УДК 556.55; 504.4

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# ВНЕШНЯЯ И ВНУТРЕННЯЯ ФОСФОРНАЯ НАГРУЗКА НА КРУПНЫЙ ТРАНСГРАНИЧНЫЙ ВОДОЕМ В УСЛОВИЯХ МИНИМАЛЬНОЙ ПРОТОЧНОСТИ

Статья поступила в редакцию 26.02.2021, после доработки 05.06.2021

Представлены результаты оценки фосфорной нагрузки на крупнейший европейский трансграничный водоем — Чудско-Псковское озеро в условиях минимальной проточности, характерной для маловодного периода 2010–2015 гг. Расчет внешней фосфорной нагрузки выполнен с использованием модели формирования биогенной нагрузки ILLM (Institute of Limnology Load Model), разработанной в Институте озероведения РАН и учитывающей вклад точечных и рассредоточенных источников. Вынос с сельскохозяйственных полей определялся исходя из содержания $P_{\text{общ}}$ в пахотном слое почвы, дозы внесения минеральных и органических удобрений на поля и их усвоения сельхозкультурами. Для оценки современных значений площадей различных типов подстилающей поверхности, являющихся входными данными для моделирования, применялись данные космической съемки, находящиеся в режиме свободного доступа. Расчет внутренней фосфорной нагрузки на озерную экосистему за счет вторичного поступления фосфора из донных отложений выполнен с привлечением данных натурных наблюдений на акватории. Использована методика, разработанная в Институте озероведения РАН и основанная на балансовых оценках основных потоков фосфора (седиментации, захоронения и поступления из донных отложений в воду) в пограничной зоне «вода–дно». Показано, что в условиях рассмотренного маловодного периода внутренняя фосфорная нагрузка превосходит внешнюю, что негативно сказывается на эвтрофировании озера.

**Ключевые слова:** озеро, водосбор, донные отложения, биогенные элементы, внешняя и внутренняя нагрузка, эвтрофирование.

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# EXTERNAL AND INTERNAL PHOSPHORUS LOADING TO A LARGE TRANSBOUNDARY WATER BODY UNDER LOW FLOW CONDITIONS

Received 26.02.2021, in final form 05.06.2021

The article presents the results of the assessment of the phosphorus load on the largest European transboundary water body — Lake Chudsko-Pskovskoye under the conditions of the minimum flow rate typical for the dry period of 2010–2015. The external phosphorus load was calculated using the nutrient load model ILLM (Institute of Limnology Load Model) developed at the Institute of Limnology of the Russian Academy of Sciences and taking into account the contribution of point and non-point sources. Phosphorous losses from agricultural fields were determined based on the $P_{tot}$ content in the arable soil layer, application rates of mineral and organic fertilisers, and nutrient uptake by crops. Free-access satellite imagery data was used to estimate the current areas of various types of land cover, which were the input data for modeling. The internal phosphorus load on the lake ecosystem

Для цитирования: *Кондратьев С.А.*, *Брюханов А.Ю.*, *Игнатьева Н.В.*, *Шмакова М.В.*, *Обломкова Н.С.*, *Коробченкова К.Д.* Внешняя и внутренняя фосфорная нагрузка на крупный трансграничный водоем в условиях минимальной проточности // Фундаментальная и прикладная гидрофизика. 2021. Т. 14, № 4. С. 77–89. doi: 10.7868/S2073667321040079

For citation: *Kondratyev S.A.*, *Briukhanov A. Yu.*, *Ignatyeva N.V.*, *Shmakova M.V.*, *Oblomkova N.S.*, *Korobchenkova K.D.* External and Internal Phosphorus Loading to a Large Transboundary Water Body under Low Flow Conditions. *Fundamentalnaya i Prikladnaya Gidrofizika*. 2021, 14, 4, 77–89. doi: 10.7868/S2073667321040079

due to the secondary phosphorus release from bottom sediments was calculated by the data from field observations in the water area. The study applied the methodology developed at the Institute of Limnology RAS and based on balance estimates of the main fluxes of phosphorus, such as sedimentation, burial, and release into the water from bottom sediments, in the "water–bottom" boundary zone. The study demonstrated that under the conditions of the considered low-water period, the internal phosphorus load exceeded the external one, having an adverse effect on the lake eutrophication.

**Key words:** lake, catchment, bottom sediments, nutrient, external load, internal load, eutrophication.

## 1. Introduction

*The aim of the study* was the quantitative assessment of the external and internal phosphorus load, which governs the process of eutrophication of Lake Chudsko-Pskovskoye — the largest European transboundary water body, with a minimum discharge on the example of the dry period of 2010–2015.

*The study object.* Lake Chudsko-Pskovskoye (Peipsi-Pihkva Jarv in Estonian) is the fourth largest lake in Europe and the largest European transboundary water body located on the border between Russia and Estonia [1]. The total area of the lake is 3.555 km$^2$, of which 1.985 km$^2$ belong to Russia and 1.570 km$^2$ — to Estonia (Fig. 1). The reservoir consists of three main parts: Lake Chudskoye with an area of 2.611 km², Lake Pskovskoye — 708 km$^2$ and Lake Teploye connecting them — 236 km$^2$. The total volume of the water mass in the lake is 25.07 km$^3$, of which Lake Chudskoye accounts for 21.79 km$^3$, Lake Pskovskoye — 0.60 km$^3$, and Lake Teploye — 2.68 km$^3$. The average depths of the Chudskoye, Pskovskoye, and Teploye Lakes are 8.3, 3.8, and 2.5 m, respectively [2]. The trophic status of the main parts of the lake is different. Lake Pskovskoye is hypereutrophic, Lake Teploye becomes hypereutrophic, Lake Chudskoye is eutrophic [3].


**Fig. 1**. Location of monitoring stations (red points) in Lake Chudsko-Pskovskoye where bottom sediment samples were taken.

The lake plays a significant role in the economy of Estonia and North-West Russia, therefore the rational use of its biological resources and the preservation of conditions for their reproduction is a priority task for both countries. The current requirements of the EU Water Framework Directive (Directive of the European Parliament and the Council of the European Union No. 2000/60 / EC of October 23, 2000) require the development of a more detailed joint Russian-Estonian program for the rational use and protection of water resources of the lake complex. The program should include the creation of a coordinated monitoring system for both the reservoir itself and the water bodies of the drainage basin, as well as the development of methods and models to assess the impact of economic activities on the water resources of the reservoir and its drainage basin. Besides, the lake complex together with the drainage basin is one of the sources of pollution load to the Gulf of Finland of the Baltic Sea regulated by the Baltic Sea Action Plan — BSAP [4, 5]

At present, the process of eutrophication of the reservoir, accompanied by the "blooming" of water and deterioration of its quality, is of particular concern. The most important factor determining the intensity of eutrophication of Lake Chudsko-Pskovskoye is the input of phosphorus to the water mass, coming both from the catchment area (external load) and from bottom sediments (internal load). The study of the nutrient load to Lake Chudsko-Pskovskoye from the Russian catchment area in 2012–2013 at the initiative of the Neva-Ladoga Water Basin Administration, formed a disappointing conclusion that "at the moment there is no information on all sources of nutrient pollution of watercourses in the lake basin" [6]. This study considered the dry period of 2010–2015 with the relevant estimation of external and internal phosphorus load on the lake. In dry years, the flow rate of the reservoir decreases, thus creating favorable conditions for accelerating the eutrophication process.

## 2. External phosphorus load on Lake Chudsko-Pskovskoye from the Russian catchment

The Russian part of the catchment area includes the territory of the Pskov Region, slightly covering the Slantsevsky, Luzhskiy and Kingiseppsky Districts of the Leningrad Region. In the Russian part of the catchment area, the main tributary of the lake is the Velikaya River with a catchment of 59 % of the total. Significant tributaries of the lake are also Zhelcha, Piusa and Gdovka Rivers. The largest tributary from the Estonian side is the Emajõgi River with a catchment area accounting for 22 % of the total. The abundance of rivers and reservoirs within the basin is explained by excessive moisture, flat relief, and poor permeability of prevailing soils. The rivers are characterized by mixed feeding, the share of melted snow water accounts for about 50 % of the annual runoff, rainwater and groundwater — for 25 % each. The swampiness of the territory is about 11 %, small lakes occupy around 7 % of the catchment area [1, 7].

Agricultural activity is one of the most important sources of nutrient load on water bodies. Above 560 operating agricultural enterprises, about 1200 peasant (farmer) households and individual entrepreneurs, and above 205 thousand private subsidiary plots are found in the catchment area. Analysis of technologies and amount of organic fertilizer use in the region shows a low level of efficiency [8, 9]. Agricultural lands have sod-podzolic soils. In some places sandy loam and peaty soil can be also found. The soil structure is predominantly light, which leads to high leaching of nutrients [10].

The boundaries and areas of the drainage basin of the Velikaya River (site — Pskov) and the entire territory of the Russian catchment area of Lake Chudsko-Pskovskoye were identified at the initial work stage. A digital terrain model SRTM version 4 [11] was used as a source of initial information. It was preliminarily subjected to hydrological correction using an algorithm for breaking the boundaries of closed depressions in the direction of surface runoff lines [12], and then along with it the boundaries of drainage basins were calculated in GIS SAGA 3.0.0. Figure 2 shows the obtained diagrams of the watershed of the Velikaya River, the river section — Pskov (Fig. 2, *a*) and the Russian part of the catchment (Fig. 2, *b*).

Methods of mathematical modeling were applied to estimate the external phosphorus load on the lake both from the catchment area of the Velikaya River and from the entire territory of the Russian catchment area of Lake Chudsko-Pskovskoye. At the same time, the model was verified for adequacy with the described processes by comparing the calculation results performed for the Velikaya River (site Pskov) with the results of long-term monitoring in the indicated section. Only after that the phosphorus loading to the lake was calculated for the entire Russian catchment territory, including the areas not covered by regular field observations of the runoff and nutrient losses.

Runoff and phosphorus load were calculated with the ILLM — Institute of Limnology Load Model (State registration No. 2014612519 of 27.02.2014). ILLM was developed based on existing experience of runoff and nutrient transport modeling [6, 13–15]. The HELCOM recommendations for assessing the load on water bodies of the Baltic Sea were also built into the model [16]. The model is designed to solve problems associated with the quantification of nutrient load from point and nonpoint pollution sources, and to predict inputs in connection to possible

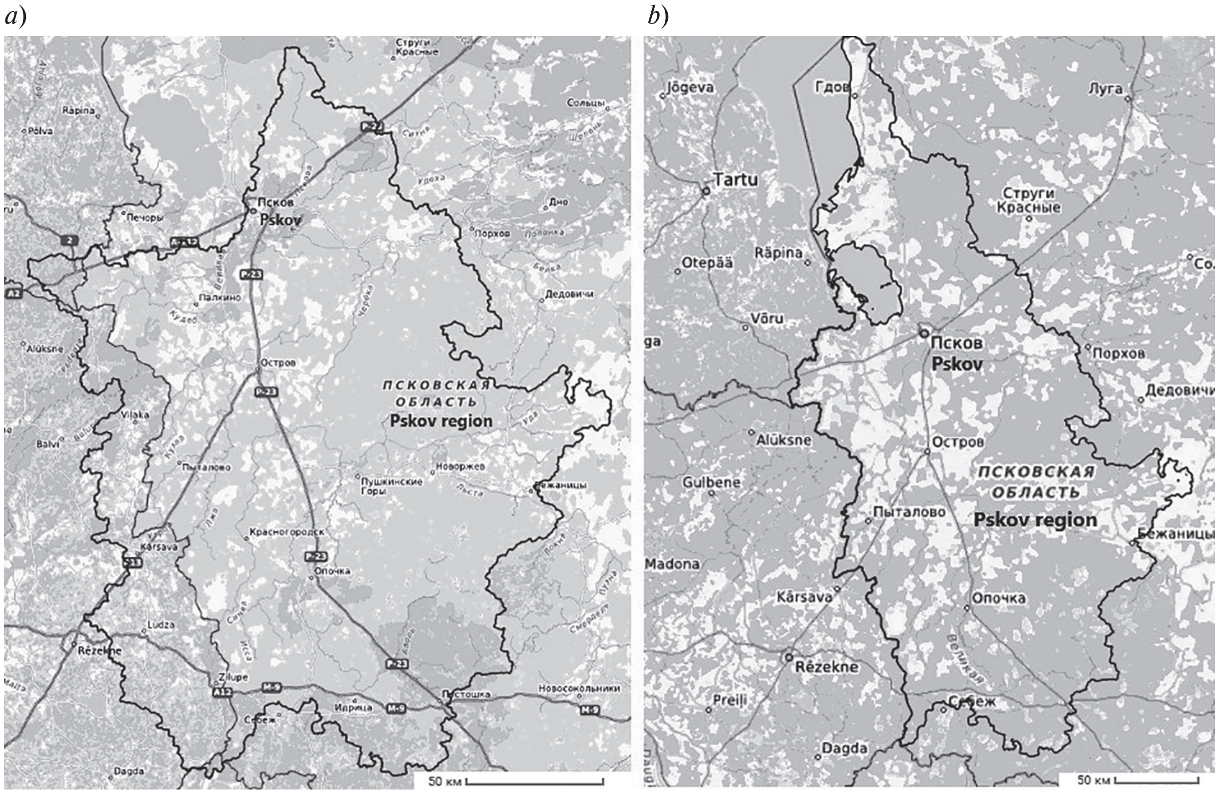


**Fig. 2**. Maps with the Velikaya River catchment area, the river section — Pskov (*a*) and the Russian part of the catchment of the whole Lake Chudsko-Pskovskoye (*b*).

anthropogenic and climatic changes. The model also allows estimating the nutrient run-off due to influence of hydrological factors and retention by the catchment. The catchment area is represented as a homogeneous storage, the time step of calculation — 1 year. The modelling result is the nutrient load estimates, including their sources distribution.

The model of nutrient loading was verified at several sites located in the Northwest region of Russia in the catchment areas of the Velikaya, Luga, Mga, Izhora and Slavyanka Rivers [13]. According to the outcomes of EU project BaltHazAR II "Building capacity within environmental monitoring to produce pollution load data from different sources e.g. HELCOM pollution load compilations" [17], "... the ILLM model can be used to calculate the nutrient load on the Baltic Sea from non-monitored and partly-monitored areas in the Russian part of catchment area". The conclusions on the project RusNIP II "Implementation of the Baltic Sea Action Plan (BSAP) in the Russian Federation" [18] mention that "The ILLM model is most suitable for use in relatively large catchments". For a more detailed description of the nutrient load coming from agricultural enterprises, the ILLM model is supplemented with the corresponding calculation block proposed by the specialists of the Institute for Engineering and Environmental Problems in Agricultural Production [8, 9].

According to the calculation pattern in the ILLM model, the main components of the total external phosphorus load on a water body ($L$) are diffuse nutrient emission by non-agricultural land ($L_e$), the load generated by agricultural activity ($L_{agr}$), discharges of point pollution sources in the catchment area ($L_p$) and atmospheric deposition ($L_a$):

$$L = (L_e + L_{agr} + L_P + L_a)(1 - R). \quad (1)$$

All terms of equation (1) have the dimension of t/year, except the dimensionless coefficient of nutrient retention by the catchment $R$.

The non-point load from natural and changed landscapes that are not currently affected by agricultural impact ($L_e$ — in formula (1)) is generated by the nutrient leaching from soils due to the emission of nutrients from soils with rainwater and meltwaters and is calculated as follows:

$$L_e = \sum_{i=1}^{n} C_i y_i A_i \,/\, 1000, \quad (2)$$

where $C_i$ is the average concentration of nutrients in the runoff from the $i$-th type of the land surface, mg/l; $y_i$ — layers of runoff from the considered types of the underlying surface, mm/year; $A_i$ — areas of the land surface types under consideration, km$^2$; $n$ is the number of land surface types under consideration.

As a rule, significant problems in modeling the nutrient inputs from large catchments arise due to the need to reliably determine the current values of the areas of various types of land surface ($A_i$ in equation (2)). In this study, free access space survey data, namely archive of images of the Landsat-8 spacecraft of the United States Geological Survey (USGS, http://earthexplorer.usgs.gov), was used to estimate the indicated areas. The land surface types on the catchment were identified by the data of 30-meter spatial resolution during the period of low-cloud weather in 2015–2017 by the method of automatic classification using the ERDAS Imagine Professional software package. Data on the distribution of the normalized difference vegetation index (NDVI) was used for the classification [19]. The following types of land surface were identified: forests, fields, meadows, swamps, urbanized zones and abandoned areas, water bodies. The calculated areas for all identified types of the underlying surface are given in Table 1.

According to the results of earlier studies [20–22], the values of the total phosphorus concentration ($C_i$ in formula (2)) in soil waters and primary links of the hydrographic network for various types of the land surface were taken to be approximately equal to 0.05 (mg/l) for natural areas (forests and swamps), 0.08 (mg/l) for fields and meadows not currently involved in agricultural production, and 0.20 (mg/l) for urbanized areas and abandoned land. The specified values were previously used in ILLM model calculations, including those produced for HELCOM PLC database [6, 23].

Nutrient inputs on inland surface waters from the fields of agricultural enterprises $L_{agr}$, [t/year] was calculated with the method proposed by the Institute for Engineering and Environmental Problems in Agricultural Production (IEEP) — branch of FSAC VIM [8, 9]. Mean annual losses to surface waters were calculated based on phosphorus content in the arable layer, the amount of organic and mineral fertilisers applied and nutrient uptake by crops, taking into account rates of nutrient leaching from the arable soil layer, distance from the fields to the water bodies, soil type and mechanical composition. Besides, the introduction of the best available techniques (BAT) for application of organic and mineral fertilisers was also considered. Annual manure output was determined with due account for current housing and manure removal systems used in the Pskov Region. Initial information about key parameters used to determine the phosphorus load on the catchment from agricultural enterprises is shown in Table 2.

Currently, the main official source of information on point wastewater discharges is the statistical form 2TP vodkhoz of the Ministry of Natural Resources and Environment of the Russian Federation. The data contained in

*Table 1*

**Areas of various types (classes) of the land surface of the catchment (km$^2$), obtained as a result of interpretation of satellite images**

| Type (class) of underlying surface | Catchment of the Velikaya River (site — Pskov) | Russian part of Lake Chudsko-Pskovskoye catchment |
|---|---|---|
| Forest | 10440 | 10565 |
| Field | 6885 | 6635 |
| Meadow | 924 | 987 |
| Swamp | 6495 | 6792 |
| Urbanized and abandoned land | 708 | 733 |
| Water areas | 410 | 443 |
| Unidentified objects (clouds) | 137 | 195 |
| Total | 25999 | 26350 |

*Table 2*

**Key parameters used to determine the agricultural load**

| Parameter | Russian part of the catchment | Velikaya River catchment |
|---|---|---|
| Cattle stock | 103900 | 69785 |
| Pig stock | 403676 | 386346 |
| Sheep and goats stock | 27062 | 24458 |
| Poultry stock | 213758 | 178150 |
| Number of horses | 2252 | 2172 |
| Fertilization area (ha) | 142518 | 132705 |
| $P_{tot}$ application rate with mineral fertilisers (kg/ha) | 6.7–21.1 | 6.7 |
| $P_{tot}$ application rate with organic fertilisers (kg/ha) | 3.2–108.4 | 3.2–108.4 |
| Current phosphorous loss (t/year) | 246.28 | 238.29 |
| Phosphorous loss in case of BAT introduction (t/year) | 235.60 | 228.34 |

these forms are given with annual averaging, which imposes limitations in this data use in the calculations and mathematical models. Nutrient inputs from point sources ($L_P$ in equation (1)) on the territory of the Russian part of the catchment in 2014–2015 was assumed to be 46 tP/year for the purposes of this study.

*In-situ* measurement of atmospheric load ($L_a$ in equation (1)) is usually associated with the hydrochemical analysis of samples of wet and dry precipitation with subsequent interpolation and extrapolation of data. The value of 5 kg/(km$^2$ a), obtained by Estonian specialists, was used in this study [3] for calculating the load from the atmosphere on the studied drainage basin.

As a rule, most of the nutrients supplied to the catchment from various sources do not reach the mouths of large rivers, owing to retention by the catchment and various components of the hydrographic network. As a result, the total load on the water body is only a part of the nutrient input to the catchment. To calculate the retention coefficient ($R$ in equation (1)), the following empirical equation is used [1, 15]:

$$R = \left(1 - \frac{1}{1 + aq^b}\right), \tag{3}$$

where $q$ is the specific instream flow, $l$/(km$^2$ sec); $a$ and $b$ are dimensionless empirical parameters, the values of which are 26.6 and −1.71, respectively. The runoff rate $q$ is related to the runoff depth $y$ (mm/year) by the empirical relationship $q = 0.03171y$. The data of actual measurements, analytical or empirical distribution curves, as well as hydrological models can be used to calculate the runoff depth and water discharge depending on specific hydrometeorological parameters [14, 24].

The background (natural) phosphorus load is caused by losses from uncultivated lands, as well as part of losses from managed land that would occur irrespective of anthropogenic factors. When calculating the background load on the catchment, all anthropogenic pollution sources (point discharges, application of mineral and organic fertilisers, export from agricultural and urbanized territories) are excluded from consideration. Thus, the background component of the phosphorus load on a water body $L_{nat}$ (t/year), related to the natural sources, is determined as follows:

$$L_{nat} = (1-R)\left[L_a + C_{nat}\; y(A\left(1 - W/_{100}\right)/1000\right], \tag{4}$$

where $W$ is the relative water surface area (% of the total catchment area). In addition, the model calculates the area specific phosphorous losses (kg/(km$^2$ a)) from the catchment, equal to $L$/(1000 A), as well as its background (natural) component, equal to $L_{nat}$ /(1000 A).

Fig. 3 shows the runoff values calculated from observational data for the period 2010–2015 from the drainage basin of the Velikaya River (site Pskov), the input of total phosphorus according to the monitoring data of the North-West Roshydromet, and the results of phosphorus load modeling. Following conclusions can be drawn based on the analysis of the abovementioned results.

The average runoff in 2010–2015 was 155 mm/year. This value corresponds to 95–97 % exceedance probability according to the previously calculated runoff distribution parameters for the Russian part of the studied basin [6]. In this case, the long-term average runoff is 242.4 mm/year [6]. 99 % exceedance probability is represented by the year 2014, when the runoff depth was 108 mm/year. Such low values of runoff resulted in a decrease in the inflow to the lake, which negatively affected its eutrophication status. When runoff is 155 mm/year, the phosphorus input calculated by the model is 262.5 t/year. Good comparability between the mentioned value and the average value for the period of 2010–2015, obtained from the monitoring data of Roshydromet for the Pskov site (253.0 tP/year), allows a positive assessment of the modeling results and the use of the model to calculate the load on the lake from the entire Russian catchment area. This conclusion is confirmed by a good agreement between dynamics of the average annual $P_{tot}$ transport from the Velikaya River catchment, estimated by the model, and the measured values (Fig. 3).

Calculation results of phosphorus load on Lake Chudsko-Pskovskoye from the Russian part of the catchment for the average run-off of the period of 2010–2015, which is 155 mm/year, are given in Table 3. According to the presented data, it can be concluded that at low flow conditions, inherent in the considered period, 622.6 tP/year are supplied on the studied catchment area. The catchment area and its hydrographic network retain 396.0 tP/year. $P_{tot}$ input to the lake from the Russian catchment area is 266.6 tP/year, of which 45 % (121.0 tP/year) is the background or natural component.

It should be noted that the calculated phosphorus load from the entire Russian drainage basin is 266.6 tP/year and close to the Velikaya River phosphorus input (262.2 tP/year). This is explained by the fact that the watersheds under consideration do not differ greatly in the area (Table 1), since the part of the Velikaya River catchment, located in the territory of Latvia (11 % of the area), was not taken into account when calculating the area of the Russian catchment area.

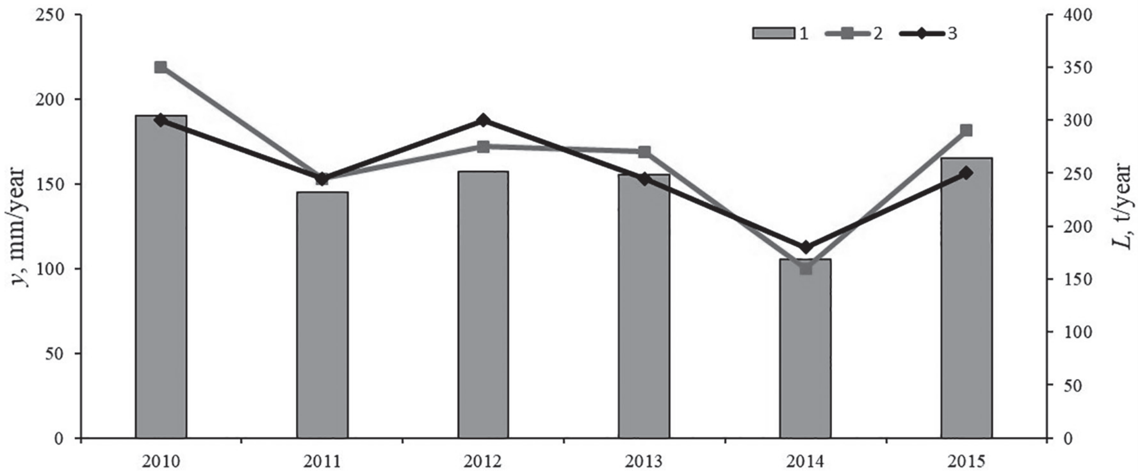


**Fig. 3**. The Velikaya River: runoff *y*, mm/year (*1*), calculated (*2*) and observed (*3*) phosphorus load *L*, t/year for the low flow period of 2010–2015.

*Table 3*

**Components of the phosphorus load from the Russian part of the catchment area of Lake Chudsko-Pskovskoye for the average flow conditions in 2010–2015 (runoff *y* = 155 mm/year)**

| | |
|---|---|
| Total load on the drainage basin's hydrographic network, t/year | 622.6 |
| Retention by the catchment and its hydrographic network, t/year | 396.0 |
| Load on a water body, t/year | 266.6 |
| Background (natural) component of the load, t/year | 121.0 |
| Area-specific load, kg/(km$^2$ year) | 10.12 |
| Area-specific background load, kg/(km$^2$ year) | 4.59 |

If we take into account the conclusion of the work [25] that the phosphorus load on the lake is distributed between Russia and Estonia almost in the same proportion as the occupied catchment area, the approximate estimate of the average total load on the lake is 445 tP/year.

## 3. Internal phosphorus load

Intra-water processes, in particular, a material exchange between water and bottom sediments, play an important role in the formation of the phosphorus pool in the water mass, which determines the level of bioproductivity of the reservoir. In the "water–bottom" boundary zone, the ongoing processes of accumulation, transformation and transport of phosphorus-containing compounds result in the main phosphorus fluxes formation: sedimentation on the bottom surface (*S*), burial in the sediment mass (*B*) and release from bottom sediments into the water mass (*J*), creating an internal phosphorus load (*l*) on the reservoir. As the eutrophication process develops in the lake, the intensity of metabolic processes increases, while the ratio of the main fluxes changes. If in oligotrophic lakes most of the phosphorus that has settled to the bottom is irretrievably buried in bottom sediments, then with an increase in the level of bioproductivity, the fluxes of phosphorus from bottom sediments into the water significantly increases also, leading to the so-called "secondary eutrophication", which aggravates the development of this negative process. Thus, in the course of eutrophication, the significance of bottom sediments as a source of phosphorus input into the water mass increases [26–28], which makes it necessary to take into account the contribution of the internal phosphorus load to the formation of the total load on the reservoir.

The formation mechanisms of the internal phosphorus load are quite diverse [26]. Diffusion and convective transfer are the main mechanisms of phosphorus compounds transport from bottom sediments to the water mass. These in turn have several components. In shallow lakes and in the littoral of deep-water lakes, where the temperature, hydrodynamic characteristics, and the intensity of biological processes in the water-bottom boundary zone are subject to seasonal dynamics, the amount of phosphorus flux from bottom sediments to the water mass also varies. Under these conditions, the water mass can be repeatedly mixed throughout the year to the bottom, affecting the upper layer of bottom sediments. If in deep water bodies the internal load is always smaller than the external one, then in shallow water it can be many times higher. To assess the effect of bottom sediments on the formation of water quality in a reservoir, it is important to know the total flux of matter from the sediment, which is formed as a result of the action of all possible mechanisms.

To assess the internal phosphorus load on Lake Chudsko-Pskovskoye, we used the method developed at IL RAS [27, 28] and previously used to perform similar assessments for different types of lakes in the North-West of the Russian Federation [27–31]. The method is based on balance calculations of the main fluxes of phosphorus (sedimentation, burial and release from bottom sediments into water) in the “water-bottom” boundary zone and allows calculating the total phosphorus flux from the bottom.

Field data for assessing the internal phosphorus load were obtained during the lake surveys. A sampling of undisturbed bottom sediment cores up to 16 cm thick was carried out at 9 stations located in different regions of the Russian territory of Chudskoye and Pskovskoye Lakes (Fig. 1). Due to the absence of sampling stations in the water area of Lake Teploye it was taken into account together with Lake Pskovskoye when calculating the fluxes, since these parts of the water system are very similar in terms of the phosphorus content in the water mass and the degree of eutrophication [32]. Three layers were taken from the sediment cores: ~ 0–0.2 cm (uppermost sediment layer), 0.2–2 cm, and 15–16 cm. The total phosphorus content was determined in samples of uppermost sediment layers and lower core depths core layers [33], samples from the depth 0.2–2 cm were used to determine the porosity and specific gravity of the dry sediment. The values of the sedimentation rates for fine-grained sediments (8 stations) — from 4 to 8.3 mm/year, also necessary for calculating the fluxes, were taken from the literature [34, 35], for coarse-grained dispersed sediments (station 13 in the south of Lake Chudskoye), a value of 2.5 mm/year was taken. The spatial distribution of the types of bottom sediments in the studied lake is presented [36].

The more highly productive Lake Pskovskoye is characterized by a higher phosphorus content in the surface sediment layer than Lake Chudskoye. So, the content of $P_{tot}$ in the solid phase of the surface layer (uppermost sediment layer) of fine-grained bottom sediments for Pskovskoye and Chudskoye Lakes is 0.99–1.25 and 0.72–1.14 mgP/g, respectively (the calculation is made for air-dry sediment). A regular tendency of an increase in the phosphorus content from coarse-grained to fine-grained sediments was noted — at the station with silty sediment the content of $P_{tot}$ in the uppermost sediment layer was 0.20 mgP/g. At a depth of 15–16 cm in the thickness of the sediment, the phosphorus content in Lake Pskovskoye, on the contrary, was lower than in Lake Chudskoye — 0.38–0.73 and 0.64–0.75 mgP/g, respectively. The porosity values of finely dispersed sediments were 0.92–0.95, coarsely dispersed — 0.70, the specific weight of dry sediments ranged from 2.24 to 2.86 g/cm$^3$.

The greater decrease in the phosphorus content with depth in the sediments of Lake Pskovskoye as compared to Lake Chudskoye indicates that a larger fraction of the phosphorus deposited on the bottom as a result of sedimentation is returned to the water mass, creating an internal load. The fluxes of sedimentation and burial of phosphorus were calculated for each station as well as the phosphorus release from bottom sediments into the water as the difference between *S* and *B*. In general, the elfkbnm sedimentation fluxes in Lake Pskovskoye are higher than in Lake Chudskoye. The largest values of fluxes relate to the zones where fine-grained sediments are found. Taking into account the spatial distribution of sediment types, it has been calculated that during the year 2.816 tons of phosphorus settle on the bottom of the lake, of which 2.049 tons in Lake Chudskoye and 767 tons in Pskovskoye and Teploye Lakes (Table 4). About 66 % of the phosphorus deposited on the bottom of Lake Chudskoye is buried in the sediment, the corresponding proportion of phosphorus in Lake Pskovskoye is slightly lower — 51 %, i.e. the phosphorus holding capacity of sediments (*B*/*S*) decreases with an increase in the trophic status of the reservoir. On average, 62 % of the sedimented phosphorus is buried in the entire lake system.

The calculated values of phosphorus fluxes from fine-grained bottom sediments are of the same order and amount to 0.99–1.19 mgP/(m$^2$day) for Lake Pskovskoye and 0.67–1.24 mgP/(m$^2$day) for Lake Chudskoye (Fig. 4). The small-

*Table 4*

**Sedimentation (*S*), burial (*B*), phosphorus release from bottom sediments (*J*) of Lake Chudsko-Pskovskoye and phosphorus retention capacity of bottom sediments (*B*/*S*)**

| Lake | *S* | | *B* | | *B*/*S*, % | J | |
|---|---|---|---|---|---|---|---|
| | g P/(m$^2$ year) | t/year | g P/(m$^2$ year) | t/year | | g P/(m$^2$ year) | t/year |
| Chudskoye | 0.87 | 2.049 | 0.57 | 1.354 | 66 | 0.29 | 695 |
| Pskovskoye and Teploye | 0.80 | 767 | 0.41 | 389 | 51 | 0.39 | 378 |
| Whole lake | 0.85 | 2.816 | 0.53 | 1.743 | 62 | 0.32 | 1073 |

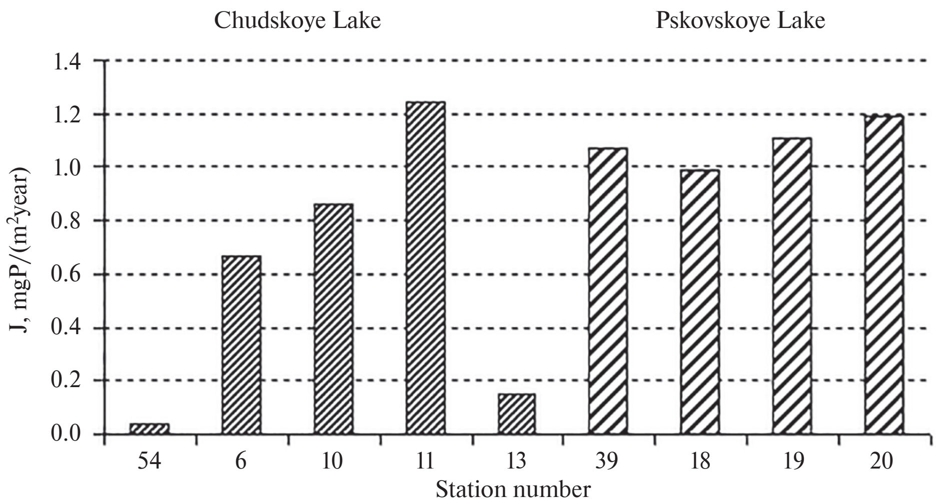


**Fig. 4**. Distribution of values of phosphorus fluxes J from bottom sediments of Lake Chudsko-Pskovskoye Lake Peipus along a conditional longitudinal transect from north to south.

est flux relates to silty sediments (station 13), as well as fine-grained sediments at st. 54. It is interesting to note the decrease in the phosphorus flux from the fine-grained sediments of Lake Chudskoye with distance from Lake Pskovskoye. Summary of literature data by M.V. Martynova (1984) shows that in freshwater mesotrophic reservoirs the amount of phosphorus released from the bottom is tenths of a milligram per square meter per day average, not exceeding 1 mgP/($m^2$day). With an increase in the reservoir productivity, the flux from the bottom increases significantly.

In general, during the considered low-water period, 1073 tons of phosphorus from bottom sediments entered the water of the lake system annually (the average flux was 0.32 gP/($m^2$year), of which 695 tons — to Lake Chudskoye and 378 tons — to Lake Pskovskoye (Table 5). The calculation did not include the lake bottom areas occupied by moraine, band clays and peat, where lacustrine sedimentation was not found. The average density of phosphorus flux from the bottom of Lake Pskovskoye was about 1.3 times higher than that from Lake Chudskoye (0.29 and 0.39 gP/($m^2$year), respectively. The average density of phosphorus flux from bottom sediments of the entire lake system was 0.32 gP/($m^2$year). The obtained estimate of the internal phosphorus load differed from the estimate of 2008 [29]. Previously only the sediment layer 9—10 cm was considered, that is, at the lower boundary of the so-called “active” layer of bottom sediments involved in the entire lacustrine metabolism, below which there is a “historical” layer that does not affect processes in the water mass. This concept was introduced by the Swedish botanist and limnologist E. Naumann back in the 30s of the last century. However, the analysis of the vertical distribution of phosphorus in the “long” columns of fine-grained bottom sediments in central parts of Lake Chudskoye performed by Estonian researchers [34, 37], the “active” layer was approximately 15—20 cm, which resulted in an overestimation of the phosphorus burial flux, and, consequently, an underestimation of the flux from bottom sediments. It should be noted that, most likely, the real value of the internal phosphorus load will be higher than the value obtained in this study. The applied estimation method ignores the convective transport during wind and anthropogenic turbidity of sediment, which is characteristic of a shallow polymictic reservoir, such as the lake under study, as well as the phosphorus turnover degree in the lake throughout the year.

## 4. Conclusion

Quantitative assessment of the external phosphorus load on Lake Chudsko-Pskovskoye from the Velikaya River catchment and entire Russian territory of the catchment for the period of 2010—2015 was performed with the use of nutrient load modeling methods accompanied by satellite images analysis to identify various types of surface areas on the catchment. The average runoff depth was 155 mm/year for these years, it is 95—97 % of exceedance. According to calculation results, 622.6 tP/year were produced on the catchment area during the studied low-water period. Phosphorus retention by underlying catchment surface and hydrographic network amounted to 396.0 tP/year. The input to the lake from the Russian catchment area was 266.6 tP/year, of which 121.0 tP/year was the background or natural component. Taking into account that the phosphorus load on the lake is distributed between Russia and Estonia almost proportionally to the occupied catchment area [7], it is possible to roughly estimate the average total external load on the lake for the considered low-flow period to be 445 tP/year.

Field observations at 9 monitoring stations in the water area of Lake Chudsko-Pskovskoye, allowed for approximate estimates of the average annual phosphorus input from bottom sediments into the water mass of the lake system. The internal phosphorus load on the lake as a whole was 1073 t/year. Lake Chudskoye accounted for 695 tons, Pskovskoye and Teploye Lakes — for 378 tons.

Thus, it was possible to show that the internal phosphorus load on Lake Chudskoye was more than 2 times higher than the external one under the conditions of the considered low-water period of 2010–2015. It has a negative effect on the intensity of anthropogenic eutrophication of the lake, since there are practically no ways to reduce the internal load in such a large reservoir in a short time. The most common methods for removing contaminated bottom sediments using dredging equipment in Russia, firstly, can be applied only locally in small areas, and, secondly, they will inevitably lead to a sharp deterioration in water quality in the area of work due to the stirring up of bottom sediments. It should be kept in mind that this is a transboundary reservoir and the reaction from the Estonian part may be extremely negative. Therefore, be aware of the possibility of the use of modern methods of restoration of water bodies such as biological reclamation. A non-alternative way to improve the status of the reservoir is to reduce the external load. This is a potentially promising measure as follows from the modeling results shown in Table 3. Reduction of the internal load is a long-term process associated with the gradual depletion and removal of nutrients accumulated in the bottom sediments of the lake. It is known that at the initial stage of eutrophication the bottom sediments restrain its rapid progression. At the same time, they are the first obstacle to the quick lake de-eutrophication. [38].

## 5. Funding

The research was funded by the study № 0154–2019–0001 of the State research plan for the IL RAS.

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