Chapter

Diffuse Runoff from Agricultural Lands within a River Basin and Water Protection Measures

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Abstract

This paper is dedicated to the study of the pollutants coming from agricultural lands located within the catchment into the Yakhroma river, a third-order tributary of the Upper Volga. The area of the river catchment is 1437 km^2. It is located in the north-eastern part of the Moscow region, which geographically belongs to the Klinsko-Dmitrov ridge (the upper part of the basin) and the Upper Volga Lowland. The slopes and floodplain included in the reclaimed lands (more than 9 th ha) are lined with cities, rural settlements, numerous kitchen gardens, and agricultural lands. Water quality, river profile from the source to the mouth, and sources of pollution within the reclaimed lands of the Yakhroma floodplain were studied from 2004 to the present. A geospatial intelligence system (GIS) was developed for the catchment area. Land areas are allocated according to the conditions of surface runoff formation, taking into account soil types and slopes. The studies of the river water quality, tributaries, and drainage network in the reclaimed lands showed biogenic pollution caused by insufficiently treated wastewater discharged from cities and agricultural land, especially within the reclaimed massif. The calculations of the removal of nitrogen, phosphorus, and potassium from surface and drainage waters revealed that the main role in the pollution of both surface and drainage waters is played by nitrogen and potassium compounds, and to a lesser extent by phosphorus compounds. For nitrogen, removal from surface runoff was 27.36 t/year; for phosphorus it was 6.06 t/year; for potassium it was 242.28 t/year; with drainage runoff, the removal of nitrogen was 98.88 t/year; the removal of phosphorus was 0.38 t/year; the removal of potassium was 37.04 t/year. To reduce the inflow of surface diffuse runoff and to purify collector and drainage waters from nitrogen and phosphorus compounds, including the creation of bioplateaus and biosorption structures, it was proposed to use a set of protective measures, which will significantly reduce the biogenic load on the river flow.

Keywords: river basin, surface runoff, drainage waters, biogenic pollution, nitrogen, phosphorus, potassium

1. Introduction

Currently, the quality of water in the largest rivers in the European part of Russia continues to deteriorate. For instance, the rivers of the Volga basin are in an unsatisfactory condition [1–3]. Over the past decade, the Volga River and its tributaries have been characterised as dirty, despite decreased wastewater discharge and increased efficiency of purification of controlled discharge from point sources due to the construction of modern treatment facilities. For 1990–2012, the discharge of polluted waters decreased almost 3.5 times; the content of oil products decreased six times; the content of sulphates decreased 19.3 times; the content of chlorides decreased 3.4 times; the content of zinc decreased 15 times; the content of copper decreased 17.8 times; the content of nitrogen decreased 3.5 times; the content of phosphorus decreased 7.2 times; total biochemical oxygen consumption decreased 7.6 times [4, 5]. However, water quality in river systems and reservoirs did not improve as expected, especially in small tributaries of the Volga River. Along with the discharge of wastewater from industrial, municipal, and other enterprises, the river network is fuelled by uncontrolled diffuse runoff from the catchment area, which according to many authors, significantly worsens the quality of water in Volga [5].

The Upper Volga basin is characterised by excessive moisture content; precipitation averages 600–700 mm per year and significantly prevails over evaporation (425–475 mm). The abundance of precipitation and high snow cover lead to the formation of surface runoff, especially during the period of snow melting when solid and liquid runoffs enter the river network. This is due to erosion, leaching, and dissolution. During erosion, suspended soil particles are mainly removed with the sorption of nutrients, in particular phosphorus, on them, whereas dissolved chemicals are sorbed during dissolution and leaching. The main factors influencing the formation of surface runoff, its quality, and removal of nutrients are climate, terrain, soil surface condition, and migration capacity of nutrients. Depending on the soil type, the amount and nature of precipitation, type of plants, dose of fertilisation on one hectare of arable land, removal can be up to 80 kg of nitrate nitrogen, 3 kg of phosphorus, and 60 kg of potassium per year [6].

The abundance of precipitation requires drainage reclamation. This zone of agricultural lands is characterised by the use of horizontal drainage. As a result, drainage runoff, which is formed along with surface runoff, is directly or indirectly discharged into the river network. Through drainage waters, water bodies are filled with organic matter, residues of mineral fertilisers, and individual ions of chemical elements [7–9]. This leads to pollution of river waters and eutrophication of water bodies. Numerous studies have established that the removal of salts from drained mineral soils depends on many natural and economic indicators such as soil type, its granulometric composition, saturation with bases, the use of mineral and organic fertilisers, agricultural practices, the composition of crops, and so on. Thus, in loamy soils, the concentration of nitrogen in drainage waters varies from 5 mg/dm^3 to 91 mg/dm^3; the concentration of phosphorus varies from 0.4 mg/dm^3 to 0.5 mg/dm^3; the concentration of potassium varies from 2 mg/dm^3 to 10 mg/dm^3; the concentration of calcium varies from 61 mg/dm^3 to 107 mg/dm^3; and the concentration of magnesium varies from 21 mg/dm^3 to 28 mg/dm^3. This corresponds to the nitrogen removal of 1.4–4.1 kg/ha, phosphorus removal of up to 1 kg/ha, potassium removal of 3–12 kg/ha, calcium removal of 20–147 kg/ha, magnesium removal of 10–76 kg/ha. The concentrations of biogenic substances such as nitrogen (2.0–121.0 mg/dm^3), phosphorus (0.2–0.3 mg/dm^3), potassium (0.2–14.0 mg/dm^3), calcium (53–74 mg/dm^3), and magnesium (13–58 mg/dm^3) were defined in soils of lighter granulometric composition [10–14].

Drainage of the floodplain lands leads to an increased removal of nutrients directly into the river due to surface runoff and discharge of drainage waters. Thus, the mean annual nitrogen removal from agricultural lands of the floodplain lands of the Ryazan region in the Oka river, a tributary of the Volga, was 23.9 kg/ha. The concentrations of nitrates, nitrites, and ammonium were 13.7 kg/ha, 1.6 kg/ha, and 8.6 kg/ha respectively [10]. Discharge of drainage water from drainage systems causes a surge in the concentrations of nutrients and minerals in river water. From the drained floodplain of the Yakhroma river (a tributary of the Volga of the third order), the discharge of drainage water caused an increase in the concentration of ammonium ions in the river water, exceeding the MPC_{fish} on average more than 2–11.5 times, so that the permissible values for the mesotrophic level increased from 4.7 to 77 times. In the summer period, an excess of the standard values of ammonia by 1.4–4 times downstream from the discharge of drainage waters was registered [15].

Thus, small rivers of the Upper Volga basin are recipients of diffuse runoff from catchments and transport impurities directly to the Volga. It seems relevant to assess the role of diffuse runoff in the general pollution of river water. The purpose of the work was to assess the diffuse runoff from the drainage basin of a small river with agricultural land in the drainage basin and to substantiate measures to protect river waters from pollution.

2. Selection of the study object and characteristics of its natural and climatic conditions

The study object was the drainage basin of the Yakhroma river located in the Moscow region with a catchment area of 1437 km^2 (**Figure 1**). The choice of the object was preconditioned by its location, a significant area of agricultural land and

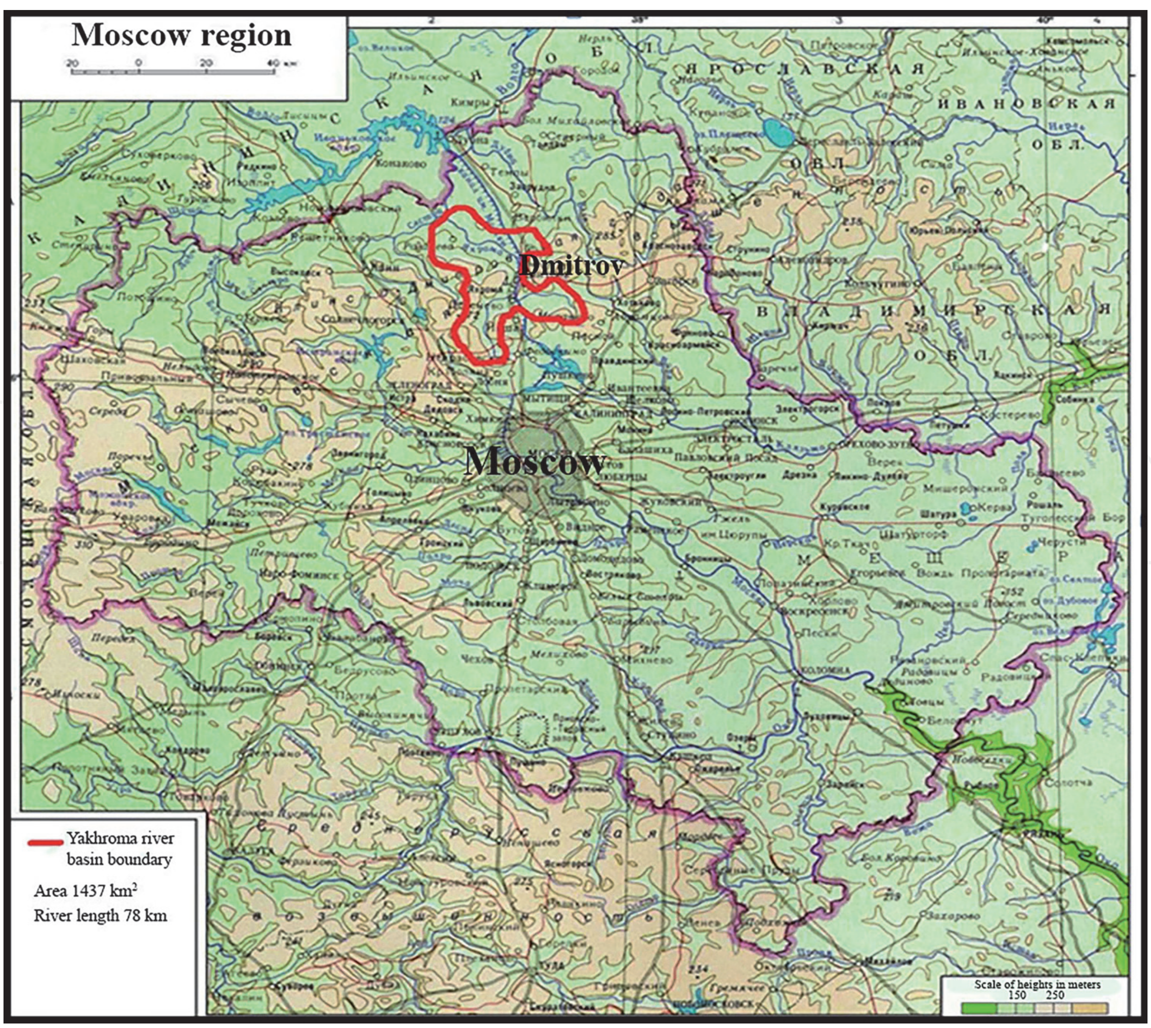

Figure 1.
Physical and geographical map of the Moscow region with the allocation of the basin of the Yakhroma river.

a large reclamation facility with an area of more than 9 th ha, on which there are 487 land use facilities and 61 drainage facilities with a total area of 26,654 ha. The studied basin comprises 249 settlements, the largest of which is the city of Dmitrov with a population of more than 68 thousand people.

Yakhroma is a third-order tributary of the Volga that flows into the Sestra river. The length of the river is 78 km [16, 17]. In the upper and partly in the middle reaches, right down to the Yakhroma reservoir, the regime of the river is natural. In the middle reaches, downstream from Dmitrov, there is a vast floodplain area, which is intensively used for agricultural production. It represents an irrigation and drainage system for bilateral regulation of the water regime of soils. Part of the area operates in polder mode. The Levyy Nagornyy canal with a system of reclamation canals built along the root bank is watered by tributaries and runoffs from settlements, which flow down to Yakhroma through a hydraulic network. Within the reclaimed massif, the Yakhroma river is canalised with its banks reinforced with dams. In the lower reach, the river flows in a low-lying area; its bed is characterised by great tortuosity (**Figure 2**).

The drainage network on the reclaimed massif is made in the form of a closed horizontal drainage 0.8–1.2 m deep with distances between drains from 12 m to 40 m. The drains flow into closed collectors, the runoff from which is discharged directly into the river through the open network. Water is taken in from Yakhroma and supplied to the irrigation network by means of mobile and stationary pumping stations. Irrigation technology is represented mainly by hose-reel sprinklers. Vegetable crops are grown on the floodplain using intensive technologies with the introduction of high doses of fertilisers and the use of various agrochemicals to combat pests and weeds. This increased load led to pollution of soil and river water with biogenic substances, mineral salts, heavy metals, and pesticides, which enter the

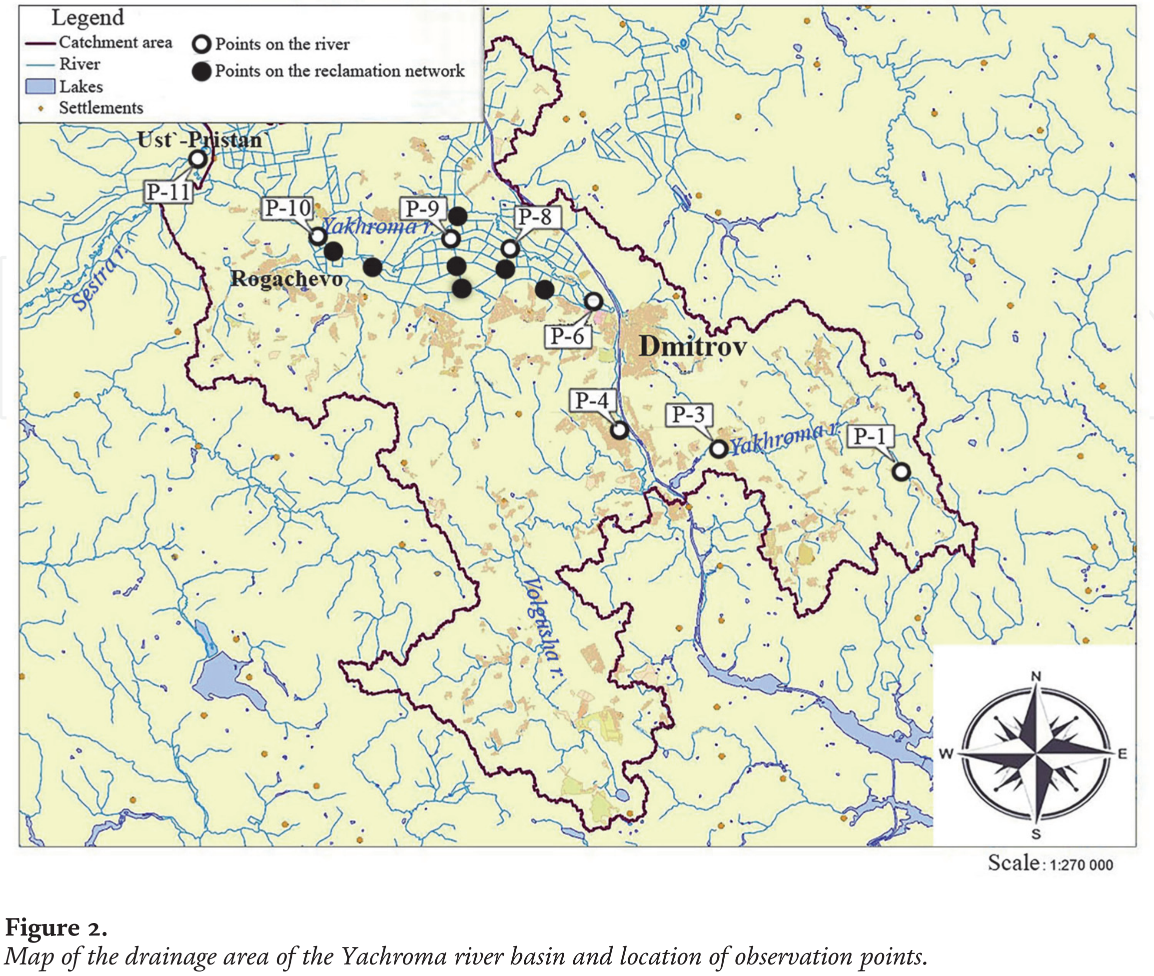

Figure 2.
Map of the drainage area of the Yachroma river basin and location of observation points.

Yakhroma river. The river serves as a drainage of flood runoff and waters from reclaimed lands of the floodplain massif.

The hydrological regime of Yakhroma is of the Eastern European type, which is characterised by high floods, low water level in the summer and winter drought periods, and increased runoff in autumn. The maximum flood discharge is, on average 10–20 times higher than the mean annual discharge [16, 17]. The share of snow supply is over 60%. Groundwater plays a significant role in nutrition.

The climate is temperate continental with frosty snowy winters and relatively humid and warm summers. According to the Dmitrov weather station, for the period 2005–2019, the mean annual air temperature was 4.9°C. The warm period with positive mean daily temperatures lasts an average of 210 days a year. The duration of the winter period with stable snow cover is more than 140 days a year. It lasts from November to mid-April. Snow height averages 55 cm. The mean annual precipitation over the past 16 years is 676 mm. Up to 70% of the annual amount of precipitation falls during the warm period from April to October. The autumn of 2019 was abnormally humid, whereas the winter of 2019–2020 was abnormally warm. Long-term dynamics of climatic conditions indicators is shown in **Figures 3** and **4**.

The soils are sod-medium podzolic, varying from gleyic to gley, light loamy sandy. The soils are depleted in organic matter (1.8–3.0%), poorly provided with mobile forms of phosphorus and potassium. Chemical elements migrate in an acidic

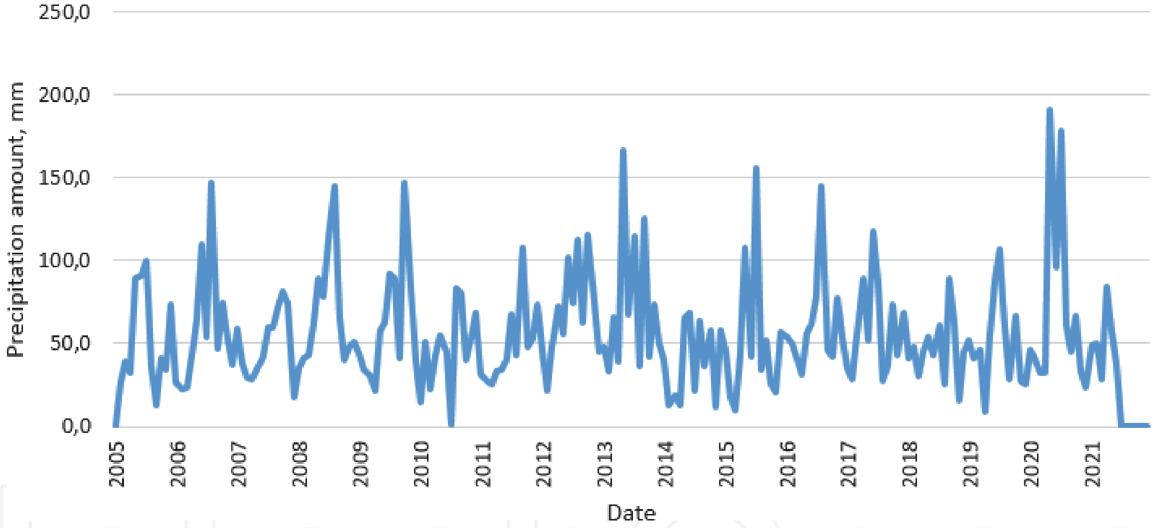

Figure 3.
Chronological graph of monthly precipitation norms according to the Dmitrov meteorological station.

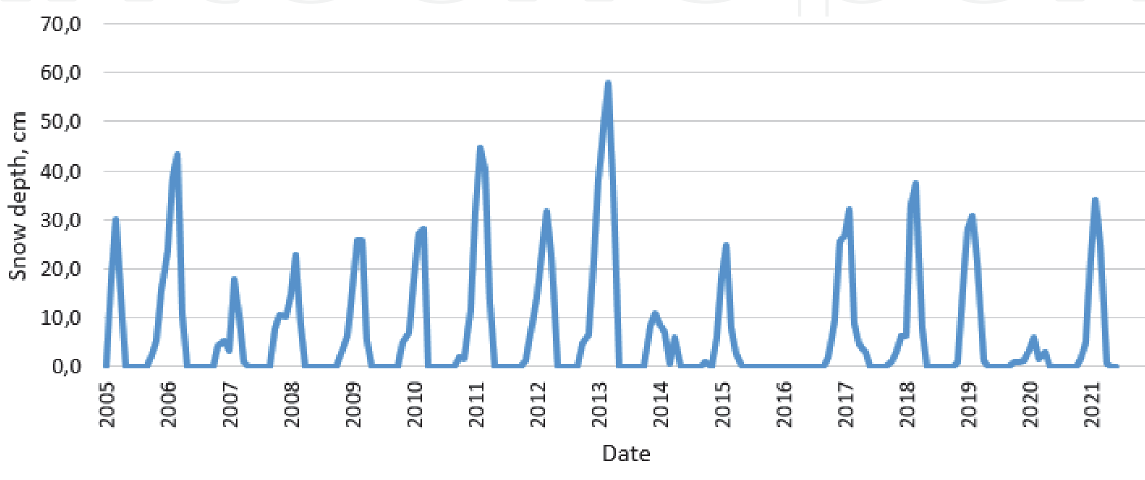

Figure 4.
Chronological graph of the snow cover height according to the Dmitrov meteorological station.

environment that leads to leaching and removal of many trace elements outside the soil profile. The valleys of the Yakhroma river are dominated by floodplain soils that form during floods, when dark, humus-rich, shallow sediments are deposited on the banks along with alluvium. The most widespread soils in the Yakhroma lowland are silt-peat, humus-peat, and humus-peaty ferruginous-carbonate gleyed. Long-term cultivation of reclaimed soils using intensive technologies with high doses of mineral fertilisers led to the secondary pollution of organogenic soil profiles with heavy metals [18].

3. Study methodology

The study methodology included reconnaissance along the entire length of the river with observation of the watercourse state. Observation and water sampling points were defined by various pollution sources in the catchment (**Figure 2**). Along the longitudinal profile of the river were selected eight sampling points: P-1 and P-3 points above the Yakhroma reservoir, where the anthropogenic load is not intense – the area comprises rural settlements, horticultural associations, and farmland. Point P-4 is located below the reservoir, in the zone of influence of the highway and cities; point P-6 is located at the beginning of the reclaimed massif of the Yakhroma floodplain, below the sewage canal of the city of Dmitrov; points P-8 and P-9 are located in the central part of the massif; P-10 is located at the exit from the massif; P-11 is located in the mouth part, near the Ust'-Pristan' settlement. Drainage runoff was studied in an open reclamation network and along the runoff from closed collectors; studies were also conducted on the flow of water into the reclamation array along tributaries and flood waters. The electrical conductivity, water temperature, and pH value were determined directly in situ using portable devices WTW's Cond 340i/SET and pH 330i/SET and HANNA instruments' conductometer HI 8733. In the samples taken for analysis in the laboratory, the content of potassium was determined by potentiometric methods; the content of nitrites, ammonium, and phosphates was determined by calorimetric methods. The content of metals and individual chemical elements in the Yakhroma river water and drainage canals was analysed by the spectrometric method of atomic emission with inductively coupled plasma (ICP) at the Engler-Bunt-Institute of the University of Karlsruhe in Germany (DVGW-Forshungsstelle am Engler-Bunte-Institut der Universheität (TH). The assessment of the quality of drainage runoff and its impact on the waters of the Yakhroma river involved the use of detailed studies conducted on the Yakhroma floodplain in different years by the professors of the All-Russia Research Institute of Hydraulic Engineering and Land Reclamation of A. N. Kostyakov such as Trifonov [19], Strelbitskaya [15], and Yashin [18, 20].

The removal of nutrients with surface and drainage runoff into the Yakhroma river was calculated taking into account cadastral and slope maps compiled using GIS technology for 1309 agricultural plots, 96 of which are classified into a separate group as reclaimed. For this, the Yakhroma river basin along the slopes of the terrain was zoned with identification of four large zones: zone 1 – weak flush (slope < 0.01), zone 2 – moderate flush (slope from 0.01 to 0.05), zone 3 – strong flush (slope > 0.05), zone 4 – reclaimed territory (floodplain slopeless massif) (**Figure 5**).

The zone of weak erosion, with a slope of less than 0.01, included 427 agricultural plots with a total area of 10,333.55 ha; five sections located on an area of 66.46 ha with a slope of more than 0.005 were brought together into the strong flush zone. When overlaying the zonal slope map on the soil and cadastral maps, the prevailing soil types were adopted for each agricultural plot and the total soil areas were determined by zones.

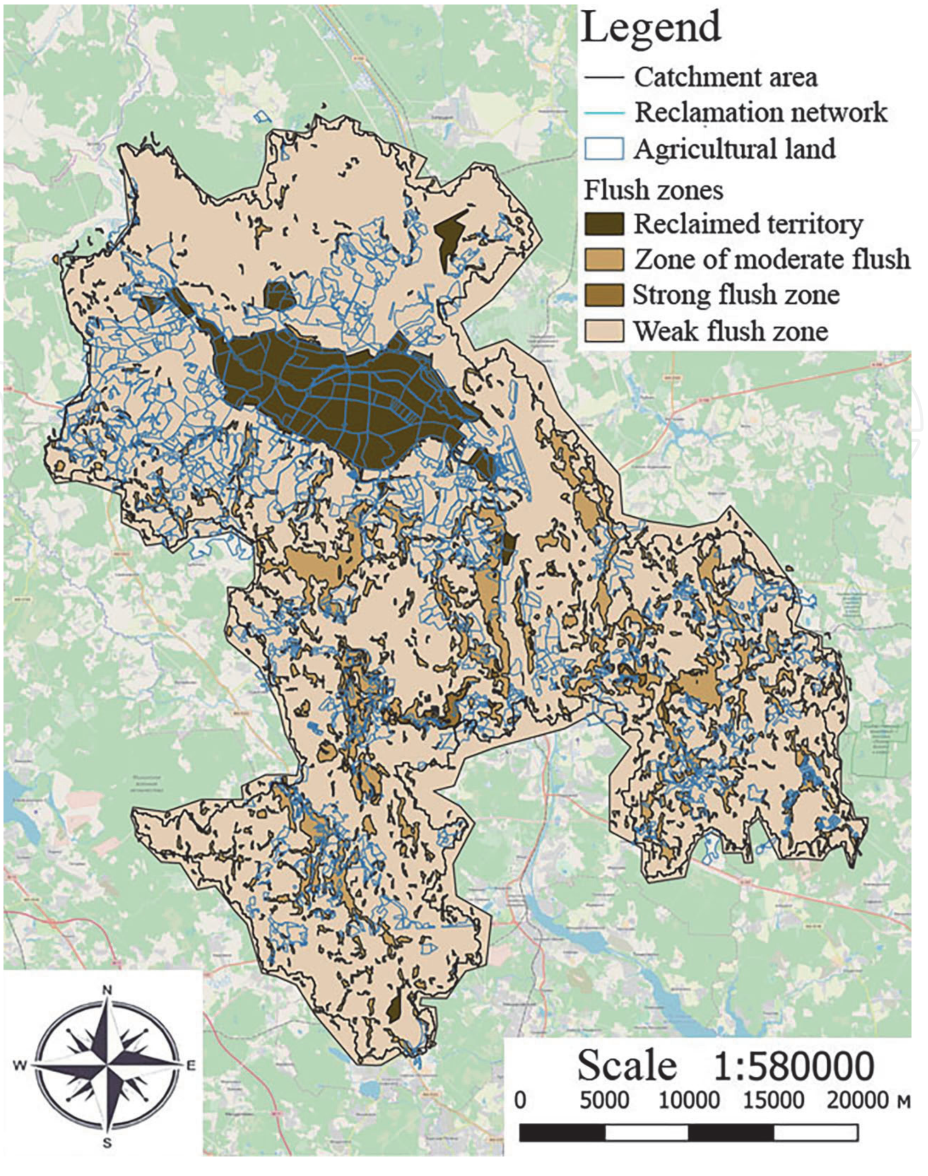

Figure 5.
Map of the distribution of agricultural plots by flush zones.

When calculating the diffuse runoff, it was assumed that potatoes are mainly grown in the weak flush zone; the moderate flush zone with sod-podzolic soils are dominated by cereals; the zone with peat soils is dominated by potatoes; in the strong flush zone, grain crops are grown on slope lands, whereas vegetables and partly potatoes are grown on reclaimed lands [21].

4. Calculation of the amount of surface and drainage water and the removal of nutrients into the river network

The amount of the surface runoff from the drained territory was estimated by the runoff coefficient *(σ)* depending on the amount of precipitation for a particular subzone of reclamation [22] using the formula:

$$\sigma = W_{surf.runoff} / W_{precip} \quad (1)$$

where $W_{surf.runoff}$ stands for the amount of surface runoff, m^3, W_{precip} is the mean annual precipitation, m^3, determined by the formula:

$$W_{precip} = 10 \cdot H^{precip}_{av.annual} \cdot F, m^3 \qquad (2)$$

where $H_{av.\ annual}{}^{precip}$ is mean annual precipitation for spring and autumn, mm; F is the water collection area, ha. It was taken into account that the surface runoff from adjacent territories enters the water intake. A river or pond having a discharge into the river was considered a water intake.

The amount of runoff was determined by the formula:

$$W_{surf.runoff} = K_{runoff} \cdot \sigma \cdot 10 \cdot H^{precip}_{av.annual} \cdot F, m^3 \qquad (3)$$

where K_{runoff} is the correction factor for the runoff of artificially drained territory. Other symbols are given above. The calculation results were compared with the data of field studies for the zone under consideration and, if necessary, were corrected [19, 20].

The flush of pollutants by surface runoff, including solid runoff, was determined by the dependencies outlined in the regulatory document [12]. The estimated dependencies take into account almost all sources of biogenic inputs into the soil, including the specific composition of mineral and organic fertilisers applied, the content of dissolved and absorbed biogenic substances in the soil by using appropriate correction factors. The residual amount of biogenic substances in the soil after being consumed from the soil by the crop was also taken into account.

The annual flush of absorbed and dissolved nitrogen by surface runoff ($Flush_N{}^{solid\ runoff}$) was calculated by the formula [12]:

$$\begin{aligned} Washout^{solid\ runoff}_{N} = \omega \cdot \left(K_2N_y + 0.002N_0 + 0.66N_n + N_{total}\right) \\ + \gamma\left(K_1N_y + 0.002N_0 + 0,07N_n\right), kg/ha \end{aligned} \qquad (4)$$

where K_1 is the coefficient determining the residual amount of mobile nitrogen forms of mineral fertilisers after consumption by agricultural plants (for ammonium nitrate – 0.02, ammonium sulphate – 0.03, ammonium chloride – 0.06); K_2 is the coefficient determining the amount of nitrogen fixed in soil and absorbed by soil microorganisms from fertilisers (for ammonium nitrate – 0.65, for ammonium sulphate – 0.35, for sodium nitrate – 0.18, for lime ammonium nitrate – 0.065); N_y and N_o stand for the rate of application of mineral (y) and organic (o) fertilisers, respectively, kg/ha; N_n and N_{total} stand for the content of mineral (n) and total nitrogen in the arable layer of soil (taken according to the survey, in this case for sod-podzolic gley soils N_n = 4000 kg/ha, N_{total} = 66 kg/ha, for sod-podzolic loamy soils N_n = 5800 kg/ha, N_{total} = 128 kg/ha, for grey forest soil N_n = 5400 kg/ha, N_{total} = 81 kg/ha, for leached chernozem N_n = 13 kg/ha, N_{total} = 195 kg/ha); ω and γ are coefficients characterising the flush of absorbed nitrogen by solid runoff and of dissolved nitrogen from the soil surface (for peat soils ω = 3.1x10^{-5}, γ = 4.3x10^{-3}; for sod-podzolic loamy soil ω = 7.2x10^{-5}, γ = 4.8x10^{-3}; for grey forest soil ω = 1.8x 10^{-4}, γ = 1.4x10^{-2}; for leached podzolised chernozem ω = 4x10^{-5}, γ = 2.4x10^{-2}).

The flush of absorbed phosphorus with solid runoff ($B_P{}^{solid\ runoff}$) over the year was determined as follows:

$$Washout^{solid\ runoff}_{P} = \omega \cdot \left(n_2P_y + n_3P_o + n_4P_n + P_{total}\right), kg/ha \qquad (5)$$

where P_y and P_o stand for the rate of application of mineral and organic fertilisers, respectively, kg/ha; P_n and P_{total} stand for the content of mineral and total phosphorus in the arable layer of soil (for sod-podzolic gley soils P_n = 300 kg/ha, P_{total} = 1820 kg/ha; for sod-podzolic loamy soils P_n = 210 kg/ha,

P_{total} = 3380 kg/ha; for grey forest soil P_n = 420 kg/ha, P_{total} = 3600 kg/ha; for leached chernozem P_n = 260 kg/ha, P_{total} = 3900 kg/ha); n_2, n_3, and n_4 are coefficients characterising the residual amount of phosphorus in mineral, organic fertilisers, and soil respectively (n_2 for light soils – 0.8; for heavy soils – 0.26; for peat soils – 0.32; n_3 = 0.0014, 0.0004, and 0.0005; n_4 = 0.85, 0.28, and 0.34).

The annual flush of absorbed and dissolved potassium by surface runoff ($Flush_K^{surf.runoff}$) was calculated by the formula:

$$\begin{aligned}\text{Washout}_K^{surf.runoff} &= \omega \cdot \left(0.2K_y + 0.0012K_{total} + 0.008K_{total} + K_{total}\right) \\ &\quad + \gamma\left[\left(\left(0,2K_y + 0.0012K_{total} + 0.008K_{total} + K_{total}\right) \cdot 0.018\right)\right]\end{aligned} \tag{6}$$

where K_y is the rate of application of the mineral fertiliser, kg/ha; K_{total} is the total amount of potassium in the arable layer of soil, kg/ha (for sod-podzolic gley soils K_{total} = 50,000 kg/ha, for sod-podzolic loamy soils K_{total} = 58,000 kg/ha, for grey forest soil K_{total} = 50,600 kg/ha, for leached chernozem K_{total} = 51,250 kg/ha).

The drainage flow (W_{dr}) was calculated based on the known dependencies of the mean annual module drainage flow:

$$W_{dr} = \frac{q \cdot F \cdot t}{1000}, m^3 \tag{7}$$

where q is the mean annual module of drainage flow, L/s/ha; F is the area of the drained area, ha; t is the number of seconds in a year, s.

A correction factor for the flush of biogenic substances for the long-term mean annual water content was introduced to determine the flush of biogenic substances with drainage runoff.

Nitrogen annual flush by drainage runoff ($Flush_N^{dr}$) is determined by the formula:

$$\text{Washout}_N^{dr} = \frac{\left(K_1 \cdot N_y + 0,0002N_0 + 0,007N_n\right)W_{dr}}{W_{limit} + W_{dr}}, \text{kg/ha} \tag{8}$$

where W_{limit} is moisture reserve in the considered soil layer to the groundwater depth or to the depth of drainage at maximum moisture capacity of soil, m^3/ha (for peat soils W_{limit} = 4500 m^3/ha, for sod–podzolic loamy soils W_{limit} = 2682 m^3/ha, for grey forest soil W_{limit} = 2138 m^3/ha, for leached chernozem W_{limit} = 2765 m^3/ha);

See other symbols above.

The annual flush of dissolved phosphorus by drainage runoff ($Flush_P^{dr}$) is determined by the formula:

$$\text{Washout}_P^{dr} = \frac{n_1 W_{arable}^{limit} \cdot W_{dr}}{W_{limit} + W_{dr}}, \text{kg/ha} \tag{9}$$

where n_1– the value characterising the content of dissolved phosphorus in the soil (for light soils it is 0.002; for heavy soils it is 0.00017; for peat soils it is 0.0015); W_{arable}^{limit} is moisture content in the topsoil, m^3/ha (for peat soils W_{limit} = 1350 m^3/ha, for sod–podzolic loamy soils W_{limit} = 537 m^3/ha, for grey forest soil W_{limit} = 428 m^3/ha, for leached chernozem W_{limit} = 553 m^3/ha).

The annual flush of dissolved potassium by drainage runoff ($Flush_K^{dr}$) is determined by the formula:

$$\text{Washout}_K^{dr} = \frac{\left[\left(0,2K_y + 0,0012K_0 + 0,008K_{total}\right)0,018\right]W_{dr}}{W_{limit} + W_{dr}}, \text{kg/ha} \tag{10}$$

where K_o is the rate of application of organic fertiliser, kg/ha,

The total volume of biogenic compounds flush was determined by the following formula:

$$B^{total} = \sum B_i^{dr} + \sum B_i^{surf} = B_N^{dr} + B_P^{dr} + B_K^{dr} + B_N^{surf} + B_P^{surf} + B_K^{surf}, \text{kg/ha} \quad (11)$$

where B_i^{dr}, B_i^{surf} stand for the flush of i biogenic element (nitrogen, phosphorus, potassium) by the drainage and surface runoff respectively.

5. Hydrochemical studies of water quality in the Yakhroma river basin

The purpose of hydrochemical studies conducted since 2001was to establish and localise sources of water pollution along the longitudinal profile of the river. They showed that over the entire observation period, the salinity of water in the river fluctuated within 80–500 mg/dm^3 and increased from source to mouth due to inflow of wastewater from the cities of Yakhroma and Dmitrov and surface runoff of tributaries and diffuse runoff from the catchment area. The data on the content of biogenic pollutants is taken from observations conducted in 2019–2020. In the spring period (samples were taken on April 12, 2019), the chemical composition of river water was determined mainly by the quality of melt water from the slopes and along the tributaries and was characterised by relatively low values of the content of dissolved salts. It was found that along the longitudinal profile of the river, the electrical conductivity naturally increased due to diffuse runoff and point sources from 56 μS/cm in the upper reaches to 229 μS/cm in the lower reaches (**Figure 6**). The highest value is confined to the site where the river receives wastewater from the city of Dmitrov and drainage water from the reclaimed massif, which are characterised by increased electrical conductivity (P-6–P-10). The electrical conductivity of the tributaries entering the Levyy Nagornyy canal varies from 285 μS/cm to 591 μS/cm; in the open drainage network it varies from 352 μS/cm to 1170 μS/cm. At the same time, increased values are typical for drainage canals with minimal flow rates.

The distribution of electrical conductivity values along the longitudinal profile of the river in the summer (July 15, 2020) and autumn (September 30, 2020)

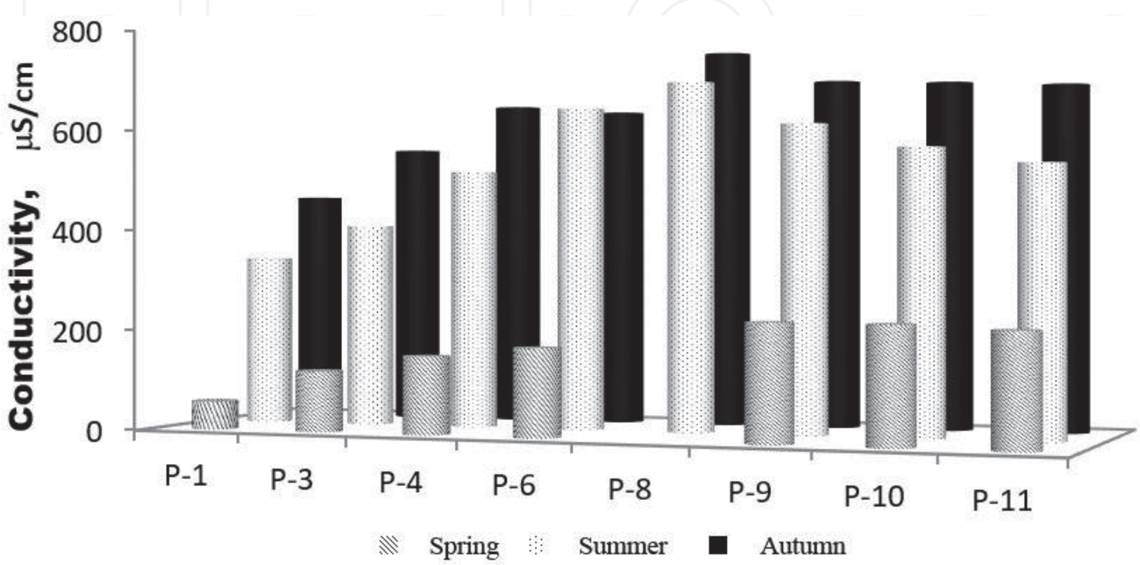

Figure 6.
Change in electrical conductivity (μS/cm) of water along the longitudinal profile of the Yakhroma river by season.

periods is similar. These seasons are characterised by higher values reaching 695–766 μS/cm. The maximum values are observed within the reclaimed massif, which is associated with drainage waters flowing into the river. The ratios of the electrical conductivity values of the water of the Yakhroma river by seasons in the sections "entry" to the reclaimed massif and "exit" from it showed that due to drainage runoff and unloading of groundwater with an increased concentration of salts, the salinity of the river runoff increases in winter–spring periods – mineral salts are withdrawn into the river by runoff from agricultural lands. In summer, due to irrigation and decreased salinity of the drainage runoff, electrical conductivity at the outlet from the massif decreases. In the autumn period, due to precipitation, these processes slow down so that the values of electrical conductivity become almost similar. The values of the electrical conductivity of almost all hydrospheric components within the reclaimed massif, tributaries from the sides of the valley (520–870 μS/cm) and pressure waters (640–650 μS/cm) show that the maximum values of electrical conductivity reaching 1100–1300 μS/cm are characteristic of the drainage runoff in autumn and winter. This is probably due to partial flush of mineral fertilisers by the surface runoff and flow of residual amounts into deep soil horizons and groundwater.

Figure 7 shows the distribution of nutrient concentrations in river water along the longitudinal profile from the source to the mouth of the Yakhroma river. The nutrient content in river water gradually increases from the source to the beginning of the reclaimed Yakhroma floodplain massif (point P-6) with some fluctuation within the land reclamation massif and a decrease towards the river mouth. A sharp increase is observed at point P-6. Increased concentrations of phosphates and ammonium are characteristic of the summer and autumn periods and are confined to the reclaimed massif of the Yakhroma floodplain (P-8–P-10). The surge in the concentrations of phosphates and ammonium nitrogen is confined to the beginning of the floodplain massif (R-6) and is caused by the influence of the discharge of insufficiently treated urban wastewater. On reclaimed lands, the content of phosphates in the reclamation network varies, as a rule, in the range of 0.06–0.54 mg/dm^3, ammonium nitrogen content varies between 1.3 and 4.5 mg/dm^3 and 11.03 mg/dm^3, which significantly exceeds the fishery standards. The potassium content varies over a wide range – from 1.7 to 33.7 mg/dm^3, while the most frequent values fall into the range 2.0–10.8 mg/dm^3. This is confirmed by detailed studies conducted earlier by A.V. Trifonov [19], who showed that the annual drainage removal of potassium oxide is 8 kg/ha. Drainage waters also contain ions of calcium, magnesium, iron, nitrogen, sulphur, chloride, potassium, phosphorus, and silicon. According to E.B. Strelbitskaya's studies [15], the inflow of drainage water from the reclaimed massif increased the concentration of ammonium ions in the river water in the area below the discharges from the drainage system, exceeding the standards for fishery reservoirs on average by more than 2–11.5 times.

The results received in 2019–2020 are confirmed by the study conducted by V.M. Yashin in 2001–2005 on the reclaimed massif of the Yakhroma floodplain [18]. The pH varies from 6.0 to 8.1 with the most frequent values in the range from 7.0 to 7.7. There are no definite patterns in pH changes for various water bodies. Artesian (0.4–0.8 mg/dm^3) and drainage waters at the mouths of closed drains and collectors (1–2 mg/dm^3) are characterised by the lowest values of dissolved oxygen. In open reclamation canals, the content of dissolved oxygen does not reach the standard (6.0 mg/dm^3) level. The maximum concentrations of biogenic pollutants are typical for the Levyy Nagornyy canal, which receives water from tributaries from the left side of the valley, including groundwater and partially wastewater from rural settlements.

The pollution of drainage and river waters with heavy metals is characterised by the data in **Table 1**. The water contains a wide range of dissolved metals. On the

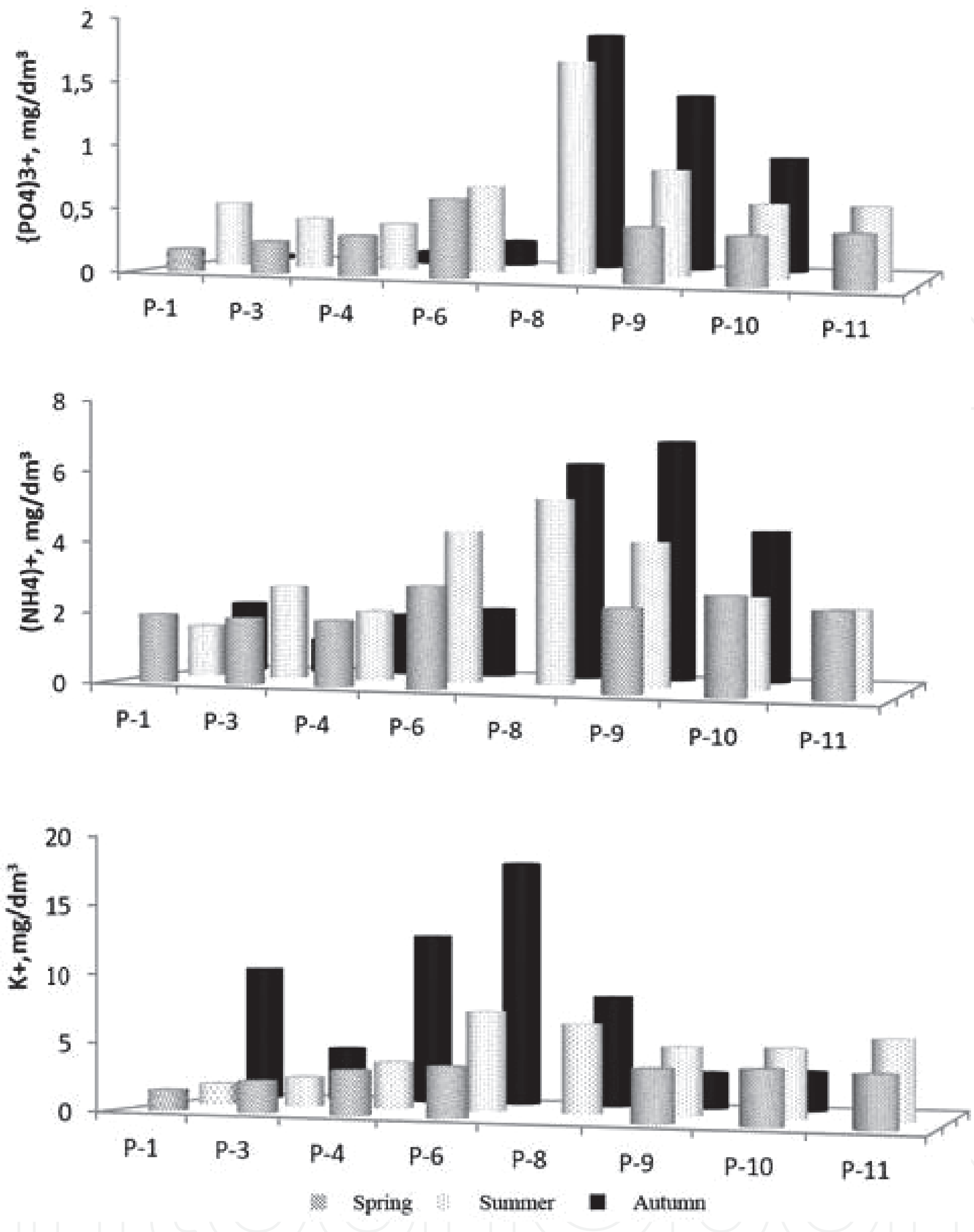

Figure 7.
Distribution of the content of nutrients along the length of the longitudinal profile of the Achromat river by seasons.

basis of the concentrations of metals drainage, river waters are divided into three groups: more than 1000 μg/dm^3 (calcium, magnesium, sodium, potassium and silicon for river waters and iron and strontium for drainage waters), 100–999 μg/dm^3 (aluminium, barium, phosphorus, manganese, and iron for drainage waters and strontium for river waters), and up to 99 μg/dm^3 (heavy metals such as cobalt, copper, nickel, lead, zinc). The concentrations of metals, except iron and strontium, in the drainage runoff exceed their content in river water, which indicates potential danger of river water pollution.

The concentrations of organochlorine (according to AEX) compounds in drainage and river waters were 23 μg/dm^3 and 8.2 μg/dm^3 respectively.

Metal	Open drainage	Closed drainage		Yakhroma river, output from massive
		KYa-26-2	KYa 26-2-12	
Ca	111,700	150,820	162,080	92,830
Mg	24,835	30,030	50,455	24,665
Na	13,380	8964	8435	18,890
K	2404	2025	2950	5170
Fe	**254**	**3230**	98	**254**
Si	983	9000	12,360	8260
Sr	**534**	**614**	**3530**	**573**
Al	13	**45**	15	26
Ba	**87**	**125**	**115**	54
Mn	**200**	**500**	**580**	**48**
Co	1	2	1	<1
Ni	<2	**12**	**50**	6
P		**42**	**199**	**271**
Pb	<5	<5	**99**	<5
Cu	**2**	**5**	**3**	<2
Zn	3	5	**100**	**13**
V	**2**	**4**	**50**	**4**

Note: metal concentrations exceeding the standards are highlighted in bold.

Table 1.
Content of metals in drainage runoff and river water, (μg/dm^3).

Thus, the study revealed increased concentrations of pollutants in the river water within the reclaimed massif of the Yakhroma floodplain. This confirms the influx of uncontrolled diffuse runoff into the river network from the catchment area.

6. Assessment of diffuse runoff from the catchment area of the Yakhroma river

To assess the diffuse runoff, the volume of surface water was calculated for the identified zones of flush and drainage water from the reclaimed massif (**Figure 5**). The average long-term module of surface runoff depends on the slope angle. In the zones of weak, moderate, and strong flushes, it equals to 0.013 dm^3/s/ha, 0.017 dm^3/s/ha, and 0.029 dm^3/s/ha respectively. On the reclaimed massif, where drainage is used, the module of surface runoff is less than 0.005 dm^3/s/ha; the calculated mean vegetation module of drainage runoff is 0.052 dm^3/s/ha; the maximum module during the spring snowmelt period reaches 1 dm^3/s/ha. The mean annual amount of surface and drainage runoff was calculated according to formulas (3) and (7) for all considered zones (**Table 2**).

As can be seen from the table, surface runoff is 12.4 mln m^3/year, while drainage runoff is 15.9 mln m^3/year. The first is formed on an area of 22.6 th ha, while the second is concentrated on a floodplain with an area of 9.7 th ha. Removal of nutrients (NPK), surface, and drainage runoff are calculated according to dependencies (4–6) and (8–10). Calculations showed that the annual surface removal of

Zone name	Zone 1, weak flush, slope <0.01	Zone 2, moderate flush, slope from 0.01 to 0.05	Zone 3, strong flush, slope > 0.05	Zone IV, floodplain massif
Area, ha	10333.55	12,233.99	66.46	9730.80
Drainage				15,957.26
Surface runoff	4173.72	6551.32	61.34	1572.11
Total flow, th m^3/year		28,315.75		

Table 2.
The results of calculating the amount of surface and drainage runoff (thousand m^3/year) from the drainage basin of the Yakhroma river.

nitrogen from agricultural land varies from 0.51 kg/ha to 1.09 kg/ha, while drainage removal is 9.96 kg/ha (**Table 3**).

The largest nitrogen removal is noted with drainage waters; its average concentration in water reaches 6 mg/dm^3; the predominant form of nitrogen in drainage water is nitrate (97% of the removed total mineral nitrogen), the content of which in drainage water according to data [23] can vary within the range of 0.42–9.66 mg/dm^3, whereas the removal reaches 5.5–8.0 kg/ha.

The removal of phosphorus from the soil by surface and drainage waters is insignificant (does not exceed 0.1% of the phosphorus content in the soil), which is explained by its low mobility (**Table 4**).

Phosphorus practically does not enter the drainage waters; its concentration does not exceed 0.02 mg/dm^3 even with the introduction of phosphate fertilisers, since orthophosphoric acid is associated mainly with trivalent metals, and especially with aluminium. In the classical experiments of the Rothamsted Experimental Station on the use of phosphorus fertilisers conducted for 130 years, the

Zone name	Zone 1	Zone 2	Zone 3	Zone 4
Nitrogen removal by surface runoff, t/year	9.59	6.42	0.03	11.32
Weighted average nitrogen removal by surface runoff, kg/ha	0.92	0.51	0.53	1.09
Nitrogen removal by drainage runoff, t/year				96.88
Weighted average nitrogen removal by drainage runoff, kg/ha				9.96
Nitrogen concentration in surface runoff	2.30	0.98	0.49	7.20

Table 3.
Results of calculating nitrogen removal from the drainage basin of the Yakhroma river by flush zones.

Zone name	Zone 1	Zone 2	Zone 3	Zone 4
Phosphorus removal by surface runoff, t/year	2.02	2.41	0.01	1.62
Weighted average phosphorus removal by surface runoff, kg/ha	0.16	0.14	0.20	0.14
Phosphorus removal by drainage runoff, t/year				0.38
Weighted average removal of phosphorus by drainage runoff, kg/ha				0.04
Phosphorus concentration in surface runoff, mg/dm^3	0.48	0.37	0.14	1.03
Concentration of phosphorus in the drainage runoff, mg/dm^3				0.02

Table 4.
Results of calculating phosphorus removal by flush zones from the drainage basin of the Yakhroma river.

Zone name	Zone 1	Zone 2	Zone 3	Zone 4
Potassium removal by surface runoff, t/year	79.67	100.94	0.52	61.15
Weighted average potassium removal by surface runoff, kg/ha	7.89	5.62	7.89	4.87
Removal of potassium by drainage runoff, t/year				37.04
Weighted average potassium removal by drainage runoff, kg/ha				3.81
Potassium concentration in surface runoff, mg/dm^3	19.09	15.41	8.53	38.89
Potassium concentration in drainage runoff, mg/dm^3				2.32

Table 5.
Results of calculating potassium removal from the drainage basin of the Yakhroma river by flush zones.

concentration of phosphorus in drainage waters was not more than 0.05 mg/dm^3 with a phosphorus content in the soil solution of up to 0.2 mg/dm^3 [24].

The removal of potassium with surface and drainage waters significantly depends on its content in the soil and the application rates of highly soluble potassium fertilisers and ranges from 4.87 kg/ha to 7.89 kg/ha (**Table 5**).

In the drainage waters of soddy-gley soils, the concentration of potassium reaches 2.32 mg/dm^3. This is due to the introduction of a large amount of potash fertilisers on the reclaimed massif, which is confirmed by the earlier studies by M.A. Borovitskaya [25]: when potassium was applied at a dose of 170 kg/ha, the removal of potassium on soddy-podzolic loamy soil increased from 3.3 kg/ha to 9.6 kg/ha, and on sandy loam it increased from 2.2 kg/ha to 10.5 kg/ha.

The total removal of nutrients, according to calculations, amounted to almost 410.0 t/year, including removal of nitrogen compounds of 124.2 t/year, removal of phosphorus of 6.4 t/year, and removal of potassium of 279.4 t/year [26]. Drainage runoff removes 96.9 t/year of nitrogen compounds, whereas surface waters remove only 27.4 t/year, which is 3.5 times less, while surface removal of phosphorus compounds is on the contrary 6.1 t/year and drainage removal is 0.4 t/year, or 15 times less. Removal of nutrients with drainage runoff on reclaimed lands is almost two times higher than with surface runoff and amounts to 134 kg/ha/year. Dissolved nitrogen compounds predominate in the drainage runoff. Their removal varies from 7 kg/ha/year to 12 kg/ha/year; drainage removal of phosphorus compounds varies from 0.02 kg/ha/year to 0.06 kg/ha/year; potassium removal varies from 0.8 kg/ha/year to 5.7 kg/ha/year. This explains the surge in the pollution of the Yakhroma river waters within the reclaimed massif.

7. Development of measures to reduce diffuse pollution of the Yakhroma river

The pollution of river waters can be reduced by decreasing surface runoff and improving its quality. Low-cost organisational and economic measures reduce diffuse runoff by 20%, agrotechnical methods reduce it by 25–50%, and agro-reclamation methods reduce it by 50–75%. Organisational, economic, and agrotechnical measures are recommended on all plots of arable land of the catchment of the Yakhroma river on an area of 32,365.5 ha.

On arable land with a slope of up to 0.01 (weak flush zone) on an area of 10333.6 ha, it is recommended to conduct accelerated ploughing to transfer part of the surface runoff to soil runoff by forming shallow parallel furrows every 4–15 m, into which surface water flows from the entire enclosure. Lands with small slopes (up to 0.01) should be ploughed towards the natural surface slope, with large slopes

Scenarios	Removal of nutrients in the current state				Predicted removal of nutrients after taking the measures			
Zone name	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**	**Zone 1**	**Zone 2**	**Zone 3**	**Zone 4**
Nitrogen removal, t/year	9.59	6.42	0.03	108.19	7.67	3.21	0.00	26.48
Phosphorus removal, t/year	2.02	2.41	0.01	1.99	1.61	1.21	0.00	0.42
Potassium removal, t/year	79.67	100.94	0.52	98.19	63.73	50.47	0.00	21.49
Total removal of nutrients, t/year	91.27	109.77	0.56	208.38	73.02	54.89	0.00	48.39
Total removal of nutrients, t/year	409.984				176.294			

Table 6.
Estimated values of nutrient removal during water protection measures.

at a certain angle to the surface slope so that the slope of the furrows does not exceed 0.01. The recommended distance between the exit furrows is 80–140 m. These techniques will reduce the surface runoff by up to 50%.

In the zone of moderate erosion on an area of 12,234 ha, it is recommended to conduct surface ridging or deep ridge ploughing. This leads to the formation of dense network of furrows, the water from which is diverted to the collectors along the drainage furrows, which reduce the diffuse runoff by 50–75%.

The strong flush zone occupy an area of 66.5 ha. To regulate surface runoff, it is recommended to create anti-erosion hydraulic structures, which are earthen embankments, that is, terraces that allow partial surface runoff without destroying the soil in cases of rainfall in excess of the calculated value.

On the reclaimed massif of the Yakhroma floodplain under study on an area of 9731 ha, where the drainage runoff is discharged directly into the river network, it is recommended to build a diversion canal with a bed bioplateau inside it, downstream from which the treated runoff is discharged into the Yakhroma river. For additional treatment of the drainage runoff, the bioplateau is planted with higher aquatic vegetation in alternating strips of 5–10 m along the width of the watercourse serving as a barrier to the incoming pollutants. The flood is passed through the retaining structure. At a depth of from 0.8 m to 1.2 m in structures, it is recommended to plant *Phragmítes austrális* and *Ceratophýllum demérsum* to absorb nutrients and *Schoenoplēctus lacūstris*, *Elodeacanadensis*, and *Ceratophýllum demérsum* to reduce the concentration of heavy metals, phenol, and pesticides. The bioplateau purifies the drainage runoff from biogenic pollutants by 55–85%.

A possible reduction in the removal of pollutants into water bodies of the Yakhroma river was also calculated when taking the above measures. Also the removal of nutrients such as nitrogen (37.36 t), phosphorus (3.24 t), and potassium (135.7 t) was determined. The total intake of nutrients (176.3 t) allows reducing the diffuse load on the water body by more than 50% (**Table 6**).

Thus, for the given catchment area, the recommended set of measures will ensure a decrease in diffuse runoff formed as a result of agricultural activities.

8. Conclusions

1. To assess the possible diffuse pollution of water bodies in the process of agricultural production, the catchment area of the small Yakhroma river was selected. The conducted studies made it possible to comprehensively consider

the formation of diffuse runoff from the surface of agricultural fields and drainage runoff from the reclaimed objects depending on climatic, soil, and organisational conditions and to estimate the volume of biogenic pollution entering the Yakhroma river.

2. Hydrochemical studies of river water quality along the Yakhroma river profile made it possible to identify pollution sources, the main of which are the point discharge of insufficiently treated municipal waters from Dmitrov and Yakhroma cities and the discharge of drainage and surface waters from the reclaimed massif of the Yakhroma river floodplain.

3. The methodological approach to the assessment of regional diffuse pollution proposed by the authors provides a solution to one of the priority tasks of environmental management and is of practical importance in assessing the pollution of any water body with biogenic substances. The study methodology is based on a comprehensive and objective analysis of the results of field studies in the region under consideration.

4. The revealed regularities of the formation of surface and drainage runoffs and the use of calculated dependences make it possible to comprehensively consider the formation of diffuse runoff from the surface of agricultural fields and drainage runoff from drainage systems depending on climatic, organisational, and economic conditions and to estimate the volume of biogenic pollution entering the water bodies of the Upper Volga.

5. It is shown that in the Yakhroma river basin the amount of surface runoff from agricultural fields is 12.4 mln m^3/year; the amount of drainage runoff is 15.9 mln m^3/year, while surface runoff is formed on an area of 22.6 th ha, and drainage is concentrated on a floodplain with an area of 9.7 th ha The total removal of nutrients, according to calculations, amounted to almost 410.0 t/year, including that of nitrogen compounds (124.2 t/year), phosphorus (6.4 t/year), and potassium (279.4 t/year). Removal of nutrients with drainage runoff on drained lands is almost 2 times higher than with surface runoff and amounts to 134 kg/ha/year. Dissolved nitrogen compounds predominate in the drainage runoff. Their removal varies from 7 kg/ha/year to 12 kg/ha/year; the removal of phosphorus compounds with drainage runoff varies from 0.02 kg/ha/year to 0.06 kg/ha/year; potassium removal varies from 0.8 kg/ha/year to 5.7 kg/ha/year.

6. Reducing and cleaning diffuse runoff will allow decreasing the diffuse load on a water body by more than 50%, protecting water bodies, and reducing risks to human life and health.

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