DIFFUSE NUTRIENT LOADING FROM AGRICULTURAL LANDS ALONG THE LUGA RIVER, LENINGRAD REGION

Eduard Vasilev, Alexander Briukhanov, Ekaterina Shalavina, Natalia Vasileva, Natalia Oblomkova
Federal Scientific Agroengineering Centre VIM, Russia
sznii@yandex.ru, shalavinaev@mail.ru, vasileva0203@yandex.ru, oblomkovan@gmail.com

Abstract. The study aimed to compare the calculated and directly measured total nitrogen input from farm fields into the water bodies exposed to crop-growing practices and livestock facilities in place. The study applied an IEEP-designed model for diffuse loading calculation. The study area was a dairy farm with 2100 head of animals and 2000 ha of fields, located in the Luga River catchment, the Leningrad Region. 40 ha were selected for elementary plots. The geoinformation systems served to identify the watercourses from the fields into the river and the water sampling points for measuring the concentration of total nitrogen and nitrate nitrogen. The calculations by the model showed the average specific nitrogen runoff from the fields was 44.96 kg ha^{-1}. The monitoring data analysis revealed the Kjeldahl total nitrogen content in the water varying from 1.4 to 3.1 mg $(dm^3)^{-1}$, and the nitrate nitrogen content – from 2.28 to 9.1 mg $(dm^3)^{-1}$ depending on the season and precipitation. The calculation of the monitoring data demonstrated the inputs of total nitrogen from farm fields into watercourses ranging from 35.24 to 36.84 kg ha^{-1}. Comparing the nitrogen runoff data, calculated by the model and directly measured by the nitrogen concentrations in watercourses, disclosed a discrepancy in the study territories from 17 to 21% explained by several factors. In general, the study demonstrated sufficient convergence, with certain assumptions, of two methods for identifying the nitrogen inputs into water bodies. The direct measurements method is hard to apply to large catchments. The method of IEEP is designed mostly for analysing the nutrient inputs from vast territories to form a comprehensive overview of current and forecast situations without taking into account specific places with possible violations. This method focuses on the elaboration and introduction of strategic measures for environmentally sustainable rural development.

Keywords: diffuse load, nutrients, ecology, farm field.

Introduction

The latest HELCOM assessments showed that the Baltic Sea still suffers from eutrophication [1]. Country-wise nutrient reduction targets were introduced by HELCOM in 2007 as part of the Baltic Sea Action Plan (BSAP) to lower nitrogen and phosphorous inputs from various sources on the catchment area and restore the marine environment [2]. From this perspective, reliable data about the nutrient inputs from different sources are needed to assess the effectiveness of measures taken to reduce pollution in the Baltic Sea catchment area.

Agriculture is seen as the main contributor to the excessive nutrients loads to the Baltic Sea. In its progression, as any other type of productive activity, it interacts with the natural environment and affects its components – air, water and soil [3-8].

The farming impact on water bodies is predominantly of diffuse nature. The input of pollutants (nutrients) from diffuse sources is difficult to record. However, such non-point pollution can be many times greater than that from the point sources under control [9].

Forecasting a sustainable state of the natural environment needs knowing the number of pollutants entering the water bodies from all sources. At the same time, when it comes to large areas, such as the entire drainage area of the Luga River, the Leningrad Region, flowing to the Baltic Sea, for example, the required knowledge cannot be acquired by direct measurements, as there is no established network of monitoring stations in place [9].

Therefore, there is a need to use reliable methods to assess the input from agriculture. In 2014 IEEP-branch of FSAC VIM together with the Institute of Limnology RAS developed a method for calculating the nutrient loss with due account for fertilization doses, nitrogen uptake by the crop, the soil type and texture on the catchment area, and the distance between the field and the water body. The method was tested on several catchments in the European part of Russia [10].

There are still many uncertainties in regard to the dominant processes and factors governing nutrient loss from land to water in catchments with prevailing agricultural land area [11; 12]. Moreover, according to [13] the nitrogen surplus cannot be used as a reliable indicator of the possible riverine pollution as far as there is weak correlation between the soil surface N surplus and losses to the waters.

DOI: 10.22616/ERDev.2021.20.TF103

The IEEP method is based on the N surplus estimation and set of migration coefficients, therefore, the study purpose was to understand if the calculation method can be considered reliable by comparing the input of total nitrogen and nitrate nitrogen from the farm fields into the water bodies calculated and directly measured in the watercourses exposed to the effect of crop growing practices and livestock facilities in place.

Materials and methods

Two sources of nitrogen emission are traditionally considered in determining the diffuse load from farming – soil and mineral/organic fertilisers. The emissions from agricultural soils are calculated taking account of the arable horizon's depth, since a prevailing part of nitrogen is lost from this soil layer. In North-West Russia this layer is 20-25 cm.

According to the methodology developed by IEEP - branch of FSAC VIM together with the Institute of Limnology RAS, the load formed on farm fields L_{agr} (t year $^{-1}$) was calculated by the formula (1) [14]:

$$L_{agr} = 10^{-3} \sum_{i=1}^{n_1} S_i \cdot (M_{\text{soil}\,i} \cdot K_1 + (\alpha_1 \cdot M_{\min i} + \alpha_2 \cdot M_{\text{org}\,i}) \cdot K_6) \cdot K_2 . K_3 \cdot K_4 \cdot K_5 \quad (1)$$

where $M_{\text{soil } i}$ – total nitrogen content in the arable soil layer, kg ha^{-1} year^{-1}, on the fields of the *i*-th farm

$M_{\min i}$ – nitrogen application dose with mineral fertlisers on the fields of the *i*-th farm, kg·ha^{-1}·year^{-1};

$M_{\text{org } i}$ – nitrogen application dose with organic fertilisers on the fields of the *i*-th farm, kg·ha^{-1}·year $^{-1}$;

S_i – arable land area of the *i*-th farm, ha;

α_1 – coefficient taking into account the crop uptake of mineral fertilisers, dimensionless;

α_2 – coefficient taking into account the crop uptake of organic fertilisers, dimensionless;

K_1 – coefficient taking into account nutrients runoff from the topsoil, dimensionless;

K_2 – coefficient taking into account the distance between the agricultural land and the hydrographic network, dimensionless;

K_3 – coefficient taking into account the soil type (by origin), dimensionless;

K_4 – coefficient taking into account the soil texture, dimensionless;

K_5 – coefficient taking into account the structure of farmland, i.e. the ratio of arable land, perennial grasses, meadows, and pastures, dimensionless;

K_6 – coefficient taking into account the use of the best available techniques (BAT) of organic and mineral fertilisers use, dimensionless.

The coefficient values were determined from a comprehensive review of the literature and experimental data obtained by IEEP regarding the Russian part of the Baltic Sea catchment area [9; 10; 14-22]. The location of agricultural land relative to the water bodies was defined and, subsequently, K_2 was calculated by the spatial analysis technique in GIS.

In 2017 IEEP started a long-term experiment for determining nitrogen loss by monitoring data on the watercourses of the Luga River flowing to the Baltic Sea, Leningrad Region. The concentrations of total nitrogen and nitrate nitrogen were regularly measured in the runoffs from agricultural lands to the river through the system of drainage canals.

This article reports the monitoring results of water streams in the drainage canals in 2019.

The nitrogen loading based on the monitoring data was calculated by formula (2):

$$l = (m \cdot \frac{\sum_{i=1}^{n} (C_i \cdot W_i / 1000)}{n}) / s, \quad (2)$$

where l – annual nutrient runoff from the area under study, kg ha^{-1};

m – number of days in the year with the surface runoff taking place (conditionally, from March 1 to November 30);

Ci – nutrient concentration in the sample collected on the *i*-th day, mg·dm^{-3};

s – area of the drainage basin of the water stream considered at the sampling point, ha;

n – number of samplings (water flow measurements).

Wi – volume of daily runoff in the water stream under study on the *i*-th day, calculated as (3), m^3·day^{-1}:

$$W_i = 3600 \cdot 24 \cdot q, \tag{3}$$

where q – measured water flow in the stream, $m^3 \cdot sec^{-1}$.

The nitrate nitrogen (NO_3) content in water samples was measured by a fluid analyzer (pH meter-ionomer) EXPERT-001-3 with an ion-selective electrode Elite-021 following the Management Directive RD 52.24.367-2010 "Mass concentration of nitrates in waters. Measuring methodology by the potentiometric method with an ion-selective electrode". Kjeldahl total nitrogen was determined with the Serenev apparatus. The organic matter content in the soils of the surveyed farmland was determined following the State Standard GOST 26213-91 "Soils. Methods for determination of organic matter". The water flow in the canal was measured following the Procedural Instruction MI 1759-87 "State System for Ensuring Uniform Measurement. Water flow in rivers and canals. Methods for making measurements by "speed-area" method".

The experimental data were analysed in *Microsoft Excel* software package. The mean accuracy was determined by Student's t-test.

The study was carried out in the Luzhskij District of the Leningrad Region, upstream of the Luga River from Luga town. The study area was the territory of the pilot cattle dairy farm. The selected farm was most typical for the Luga River catchment area, with 2,100 head of total animal stock and 2000 hectares of fields. The farm produced and made use of solid and liquid organic fertilisers.

The field of 40 hectares was chosen as an elementary plot for direct measurements in the close proximity to the Luga River (Fig. 1).

Fig. 1. **Example of a catchment area within the study area with a marked water sampling point 1 (blue mark)**

To assess the effect degree of agricultural production on Kjeldahl total nitrogen and nitrate nitrogen in the water, the average concentrations of these substances were compared in the zone exposed to the pilot farm activity and beyond it – at the point with background concentrations. The background point was located about 35 kilometres from the pilot farm; it characterised the water quality in a forest stream that was not subject to significant anthropogenic impact.

Results and discussion

Taking into account the declared fertilisation areas, the average application dose of organic fertilisers was $M_{org\,i}$ = 133 kg N ha^{-1}. According to the results of laboratory analysis of soil samples, the total nitrogen content in soil M_{soil} was 4500 kg ha^{-1}.

Table 1 shows the coefficient values obtained for the pilot territory from literature review, geoinformation systems and the visits to the farm.

Table 1

Initial data used in calculating the diffuse load by the method developed in IEEP-branch of FSAC VIM (2019)

Indicator	Unit	Value
S_i, – land area under investigation	ha	40
M_{soil} – total nitrogen content in the arable soil layer	kg ha^{-1}	4500
$M_{min\ i}$ – average application dose of N with mineral fertilisers,	kg ha^{-1}	48.7
α_1 – coefficient taking into account the crop uptake of mineral fertilisers	dimensionless	0.3
α_2 – coefficient taking into account the crop uptake of organic fertilisers	dimensionless	0.1
K_1, – coefficient taking into account nutrient runoff from the topsoil	dimensionless	0.03
K_2 – coefficient taking into account the distance between the agricultural land and the hydrographic network	dimensionless, average value for the territory under investigation	0.6
K_3 – coefficient taking into account the soil type (by origin)	dimensionless, sod-podzolic soil	1.0
K_4 – coefficient taking into account the soil texture	dimensionless, heavy clay and clay loam	1.0
K_5 – coefficient taking into account the structure of farmland	Dimensionless, fodder crops	0.46
K_6 – coefficient taking into account the use of best available techniques (BAT) for mineral and organic fertiliser use	dimensionless	1

Calculations of the specific nitrogen loading by formula (1) from the IEEP-INOZ RAS methodology and using the initial data of the pilot territory from Table 1, resulted in the formed nitrogen load L_{agr} as 1.798 t·year^{-1}, which corresponded to 44.96 kg·ha^{-1}·year^{-1}. This value referred to the particular territory with certain characteristics. The average value of the specific nitrogen load for the entire catchment area of the Luga River from agricultural fields was 25 kg·ha^{-1}·year^{-1} [14].

Water samples were collected with the frequency as specified in the approved research methodology (Fig. 2). Table 2 shows the list of substances and the analysis results, including uncertainty of chemical analysis (25% for Kjeldahl nitrogen and 28% for nitrates).

Fig. 2. **Water sampling in a drainage canal 250 meters from the Luga River**

Table 2

Results of laboratory analyses of water samples collected at the sampling point 1 (2019)

Indicator	Sampling month					
	May	July	August	September	October	Average
Kjeldahl total nitrogen content in the water, mg·dm^{-3}	2.45 ± 0.61	3.1 ± 0.78	2.9 ± 0.73	2.45 ± 0.61	1.4 ± 0.35	2.46
Nitrates (NO_3) content in the water, mg·dm^{-3}	2.28 ± 0.64	2.86 ± 0.80	3.28 ± 0.91	4.63 ± 1.29	9.1 ± 2.55	4.43

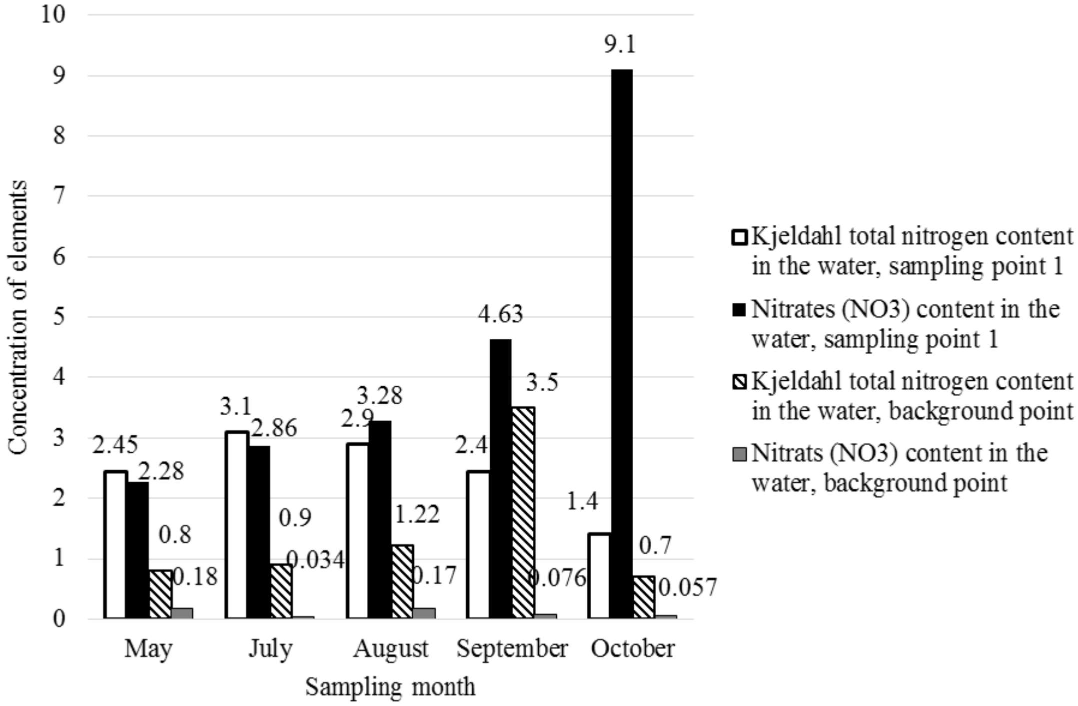

Fig. 3. **Kjeldahl total nitrogen and nitrates concentrations in the sampling point 1 exposed to the pilot farm activity and in the background sampling point (measurement unit of indicators – mg (dm^3)$^{-1}$)**

Fig. 3 demonstrates that the concentrations of the considered elements at the background point are much lower than those at the sampling point under the anthropogenic impact and natural influence of the fields. Total nitrogen concentration can be estimated as the sum of considered elements and amounts for on average 3.46 mg·l^{-1}. Recent studies showed that total nitrogen concentration in streams is usually higher than 2.3 (5% percentile) and is lower than 12 mg·l^{-1} (95% percentile), on average it makes up 7 mg·l^{-1} – almost the same as in the present study. Detected nitrate nitrogen is also in line with the values found in the rivers near agricultural areas all over the Baltic Sea – its content does not exceed 10 mg·l^{-1}, the average concentration is 6 mg·l^{-1} [23; 24].

According to the monitoring data, about 285 thousand m^3·year^{-1} of water flows into the Luga River by the drainage canal under investigation through the sampling point 1. Average concentration of total nitrogen (3.46 mg·l^{-1}), which being converted into the nitrogen runoff from the study area by formula (2), makes about 35 kg·ha^{-1}·year^{-1}. These values are comparable with the data on total nitrogen losses, acquired for different catchments around the Baltic Sea in several studies: the average losses account for 17 kg·ha^{-1}·year^{-1} and in most cases they are lower than 51 kg·ha^{-1}·year^{-1} [23; 24].

During the monitoring from 2017 to 2020, there was found a site near a livestock barn and in the zone of the settlement influence, where high doses of organic fertilisers were applied annually and semi-liquid manure was periodically stored before being applied in spring (Fig. 4). This resulted in an increase in the soil and runoff nutrients content.

Fig. 4. **Catchment area where high doses of organic fertilisers were applied and semi-liquid manure was periodically stored before application in spring with a marked water sampling point 5**

The water samples collected at the sampling point 5 at the drainage canal outlet had the Kjeldahl total nitrogen content of 2.96 $mg \cdot dm^{-3}$ and nitrates content of 16.8 $mg \cdot dm^{-3}$. Being converted into the nitrogen runoff from the study area by formula (2), it made about 124 $kg \cdot ha^{-1} \cdot year^{-1}$ of total nitrogen, i.e. 3.5 times more than the nitrogen loss from the remaining fields of the pilot farm, where the super-high doses of organic fertilisers were not applied. This value is high compared to N_{tot} loss for agricultural areas in the Northern parts of the Baltic Sea catchment and obviously caused by extreme conditions and improper manure management [23].

Comparing the nitrogen runoff data, calculated and obtained by direct measurements of nitrogen concentrations in watercourses, showed a discrepancy in the territories under investigation from 17 to 21%, which on the one hand, can be due to uncertainty of the chemical analysis etc. and, on the other hand, may be explained by several factors: during the monitoring it was hard to establish the exact runoff amounts entering the drainage canal and leaching into deeper soil layers and, consequently, entering the water bodies with the groundwater; the IEEP calculation method may not take a full account of the processes of self-purification of runoffs as a result of biochemical processes and the dilution of more concentrated runoffs with additional incoming groundwater and other sources [25; 26].

The study demonstrated sufficient convergence, with certain assumptions, of the results of two methods for determining the nitrogen inputs into water bodies. The method of direct measurements is hard to apply to the large catchment area. The method of IEEP - branch of FSAC VIM is designed mostly for analysing the nutrient inputs from vast territories to form a comprehensive overview of current and forecast situations without taking into account specific places featuring possible violations. This method aims to elaborate and introduce the strategic measures for environmentally sustainable rural development.

Conclusions

1. The study and monitoring results showed that intensive agricultural production inevitably affects the status of adjacent water bodies due to nutrient inputs from fields via polluted runoffs. At the same time, the systematic application of large doses of organic fertilisers and the field-edge pre-spreading storing of fertilisers in winter result in the multiple increase (3.5 times) in nutrient inputs compared with the cases when all agro-technical operations comply with the regulatory requirements.
2. Comparing the nitrogen runoff data, calculated and obtained by direct measurements of nitrogen concentrations in watercourses, showed a discrepancy in the territories under investigation from 17% to 21% that may be explained by several factors, as well as by measurement uncertainty.

3. The study demonstrated sufficient convergence, with certain assumptions, of the results of two methods for determining the nitrogen inputs into water bodies. The method of direct measurements is hard to apply to the large catchment area. The method of IEEP - branch of FSAC VIM is designed mostly for analysing the nutrient inputs from vast territories to elaborate and introduce the strategic measures for environmentally sustainable rural development.

References

[1] HELCOM Thematic assessment of eutrophication 2011-2016. Baltic Sea Environment Proceedings No. 156, 2018, 83 p. [online] [15.04.2021]. Available at: http://www.helcom.fi/baltic-sea-trends/ holistic-assessments/ state-of-the-baltic-sea-2018/ reports-and-materials/

[2] HELCOM Baltic Sea Action Plan. HELCOM Ministerial Meeting, Krakow, Poland, 15 November 2007, 101 pp. [online] [15.04.2021]. Available at: http://www.helcom.fi/stc/files/BSAP/BSAP Final.pdf

[3] Jansson, T., Andersen, H.E., Gustafsson, B.G. et al. Baltic Sea eutrophication status is not improved by the first pillar of the European Union Common Agricultural Policy. Reg Environ Change, 2019, vol. 19, pp. 2465-2476, DOI: 0.1007/s10113-019-01559-8

[4] Sources and pathways of nutrients to the Baltic Sea. Baltic Sea Environment Proceedings No. 153. HELCOM, 2018. 48 p. [online] [23.12.2020]. Available at: https://www.helcom.fi/wp-content/uploads/2019/08/BSEP153.pdf

[5] Priekulis J., Laurs A., Melece L. Ammonia emission reduction measures in dairy cattle farming. Proceedings of 18th International Scientific Conference “Engineering for Rural Development”. May 22-24, 2019. Jelgava, Latvia. Vol.18. pp. 83 – 87.

[6] Atilgan A., Yuecel A., Markovic M. Determination of relationship between water level, volume and meteorological variables: study of lake Egirdir. Proceedings of the 19th International Scientific Conference “Engineering for rural development”. May 20-22, 2020, Jelgava, Latvia. Vol.19. pp. 140 – 146.

[7] Oskin S., Miroshnikov A., Didych V. Ways to reduce environmental damage in rural areas from unreliable pumping stations of sewage systems. Proceedings of the 19th International Scientific Conference “Engineering for rural development”. May 20-22, 2020, Jelgava, Latvia. Vol.19. pp. 263 – 269.

[8] Frolova O., Priekulis J., Berzina L., Aboltins A. Trend of ammonia emissions from livestock sector in Latvia. Proceedings of the 19th International Scientific Conference “Engineering for rural development”. May 20-22, 2020, Jelgava, Latvia. Vol.19. pp. 598 – 602.

[9] Кондратьев С.А., Шмакова М.В., Брюханов А.Ю., Викторова Н.В., Ершова А.А., Обломкова Н.С. К оценке биогенного стока в Финский залив Балтийского моря (To the evaluation of nutrient removal to the Gulf of Finland of the Baltic Sea). Scientific notes of the Russian State Hydrometeorological University: Ученые записки РГГМУ. 2018. No. 51. pp. 109-120 (In Russian)

[10] Брюханов А.Ю., Кондратьев С.А., Васильев Э.В., Минакова Е.А., Терехов А.В., Обломкова Н.С. Оценка сельскохозяйственной биогенной нагрузки, сформированной на речных водосборах бассейна Куйбышевского водохранилища (Assessment of agricultural nutrient load generated on the river catchment areas within the Kuybyshev Reservoir basin). Technologies, machines and equipment for mechanised crop and livestock production: Технологии и технические средства механизированного производства продукции растениеводства и животноводства. 2018. No. 96. pp. 175–186 (In Russian)

[11] Buciene, A., Povilaitis, A., Langas, V. et al. Changes in nutrient concentrations of two streams in Western Lithuania with focus on shrinkage of agriculture and effect of climate, drainage runoff and soil factors. Water. 2019. Vol.11. DOI: 10.3390/w11081590

[12] Stålnacke P., Grimvall A. Libiseller C., Laznik M., Kokorite I. Trends in nutrient concentrations in Latvian rivers and the response to the dramatic change in agriculture. Journal of Hydrology. 2003.Vol. 283, pp. 184– 205 DOI: 10.1016/Soo22-1694(03)00266-X

[13] Ilnicki P. Emissions of nitrogen and phosphorus into rivers from agricultural land – selected controversial issues. Journal of Water and Land Development. 2014. No. 23 pp. 31–39.

[14] Брюханов А.Ю., Кондратьев С.А., Обломкова Н.С., Огуздин А.С., Субботин И.А. Методика определения биогенной нагрузки сельскохозяйственного производства на водные объекты

(Calculation method of agricultural nutrient load on water bodies). Technologies, machines and equipment for mechanised crop and livestock production: Технологии и технические средства механизированного производства продукции растениеводства и животноводства. 2016. No. 89. pp. 175–183 (In Russian)
[15] Гинзбург К.Е. Фосфор основных типов почв СССР (Phosphorus of the main types of soils in the USSR). Moscow: Nauka Publ: М.: Наука, 1981. 242 p. (In Russian)
[16] Методические указания по расчету поступления биогенных элементов в водоемы от рассредоточенных нагрузок и установлению водоохранных мероприятий (Methodological guidelines for calculating the input of nutrients into water bodies from dispersed loads and establishing water protection measures). Moscow: Gosagroprom Publ: М.: Госагропром, 1988. 87 p. (In Russian)
[17] РД-АПК 1.10.15.02-17 Методические рекомендации по технологическому проектированию систем удаления и подготовки к использованию навоза и помета (Management Directive for Agro-Industrial Complex1.10.15.02-17. Recommended Practice for Engineering Designing of Systems for Animal and Poultry Manure Removal and Pre-application Treatment). Moscow: Rosinformagrotekh, 2017. 173 p. (In Russian)
[18] Справочник агрохимика. Под ред. Д.А. Коренькова (Handbook of an agrochemist. Ed. D.A. Korenkov) Moscow: Rosselkhozizdat: М.: Россельхозиздат, 1976. 350 p. (In Russian)
[19] Amberger A., Schweiger P. Wanderung der Pflanzennahrstoffe in Boden und deren Bedeutung in einer umweltbewussten Landwirtschaft. Die Bodenkultur. 1973. No. 24. pp. 221–237 (In German)
[20] Johnes P.I., Heathwaite A.l. Modelling the impact of land use change on water quality in agricultural catchments. Hydrological Processes. 1997. No. 11. pp. 269–286.
[21] Barrows H.L., Kilmer V.J. Plant nutrient losses from soil by water erosion. In: Normann A.G. (ed.) Advances in Agronomy. 1963. vol.15, pp 303-316
[22] Единый государственный реестр почвенных ресурсов России (Unified State Register of Soil Resources of Russia. [online] {23.12.2020]. Available at: http://atlas.mcx.ru/materials/egrpr/content/1DB.html (In Russian)
[23] Stålnacke P., Aakerøy P., Blicher-Mathiesen G. et al. Temporal trends in nitrogen concentrations and losses from agricultural catchments in the Nordic and Baltic countries. Agriculture, Ecosystems & Environment. 2014. Vol.198. DOI: 10.1016/j.agee.2014.03.028
[24] Kyllmar, K. Nitrogen Leaching in Small Agricultural Catchments - Modelling and monitoring for assessing state, trends and effects of counter-measures. Doctoral thesis. Swedish University of Agricultural Sciences, Uppsala, 2004, 37 p.
[25] Кондратьев С.А. Формирование внешней нагрузки на водоемы: проблемы моделирования (Formation of external load on water bodies: problems of modeling). Saint Petersburg: Nauka Publ: СПб.: Наука, 2007. 253 p. (In Russian)
[26] Кондратьев С.А., Шмакова М.В., Уличев В.И. Детерминировано-стохастическое моделирование стока и биогенной нагрузки на водные объекты (на примере Финского залива Балтийского моря) (Deterministic-stochastic modeling of runoff and nutrient load on water bodies (on the example of the Gulf of Finland of the Baltic Sea). Saint Petersburg: Nestor-Istoria Publ: СПб, Изд. Нестор-История, 2013, 36 p. (In Russian)