2. Catchments of studied small rivers on the northern (a) and southern (b) coasts of the Gulf of Finland: Peschanaya (1), Velikaya (2), Chulkovka (3), Polevaya (4), Drema (5), Matrosovka (6), Gororkhovka (7) and Chernaya I (8), Strelka (9), Shingarka (10), Karasta (11), Chernaya II (12), Lebyazh'ye (13), Kovashi (14), Voronka (15), Sista (16) and Khabolovka (17).

Рис. 2. Водосборы изученных малых рек на северном (a) и южном (b) побережьях Финского залива: Песчаная (1), Великая (2), Чулковка (3), Полевая (4), Дрема (5), Матросовка (6), Гороховка (7) и Черная I (8), Стрелка (9), Шингарка (10), Караста (11), Черная II (12), Лебяжья (13), Коваши (14), Воронка (15), Систа (16) и Хаболовка (17).

К статье *Кондратьев С. А.* и др. Биогенная нагрузка...

Kondratyev S. A. et al. Nutrient Load...

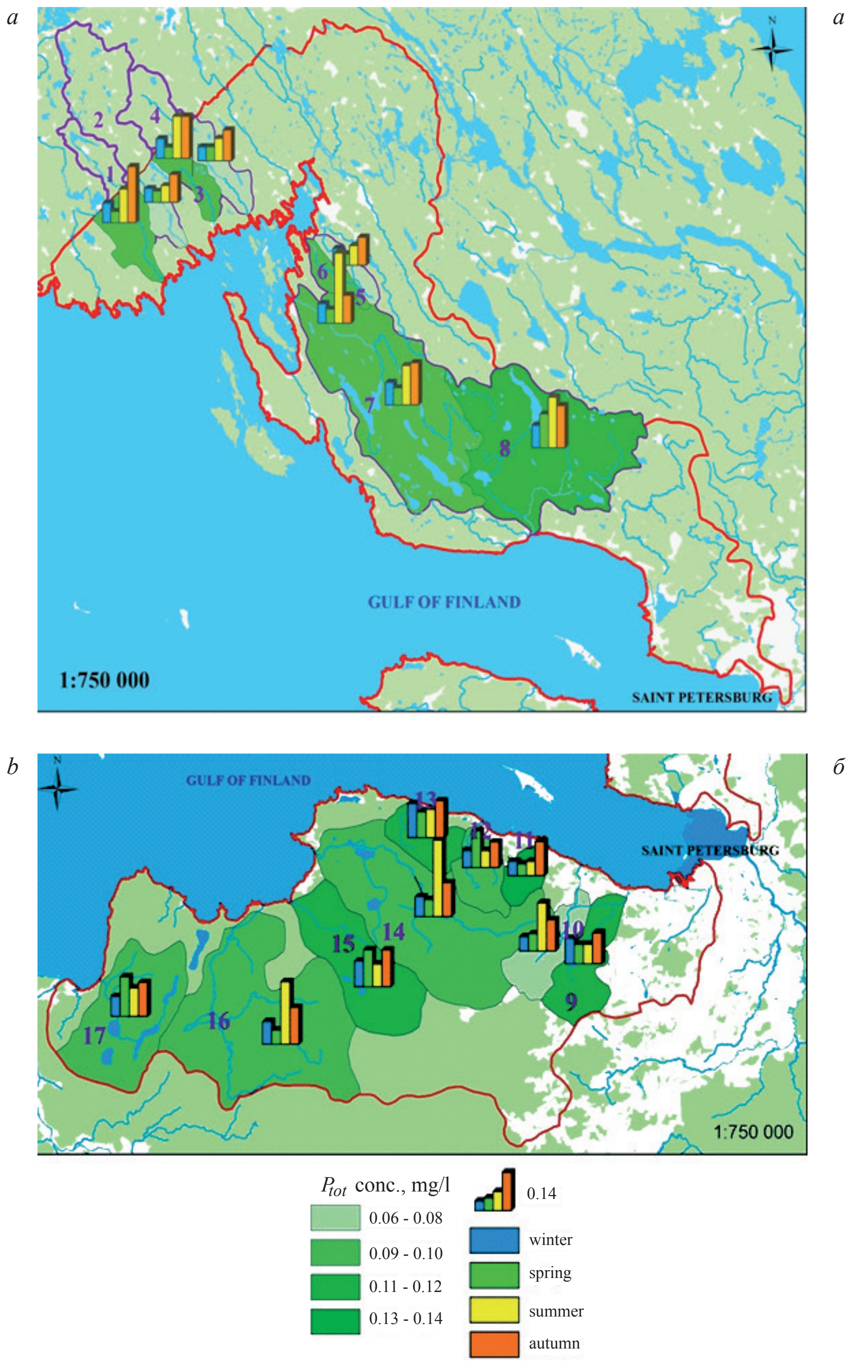

Fig. 3. Spatial and temporal distribution of P_{tot} concentrations, mg/l
(*a* — North-Eastern part, *b* — South-Eastern part of the Gulf of Finland immediate catchment).

Рис. 3. Пространственно-временное распределение концентраций $P_{общ}$, мг/л
(*a* — Северо-Восточная часть, *b* — Юго-Восточная часть частного водосбора Финского залива).

К статье *Кондратьев С. А.* и др. Биогенная нагрузка...

Kondratyev S. A. et al. Nutrient Load...

a *а*

b *б*

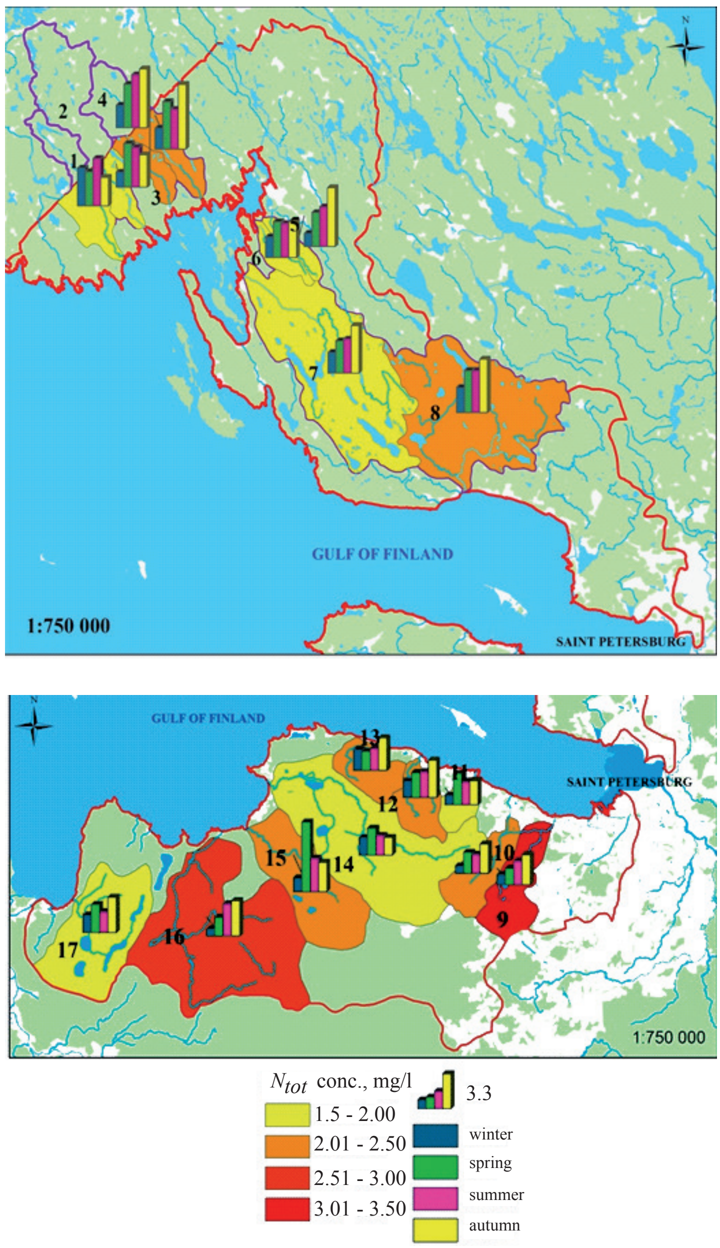

Fig. 4. Spatial and temporal distribution of N_{tot} concentrations, mg/l
(*a* — North-Eastern part, *b* — South-Eastern part of the Gulf of Finland immediate catchment).

Рис. 4. Пространственно-временное распределение концентраций $N_{общ}$, мг/л
(*а* — Северо-Восточная часть, *b* — Юго-Восточная часть частного водосбора Финского залива).