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INTERNAL PHOSPHORUS LOAD OF THE IVAN'KOVSKOE RESERVOIR

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The work is devoted to the study of internal phosphorus load in Ivan'kovskoe reservoir according to observations in 2020–2024. The calculation results are based on the experimental average data of mineral phosphorus flux from sediment sample studies, which were conducted in different seasons. The greatest phosphorus flux from sediments is associated mainly with periods of oxygen deficiency in the bottom layer and areas with sediments rich in organic matter. The use of the HRM-MSU mathematical model made it possible to calculate the duration of these periods in the absence of regular monitoring data. The internal phosphorus load is amount under other favorable conditions to 1646–1903 *t* P-PO_4/year and exceeds the external one.

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***Keywords*:** phosphates, internal load, reservoir, bottom sediments, dissolved oxygen.

Introduction. The main reason for eutrophication of water objects is considered to be the excessive inflow of nutrients into them. Under otherwise favorable conditions it can lead to an acceleration of primary production and an increase in the trophic status of the reservoir [1]. The influence of nutrients, especially such as nitrogen and phosphorus, accelerates the processes of eutrophication of river sections that are under direct or indirect contact with fresh manure or incompletely processed animal waste [2]. Under conditions of climatic changes, with an increase in water temperature and in the duration of oxygen deficiency periods [3], the internal load may increase. The predicted increase in the frequency and intensity of extreme hydrological events (high floods and periods of low water content), as well as the projected increase in the nutrient load on reservoirs due to changes in the flow regime and anthropogenic impact on the catchment area may also lead to an increase in nutrient load [4]. As a result, the flux of organic matter (OM) and related nutrients into sediments also increases. It leads to an increased reverse flux of phosphorus and labile forms of nitrogen from sediments into the water. In eutrophic reservoirs, it

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becomes an important source of additional nutrients entering the water even if pollution from the catchment area is diminished.

Bottom sediments (BS) are an active component of the ecosystem with active biological and physico-chemical processes in them. Dissolved phosphorus is released from BS in the form of diffusion flux, stirring, bioturbation, and gas release. The main factors influencing the flux of phosphorus from BS are: redox potential, pH and temperature, as well as microbiological activity [5]. The water of the pore solution, in close interaction with OM and mineral particles of the sediment, is enriched with phosphorus as a result of various physical, chemical and biological processes. Therefore, a concentration gradient of dissolved phosphorus arises and is maintained at the water-sediment boundary, which determines the presence of diffusion fluxes that are directed from BS into the water. When the dissolved oxygen content is more than 8 *mg*/*L*, mineral phosphorus is sorbed on hydroxides or forms insoluble complexes with them, and BS become an "absorber". Under anaerobic conditions, iron, manganese and phosphorus actively diffuse into water during the breakdown of hydroxides and the reduction of complex compounds [6].

In most reservoirs, phosphorus accumulation in BS, according to Kotserki H.-P., is 2–90% of the external load, and phosphate output from bottom sediments (secondary pollution) in eutrophic lakes can exceed 50% of their accumulation in BS, and in reservoirs – up to 25% [7]. In literature the data on the ratio of internal and external phosphorus loads on reservoirs vary greatly. And not only because of the wide variety of reservoirs, their catchments and the peculiarities of the phosphorus compounds transformation in BS, which determine the amount of its flux into the water, but also because there is currently no generally accepted definition of the internal nutrient load. S.P. Kitaev proposed calculating the internal nutrient load as the difference between the content of nutrients in gross primary production (phytoplankton, macrophytes, periphyton, phytobenthos) and the magnitude of their external load [8]. In this case, in 37 reservoirs of Russia, Europe, and North America analyzed by him according to literature data, the internal phosphorus load significantly exceeds the external one and averages 80% of the total load on the reservoir.

The internal load consists not only of nutrients from BS, it is necessary to take into account other internal sources of their inclusion in the biotic cycle: the release with the excrement of planktonic and benthic organisms, invertebrates, fish, as a result of the vital activity of macrophytes, bacteria, decomposition of dead organisms in water. In this case, according to data on 26 different reservoirs, the internal phosphorus load can be from 1 to 71% of the external load [7–8], with an average value of 18%. Recent works indicate that phosphorus flux from BS in conditions of minimal flow, typical for low-water periods, may exceed the amount of phosphorus inflow from the catchment area [9].

The purpose of the work is to evaluate the internal phosphorus load from BS in Ivan'kovskoe reservoir based on the results of field observations and experimental studies, taking into account their spatial heterogeneity and intraannual variability of phosphorus flux and to compare it with the inflow of phosphorus from the catchment area.

Materials and Methods. The object of the work is the valley-type Ivan'kovskoe reservoir with seasonal flow regulation and significant anthropogenic stress, especially in the catchments of right-bank tributaries. It is part of the River Volga cascade and was created in 1937 to improve municipal and industrial water supply, solve issues of navigation and hydropower, as well as to develop fisheries and recreation. Its area is 316 km^2, the volume is 1.22 km^3, the average and maximum depth are 4 *m* and 19 *m* [10]. The reservoir is relatively shallow (depths 0–2 *m* occupy 48% of the reservoir area) [11]. The average water exchange coefficient is 10.3 yr^{-1}, while the reservoir is characterized by both intraannual and interannual variability in the intensity of water exchange depending on the water inflow of the year.

BS of the Ivan'kovskoe reservoir is represented by a diverse type of material depending on the area and morphological parts of the flooded valley: relatively organic-rich BS predominate in the riverbed, silted sand prevails on the floodplain and in the upper part of the reservoir [12].

To determine the external phosphate load of the reservoir monthly sampling was carried out in the mouths of 14 tributaries in 2022–2023 (Fig. 1). Water discharge was not measured during sampling, so the obtained data were used as a characteristic value for the month.

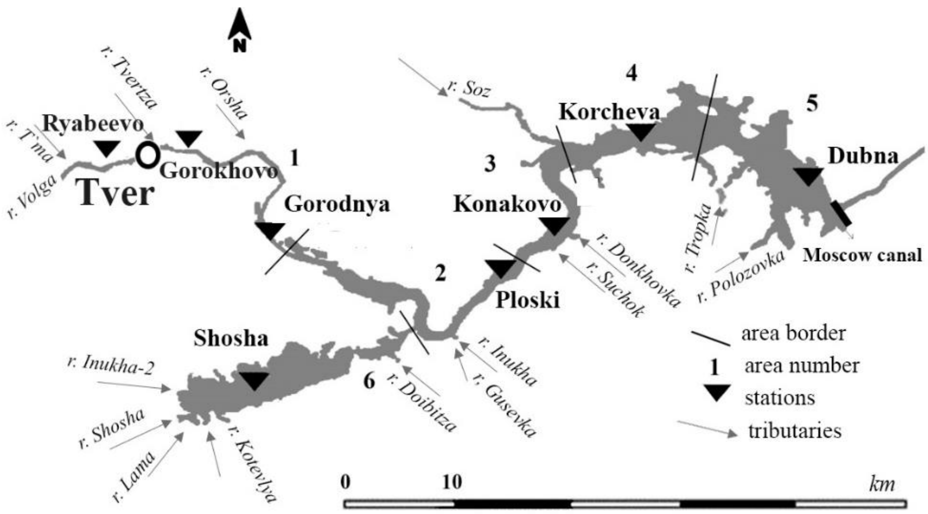

Fig. 1. Diagram of the tributaries of the Ivan'kovskoe reservoir and its division into districts during hydrological and hydrochemical surveys.

According to [11], the percentage of small tributaries in the total surface inflow of water into the Ivan'kovskoe reservoir is about 18.1%, more than half of the inflow comes from Volga River (54.2% of the inflow in the Staritsa gauging station), Tvertsa River − 19.6%, T'ma River − 3.3%, Shosha River and Lama River – each per 2.4%. Sampling in the Volga River was carried out in Ryabeevo upstream Tver and in Gorokhovo below the output of Tver sewage treatment plants 12 *km* below the mouth of the Tvertsa River to assess the contribution of urban runoff to the external phosphorus load of the reservoir. For large tributaries: the Volga, T`ma, Tvertsa, and Lama Rivers, information on water discharge was obtained from the open source: Automated Information System for State Monitoring of Water bodies (https://gmvo.skniivh.ru/, closed in September 2025), and the Shosha runoff was obtained by analogy from the Lama River. The runoff from the Volga catchment area between Staritsa and Tver was determined by the runoff module of the River T`ma. For the calculation of phosphates inflow from a hydrometrically unexplored area, their concentration was determined based on the results of analyses of water samples from small rivers as a weighted average value, taking into account the area of their catchment. The discharge of water from the unexplored part of the catchment was determined by the difference between the total inflow into the reservoir and the total inflow of rivers covered by observations.

The phosphorus flux from bottom sediments was determined using a tube method [7, 13, 14] during the period of surveys in 2020–2024. The advantage of this method, which has ensured its wide distribution and application, is the direct determination of the flux. The peculiarity of our studies is the exposure for 1 day at a temperature close to the measurements in bottom layer without forced aeration or the creation of oxygen-free conditions. After exposure the water from the tubes was drained with a siphon and the phosphorus content was determined in it, as well as the content of dissolved oxygen and HCO_3^- (to determine the total destruction of OM in BS). Measurements were carried out at six stations (Fig. 1): “Gorodnya”, “Shosha”, “Ploski”, “Konakovo”, “Korcheva”, “Dubna”. Measurements of the vertical distribution of water temperature, dissolved oxygen and electrical conductivity were performed with YSI ProODO and YSI Pro30, water transparency was measured using a Secchi disk. The methodology of the work is given in [15]. The chemical analysis of the selected water samples from rivers, reservoir and experiments was performed at the accredited chemical laboratory of the IWP RAS Ivan’kovskoe research station (certificate of accreditation RA.RU.21AH96) by standard methodologies: the Murphy-Riley method for phosphorus and titrimetric for HCO_3^-.

The main factors determining the internal nutrient load include changes in the primary productivity of a reservoir and its oxygen regime [5]. To clarify the periods with oxygen deficiency in the bottom layer (less than 2 *mg*/*L*, during which phosphorus is intensively released from BS, the mathematical quasi-two-dimensional hydrological reservoir model HRM-MSU model [16] was used. It is based on a one-dimensional algorithm for calculating the vertical structure of a reservoir [17], applied to the sequence of compartments, into which the reservoir is divided (Fig. 1). In addition to calculating the balance and hydrodynamic components of the reservoir regime, the model algorithm also includes an ecological block for changing the chemical and biological characteristics: the content of persistent and labile OM, concentrations of mineral compounds of nitrogen and phosphorus, alkalinity, pH, mineralization, iron, manganese, suspension, dissolved oxygen, biomass of phyto- and zooplankton.

The dependence of the intensity of oxygen consumption by the bottom on the type of BS, the distribution of which is determined by the morphological structure of the reservoir bed (flooded riverbed, floodplain and floodplain terraces), was estimated based on experimental observations [18] and modern results. A complete description of the structure of the model algorithm, its verification, and practical application are presented in [19].

Results and Discussion. The phosphate content in the tributaries of the Ivan'kovskoe reservoir is shown in Fig. 2. The largest median values of the tributaries are found in the Tropka and Kotevlya Rivers.

But the highest phosphate content is in Polozovka River (is not shown in Fig. 2): the median value, 75%, 25% of the quartile and the highest value for it were 2.69 *mg*; 0.33 *mg*; 5.27 *mg* and 8.21 *mg* PO_4/L, respectively, which is several times higher than these indicators for other tributaries. Significant maximum values typical for these three rivers are due to irregular pollution from the v. Kozlovo for Kotevlya River and agricultural holding "Dmitrova Gora" for Tropka and Polozovka Rivers. Anthropogenic influence from residential areas is responsible for high phosphate values in Inyukha (in Iskrino), Doibitsa, Donkhovka and Volga Rivers (in Gorokhovo). The lowest phosphate content is typical for the Soz, Suchok, Shosha, Lama, and Volga Rivers (in Ryabeyevo above Tver). The median value of phosphate content in Gorokhovo downstream from Tver is twice as much as in Ryabeevo.

According to the sampling data in 2022 and 2023, the total inflow of phosphates into the reservoir using data from Gorokhovo amounted to 1 359 *t* and 2 125 *t*, respectively. That is, the external phosphorus load on the reservoir by factor of 1.8–2.0, taking into account the influence of wastewater from the city, because the inflow of phosphates from the catchment area above Tver amounted to 529 and 653 *t*/year for the Volga River in Ryabeevo and 220 and 392 *t*/year for the Tvertsa River (total of 749 and 1 045 *t*/year, respectively). These results correspond to the calculations of Yu.S. Datsenko [20]: for the period 1958–2004, the average annual inflow of phosphates was 1 047 *t*/year. The excess of phosphate content in river water below the city over its content in the Volga above the city is maximum in summer (more than 4 times) and minimum during the winter and spring high water periods. This is due to the dilution of pollution and a decrease in anthropogenic load in winter due to seasonal population migrations [21]. Phosphorus intake from the rest catchment area (basins of Lama, Shosha and other tributaries, Fig. 1) amounted to 160 and 246 *t*/year in 2022 and 2023, respectively. In total, the inflow of phosphates into the reservoir with rivers is estimated at 1 519 and 2 371 *t* PO_4/year or in terms of phosphorus – 495 and 773 *t* P/year.

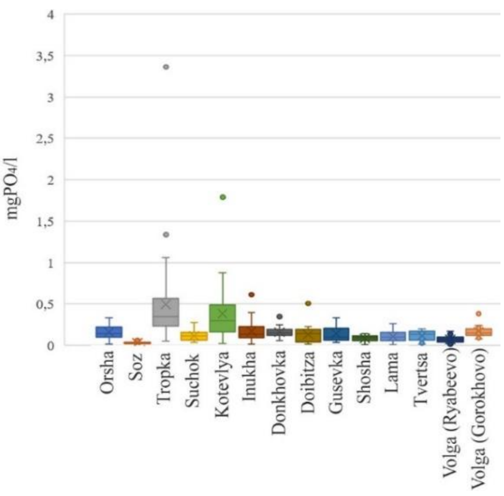

Fig. 2. Phosphates in tributaries of Ivan'kovskoe reservoir.

The Table contains data on phosphorus flux from BS parameterization, based on measurements in different seasons of 2020–2024 and similar data, obtained at the Moskvoretsky reservoirs in earlier years [22].

In winter, for the floodplain areas of the reservoir with a predominance of silted sand and OM content of 6–10%, the flux of mineral phosphorus (P_{min}) was assumed to be 2 *mg* P/*m*^{2}day, and in the spring and summer–autumn periods – in accordance with the dependences of the P_{min} flux at floodplain stations on the observed values of total destruction and content of OM in the BS of various reservoir areas. In the upper region 1 (“Gorodnya”), BS are mainly of silted sand with an OM content less than 1%, therefore, the phosphorus flux for this site is assumed to be identical for both the floodplain and the riverbed to its flux from floodplain areas in winter. The average data for August were used for the calculation during periods of anoxia, and for the rest of the year, during aeration of the bottom horizons, the calculation was based on the experimental data for May–June (see Table). The data obtained are consistent with the results of studies in water bodies around the world: phosphorus yields in the presence of an anaerobic zone are 6–28 *mg* P/*m*^{2} day [23]. Higher flux values are associated with the relative shallowness of the reservoir and its trophic status.

Bathymetric curves obtained from [24] were used to determine the areas of morphological sites. The area of the flooded riverbed was taken at dead volume level 119.39 *m* abs [10]. The remaining area (243 *km*^{2}) belonged to the flooded floodplains and terraces. By multiplying the amount of phosphorus flux from the sediments of the region on their area, it was obtained that in 2020–2022 the mineral phosphorus output amounted to 1 903, 1 717 and 1 646 *t*, respectively. At the same time, the riverbed accounts for 36–38% of the total output due to its smaller area.

Mineral phosphorus flux from bottom sediments of the Ivan’kovskoe reservoir areas, taking into account their spatial heterogeneity, mgP/m^2 day

Area	“Gorodnya”	“Ploski”	“Konakovo”	“Korcheva”	“Dubna”	“Shosha”
Averaged results of output from BS of flooded riverbed						
March	2	5	6.6	4.3	3.8	10.5
May–June	2	43.5	31	34	47.3	11.1
August	2	51	46	51.3	59.2	42.4
Output from the flooded floodplain and terrace according to [23] data, depending on the content of OM and total destruction						
March	2	2	2	2	2	2
May–June	2	15	15	35	35	15
August	2	10	15	35	35	10

Comparing the values of phosphorus flux from sediments obtained in the previous section with the assessment of their inflow with surface waters, we can conclude that the autochthonous load plays a significant role for the Ivan’kovskoe reservoir, exceeding the inflow from tributaries.

The calculations of the external and internal phosphorus load of the Ivan’kovskoe reservoir clarify the previously published estimates. In [8], the external and internal loads were estimated at 0.336 and 1.664 *g*/*m*^{2} per year, respectively, which, with a reservoir area of 316 *km*^{2}, according to [10] gives values of 115 and

525 *t*/year. These estimates are based on observations conducted before 2007. In an earlier paper [7], an estimate of phosphorus removal from bottom sediments was given: when calculating specific values per reservoir area, phosphorus load from BS ranged from 57 to 101 *t* per year. In this case, the specific phosphorus flux is given only for aerobic conditions. Perhaps, before 1984, when the work was published, the anaerobic conditions in the Ivan'kovskoe reservoir were not typical.

In this paper, the data on the external and internal load are updated based on the materials of modern observations. For the first time, the impact of Tver on the inflow of phosphorus into the reservoir was assessed. Taking into account the additional phosphorus intake due to the operation of wastewater treatment plants in a large regional center and the overall growth of the urban agglomeration reduces the share of the internal phosphorus load from 83.2% to 73–77%. At the same time, the absolute values of the external and internal load increased compared to previous estimates. This may be due to the frequent occurrence of conditions with oxygen deficiency in the bottom layer due to changes in the intraannual distribution of water inflow and climatic changes [25].

Conclusion. The autochthonous load of phosphates coming from the reservoir sediment complex exceeds their inflow from river water masses. The highest concentrations were observed in the Rivers Kotevlya, Tropka and Polozovka. Maximum phosphorus flux is typical of flooded riverbed. Phosphorus output from bottom sediments increases during periods with anoxic conditions, which are more often observed in the second half of summer. This means that with a decrease in the river inflow in the low-flow period, the role of phosphate load from bottom sediments increases. The assessment of Tver's contribution to the allochthonous load is a scientific novelty of this work. Nearly 40–46% of total phosphorus load is due to wastewaters and diffuse pollution from Tver. Their influence is maximum in summer–autumn low-flow period and minimum during the flood and winter.

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ԻՎԱՆԿՈՎՍԿՈՅԵ ՋՐԱՄԲԱՐԻ ՆԵՐՔԻՆ ՖՈՍՖՈՐԱՅԻՆ ԾԱՆՐԱԲԵՌՆՎԱԾՈՒԹՅՈՒՆԸ

Ամփոփում

Այս ուսումնասիրությունը ուսումնասիրում է Իվանկովսկոյե ջրամբարի ներքին փոսֆորի բեռը՝ հիմնվելով 2020–2024 թ-րի դիտարկումների տվյալների վրա: Հաշվարկի արդյունքները հիմնված են տարբեր եղանակներին հավաքված հատակային նստվածքների նմուշներից ստացված հանքային փոսֆորի հոսքի վերաբերյալ փորձարարական միջին տվյալների վրա: Հատվածային նստվածքներից փոսֆորի ամենաբարձր ներհոսքը հիմնականում կապված է ստորին շերտում թթվածնի անբավարարության ժամանակահատվածների և օրգանական նյութերով հարուստ նստվածքներ ունեցող տարածքների հետ: GMV-MSU մաթեմատիկական մոդելի միջոցով մենք կարողացանք հաշվարկել այդ ժամանակահատվածների տևողությունը կանոնավոր դիտարկումների բացակայության դեպքում: Ներքին փոսֆորի բեռը կազմում է տարեկան 1646–1903 *տ* և գերազանցում է արտաքին բեռը:

М. Г. ГРЕЧУШНИКОВА, Д. В. ЛОМОВА

ВНУТРЕННЯЯ ФОСФОРНАЯ НАГРУЗКА ИВАНЬКОВСКОГО ВОДОХРАНИЛИЩА

Резюме

Работа посвящена изучению внутренней фосфорной нагрузки в Иваньковском водохранилище по данным наблюдений за 2020–2024 гг. Результаты расчетов основаны на экспериментальных средних данных о потоке минерального фосфора, полученных в результате исследований проб донных отложений, которые проводились в разные сезоны. Наибольший приток фосфора из донных отложений связан главным образом с периодами дефицита кислорода в придонном слое и участками с отложениями, богатыми органическим веществом. Использование математической модели ГМВ-МГУ позволило рассчитать продолжительность этих периодов в отсутствие регулярных наблюдений. Внутренняя нагрузка по фосфору составляет 1646–1903 *т*/год и превышает внешнюю.