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Article

Runoff of Water and Its Quality under the Combined Impact of Agricultural Activities and Urban Development in a Small River Basin

Fedor N. Lisetskii [1,2,*] and Zhanna A. Buryak [1]

[1] Federal and Regional Centre for Aerospace and Ground Monitoring of Objects and Natural Resources, Belgorod State National Research University, 85 Pobedy Str., Belgorod 308015, Russia; buryak@bsu.edu.ru
[2] Institute of Ecology and Environment, Kazan Federal University, 18 Kremlyovskaya Str., Kazan 420008, Russia
* Correspondence: fnliset@mail.ru

Abstract: The basin of the small river studied here (the Vezelka River, Belgorod Oblast of European Russia) is located within an urban area (22% of the basin). This circumstance determines its specificity as an object of synergetic anthropogenic impact. The purpose of the work was to develop and test approaches to the integral assessment of the hydroecological situation both in the watershed and riparian zones based on hydrological, hydrochemical, and hydrobiological data and estimates of soil erosion, river water quality, and the pollution of river bottom sediments. The selection of the Vezelka River and its watershed for the study was due to the presence there of two water intakes for a town with a population of 2439 people per sq. km, repeated bottom deepening in the riverbed, and the fact that there is a single regional small-river hydrological station (although there are 567 rivers < 25 km long in Belgorod Oblast). Analysis for 1951–2021 showed a steady decline in water discharge since 1991; thus, over the past three decades, the discharge has decreased by 2.4 times. The reduction in the length of the river network of the study region by 38% over the past 250 years and the assignment of water (at 10 gauging stations) to 3–4 quality classes (extremely and heavily polluted) indicated the exhaustion of the possibilities for the self-purification of the river water. These estimates for large and medium rivers were clearly confirmed by the investigation of the water in the small river studied. In the summer low-water periods, the maximum allowable concentrations in fishery water bodies were exceeded by 2–10 times in terms of Cu, Fe, ammonium, oil, and biochemical oxygen demand. The reconstruction of the floodplain–channel subsystem of river–valley landscapes was substantiated as the final stage of the concept of basin nature management, replacing the continuous deepening of the channel without proper erosion control measures in the watershed area and the organization of buffer zones along the river banks.

Keywords: small river; hydroecological assessments; saprobity; watershed area; soil erosion

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Citation: Lisetskii, F.N.; Buryak, Z.A. Runoff of Water and Its Quality under the Combined Impact of Agricultural Activities and Urban Development in a Small River Basin. *Water* **2023**, *15*, 2443. https://doi.org/10.3390/w15132443

Academic Editors: David Dunkerley and Renato Morbidelli

Received: 26 May 2023
Revised: 24 June 2023
Accepted: 30 June 2023
Published: 2 July 2023

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1. Introduction

All the ancient great civilizations were 'riverine civilizations' whose prosperity depended on being able to develop agriculture in fertile water meadows. However, such components of the hydrological cycle as snowmelt-induced and rainfall-induced floods have not only been involved in the formation of alluvial soils for millennia, but have also threatened riverine areas occupied by inhabited agricultural landscapes [1]. Considering the worldwide regularity in the location of not only of many rural settlements but also cities, as well as the need to ensure the rational use of water resources, the viability and sustainability of cities and towns correspond to the implementation of the global Sustainable Development Goals approved by the UN General Assembly in 2016 [2].

Small rivers are the most numerous types of permanent watercourses. They constitute approximately 95% of all the permanent water courses on the Earth and are situated mostly in humid valleys, where the most active nature management is notable. In particular, according to an estimate by the Ministry of Natural Resources and Environment of the Russian Federation, the percentage of watercourses ≤25 km long is 94.9% of the total length of the river network of the country (12.4 million km). The local conditions during the formation of a river channel greatly determine the hydrological and environmental terms of the use of small rivers as a resource base for various sectors of the economy and human life. Small rivers are watercourses with a catchment area of not more 100 km^2 and a length less than 100 km; the width of their channel, as a rule, is less than 30 m; and the depth in the shallows can decrease to 20–30 cm. Small rivers form the water resources, hydrological regimes, and water quality of medium and large rivers. Large rivers, being formed from smaller streams of different genesis with basins with different landscapes, experience inertia when the state of the aquatic ecosystem changes under the influence of climatic instability and anthropogenic pressure on their basins. There is a reasonable idea that a network of rivers is a unique structural element of the landscape sphere [3], since small rivers combine two elements interconnected in a cascade: a watershed, as an arena for the formation of watercourses, and a riverbed, where the latter are concentrated. Small rivers located in the conditions of a single landscape have insignificant water discharges. Therefore, the active influence of natural and economic factors on the rivers of this class manifests itself more clearly and faster than is observed in large rivers. For this reason, it is considered that small rivers are more sensitive and, therefore, more vulnerable to anthropogenic impacts [4–7]. The river basins most developed in agriculture are distinguished by the most significant changes in water and sediment discharge, as well as the intensity of erosion in their basins [8].

Small rivers that experience the anthropogenic impacts of civil and industrial construction in their lower reaches are a unique object of hydrological investigation due to a number of reasons, such as the importance of specific aspects of nature management in urban watersheds [9–11], as well as the necessity to delineate the boundaries of flood zones and estimate the risk of flooding in urban areas [12–15]. The amounts of river sediments and their compositions are formed under the influence of erosion, sedimentation, and physicochemical and biological processes, which determine the need for an integrated hydrological and geochemical approach to their study [16]. Along with alluvium, formed in rivers and floodplains as a result of soil erosion in the interfluve, in urban areas, inorganic and organic substances with wastewater discharge can be additional sources [17]. An assessment of bottom sediment pollution with heavy metals (HMs) showed [18] that their concentrations depended on the content of sand and, to a greater extent, of silt, while, along with the ensemble of geogenic sources, the anthropogenic factor (agriculture, road traffic) contributes to the concentration of Zn and Ni. In addition, it is important to note that fine-grained particles and organic matter contribute to the availability of macronutrients in bottom sediments [19].

The evolution of a river valley presenting a peculiar paragenetic landscape Is controlled by such a key factor as the water erosion process (surface washout, gully and riverbed erosion) with accompanying phenomena including lithodynamic processes, the migration of matter, and the siltation of the floodplain. In the structure of a river valley, the slope/terrace and floodplain/riverbed series of landscapes are distinguishable, implying a combination of geosystems with belt structures bordering a system-formative line of the stream (riverbed) [20]. The riverbed and floodplain are engaged in continuous interaction and interinfluence. The floodplain and landscapes are formed under the impact of the riverbed processes or during the submerging of the floodplain by floods, whereas the topography and composition of the floodplain, in turn, affect the riverbed's processes. Therefore, it was proposed [21] to consider the riverbed and floodplain as an integral natural formation, i.e., an independent subsystem within the river valley landscape, and to call it a floodplain/riverbed complex. It is obvious that the water flow determines the concentration of suspended sediments in the river to a decisive extent. Thus, interdisciplinary studies [16] have shown that channel and lateral erosion in low-water periods cause an average increase in sediment, although, in some parts of the main channel, there is a significant (up to 30%) decrease in the concentrations of suspended sediments. The geomorphological aspect in explaining the specifics of river silting also concerns the study of the specific organization of floodplain sediment accumulation, especially in low-level floodplains near the channel, which are most prone to floods and flooded for the longest periods [22].

An assessment of the contributions of the key factors determining the material composition of the floodplain/riverbed sediments and the estimation of the rate of their accumulation are considered [23] to be difficult tasks because of the presence of numerous 'filters' of a geomorphological, landscape-related, and anthropogenic nature.

The thus-far-accumulated experience in the study and assessment of sedimentation in the floodplains of rivers in Western Europe [24–26], Ukraine [27–30], Russia [31–34], Asia [35,36], the USA [37,38], and Australia [39] presents a considerable range of methods and technologies. In addition, the effectiveness of the concept of a joint erosion–sedimentation process [40]—according to which the entire set of watercourses, from temporary slope watercourses to large rivers, is an interconnected system—is gaining increasing recognition. Small rivers are an intermediate link in this system, which is affected by processes in the watershed, and thus they represent a buffer between watersheds and higher-order rivers.

An active analysis of the problems of modeling linear and sheet erosion is necessary due to the fact that the surface component of the hydrological cycle is organized mainly within the framework of drainage networks [41]. New opportunities to study and parameterize land use conditions and watershed regimes arise when using GIS technologies [42–44] and neurotechnologies [45]. Erosion risk assessment at the regional level [46–48] and justification of the allowable soil loss (T-value) [49,50], together with the assessment of indirect damage from sediment accumulation in the hydrographic network [51], are the foundations of modern soil and water protection in erosion control landscapes. The combined use of the SEA/Balance (soil erosion/sedimentation balance) and WaTEM/SEDEM models is promising in terms of mapping the sediment balance in river basins [52]. However, the estimation of soil loss using a successful combination of WaTEM/SEDEM (rain erosion) models and the calculation of the rate of erosion during snowmelt has a major drawback, associated with the relatively low accuracy in estimating the volume of deposits and determining the zones of deposits [53]. Meanwhile, this modeling component is important in determining the locations within the landscapes of river valleys that are sources of sediments involved in the silting of river channels. The interdisciplinary multi-objective method, including vulnerability analysis, exposure hazard analysis, and flood risk analysis [13], compares favorably with traditional approaches that focus on only one problem.

The comparison of river basins from the point of view of their anthropogenic transformation should be carried out according to four main indicators: the coefficient of anthropogenic transformation; the land degradation index; the urban index; and the degree of anthropogenic transformation [54]. As an innovative basis for the modeling of soil erosion [55] and the arrangement of agrolandscapes [56], an object-oriented approach has been adopted, which allows the structuring of information from the point of view of controllability and the corresponding methodology. The basin-scale approach to the integration of agro- and hydroecological monitoring and the soil protection management of watershed lands on basin principles [57–60] is a well-established concept that is already being applied in practice.

In the Central Chernozem region of the European part of Russia, which is the focus of this study, significant changes in the water discharge of small rivers have been recorded [61]. This was due to increased economic activity within the watersheds, as well as significant climate change. During two or three centuries of the intensive development of watersheds for agricultural needs, the rivers have become heavily silted, although, after the collapse of the USSR in 1991, a significant decrease in the intensity of erosion and river runoff of suspended sediments was noted in the forest steppe zone of European Russia [62]. Under the conditions of the active intensification of soil erosion in watersheds, the main part of the floodplain—although it is regularly flooded with water and grows due to the vertical accumulation of sediments—is nevertheless not eroded and is not renewed by a concentrated channel flow of water. This is why the phenomenon of the degradation of small rivers can be observed everywhere, since the latter cannot cope with the movement of all sediments formed on the watershed area. Earlier, an important conclusion was made [63] that the decrease in the volume of spring flood runoff, which is characteristic of the rivers in the European part of Russia, acts as a factor in the dynamics of the water richness of small rivers and, at the same time, as a factor in their degradation in the upper reaches.

Thus, the modern consideration of the problem has shown that a comprehensive analysis of the natural and economic situation in small river watersheds and its purposeful reflection in the water masses of the channel offers a scientific basis for the development of measures to regulate anthropogenic loads and prevent or mitigate their negative consequences. The purpose of the present work was to develop and test approaches to the integrated assessment of the hydroecological situation of a small river, which combines the consequences of ploughing watersheds and the influence of an urban area at the mouth (using the example of a typical river in the forest steppe zone based on observations of its hydrological regime).

2. Materials and Methods

2.1. Study Area

The entire territory of Belgorod Oblast (27.1 thousand km^2) is located in the basins of 152 small and medium-sized rivers. Of these, 24 rivers (16%) belong to the group of 5th-order rivers (according to the Filosofov-Strahler classification [64]). The Vezelka is a right tributary of the Seversky Donets River, which belongs to the basin of the Don River. It is 30.6 km long with a basin area of 406 km^2 (Figure 1). The river basin is part of a typical forest steppe landscape region where the period of active vegetation (160 days) is provided by the sum of active temperatures (>10 °C) equal to 2630°, with total precipitation of 300 mm. Thus, before the start of the active economic activity, this area was characterized by high forest cover (with a predominance of oak forests), and the second component of zonal vegetation was represented by meadow steppes. The basin of the Vezelka River is characterized by significant anthropogenic transformation (arable land 60%, forest cover 7%; 15 ponds with a total volume of 4 million cubic meters have been built). The climate is moderately continental, with hot dry summers (average air temperatures in July are from 19.4 to 21 °C) and moderately frosty winters (air temperatures in the winter months are negative, from –1 to –7 °C). From west to east, the river crosses the suburban Belgorod district and the city of Belgorod. The watershed area of the Vezelka River occupies 55% of the territory of the city of Belgorod, with a population of approximately 340,000. A number of industrial enterprises are located in its floodplain so that, considering the intensive water consumption, the river is subjected to an extremely heavy anthropogenic load. This is why this typically urban river can serve as a highly informative testing ground for the study of the response of the hydroecosystem to the impact of various anthropogenic factors. Secondly, it is noteworthy that the gauging station of this river is the only one in the region.

2.2. Data Sources

The orders in the hydrographic network in the watershed were identified through an analysis of cartographic materials of a large scale using Filosofov-Straler's system, according to which the first order is assigned to elementary water courses without tributaries, whereas the confluence of watercourses of an equal order determines the transition to a higher order. This method enables us to distinguish order-forming watercourses and junctions of riverbeds among the structure of the riverine network [64]. Large-scale field inventory investigations of springs have been conducted using a hydroecological certificate designed by the authors. It includes such sections as the address (coordinates), the state of the spring, the evaluation of the debit by a volume method (at least five repetitions), the measurement of the distance to the riverbed, the ecological situation of the surroundings, and the nature of the exploitation of the spring.

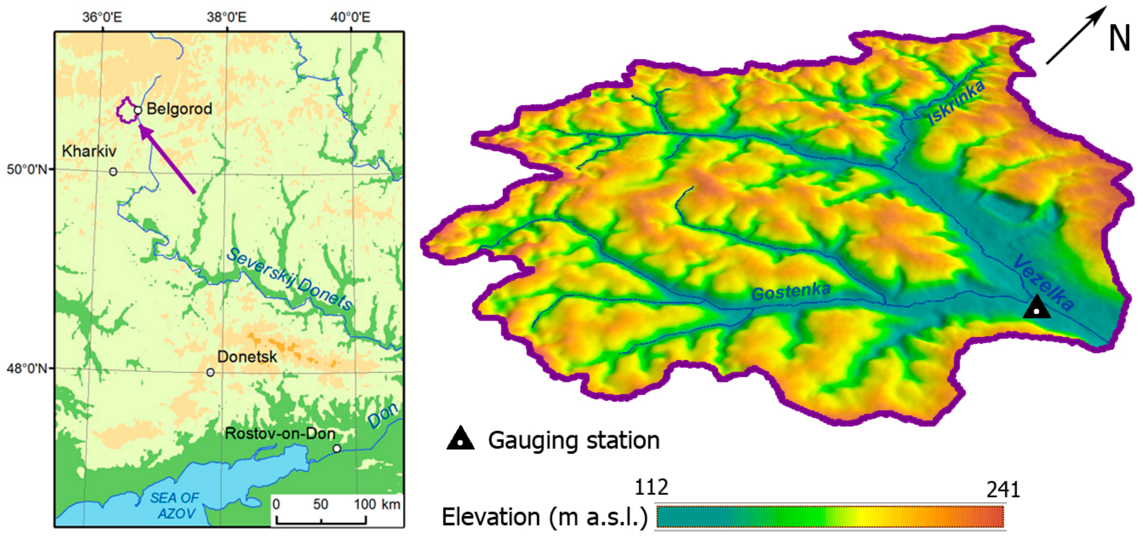

Figure 1. Study area map.

Mapping with elements of spatial analysis was carried out using ArcGIS 10.5. Satellite surveying data of different periods used for deciphering were obtained from the Google Earth resource.

The form of the natural riverbed of the Vezelka River was established using an archive aerial photograph from 1941. The main stages of the widening of the riverbed by hydromechanical means in the urban area were visualized through Landsat satellite images for 1984–1988. The present-day situation regarding the involvement of the lands in economic activities was reflected by 10 LULC classes according to the NLCD Classification [65]. A retrospective development analysis for the last 200 years was carried out employing archive cartographic materials: the *Plan of the general land-division of Belgorod Uyezd in 1785* (scale 1:42,000) and a three-*verst* military topographic map of the Russian Empire, 1875–1911 (scale 1:126,000). The geodatabase in GIS was reduced to a single scale of 1:50,000 for the basin and a scale of 1:5000 for the urban area.

The climatic data were drawn from the information of weather station 34009 in the city of Kursk (130 km from the studied object). At the Bolkhovets (Vezelka) River, under the authority of the Office for Hydrometeorology and Monitoring of the Environment, in August 1943, the Belgorod City gauging station (old station) was constructed, situated two kilometers from the mouth; it was closed in 1960, and, since then, the information has been provided by the gauging station 'Belgorod City' (new station), at 114.5 m a.s.l., downstream of the last tributary of the river and 2.4 km from the mouth (Figure 2A,B,d). Thus, long-term observations of 'Bolkhovets—Belgorod City' from this gauging station reflect the overall hydrological situation of the entire watershed. This is an extremely rare case as the basin of a small river is concerned. The information on the annual average water discharge (the gauging station Bolkhovets) covers the period of 1951–2021.

The average annual potential soil losses from the watershed were calculated according to the model USLE [66], adapted for European Russia's environmental conditions [67,68], taking into account the annual rainfall erosivity factor from 1961 to 2021. The volume of the solid sediments annually entering the river network was defined by taking into account the sediment delivery ratio (*SDR*). Its value was determined by means of an empirically established dependence [69] on the change in the watershed area (*F*, km):

$$SDR = 0.65 \times F^{-0.27}. \quad (1)$$

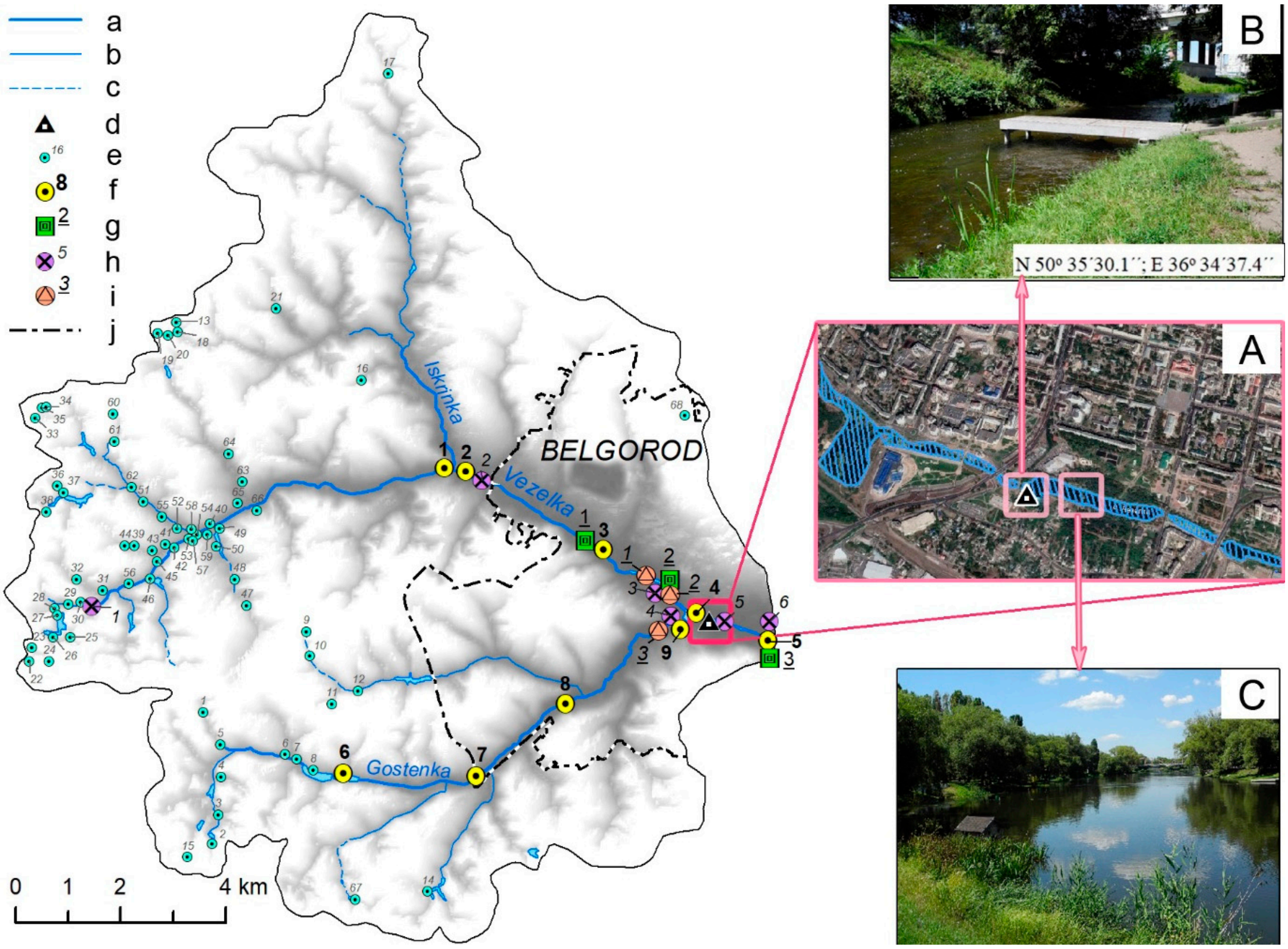

Figure 2. Structure of the fluvial network in the Vezelka River basin and the distribution of hydroecological monitoring sites. Key: (a) river; (b) stream; (c) drying up of stream; (d, **A**,**B**) gauging station; (e) spring; (f) sampling sites of saprobic level; (g) sampling sites for algoflora; (h) sampling sites for hydrochemical analysis; (i) sampling sites for bottom sediments; (j) city boundary. (**C**) The lower reaches of the river with a zone of channel dredging by means of hydromechanization. The numbers for sites e, f, g, h, i reflect the sampling location.

2.3. Methods of Evaluation of the River Water Quality and Sediment

The locations of the hydroecological monitoring sites were selected by the authors during the implementation of a project for the Belgorod Ecological Fund. The assessment of the water quality through sanitary–chemical indices was conducted using the data for June–August (summer low-water period) at six monitoring points (Figure 2h). These points indicated the dynamics of the quality transformation from the river source (point 1) to as far as its mouth at the site of its inflow into the Seversky Donets River (point 6). The selection of the monitoring period in the hottest month was determined by the objective of establishing the utmost concentration of contaminating ingredients produced by the increased evaporation and the reduction of the general water richness of the river network. The collection, storage, and transportation of the water samples were carried out in accordance with the governmental standards (GOSTs). The analysis of the water samples was conducted in laboratory conditions (triple repetition) in accordance with GOST 1030-81, 'Housekeeping and potable water. Field methods of analysis' [70], and GOST 24902-81, 'General requirements for field methods of analysis' [71], focusing on a number of components that correspond to the natural composition of river water, as well as according to the list of sanitary–chemical indices characterizing the overall safety of water bodies in accordance with the act titled 'Approving of standards of the quality of water from aquatic objects of the fishery purpose including the norms of the Maximum Allowable Concentration (MAC) of hazardous substances in the water of aquatic objects for fishery purpose' (Act of the Federal Agency for Fishery of 18.01.2010, No. 20). The list of 18 indices characterizing the water quality in the Vezelka River included both qualitative (odor and intensity, chromaticity, and turbidity) and quantitative parameters (general chemical and sanitary–chemical indications) (Table A1). These studies were supplemented in the summer low-water period with the bioindication of the water condition (by bioindication methods for the monitoring of water plants and animals) using organisms' indicators to define the water quality along the course of the river over nine points of sampling within the urban area.

The calculation of the total indicator of bottom sediment contamination (Z_y) was carried out according to Formula (2) [72], taking into account the MAC level for heavy metals and As, as well as the regional geochemical background (RGB) established by the authors and the scale of the ecological and geochemical state of bottom sediments [73].

$$Z_y = \Sigma K_k - \log_2 n, \tag{2}$$

where K_k is a concentration coefficient calculated relative to the rough background concentrations; n is the number of considered elements.

2.4. Identification of the Composition of Aquatic Microflora and the Degree of Saprobity

The assessment of the influence of the urban ecosystem on the species composition of the aquatic microflora determined the position of three conjugated monitoring points (Figure 2g), where a total of 22 algosamples were taken in August–November. The examination of the samples of plankton (sifted and precipitated), microphytobenthos, and periphyton was carried out using the 'Biolam S-13' (magnification/aperture 85·1.0) and 'MIKMED LCD 1000X 2.0' microscopes. The degree of saprobity of the river water was evaluated at nine monitoring points (Figure 2f) using R. Kolkwitz and M. Marsson's system for the determination of saprobity, the modified version of which includes more precise species/indicators of organic contamination. The conversion of qualitative estimates into quantitative values was carried out by means of the determination of an index of saprobity [74].

3. Results

3.1. Hydrography and Surface Water Bodies in the Basin

3.1.1. Fluvial Network and Water Bodies

The basin of the Vezelka River (Figure 3) comprises 469 erosion forms of five orders. For the erosion network of the basin, the share of the erosion forms of the first and second order is 76% of the total length (456 km) and 81% of the number of erosion forms. Some tributaries and the upper reaches of the river are dried out during the low-water period. Erosion forms of the fourth and fifth order are represented by valleys with a constant water discharge, a distinctly marked bed, a floodplain, and terraces. The estimation of the contribution of the fluvial network using the results of the analysis of cartographic materials and data from remote sensing showed that 137 erosion forms from the third to fifth order with a total length of 108 km participate in the formation of the water regime of the Vezelka River [75]. The river systems of the Vezelka River and its right tributary, the Gostyonka River ('*urban rivers*'), were the most susceptible to degradation, as their basins are characterized by a considerable reduction in forest area, high population density, the intensive intake of underground water, and the deterioration of the hydrochemical regime, simultaneously with the considerable cultivation of lands in agricultural watersheds.

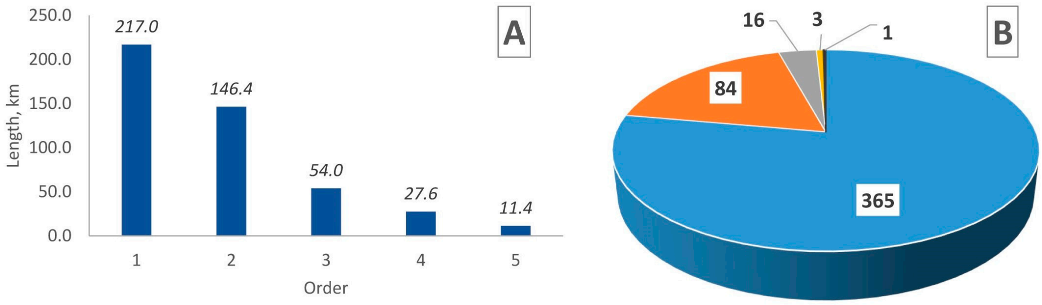

Figure 3. Distribution of orders of erosional forms by total length (**A**) and their amount (**B**).

3.1.2. The Overregulation of the Runoff by Ponds

Several decades ago, the basin of the Vezelka River numbered 14 ponds and water reservoirs. By the early 2000s, 28 ponds had been registered. Many of them were constructed through the efforts of economic players according to simplified design documentation and at a low engineering level; the earthen dams had no reinforced slopes or water discharge installations. Only 13 ponds have outlets into the riverbed. As a result, 30% of the territory is cut out from the total area of the basin. Moreover, of the total number of 28 ponds, there are only seven within the limits of the watershed area. The runoff at the headwaters of the Gostyonka River is especially heavily regulated (a cascade of nine ponds). The river network of the basin of the river now is overregulated by 20 ponds, concentrated mainly in its upper reaches (Figure 2). They intercept the solid runoff and thus 39% of the sediments (approximately 10 thousand tons per year) formed on arable land accumulate in the ponds, without reaching the main riverbed. The water quality in the urban area has become less dependent on solid sediment input from the catchment due to interception in the widening zone created by dredging at the entrance to the city.

3.1.3. The Distribution of Water Springs within the Catchments

The sources of the rivers in Belgorod Oblast are most often constituted by springs that flow out from gullies, *balkas* (small dry valleys), and other linear types of the erosion network. The hydrological role of the springs nourished by underground waters formed by the infiltration of atmospheric precipitation is determined by their participation in the establishment of the water balance in the low-water periods. In the given climatic conditions, this period lasts for approximately seven months. Based on the results of field investigations in the Vezelka River basin, we first observed 68, springs mostly concentrated (57%) in the left bank area of the upper reaches of the Vezelka River, at a distance of 27 km from its mouth (Figure 2e). It is important to note that only 35 springs are connected with the riverbed, and some of these replenish the ponds situated lower down in the river. Of the 14 springs in the basin of the Gostyonka River, only five participate in the replenishment of the runoff of the Vezelka River, the discharge of the others being intercepted by the ponds. Only eight springs are rich in water (>1 L s^{-1}) (two of them situated near the riverbed of the Gostyonka, and four and two on the left and right banks of the Vezelka River valley, respectively). Many of the springs spouting on the steep slopes and in areas with sharp bends in the river valleys become lost in the thick slope sediments, often without reaching the riverbed. As our estimates for July have shown, the summary debit of 35 springs reaching the bed of the Vezelka River was 0.008 m^3 s^{-1} (for comparison, the minimum summer monthly average water debit of 95% probability in the zone of the gauging station is an order higher, equaling 0.077 m^3 s^{-1}). Of all the springs nourishing the riverbed in the summer period, only two had debits of 1–6 L s^{-1}, so they could be classified as average-debited ones, whereas the others were small-debit springs (0.02 $\pm$ 0.01 L s^{-1}). At present, the springs with the highest debits serve economic and drinking purposes, but, more frequently, they are noted for their recreational and cultural use. During the last few decades, a regional project involved the cleaning and beautification of the springs has been underway.

3.2. The Relief and Soil Erosion Loss

The relief of the basin under study is hilly, with the absolute drop in altitude amounting to 129 m. The river basin is heavily dissected by a network of gullies/balkas (1.1 km km^{-2}). Water erosion processes actively occur on the plowed slopes. The estimates obtained using the USLE model adapted for the regional specifics (climate, soils) showed that the annual average washout from one hectare of the arable land of the basin constituted 2.6 t ha^{-1}, i.e., the annual losses of soil from the cultivated area are more than 26 thousand tons. The annual average rates of the erosion losses exceed 2.5 t ha^{-1} for 30% of the arable soils, while >5 t ha^{-1} are lost in 12% of the tilled fields in the basin (Figure 4). The modeled erosion rates are generally consistent with the results of similar regional studies at large- and medium-scale levels, which show average annual soil loss values ranging from 1.3 to 10 t ha^{-1} [76].

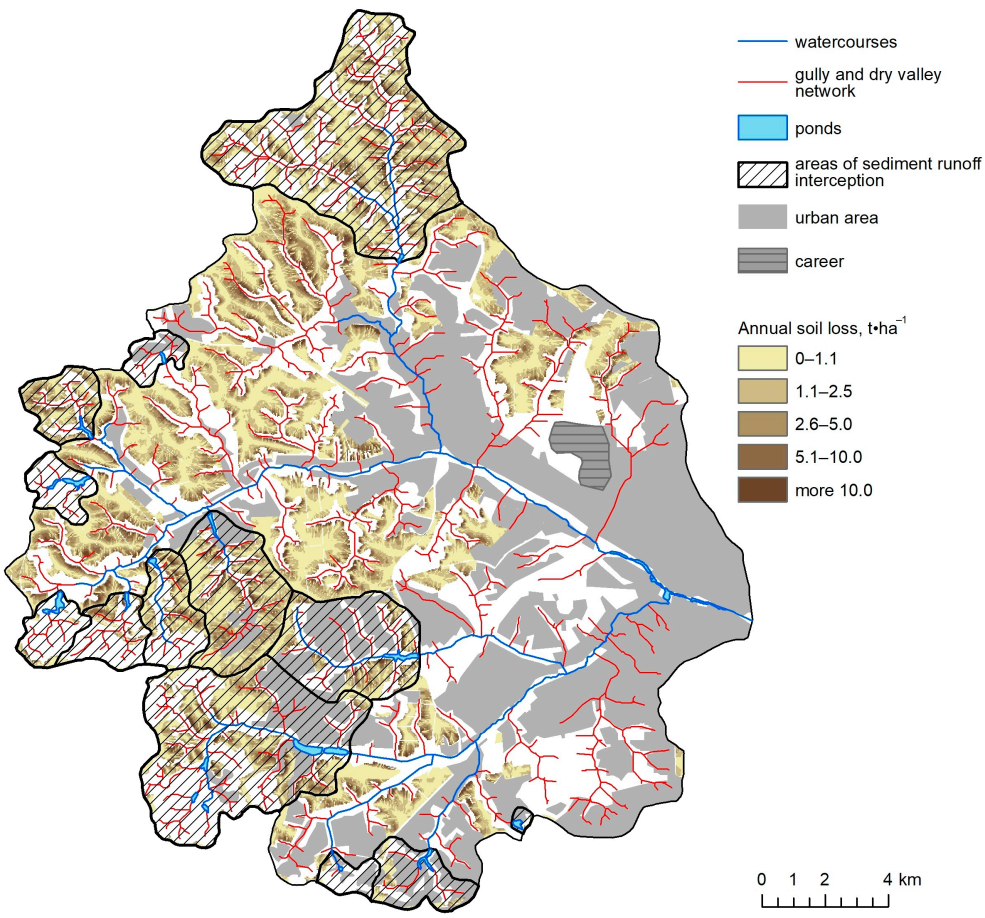

Figure 4. Annual average potential soil losses (t ha^{-1} yr^{-1}) from the arable land of the Vezelka River basin.

The soil washed out from the plowed slopes reaches the gully network in the form of solid sediments; part of the latter is accumulated and redeposited in the waterless valleys, while the other part, dragged by temporary water streams, enters the runoff. This process, after centuries of agricultural loads exerted on the slopes of the basin, has led to the active accumulation of sediments in the floodplain/riverbed zone of the river valley. The calculated volume of the annual washout of sediment (taking into account their amounts intercepted by ponds) is approximately 2.2 thousand tons, considering the sediment delivery ratio (*SDR*) for the Vezelka River basin (*SDR* = 0.14). In terms of the quantity of the erosion forms adjacent to the main riverbed and their density, the basin possesses no distinct asymmetry. Thus, the locations of the discharge of the solid runoff from the watershed area are presented by eight and nine near-riverbed gullies of the first order on the right and left banks, respectively.

3.3. Land Use/Cover Structure

The Vezelka River is one of the rivers running throughout the territory of the administrative center of Belgorod Oblast—the city of Belgorod. Within the boundaries of the latter, 22% of the area of the river's basin is included. Belgorod has the status of an urban district, where the population density is 2439 people per km^2 (2022). Among the structure of the land use in the basin (Figure 5), the developed districts occupy 38.2% of the total area (the city itself and the adjacent territories of the urban agglomeration, including 6400 ha of the blocks of the individual residential houses). The second-largest proportion (31.7%) of the area is represented by cultivated fields. The plowed land is stretched over erosion-prone slopes, with one third of them inclined at more than 3°. Thus, the nature of the anthropogenic load on the basin of the Vezelka River combines equally urbogenic and agrogenic features, finally effecting the conditions of the water resources of the river.

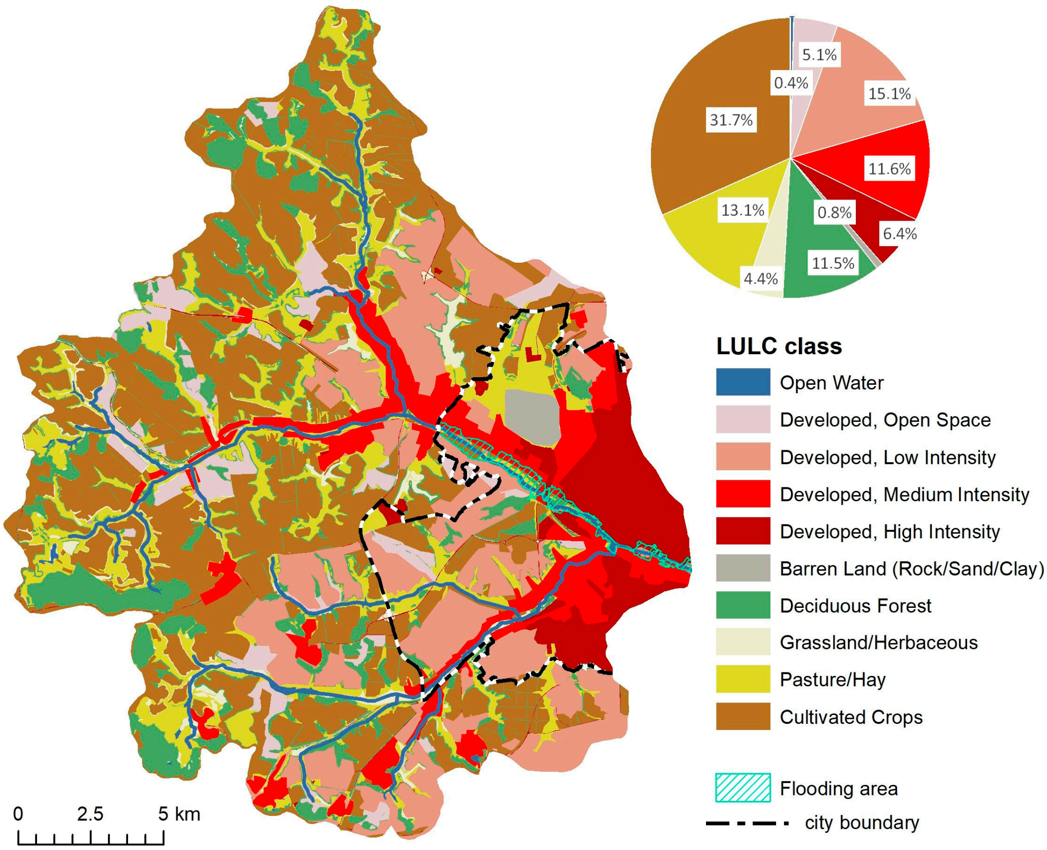

Figure 5. Land use/cover map of the studied basin (according to NLCD Classification).

The length of the riverbed within the boundaries of the urban territory is 10.5 km. For the assessment of the risks of negative impacts of the aquatic objects on the adjacent built-up territories, previously, a simulation of the limits of the submergence zones was carried out based on the results of the calculation of the maximum water levels and a spatial analysis of the digital elevation model [77]. The absolute flooding elevations of 1% expected probability of occurrence in the Vezelka River basin ranged from 127.8 m to 116.6 m at the mouth, and the difference in flooding height was 11.2 m. The flooded area amounts to 377 ha, which covers 2.3% of the city's territory.

3.4. The Dynamics of the Formation of the Urban Area

The hydrological problems of the region under study are, in many respects, related to the established features of the system of settlement of the population. The most industrially developed cities are located along the beds of the major rivers. This is why these rivers are, in the first place, subjected to anthropogenic pressing. It has been previously established [78] that in the 13th–14th centuries, a large number of early Russian settlements arose in the river floodplains because the high waters were smoothed out over time and the floodplains were not inundated; however, after 300 years of deforestation and ploughing of the regional steppes, the intensity and height of the spring (snowmelt-induced) floods increased, while the nature of the settlement of rural residents changed from the predominantly floodplain valley type to a continuous watershed variant. In the studied region, a peculiar system of settlement started to develop in the rural areas from the mid-17th century [79]. It was adapted to such a landscape feature of the southwestern slopes of the Central Russian Upland as the territory was cut with broad and relatively deep (up to 75–100 m) river valleys. Often, the housing estate was located on a high bottomland or terrace, preventing submergence, while the low floodplain was used for vegetable gardens, needing, as a rule, no river water for irrigation.

In 1646, the town fortress of Bolkhovets was built near the river (now, it is the southwestern part of Belgorod), while, 10 km downstream of the Vezelka River, in 1650, the Belgorod fortress was built (the modern center of the city). The area of the basin under study began to be actively developed in the 17th–18th centuries. During this period, the river valley type of settlement was characteristic: the large settlements were associated with the floodplain of the Vezelka River; they grew and merged, occupying new areas of the floodplain. However, during the last 30 years, the nature of settlement has changed: for the arrangement of masses of individual residential buildings in the suburbs, the authorities began to allot flat country areas to the citizens (Figure 6). Some of the plowed fields were withdrawn from agricultural use and used for settling. The suburban situation predetermined the large-scale construction of dachas (summer cottages) and gardens in these areas, inducing new environmental effects (occupation of erosion-prone lands, deterioration of the sanitary–epidemiological situation, etc.).

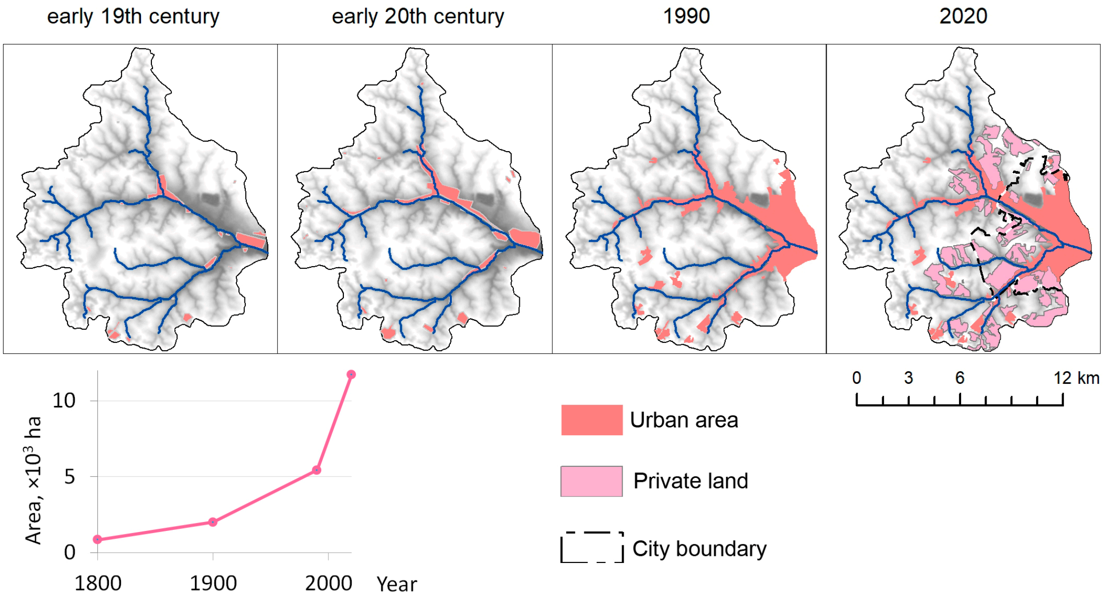

Figure 6. Dynamics of the urban area within the Vezelka River basin during the past two centuries.

The sources of the sediments transported to the riverbed, along with the effects of the water erosion from the watershed, are constituted also by plowed areas of the floodplain, not unfrequently located near the water's edge. In 1990–2000, even the river floodplain, with its semi-hydromorphic soils, was allotted as plots of 600 m^2 in area to citizens for orchards and vegetable gardens with summer cottages (mostly deserted now).

From the beginning of the 1990s and until the present time, the area of construction in the basin has increased by more than two times owing to individual residential house building (Figure 6). It is noteworthy that this period is characterized by a sharp decrease in water flow from the Vezelka River. It may be supposed that, along with the bottom-deepening works in the city, the growth of residential construction at the watershed possibly also has influenced the reduction in the water discharge in the river. This is due to the sharp growth in the general water intake from the basin for drinking water and for the everyday household needs of the populations of the new districts. This intake has possibly decreased the contribution of the underground constituent to the total runoff.

3.5. The Climate and Its Dynamics

The annual average precipitation, according to the data from a meteorological station in Kursk for the period of 1951–2021, amounts to 602 mm. The precipitation is distributed relatively uniformly throughout the months, but, during the warm period, liquid precipitation prevails, with a maximum in July (Figure 7). The annual average air temperature is 6.3 °C; July is the warmest month (19.5 °C), while January is the coldest one (−7.3 °C).

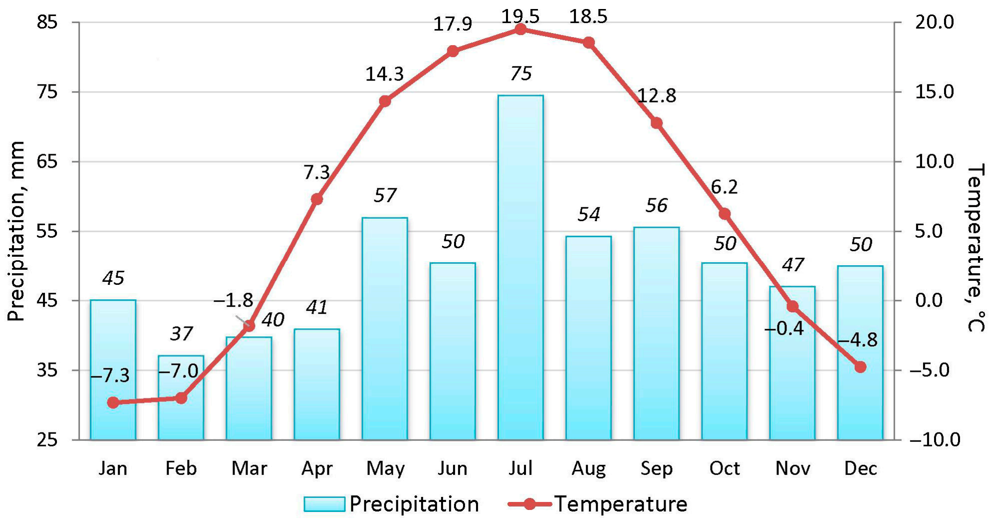

Figure 7. Intra-annual distribution of air temperature and precipitation in Kursk.

The transformation of the regional climatic system determines the trends in the hydrological regime. The annual precipitation has been reduced from 605 to 523 mm in the last ten years, compared to the preceding 20-year period, while the annual average air temperature, on the contrary, has risen from +7.7 °C to +8.2 °C, respectively. The considerable changes in the characteristics of the vernal runoff and water discharge during the summer and winter low-water periods observed in recent times suggest that the redistribution of the discharge during the seasons of a hydrological year should be taken into account in the hydrological calculations and prognoses for the assessment of the ecological/environmental conditions of rivers and water reservoirs linked with the latter [61].

3.6. Hydrological Parameters

The average slope of the river from the source to the mouth is 2.1%. Its depth varies from 0.85 to 3.5 m, and the width varies from 14 to 40 m. The average water discharge is 0.21–0.43 m s^{-1}. The duration of inundation of the floodplain is 20–30 days. The high water is formed by snowmelt and is the main phase of the hydrological regime (with an average duration of 26 days). The largest discharge of water is observed in the third week of March. In the estimation of the exceedance probability, 1% of the spring high water amounts to 211 m^3 s^{-1}, while that of rain floods is 25.5 m^3 s^{-1}. The minimum monthly average discharge of water during the summer is 0.19 m s^{-1}. The base flow is observed in the period of May up to the second week of November, and then the winter low-water period follows, which continues until the high waters arrive.

The water discharge is the major characteristic of the river flowage. It influences the variations in the level, flowing speed, incline of the water surface, transportation of sediment, etc. Estimates of the exceedance probability show that 50% of annual runoff depth is 100 mm, which is equivalent to a water discharge of 1.25 $m^3 s^{-1}$. The data on the annual average water runoff were obtained from the results of many years of observations at the gauging station on the Bolkhovets River (Figure 2d). The hydrological regime of the river can be divided into two periods. Until the early 1990s (period 1), alternations between a raised and lowered water flow were observed. This is typical of the stable formation of a river's runoff (Figure 8). Since 1981, the discharge of water has decreased and it has never been restored to the previous level. Since 1991, stably low water discharge below the norm has been established (period 2). The values changed over the period of 1991–2021, from 0.24 to 0.88 $m^3 s^{-1}$, with the normal rate being 0.99 $m^3 s^{-1}$, while the mean value for this period amounted to 0.51 $m^3 s^{-1}$. The same tendency was characteristic also of the annual average water level (Figure 9). With its norm of 84 cm, its value amounts to 26 cm for the last 30 years. The value of the average water discharge throughout the entire agricultural zone of the basin (242 km^2) in the modern climatic situation (from 1990) is 2.19 $m^3 s^{-1}$, whereas, within the actual arena of discharge formation (without the territory of 145 km^2 intercepted by the ponds at the upper reaches), the discharge of water is estimated as 3.66 $m^3 s^{-1}$.

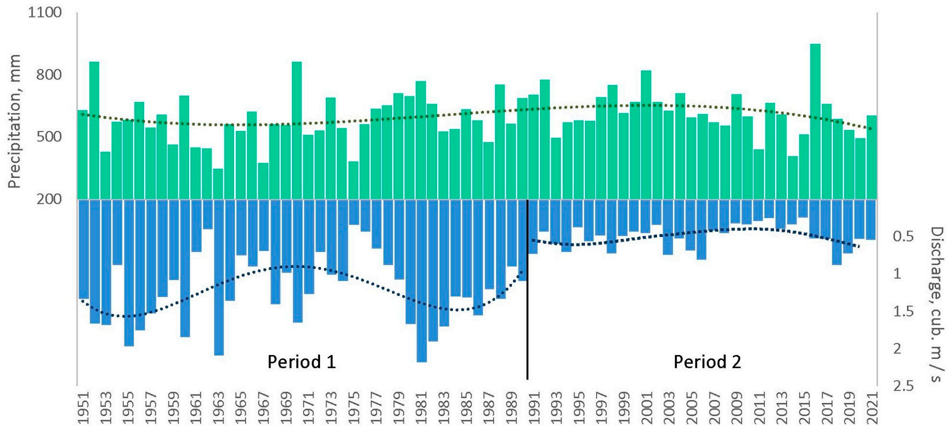

Figure 8. Changes in annual precipitation (in green) and annual average water discharge (in blue) at the studied gauging station on the Bolkhovets (Vezelka) River during 1951–2021.

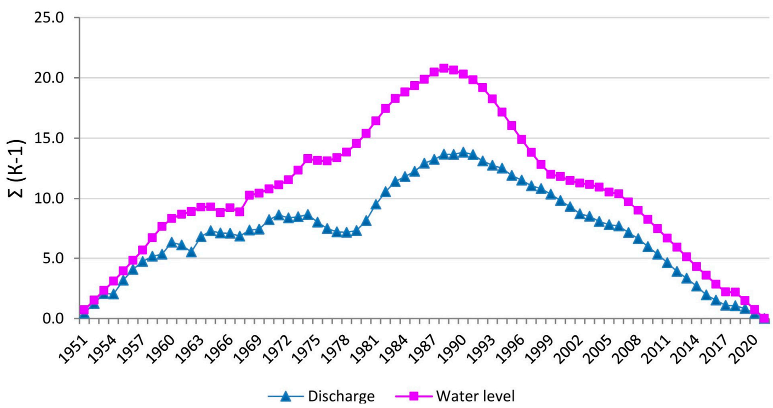

Figure 9. Difference integral curves (cumulative deviation from the mean) for the annual average water discharge ($m^3 s^{-1}$) and the annual average water level (cm) at the studied gauging station on the Bolkhovets (Vezelka) River during 1951–2021.

Difference integral curves of the dynamics of annual precipitation and discharge, representing the rising sum of the deviations of the modulus coefficients from the mean many-year value of the time series by the end of each year, reflect the holistic cycle of the full-water phase, as can be established from the long series of observations. Analysis of the dynamics of the annual average discharge of water at the gauging station for 1947–2021 shows that the stable lowering of the river runoff has taken place since 1991. The annual average discharge of water amounted to 1.23 ± 0.07 ($0.34 \div 2.18$) m^3 s^{-1}, in the period of 1947–1990 it has essentially decreased to 0.51 ± 0.03 ($0.24 \div 0.88$) m^3 s^{-1} over the last three decades.

The question arises as to the contribution of the natural climatic factors to the formation of the water discharge dynamics, as well as concerning the possibility of its simulation and prognosis on the basis of only the data on the sum of the precipitation and annual average air temperature. This relation can be described using a piecewise regression model for a series of observations from 1951 to 2006. Based on this model, a prognosis is presented for the period of 2007–2021.

The piecewise regression model is

$$Y = \begin{cases} -0.00018 \times X_1 - 0.04512 \times X_2 + 0.901, & \text{if } 0 < Y \le 1.045 \\ 0.007 \times X_1 + 0.00757 \times X_2 + 1.047, & \text{if } Y > 1.045 \end{cases}, \quad (3)$$

where Y is the average water discharge of the Vezelka River; X_1 is the sum of precipitation; X_2 is the annual average air temperature.

The correlation coefficient of the influence of the factors on the dynamics of the river water discharge amounts to 0.86 (Figure 10). The explained share of the dispersion of the influences of the factors equals 0.74. However, the model functions poorly when the extrapolation of the obtained relation is attempted for the period up to 2021.

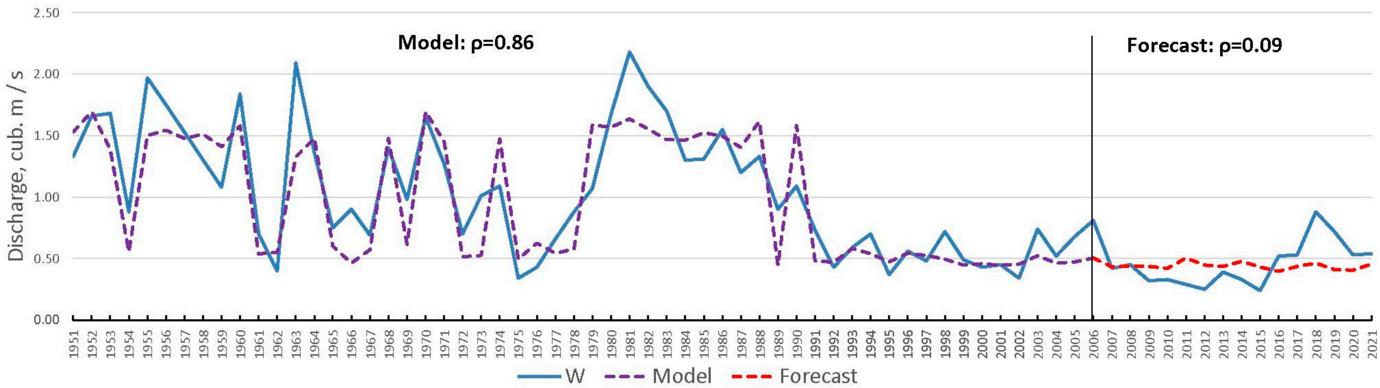

Figure 10. Modeling the influence of climatic factors on the dynamics of water discharge (W) of the Vezelka River.

The closeness value of the relationship of the water discharge and the climatic parameters is small (the correlation coefficient equals 0.09). The large-scale hydraulic transformation of the riverbed has led to the almost complete degradation of the mechanisms of the natural functioning of the river system and to the latter's exhaustion. In these conditions of anthropogenic transformation, it is practically impossible to give reliable prognoses for the water discharge based only on the natural (climatic) predictors.

3.7. Assessment of River Water Quality According to Sanitary Indicators and the Use of Bioindication Methods during the Summer Low-Water Period

The water at the head of the Vezelka River, as shown in Table A1 (sample 1 taken as a reference in this study), is clear, without odor and color; it contains no iron and is characterized by relatively low values of acidity and alkalinity (0.9 and 6.0 mol L^{-1}, respectively; the pH value is equal to 7.0). The content of the components marking the natural composition of river waters is determined by the mineral composition of the contacting rock species. However, in all the samples examined (Figure 2h), the content of these minerals does not exceed the MAC. Thus, among the cations, those of calcium (Ca^{2+}) and magnesium (Mg^{2+}) predominate (the limits of their content are 80–128 mg L^{-1} and 17–35 mg L^{-1}, respectively). Among the anions of the natural background, the most widely distributed are hydrocarbonate, chloride, and sulfate ions. However, at all locations (at the upper reaches, at the entrance to Belgorod, in the city's precincts, and at the mouth), the presence of different forms of fixed nitrogen has been noted, with content exceeding the MAC (two times the nitrate and almost five times the nitrite concentration in sample No. 5).

The large quantities of biogenic and organic substances in the surface waters are caused both by the natural peculiarities of the region and by the nature of the anthropogenic effects. The presence of the entire triad of nitrogen-containing substances in the river water is an indication of the continuous contamination of this water body with organics (runoff from stock farms, washout of fertilizers, influence of dacha settlements, and the discharge from the sewage and rain drainage), which may be a source of causative agents of infections. The facts mentioned above are confirmed by the high values of the chemical oxygen demand (COD) equal to 25–34 mg L^{-1}, as was detected during the analysis of all the studied samples (in excess of the maximum allowable COD value, which is set for water bodies within the boundaries of settlements (30 mg O L^{-1}) at the confluence with the tributary and at the mouth (Figure 2f: sampling sites 4 and 6)). This value serves as a summary index of the anthropogenic contamination of aquatic objects, since it correlates with the content of almost all the organic substances. This fact indicates an extremely unfavorable (by the period of sampling) epidemiological situation in the Vezelka River's water. Meanwhile, its lower course in the urban area is actively used in the warm period as a popular recreation zone.

In our study, the assessment of the water quality through sanitary–chemical indices was supplemented by diagnostics of the saprobity index of water using bioindication methods. The background (natural) state of an aquatic ecosystem must correspond to the β-mesosaprobic level (water purity class II—moderately contaminated). The species saturation of the animals was rising in three monitoring points (from the river's source up to its entrance to the urban area), but it decreased downstream. As the river becomes shallow during the summer low-water period, and correspondingly the concentration of organics grows in the water, in all the samples, the species predominantly belonged to the α- and β-mesosaprobic classes, while, in two samples from the center of the urban area, there were even species of the polysaprobic class. The incompleteness of the representation of indicator groups in the urban area obviously is related to the inflow of toxic substances into the river. According to the results of the analysis of the water from the Vezelka River, the water quality class in June was estimated as 6 (very dirty), while, in August, the class was reduced to 4 (contaminated). The MACs, which are fixed for fishery water bodies for such indices as copper, general iron content, oil, ammonium nitrogen, and biochemical oxygen demand BOD_5, were exceeded by 2–10 times. In addition, increased content of sulfates and nitrite nitrogen was identified in the river water.

3.8. Characterization of Microalgae at Monitoring Points within the Urban Area

In total, 207 species and intraspecific taxa belonging to seven sections have been found in the algoflora of the Vezelka River during the period of study. The most diversely represented were the following genera: *Navicula* Bory—16 species (20 species and intraspecific taxa), *Nitzschia* Hass.—8 (9), *Scenedesmus* Meyen—8 (9), *Gomphonema* Ag.—7 (12), *Pinnularia* Ehr.—7 (8), *Cymbella* Ag.—7 (7), and *Synedra* Ehr.—4 (11). The distribution of algae species over the monitoring points showed a logical change in the hydrological situation induced by the transformation of the hydrological parameters and the strengthening of the anthropogenic load downstream of the river, within the precincts of the urban area (Table 1). At point 1, a predominance of diatomic algae was registered, represented by 183 species and intraspecific taxa (65% of the total number of the species noted at that point).

Table 1. Taxonomic spectrum of algae (species and intraspecific taxa).

Taxa	By Sampling Point (According to Figure 2g)			Total for the River
	1	2	3	
Cyanophyta	14 (14)	4 (4)	13 (15)	24 (26)
Cryptophyta	0 (0)	3 (3)	2 (2)	3 (3)
Chrysophyta	0 (0)	0 (0)	2 (2)	2 (2)
Xanthophyta	1 (1)	1 (1)	1 (1)	2 (2)
Bacillariophyta	63 (83)	41 (55)	58 (79)	81 (112)
Chlorophyta	20 (21)	19 (19)	39 (42)	47 (50)
Volvocophyceae	3 (3)	2 (2)	6 (6)	7 (7)
Chlrococcophyceae	10 (11)	10 (10)	25 (28)	26 (29)
Ulothrichophyceare	3 (3)	4 (4)	3 (3)	6 (6)
Conjugatophyceae	3 (3)	4 (4)	3 (3)	6 (6)
Euglenophyta	9 (10)	2 (3)	5 (7)	11 (13)
In total	106 (128)	70 (85)	120 (148)	169 (207)

Blue-green algae are less important, with 14 (10.9%), as well as chroococcophyceae, with 11 (8.6%). Only for this point, we noted colorless euglenophyceae *Heteronema globuliferum* Stein and *Peranema macromastix* Conrad. This is due to the fact that the river forms a slight backwater in this area. Of the blue-green algae, only at point 1 did we find the species *Gloeocapsa minuta* (Kütz.) Hollerb., *Lyngbia aestuarii* (Mert.) Liebm., *L. contorta* Lemm., and *Phormidium molle* (Kütz.) Gom.; of the diatomic ones, we found *Achnanthes lanceolata* (Bréb.) Grun., *Cymatopleura elliptica* (Bréb.) W.Sm., *Fragilaria inflata* (Heid.) Hust, *Navicula laterostrata* Hust, *N. oblonga* Kütz., *N. radiosa* Kütz., *Pinnularia major* (Kütz.) Cl., *P. viridis* (Nitzsch) Ehr., and *Surirella linearis* W.Sm.; of the ulotrichales, we found *Geminellopsis fragilis* Korsch.; and of the conjugatophyceae, we found *Closterium acerosum* Schränk. Ehr. Some of the above-listed species are oligo- or xenosaprobes characteristic of pure waters.

At control point 2, a smaller diversity of algae was found—85 species and intraspecific taxa (41.1% of the total species recorded in the river). The leading role there is played by diatomic algae—55 species and intraspecific taxa (65% of the number of species at point 2). The quantity of chroococcophyceae was reduced to 10 (11.7%) and that of the blue-green algae to four (4.7%); however, some of these species attained mass propagation in the summer months, forming a 'green scum' in the water. Point 3 is characterized by the greatest species diversity, constituting 148 species and intraspecific taxa (71.5% of the species typical to the river). At this point, the river algoflora undergoes qualitative transformations. The diatomic algae, as at points 1 and 2, play a substantial role in the formation of the flora—79 species and intraspecific taxa (53% of the number of species characteristic of point 3). Generally, the potamoplankton at point 3 may be defined as diatomic–chlorococcous, where the enrichment of the species composition with chlorococcous algae can be related to the rise in the concentration of nitrogen-containing substances in the river water. At point 3, during the entire period of study, the abundant propagation of the volvox algae, only here found in such quantities, was observed. In the plankton, with the estimate 'often', representatives of chrysophyceae were also encountered, which are fairly resistant to the increased contamination of a river. Only at this point, blue-green algae and the largest number of species of chlorococcous algae were registered in the intra-annual dynamics.

Microalgae from phytoplankton and microphytobenthos are more important than macroalgae when assessing water quality in freshwater ecosystems [73]. A comparison of the systematic list of algae with the list of organisms' indicators shows that as the river waters pass through the city, the rate of saprobity grows, with its index attaining the maximum in the summer months at all the studied segments of the river. The growth of the colonies of *Bacillaria paradoxa*, which are indicators of high chloride content, as well as the presence of the xenosaprobic species *Pinnularia gibba* Ehr, probably affected by the adaptation of this species to the constant contamination, has been recorded at all points of monitoring. Fairly often, at points 1 and 3, there were found oligosaprobes;

meanwhile, the following are the species adapted to the regular inflow of pollutants into a river: *Gloeocapsa minuta*, *Cyclotela comta* (Ehr.) Kütz., *Pinnularia microstauron* (Ehr.) Cl., and *Ulothrix variabilis* Kütz.

On entering the city, the Vezelka River is of a mesosaprobic nature (Table 2). Near the mouth (point 3), the river acquires already a distinctly expressed β-mesosaprobic nature with a bias towards o-β-saprobity.

Table 2. Distribution of the number of types of saprobity indicators by sampling point.

Saprobic Index	Sampling Points (According to Figure 2f)		
	1	2	3
x	1	0	1
o	3	0	4
o-β	7	7	13
β	37	33	49
β-α	7	3	4
α-β	2	2	2
α	7	7	9
p	0	0	1

3.9. Reconstruction of the Riverbed within the Urban Area

Due to the effect of silting up (in some places up to 1.5 m), the river has become very shallow and overgrown with boggy vegetation. Over the last 60 years, most of the riverbed of the Vezelka River within the city of Belgorod has been completely transformed (Figure 11). From the beginning of the 1960s, step-by-step large-scale works were carried out for the straightening, bottom deepening, and widening of the riverbed in order to improve the hydrological, sanitary, and ecological conditions, to increase the throughput capacity and dry out the floodplain areas. The transformation of the Vezelka's riverbed was carried out in several stages. Major works took place in 1960–1970. The riverbed was drawn aside several times in connection with the active construction of auto and railway bridges, after which it was straightened and widened. By 1984, an area of 2.6 km in the central part of the city had been completely transformed; further on, areas higher along the stream in the urban area were widened (Figure 12). The present-day configuration of the riverbed had been established by the early 1990s. The broadened area of the Vezelka's riverbed within the city of Belgorod, after cleaning by means of hydraulic mechanisms in 1999–2000, acquired the following parameters: a width from 37 to 45 m and a depth of 2.4–2.5 m. During the period of 1990–2010, the engineering works were concerned with the regular cleaning and bottom deepening of the previously widened areas using a dredger. While, at the river upper reaches, the width of the riverbed is 2–7 m, within the precincts of the city of Belgorod, the river width amounts to 6–10 m with a depth of 1.0–1.5 m; in the areas subjected to dredging, however, the width reached 20–40 m with a depth of up to 6 m. Now, the riverbed of the Vezelka River, at a length of >4 km, represents a cascade of technogenic reservoirs, considerably slowing down the water exchange rate in the river and partly fulfilling the function of the accumulation of urban sewage (rainwater). An investigation of the modern transformation of the floodplain type of the locality [63] has shown that, as a result of the reduction in the length of the riverbeds for the period of 1964–2008, the reconstruction of the localities took place, as well as the replacement of the floodplain type for the post-floodplain case. On the former floodplain meadows, there are now areas of multi-storey and residential buildings and social, business, and recreational zones. Within the urbanized landscape, the lower watercourse of the river, functioning in a lacustrine mode, is located in the park zone and serves recreation purposes. However, according to our data, the water quality is changing within the intra-annual regime from the fourth class (dirty) to the sixth class (very dirty). Moreover, values exceeding the MACs established for fishery water bodies are observed through such indices as the content of copper, general iron content, BOD_5, petroleum products, and ammonium nitrogen.

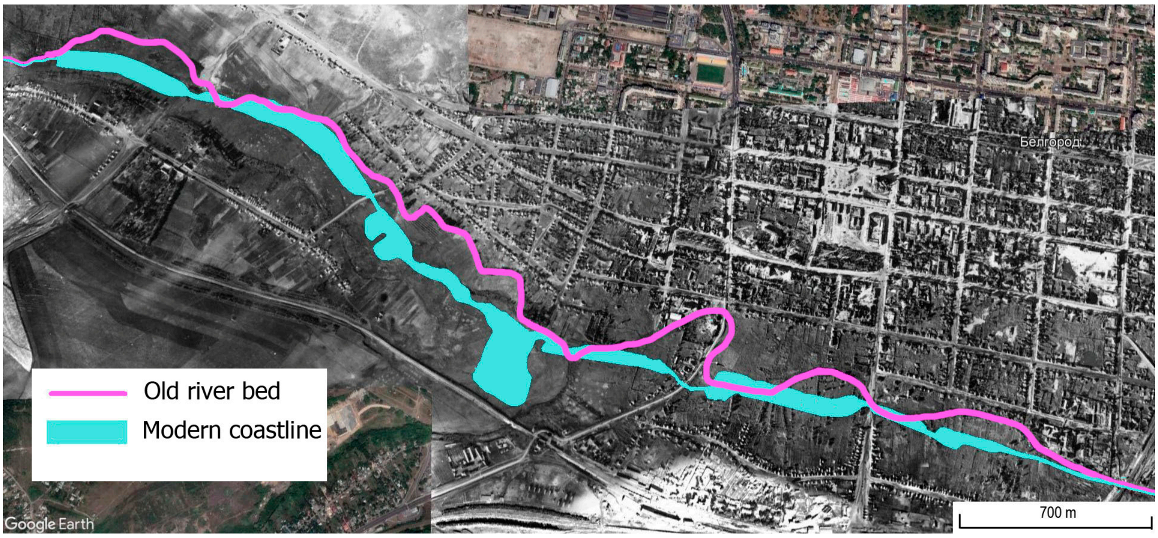

Figure 11. The form of the natural channel of the Vezelka River in comparison with the modern transformed riverbank line in the central part of the city of Belgorod (archive aerial photograph of 1941 in the background).

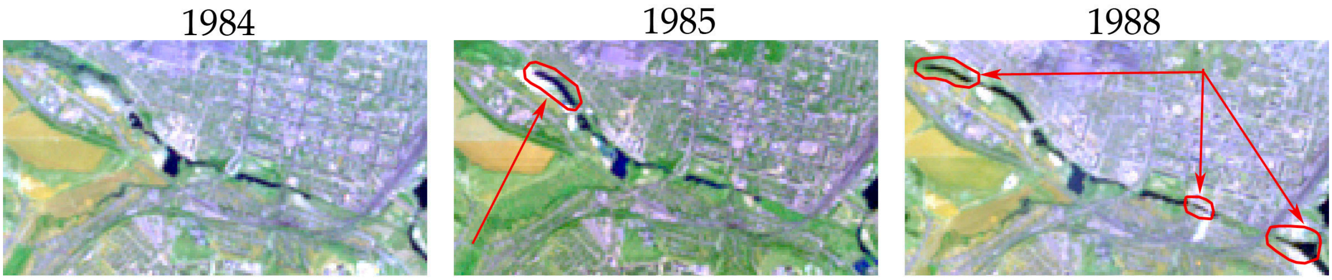

Figure 12. Stages of expansion of the Vezelka River channel in the city of Belgorod in 1984–1988, according to Landsat images.

The large-scale transformation of the riverbed for the length of 4.6 km undoubtedly had an impact on the hydrological regime of the river. The bottom-deepening works have not had a positive effect on the hydrological regime of the river. The water level and discharge after the completion of the works continue to decrease. The activities aimed at removing the bottom deposits and flooding with high water levels are able to raise temporarily the water richness but, after 1–2 years, the water level drops again relative to the previous years [80]. The discharge value for the period of the opened (ice-free) riverbed is mostly below the norm. In terms of the amelioration of the sanitary–epidemiological situation of the river, the earthen works bring positive results but, as to the river's hydrological regime, they influence it rather negatively, with a decrease in the speed of the flow and the overgrowth of the riverbed due to the stagnation of the water. These facts, along with the intensive erosion processes in the river's watershed (in the first place, on the plowed slopes), induce the activation of the process of the silting up of the riverbed. Based on the results of the simulation of the rates of soil erosion in the basin (see above), it has been established that, since 1991, the sediment load from the watershed has been 3.5 times higher than the transporting capacity of the river. In a simulation of the rates of the Vezelka River's silting up [81], the conclusion was drawn that, even during the years of the highest waters, sediment clearance processes were not activated and the silting of the river continued.

The liability of the urban segment of the Vezelka River to silting up is confirmed by the results of the last stage of works to clean the river in 2022. The average thickness of the bottom deposits along the broadened segment of the river amounted to 0.46 m, with a maximum of 2.2 m. The total volume of the silt was estimated as 133.3 thousand cubic m; there was, on average, 0.49 cub. m of silt per one square meter of the water area.

Although the causes of the considerable decrease in the water discharge in the river mouths for the last 70 years are not directly related to the sharp growth (almost three times) in residential construction, the latter is, however, one of the triggers that has fueled such dynamics. A particular tension suffered by the Vezelka River is caused by the fact that, at its lower reaches, the city's industry is concentrated. Besides being a source of sewage, the latter is the major consumer of underground water. In particular, the water intake from the river's basin amounts to over 30 million m^3 per year, while the replenishment of the underground waters by precipitation is estimated only as 16 million m^3. The depression funnel that arose in 2000, stretching along the Vezelka River's valley, is five kilometers in radius and up to 20 m in depth [75].

3.10. The Bottom-Deepening Works According to a Regional Project

A modern city is a natural, social, and economic complex (urbosocioecosystem) that, in the presence of aquatic objects in its territory, drastically influences the transformation both of the surface and underground runoff. The mouth zone and the lower course of the studied river within the boundaries of the urboecosystem present only an integrative reflection of the varied natural and economic conditions over 40 thousand ha of the river basin. The studied river basin of a relatively small area is often the focus of attention among the city's authorities and the residents of the city. This is due to the fact that, within its watershed, there are the two main water intakes within the city of Belgorod, with the total volume of daily consumption reaching over 60 thousand cubic m. In the sanitary zone of the third water intake of Belgorod (volume of consumption equal to 40 thousand cubic m daily), the last reconstruction of the riverbed, 255 m long, was carried out. The river is hydraulically connected to the alluvial water-bearing horizon, which is bedded at the depth of 0.7–2.9 m. Due to the right bank, the riverbed was widened to 37–45 m (along the water's edge). The thickness of the extracted bottom sediments was 2.4–2.5 m (Figure 13).

Figure 13. Extraction of bottom sediments by the Watermaster dredger in the Vezelka River in Belgorod (2 km upstream of the gauging station) as part of the implementation of the Program for Clearing and Rehabilitation of the Rivers of Belgorod Oblast (November 2022).

However, the similar reconstruction of the riverbed by means of hydraulic mechanisms endangers the protective properties of the water-resisting layer and also contaminates the underground waters of the artesian basin. Drilling showed that the layer of clay up to 7.5 m thick presents an aquifer of the alluvial water-bearing horizon, whereas, already at depths of 5–6 m, there is a roof of chalky, often fissured rock.

Points 1 and 2 for the sampling of sediments (at 30 cm layer) in the riverbed of the Vezelka River were located upstream of the gauging station, at the distance of 2.44 km and 1.92 km, respectively; the sampling point in the riverbed of the Gostyonka River was situated 1.3 km upstream of the mouth (Figure 2i). The background indices of heavy metals and arsenic were determined in the bottom deposits of the upper reaches of the Vezelka (50.600694° N; 36.336054° E), Vorskla, and Pena (April 2023) rivers (Table 3).

Table 3. Concentrations of heavy metals (HM) and arsenic in bottom by sector of the Vezelka River (S1, S2) and Gostyonka River (S3) (Figure 2i) and levels of regional geochemical background (RGB) and MAC.

HM	Unit	S1	S2	S3	RGB	MAC
Pb	mg/kg	43.11 ± 0.51 **	12.16 ± 0.15	16.58 ± 0.47	18.7 ± 1.0	32
Zn	mg/kg	155.43 ± 1.16 **	30.32 ± 0.82	53.95 ± 0.12 *	44.0 ± 4.0	150
Mn	mg/kg	131.13 ± 0.73	885.05 ± 1.07	136.60 ± 1.38	174.6 ± 36.9	1500
Cu	mg/kg	28.15 ± 0.52 *	7.33 ± 0.27	23.33 ± 0.27 *	20.8 ± 2.3	40
Co	mg/kg	15.40 ± 0.61	11.24 ± 0.39	8.06 ± 0.30	15.7 ± 0.6	30
V	mg/kg	72.00 ± 0.24 *	19.94 ± 1.38	64.22 ± 1.59 *	63.5 ± 2.6	150
Cr	mg/kg	75.06 ± 1.18	13.42 ± 0.33	60.46 ± 1.79	75.7 ± 3.7	80
Fe_2O_3	%	4.11 ± 0.02 **	1.05 ± 0.01	2.81 ± 0.01 *	3.0 ± 0.2	2.75
Ni	mg/kg	33.61 ± 0.23 *	5.25 ± 0.23	25.87 ± 0.48	26.3 ± 2.9	45
As	mg/kg	4.50 ± 0.56	0.32 ± 0	5.39 ± 0.34	6.8 ± 0.3	20

Note: Exceeded levels of RGB and MAC are shown with * and **, respectively.

It is noteworthy that the water from the Vezelka River, even at its source, in comparison with the sources of other rivers, is marked by higher values of such indices as the content of ammonium nitrogen (3.1 times), petroleum products, and nitrates (by 1.4 times). Among all the elements, the exceedance of the MACs has been recorded for Pb, Zn, and Fe_2O_3 and, moreover, most frequently, they were found at the line of the cleaned riverbed of the Vezelka River, at its entrance to the urban area (point 1). This fact can be explained primarily by the difference in the profiles of the riverbed in lines 1 and 2. After the bottom-deepening works in the lower widened segments, and at the site of the transition to the narrower riverbed (in point 1), the backwater is formed, impeding the migration of sediments. Point 1 is located in the first backwater area and accumulates all sediments transported from the watershed situated higher up, where the urban zone comprises industrial and warehouse areas, three plants of building materials, and a large transport interchange of an auto highway and the railway. Deposits at point 2, located 520 m downstream, in the middle of the widened riverbed, reflect predominantly the influence of near-river lands.

Among the heavy metals in the bottom sediments of the rivers and ponds of the study region, the highest MAC exceedances were noted for Mn, Cu, and Pb. Since the values of RGB were greater than the MAC indices (except for iron), the summary concentration index (Z_y) calculated relative to the MAC showed that, in all the water ranges, the sediments had $Z_y < 5$ and belonged to the category of pure ones, corresponding to the natural background. However, if the values of RGB are used, then the sediments, including those in point 2 on the Vezelka River and Gostyonka River, are assigned to the category of weak contamination, whereas, in point 1 on the Vezelka River, they are included in the category with a medium level of contamination (in the concentrations of Pb, Zn, Cu, V, Ni, and Fe_2O_3). This fact places certain limits on the further utilization of the bottom deposits after the completion of the bottom-deepening works.

4. Discussion

Small rivers in the forest steppe zones of European Russia were characterized by a natural hydrological regime in the 1940s, but now they are rapidly degrading. The Vezelka River, as a typical small river (among ca. 600 regional rivers of the same class), is especially sensitive to the applied anthropogenic load and has demonstrated its representativeness as an informative object for the study of the extremely strong pressure on watershed and floodplain/channel hydroecosystems. Small rivers and their short tributaries, due to the effect of their rather insufficient water richness and low capacity for self-purification, do not cope with the rising contamination of the water masses. During periods of abundant snowmelt and heavy rains, the river receives a large quantity of mud from the thalwegs of the gully network and soil washout from agricultural fields. Due to silting, the river under study has become fairly shallow and overgrown with boggy vegetation. The former water richness of the river is evidenced by the fact that, at the end of the 16th century, there was a ship wharf at the lower course of it. The data from the chemical analysis of the water exceeded the MACs in many indices fixed for fishery water bodies. A significant part of the spawning grounds has been lost; wintering pits, still preserved in the middle reaches, where dredging has not been carried out, are currently losing their fishery importance.

According to the data from ten gauging stations of the Hydrometeorological Service of the Russian Federation, the waters of the rivers of Belgorod Oblast are of the third and fourth quality classes (polluted or especially dirty). This fact indicates that the potential for self-purification and self-recovery of the aquatic objects is essentially exhausted in the region under consideration. The results of previous investigations of the hydroecological situation have demonstrated that the main sources of contamination of surface waters are represented by poorly refined wastewater, water disposal from industrial enterprises, and surface drainage from the urban area. The hydrobiocenoses form a system responsible for the biological self-cleaning of water bodies and, therefore, it is necessary to determine the specifics of the vital functions of this system under the conditions of anthropogenic impacts of different levels. Even information on the species composition of the hydrobionts allows us to judge the ecological 'health' of a river. However, of great importance for such an estimate is not only the fact of the presence or absence of certain hydrobionts in the water body, but also the extent of their quantitative representativeness: the greater the diversity of hydrobionts in a water body and the more intense their metabolism, the more organic substances undergo biological oxidation and the more vigorously the process of the purification of water bodies proceeds. The species diversity is, in addition, an important characteristic and a criterion for the stability of an ecosystem. Hydrobiological investigations have established that there exist groups of aquatic organisms that have adapted to survival only in the conditions of a particular level of contamination and saprobity of the water bodies. These features of the hydrobiocenoses can serve as a bioindication of the water quality and the state of a fresh water body. The data of biotesting and chemical analysis correlate well with each other. Therefore, the organisms distinguished as bioindicators of the contamination levels of river waters can form the basis for a more detailed period of monitoring during the warm period of the year, as compared with the more laborious and expensive chemico-analytical techniques.

It is important to highlight the negative role of bottom-deepening works at the riverbed within the boundaries of the city. Primary producers, including algal assemblages, as the first component in the food chain, sensitively change their composition depending on the dynamics of the hydrological and hydrochemical transformation of the water body [82]. The action of a dredger, which discharges the water into the river under pressure and at large velocities, aggravates the sanitary–biological regime of the water masses, negatively influencing the qualitative composition of the algoflora, and raises the eutrophication level of the water body. An indicator of this process is represented by the mass propagation of volvox algae, which usually are found in large quantities in eutrophic shallow water bodies. The 'flowering' (green scum) of the water in the summer months, provoked by chroococcophyceae, indicates the raised content of nitrogen in the river water. Moreover, blue-green algae, including their toxic species (*Aphanizomenon flos-aquae* and *Microcystis aeruginosa*), represent the causative agents of the summer green scum. Their toxic action is manifested in the mass death of hydrobionts and a harmful effect on the human organism, limiting the recreational potential of the broadening riverbeds at the mouth, which produces weak flowage of a lacustrine type.

The basin of the Vezelka River, with an area of 406 km^2, is characterized by the considerable anthropogenic transformation of its landscapes. Presently, it is understood that there is a necessity to realize not a patchwork-economy measure but a river-basin-scale approach to the management of the natural resources in the watershed area, and to design projects for the ecological sanitation of the water of small rivers. The area of the watershed in the upper and middle reaches (agricultural area) of the river was the subject of projects focused on basin management, which after the start of their realization in 2015, have helped to slightly alleviate (in terms of the qualitative gradation, from unstable to somewhat stable) the severity of the ecological and economic situation. The measures for the cleaning of the riverbed and deepening of the bottom, in our opinion, should be only the concluding stage of the design and implementation of soil and water protection measures in the territory across the entire area of the watershed. In this sense, a transition from the now-practiced technology of cleaning riverbeds with the construction of channel-type beds to the reconstruction of the cascades of stretching hollows and sandbars in the floodplain/riverbed segment of small river valleys is promising. This method, however, will require the application of calculation designs adequate for the local hydrological conditions. We expect that the increase in the hydrological efficiency of the program for the cleaning and improvement of springs implemented in the region will be associated with targeted projects for the hydroreclamation of the small-debit springs that feed the channel during low-water periods.

The ecological situation in the Vezelka River basin is sharply deteriorating around the arch, with the outer perimeter distanced 6–11 km from the boundary of the city of Belgorod. In the riverbank zones of the Vezelka River and its main tributaries, a ban must be imposed against the ploughing of land strips no less than 20 m wide, particularly near the boundaries of dachas, orchards, or vegetable gardens.

Given the absence of a natural floodplain/riverbed process, it is reasonable to transform the lower links of river valley paragenetic landscapes into controllable natural and technical systems [20]. Within the limits of the city of Belgorod, it is necessary to introduce a specific regime for the ten-kilometer segment of the mouth zone of the Vezelka River in the territory of water protection zones (with a width of no less than 100 m along both banks). This regime should comprise a complex of nature protection measures for the amelioration of the hydrological, hydrochemical, hydrobiological, sanitary, and ecological conditions of the river and beautification of the latter's bank areas. It should be ensured that the nature protection zones are provided with meadow and forest land-improving measures and also serve as testing grounds for carbon sequestration (within the framework of carbon farms). In the riparian protection zones (35–55 m wide) employed as recreational areas within the urban limits of the city of Belgorod and other towns in this administrative region of Russia, systematic sanitary measures should be planned (removal of trash, installation of trash bins, planting of perennial grasses, etc.).

The scope of the regional legislation allows us to introduce such a new category of specifically protected natural territories as 'protective river valleys'. This is why the authors propose to include into the protected river valleys the ten-kilometer section of the Vezelka River within the city precincts, with the corresponding regulation of land management. This measure will allow us to fix in the city's general plan the boundaries of the water protection zone and other protective areas, particularly in water intake areas. This is especially important because the water intake from the Vezelka's basin is underground. From this position, the measures that we propose for the arrangement and legal regime of land use in water intake zones could be useful to specialists in the field of the extraction and development of mineral water deposits [83].

The most complete register of permanent and drying-out watercourses in the territory of Belgorod Oblast numbers 601 rivers with a total length of 4564 km. In addition, by now, there have been constructed over 1200 ponds and water reservoirs in the region. Through a comparative analysis of cartographic materials of different periods, it has been established that, during the period from the end of the 18th century up to the 20th century, the length of the river network in Belgorod Oblast has been reduced by almost 38%, with the average rate of degradation of the running waters equal to approximately 15 km per annum. These facts, as well as estimates of the hydrological and water economy situation obtained by scientific institutions, have greatly promoted the formation of a complex program for the sanitation of surface aquatic objects in the region. Since 2022, in accordance with the governmental project 'Development of the aquatic economy and forestry in Belgorod Oblast', there has been realized the cleaning of aquatic objects in the region, possibly unprecedented in scale, not only for this territory but also for the entire country. The peculiarity related to the selection of the priority objects for the cleaning of segments of riverbeds and water areas of ponds and reservoirs was in the opportunity for online voting on this issue, presented to local communities via social networking. The local communities organized a pool of 740 such objects (rivers, water reservoirs, and ponds), more than 2000 km long and with a total area of 5000 km^2. In 2023, in the framework of the new regional programme 'Our Rivers', it is planned to carry out the cleaning of the riverbeds and water areas of 50 aquatic objects. In particular, it is planned to clean the riverbed of one of the tributaries in the basin of the Vezelka River.

It is of note that the realization of the project for the cleaning of riverbeds and water areas was preceded by large-scale works for the identification of the zones of flooding in the river floodplains, which allowed for the definition of the boundaries of the areas inundated during the maximum water levels of 1, 3, 5, 10, 25, and 50 percent exceedance probability. The boundaries of the flooding zones were determined by the method of excesses with the application of a digital elevation model and data on the highest levels of water in the rivers of the region. Since this component of the design procedure has become part of the complex program, we can discuss the timely transformation of the conceptual flood prevention scheme, i.e., a transition from direct protection against the flooding of settlements in river valleys to controlling the risk extent.

The complex of works on the development of measures for the cleaning of priority sections of riverbeds and water areas of ponds and reservoirs includes the following tasks: assessment of the current state and prognosis of the probable changes in the environment during the cleaning of the channels and banks of rivers and other water bodies; the collection of samples of water and bottom sediments; the identification of the chemical compositions and risk classes of the bottom sediments; the estimation of the ecological conditions of the flora and fauna; the development of recommendations to prevent adverse impacts; and the restoration and improvement of the natural environment in the implementation of the planned activities. Works aimed at cleaning the bottom of a water body are an environmental protection measure carried out without capital construction, beautification, or landscaping. A Watermaster dredger is used to clean the shores from hard water plants and to remove bulky waste. From an ecological point of view, locations of redeposited alluvium have been mapped at the necessary scale.

5. Conclusions

The scale of the anthropogenic load has arisen to a level at which it is necessary not only to strengthen the hydrological control over residential, industrial, and agricultural human activities but also to ensure the more effective functioning of sewage works. This general assessment is confirmed inter alia by the results of our investigations of a typical small river, where the quantitative and qualitative runoff responses reflect, over intervals, the natural and economic situation of the basin subjected to the joint influence of agricultural use and a built-up urban area.

The unfavorable integral estimates of the quality of the river water in the urban area through sanitary–chemical indices obtained for low-water periods of the year, when the demand for citizens' recreational activities along the river is especially high, corroborate the necessity to correct the periodicity of the monitoring in warm periods with the establishment of the sources of the external, mostly anthropogenic, factors of the sanitary–epidemiological problems. The characteristics of the taxonomic spectrum of microalgae and the list of the organism indicators of saprobity within the urban area have demonstrated that, along with the influence of drainage waters from the watershed area and the reduction in flow caused by dredging works at the river mouth, the complex of negative impacts on the qualitative composition of the algoflora increases, which intensifies the processes of eutrophication. As a result, we must state that the modern anthropogenic load on a small river, particularly in its low reaches within the urban area, exceeds the self-cleaning abilities of the river.

A comprehensive solution to the problems of soil protection in the drainage basin and the hydroecological problems in the landscapes of river valleys is expected in the course of the introduction of the river basin nature management, which implies the consideration of a basin as a single natural and anthropogenic system where the movement of the substance, energy, and information occurs regularly from the watershed to the thalweg of the river valley. The structural parts (level, slope, and hydrological) of the basin system are characterized by spatial contiguity and genetic conjugation. Being a zone of interaction between nature and society, the river basin is considered both as an arena for nature management and as a managed object, representing an integral natural and economic–demographic system. The application of the basin approach in nature management is beneficial for many reasons, including the organization of unidirectional flows of substance, energy, and information; the localization of anthropogenic sources of contamination of the environment along the axes of watersheds, i.e., water runoff; the established systems of settlement and nature management; a hierarchical structure that enables us to incorporate different territorial levels of management; and geosystem interconnections. This all allows us to realize environmental monitoring of different types.

Along with the organization of basin-scale nature management, the following measures should be included among the priority tasks for the improvement of small rivers and their watersheds:

1. The introduction of a legislative approach to establishing the widths of water protection zones; in particular, they should be no more than 100 m, with a river length of 10 to 50 km. A landscape approach is necessary that makes it possible to differentiate the parameters of these zones, taking into account the locations of the mouths of large fluvial landforms as places of sediment discharge, which are potential barriers for lateral mass transfer to the final links of solid substance migration—the riverbed network. In practice, it is advisable to have buffer grass zones of an isometric shape to reduce the rate of surface runoff and sedimentation [84].
2. The improvement of springs with a high debit so that their waters reach the riverbed.
3. The assessment and optimization of water flow control in ponds, especially when using blind dams.
4. The rationing of water intake to meet drinking and industrial needs from underground water sources in the basin.

Prospects for the further development of the concept of landscape improvement in small river basins have been considered by us in several key areas. An alternative to the regularly practiced deepening of the riverbed bottom with the help of hydromechanisms is proposed in the concept of improving the soil and water protection of agricultural landscapes based on basin principles. There, the reconstruction of the floodplain/riverbed system is only the final stage of the hydroecological program for the rehabilitation of anthropogenically transformed small rivers and their watersheds. This concept has not only been presented in detail [85], but also put into practice throughout the region [59]. The authors believe that there is no alternative to the application of the method of river analogies under the conditions of the underdevelopment of the network of hydrological monitoring of small rivers. This is due to the fact that, for the use of stable hydrological indices, the time series should not be less than 50 years long. In the framework of previously fulfilled hydrological and geographical zoning, rivers devoid of many-year series of observations can be provided with data for the designed hydrotechnical works by means of the method of hydrological analogies with the substantiation of similarity criteria and arguments for calculation formulae. A project for the rehabilitation of the water richness of a small river must be based on an analysis of the parameters of the distribution of the runoff throughout the water economy years of the climate change trends, rather than over the calendar year. The areas for further research are related to the systematic monitoring of the effectiveness of management measures, based on new additions to the hydrological series in the context of a changing climate and increasing anthropogenic pressures on urban areas.

Author Contributions: Conceptualization, F.N.L.; data curation, Z.A.B. and F.N.L.; formal analysis, F.N.L. and Z.A.B.; funding acquisition, F.N.L. and Z.A.B.; investigation, F.N.L. and Z.A.B.; methodology, F.N.L. and Z.A.B.; project administration, F.N.L.; software, Z.A.B.; supervision, F.N.L.; validation, F.N.L. and Z.A.B.; visualization, Z.A.B.; writing—original draft, F.N.L.; writing—review and editing, Z.A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Russian Science Foundation, project no. 23-17-00169, https://rscf.ru/en/project/23-17-00169 (accessed on 29 June 2023) (analysis of the structure of the ravine network, determination of sediment interception zones and modeling of average annual soil erosion losses). The work was also carried out in accordance with the Strategic Academic Leadership Program 'Priority 2030' of the Kazan Federal University of the Government of the Russian Federation (assessment of hydrological, hydrochemical and hydrobiological parameters; assessment of the role of environmental factors).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We are grateful to our colleagues who assisted with the field work, namely A.V. Degtyar, O.A. Chepelev, M.E. Rodionova, and M.V. Kitov.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Water quality indicators in the Vezelka River from the source to the mouth.

Index	Quality Standard	Water Sample Index for Six Monitoring Points *					
		1	2	3	4	5	6
Smell intensity	≤2 points	0	2	2	2	2	2
Color and haze	quality units	0–0	1–1	1–1	0–1	1–1	0–1
pH	4.5–8.0	7.0	8.20	7.85	7.20	8.0	8.08
General acidity	mmol (Eq) L^{-1}	0.9	0.2	0.2	0.6	0.2	0.2
General basicity	mmol (Eq) L^{-1}	6.0	16.8	15.4	16.6	15.0	13.9
HM (Cu^{2+}, Pb^{2+}, Zn^{2+})	0.0001 mmol L^{-1}	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
GH	10 mol (Eq) L^{-1}	7.5	7.9	6.8	8.6	6.8	6.9
Ca^{2+}	200 mg L^{-1}	106.2	112.2	108.2	128.2	104.2	80.2
Mg^{2+}	100 mg L^{-1}	26.8	28.0	17.02	26.8	19.5	35.3
HCO_3^-	1000 mg L^{-1}	732	1024	939	1012	915	902

Table A1. *Cont.*

Index	Quality Standard	Water Sample Index for Six Monitoring Points *					
		1	2	3	4	5	6
Cl^-	350 mg L^{-1}	205.0	170.4	227.0	189.0	213.0	170.4
$SO_4{}^{2-}$	500 mg L^{-1}	114	112	108	136	136	136
$NH_4{}^+$	2.5 mg L^{-1}	0.20	0.20	0.10	0.10	0.20	0.20
$NO_2{}^-$	0.1 mg L^{-1}	0.10	0.05	0.01	0.02	0.50	0.05
NO_{3-}	45 mg L^{-1}	<100	<10	100	>100	<100	<10
Na^+	200 mg L^{-1}	0.04	0.08	0.04	0.04	0.04	0.05
TDS	1000 mg L^{-1}	570	660	800	730	620	770
COD	30 mg L^{-1}	28.0	25.0	28.0	32.0	29.0	34.0

Notes: * Monitoring points are shown in Figure 2h. River source (1); at the entrance of the river to the urban area (near the ecological station) (2); section of the river downstream of the cement plant to the confluence of the right inflow: Gostyonka River (3); the location of the confluence of the Gostyonka River (during the selection period, it was almost dry) (4); the left bank of the Vezelka River, in the area after the confluence of the Gostyonka River and the cement plant (5); the mouth of the Vezelka River at the exit from the city of Belgorod and at the confluence with the Seversky Donets River (6). Smell intensity points: 0—smell is not noted, 2—smell is faintly perceptible. Color and haze: 0–0—colorless and transparent, 0–1—colorless and weakly turbid, 1–1—slightly yellow and weakly turbid.

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