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Cesium-137 Distribution Patterns in Bottom Sediments of Beaver Ponds in Small Rivers in the North of the Volga Upland, European Russia

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Abstract: This paper presents the results of the analysis of the redistribution of cesium-137 (^{137}Cs) in the bottom sediments of beaver ponds in two small rivers in the forest-steppe north of the Volga Upland, which is one of the most contaminated areas of the Middle Volga region (European Russia) with artificial radionuclides. This study is based on fieldwork materials, laboratory analyses of the specific radioactivity of ^{137}Cs in soil and bottom sediment samples, their granulometric composition, and the content of organic matter in them. The obtained results indicate a significant decrease in the specific activity of ^{137}Cs in the direction from near-water-divide surface soils (on average, 54 Bq/kg) to the bottom sediments of beaver ponds of the studied rivers (on average, no more than 6 Bq/kg). A weak (statistically insignificant) tendency towards a decrease in the specific activity of ^{137}Cs in the bottom sediments of beaver ponds downstream of rivers was also revealed. With this detected trend, no statistically significant relationship was found between changes in ^{137}Cs and changes in the granulometric composition of bottom sediments. However, a relatively good relationship was identified with changes in the content of total organic matter. The stage-by-stage accumulation of sediment thickness in one of the beaver ponds was revealed, with the highest concentration of ^{137}Cs in the layer with the highest content of finely dispersed fractions and organic matter. The obtained results indicate that for a correct quantitative assessment of the migration of pollutants (including radioactive ones) in floodplain-channel systems, it is necessary to consider beaver structures (primarily ponds), which act as zones of their intensive accumulation.

Keywords: river; river basin; Eurasian beaver; *Castor fiber* L.; erosion; sediment; sedimentation; radionuclide; organic matter; granulometric composition

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1. Introduction

The development of nuclear energy, which began in the 1940s, was accompanied by emissions of artificial radioactive isotopes into the environment [1,2]. One of the relatively long-lived isotopes is cesium-137 (^{137}Cs; half-life is 30.17 years), which appeared in the natural and anthropogenic landscapes of Earth as a result of nuclear weapon tests in the stratosphere from the 1950s to 1990, from where this isotope, as a result of mixing, passed into the lower layers of the troposphere [3,4] and fell to the Earth's surface, primarily via atmospheric precipitation, over several years [5,6]. The most intensive nuclear tests in the

Northern Hemisphere were carried out in 1954–1958 and 1961–1962 [3], after which peak fallouts of the cesium-137 isotope on the Earth's surface were observed. Approximately 90% of all nuclear tests were conducted (primarily by the USA, USSR, and China) in the Northern Hemisphere and only 10% in the Southern Hemisphere (by France and the UK) [7]. Therefore, significantly more ^{137}Cs fell out from the Northern Hemisphere compared to the Southern Hemisphere [8]. It is important to note that the higher radioactivity of the Northern Hemisphere is also due to other factors, such as accidents at nuclear power plants [9], including the Chernobyl Nuclear Power Plant accident on 26 April 1986, when the area of ^{137}Cs fallout covered mainly Eastern and Central Europe, as well as Scandinavia [10]. After falling via atmospheric precipitation, ^{137}Cs was firmly adsorbed primarily by clay particles in soils and grounds [11–14], which, as a result of surface washout due to meltwater and rainwater, ended up primarily in the upper links of the fluvial network (including small rivers), lakes, and ponds.

After accidents at nuclear power plants (Chernobyl (1986) and Fukushima Daiichi (2011)), it was shown that closed and semi-closed water bodies, such as lakes and ponds, characterized by a high content of organic matter and, accordingly, increased concentrations of ammonium in the water, are most sensitive to contamination by radiocesium [15–18]. The distribution of ^{137}Cs in pond bottom sediments is closely related to the initial amount of radiocesium deposition, the content of organic matter, silt particles, the depth and volume of the water body, its catchment area, hydraulic residence time, pH, and the content of Na+, K+ and NH_4+ cations [19–21]. Since cesium is an alkali metal, it is highly soluble in water and exists almost exclusively as the monovalent cation Cs+ in an aqueous solution [19]. The solubility and mobility of cesium increase significantly with decreasing pH values [20]. Researchers have also attributed a significant role to organic matter content in the accumulation and migration of ^{137}Cs [12]. The presence of K+ and NH_4+ significantly complicates the adsorption of cesium [22]. At the same time, the amount of radiocesium carried outside river basins from the total reserves as a result of the Chernobyl fallout does not exceed 1% [23]. However, even such relatively small reserves of radiocesium pose a potential threat when they accumulate in water bodies, including in the relatively recently appeared beaver ponds, from which secondary pollution can occur in the event of a dam break.

The accumulation of Chernobyl-derived ^{137}Cs was monitored in the bottom sediments of several Finnish lakes over many years (1969, 1978, 1988, 1990, 2000, and 2003), and both increasing and decreasing tendencies were observed 14 years after the accident [21]. Another study looked at yearly and spatial changes in ^{137}Cs in surface sediments (0–5 cm) in a cooling basin of the Ignalina Nuclear Power Plant [24]. The results indicated complicated sedimentation features, which may have been affected by some natural and anthropogenic factors, resulting in the mixing, resuspension, and remobilization of sediments and radionuclides. Seasonal variations of ^{137}Cs due to its remobilization in bottom water have been reported in Lake Juodis (Lithuania); however, this process was considered site-specific [25]. Kansanen et al. [26] reported a tendency for radiocesium concentrations to increase with depth in the sediments of Lake Paijanne, Finland, and considered this a result of the focusing effect. However, limited investigation has been performed on the temporal changes in the vertical profiles of ^{137}Cs within the framework of sedimentation processes in lakes.

Some processes have been considered for the simulation of the vertical profiles of radiocesium in sediments to reproduce the measured profiles. These include bioturbation [27], physical mixing [28], sediment resuspension [29], non-local mixing (direct injection of a part of the flux into deeper sediment layers) [30], initial deposition (penetration through connected pore spaces) [31], incomplete mixing zone (fast and homogeneous mixing of a mobile fraction, and the sedimentation of an irreversibly bounded fraction) [32], buoyancy effect (disturbances in the thermohalinic stability of sediment interstitial liquids inducing their interfacial transfer) [33], and release from sediments [25].

The construction activity of beavers leads to the transformation of river systems [34–36], which is manifested in the formation of ponds; the accumulation of sediments [36–39], organic matter [40–42], and pollutants [43] in these ponds, resulting in changes in river biocenoses [44–47]; and the hydrological regime of rivers [48–50]. Beaver ponds with their bottom sediments can also function as objects of increased accumulation of radioactive elements, including radiocesium-137.

Despite that, at the beginning of the last century, the Eurasian beaver (*Castor fiber* L.) was on the verge of extinction in the vast territory of the former Russian Empire due to predatory hunting; the beaver population, thanks to protection and reintroduction, increased annually, and by the end of 2022, the number of these animals in the Volga Federal District (1.036 million km^2) of European Russia amounted to about 200 thousand individuals and continues to grow [51]. The intensive settlement of small rivers in the region by these animals led to the appearance of cascades of ponds along with them, which could potentially lead to changes in radionuclide concentrations during their redistribution in river basins. Even though there is a fairly large number of works on radionuclide contamination in natural lakes, anthropogenic reservoirs, and ponds, this problem has been very poorly studied in relation to beaver ponds. It is only noted that beaver structures affect the concentration of radionuclides in water [52] and also contribute to their accumulation in aquatic organisms [53] and in bottom sediments [53,54] near objects with radioactive waste.

Developing a strategy to minimize negative environmental and economic consequences in the region's river network is currently impossible without taking into account the results of beaver activity, which also has a noticeable impact on the redistribution of pollutants, including radioactive ones, in the floodplain-channel complexes of small river valleys, since beaver dams and ponds serve as natural barriers to the migration of artificial isotopes. Considering the above, in this study, we attempted to evaluate the most general patterns of spatial redistribution of ^{137}Cs in the direction from the soils of near-water-divide surfaces to the bottom sediments of beaver ponds using the example of two small rivers in the forest-steppe zone of the far north of the Volga Upland. This region is the most contaminated with Chernobyl ^{137}Cs fallout within the Republic of Tatarstan; in one of the administrative regions of European Russia where our research took place, in the north of the Pre-Volga Region of the Republic of Tatarstan, this contamination was 10–20 kBq/m^2 at the time of the fallout (1986), increasing to the southwest to 20–40 kBq/m^2 (Figure 1). For comparison, in the rest of the Republic of Tatarstan, it was estimated to be, on average, many times lower, 2–4 kBq/m^2, and only in small areas, up to 4–10 kBq/m^2 [10]. As far as we know, such studies in the Middle Volga region and, apparently, in the east of the Russian (East European) Plain are being conducted for the first time. In addition to scientific significance, the results obtained are also of practical importance for predicting the impact of beaver activity on the quality of water and bottom sediments, as well as on the general functioning of small river ecosystems and their floodplain-channel complexes in river basins, especially in areas of intensive human development of natural landscapes contaminated with long-lived radionuclides.

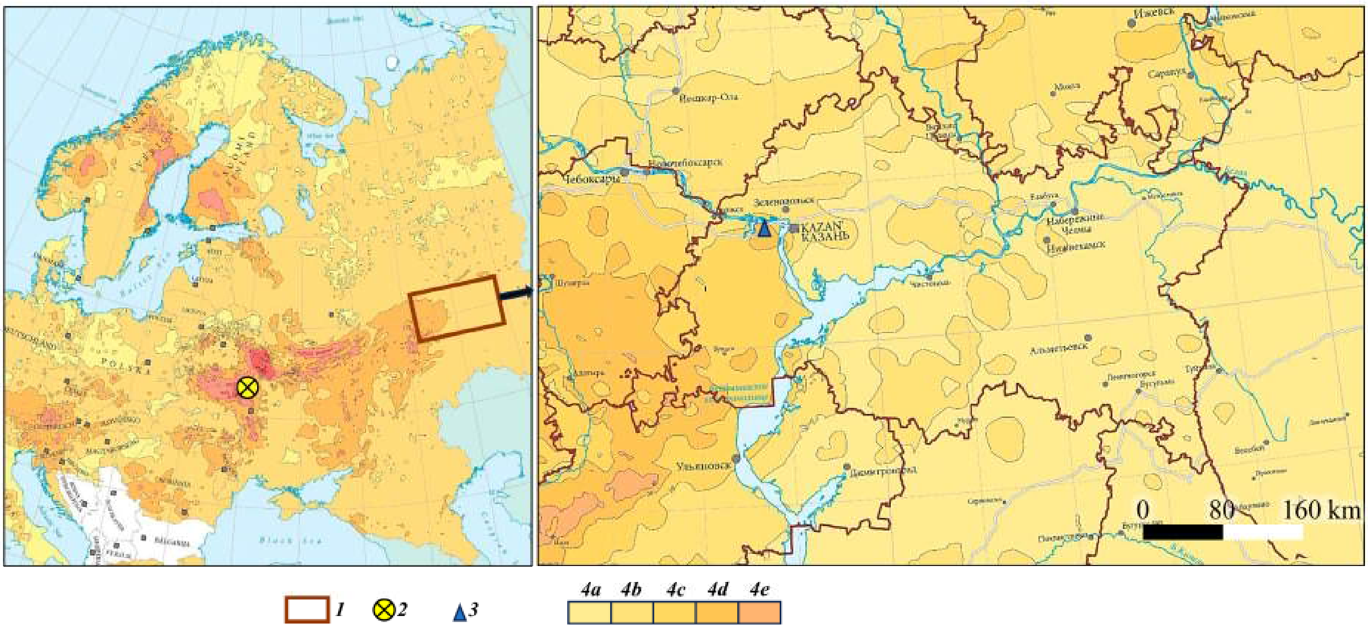

Figure 1. Contamination of Eastern Europe (**left**) and the Republic of Tatarstan (**right**) with radioactive cesium-137 immediately after its fallout in 1986 [10]. *1*—location of the Republic of Tatarstan, which is part of the Volga Federal District; *2*—location of the Chernobyl Nuclear Power Plant; *3*—the study area, *4*—the total cesium-137 deposition (in kBq/m^2): *a*—2–4, *b*—4–10, *c*—10–20, *d*—20–40, *e*—40–100.

2. Materials and Methods

2.1. Study Objects

Fieldwork was carried out in the summer and autumn of 2022 in the basins of two small rivers, the Morkvashinka and Morkvashka rivers, which are direct right tributaries of the Volga River (Kuybyshev Reservoir), in the far north of the Volga Upland within the Pre-Volga Region of the Republic of Tatarstan (Figure 2). The structure of the valleys of the studied rivers is typical not only for the region under consideration but also for the entire north of the Volga Upland [1]. Despite their geographical proximity, the rivers differ in length, channel slopes, and the degree of anthropogenic transformation of natural landscapes and their basins (Table 1).

The Morkvashinka River is characterized by a symmetry of the slopes of its valley. The right-bank slope is steep and high almost throughout its entire length; the left slope is gentle. The Morkvashka River valley is relatively more symmetrical [55]. In the valleys of the rivers under consideration, the low and high floodplains are morphologically expressed in small fragments with an average height of 0.7 and 1.5 m, respectively, and the first floodplain terrace with a height of up to 4–5 m is expressed in larger fragments [55]. Information on the lithological structure of the river basins is given in Table 1. Geodetic coordinates of the mouth of the Morkvashka River are X: 48.79267707, Y: 55.78247276, and the mouth of the Morkvashinka River are X: 48.85258569, Y: 55.77880625.

Heavy loamy and clayey gray forest residual carbonate soils are common in the studied river basins. Native vegetation is represented by linden-oak forests with an admixture of maple, beech, elm, etc. [56]. The river basins, in general, have been strongly altered by humans, which is expressed in high plowing and the construction of summer cottages and multi-story buildings (the city of Innopolis in the Morkvashka River basin). At present, as a result of the active activity of beavers, the floodplains of the rivers are heavily overgrown with willow, and only some of their areas are used for pastures and haymaking.

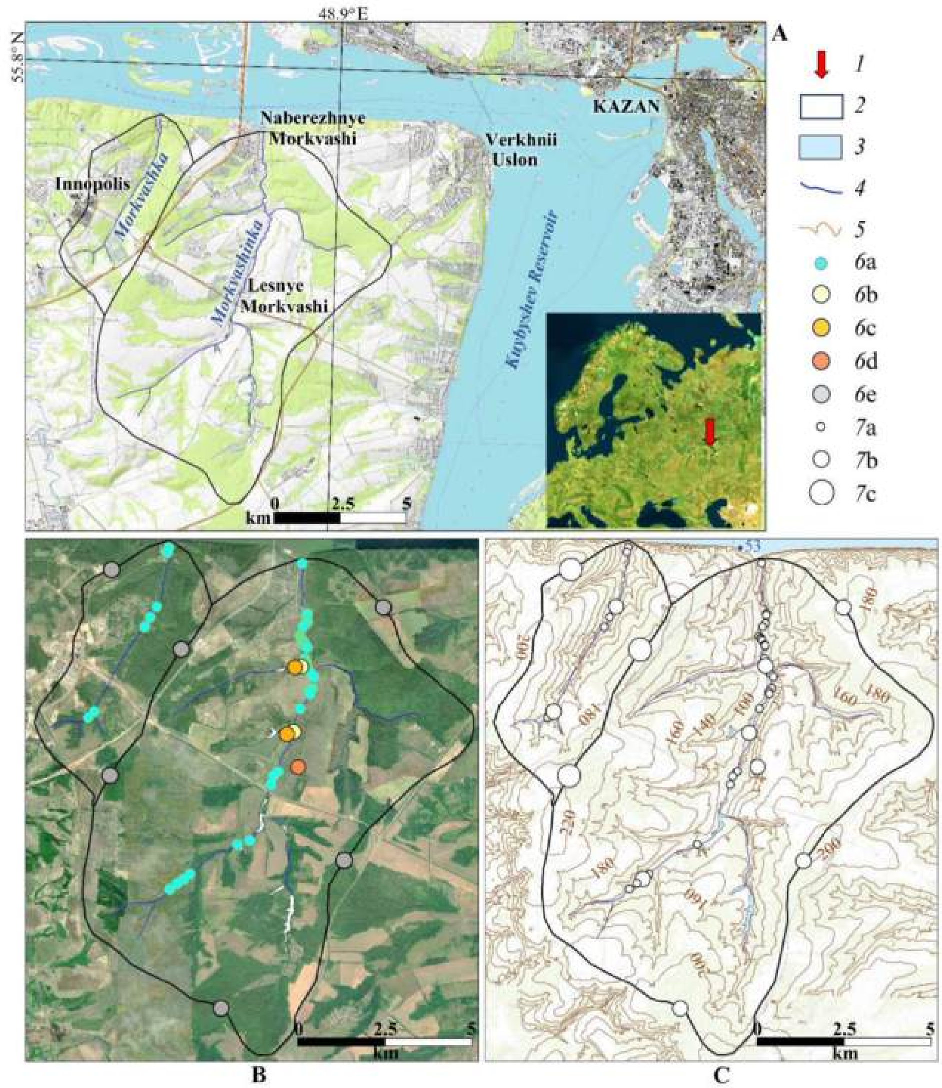

Figure 2. (**A**) Location of the studied objects, (**B**) soil and bottom sediment sampling sites, and (**C**) ^{137}Cs's specific activity in them. *1*—location of the studied objects, *2*—boundaries of the studied river basins, *3*—water bodies (ponds and reservoirs), *4*—river network, *5*—contours (drawn every 20 m), *6*—locations of sampling points (a—riverbed and low floodplain flooded by ponds, b—drained high floodplain, c—lowest floodplain terrace, d—river valley slope, e—near-water-divide surface); *7*—specific activity of ^{137}Cs, Bq/kg (a—0–10, b—10–50, c—50 and more).

Table 1. Some characteristics of the studied small rivers and their basins.

River	Parameter								
	L, km	*S*, km^2	*H*, m	Δ*H*, m	*α*, %	*R*, mm	*Lit*	*Ant*, %	*F*, %
Morkvashka	7.8	20.4	165	154.4	1.98	146 (2.9784)	Lm/Lim	3	55
Morkvashinka	16.6	86.9	152	152.1	0.92	136 (11.8184)	Lm/Lim	20	43

Notes: *L* is the length of the river from its source (including the dry valley (ravine) in the upper reaches) to its mouth; *S* is the area of the river basin; *H* is the average elevation of the river basin; Δ*H* is the fall of the river (according to https://www.dwtkns.com/srtm30m/; accessed on 20 December 2024); *α* is the slope of the river; *R* is the average long-term annual depth of water runoff in the river basin (according to https://bassapr.kpfu.ru/mapbender/application/bassepr; accessed on 24 December 2024) (average long-term water flow values are given in parenthesis, $\times 10^6$ m^3 per annum); *Lit* is the predominant rocks/sediments on the surface of the river basin; Lm is deluvium-solifluction loams; Lim is Upper Permian limestones (according to https://webmapget.vsegei.ru/?ysclid=lq57uwqvj7713899222; accessed on 23 December 2024); *Ant* is the share of cultivated (excluding abandoned) land in the total area of the river basin; *F* is the forest cover of the basin (according to https://esri.maps.arcgis.com/apps/mapviewer/index.html?webmap=c03a526d94704bfb839445e80de95495; accessed on 23 December 2024).

The total length of the Morkvashinka River, according to a previously conducted geodetic survey [57], is 16.2 km (together with the dry valley in the upper reaches—16.6 km), and the Morkvashka River is 7.4 km (7.8 km) long. The construction of a cascade of anthropogenic ponds in the upper reaches of the Morkvashinka River and water intake for private households led to a significant decrease in water flow, especially during the summer–autumn low-water period. An important role in reducing the water flow is also played by high evaporation from the surface of beaver ponds, especially in recent years with extremely high average air temperatures in the summer months. All this leads to the appearance, in certain places, of dry sections of the riverbed (see Figure A1 in Appendix A). The presence of runoff in the riverbed in such sections during the summer low-water period is often associated with small lateral tributaries that discharge the underground waters of the Permian aquifers.

2.2. Fieldwork

To identify the background values of ^{137}Cs concentration in the basins of the studied rivers, samples of the upper soil layer (gray forest soil) were collected in the summer and autumn of 2022 at six sites located on their near-water-divide surfaces (Figure 2). The main criteria for selecting sites were the presence of relatively mature woody vegetation (at least 40 years old); low tree density, which determined the natural deposition of ^{137}Cs during its fallout; as well as the absence of signs of erosive soil loss. In addition, five sites (in total) were laid out on the high floodplain, the first terrace, and the deluvium-solifluction slope of the Morkvashinka River valley.

On each site, bulk soil samples were collected (Figure 3) at three points at a distance of 4–5 m from each other (at the vertices of an equilateral triangle), from a depth of 0–10 cm (excluding forest litter or sod) and a fixed area of 15 × 15 cm^2, to obtain integral samples using the quartering method.

Figure 3. Processes of sampling bottom sediments and soils in beaver ponds of the Morkvashinka and Morkvashka rivers and their interfluves.

A detailed examination and geodetic survey of the two rivers under study, the methodology and results of which were presented in our earlier papers [57,58], allowed us to select the most representative beaver ponds in different sections. Samples of bottom sediments in the ponds were collected in their near-dam section using a hand sampler (EIJKELKAMP 04.23.SA; internal diameter: 3.6 cm) from a depth of 0–20 cm in a total of 39 sites (see Figures 2 and 3). Each analyzed sample is a mixture of three samples collected at three points from different parts of the pond's near-dam bottom: one in the flooded riverbed sediments and the other two from the sediments on the right bank and left bank of the flooded floodplain. In addition, at one site on the bottom of one of the ponds, naturally drained during the fieldwork (see Figure A2 in Appendix A), cores of bottom sediments were collected using a Burkle Purkhauer drill at three points located at a distance of 2 m from each other (at the vertices of an equilateral triangle). Based on the change in color and structure of the cores, accumulative layers were identified, and their thickness and depth were determined. By mixing samples from one layer but from different cores, integral samples were prepared, and the averaged above-mentioned morphometric characteristics for each layer were calculated. A total of 52 samples of soils and bottom sediments were collected during the fieldwork.

Based on the results of a geodetic survey in areas with a natural riverbed located above and below the cascade of beaver ponds in the studied rivers, in the spring (April) of 2023, hydrometric (gauging) sections were laid perpendicular to the average direction of the river flow to determine the one-time water flow rates and collect samples for sediment concentration. The water flow rates were measured using a Russian-made ISP-1M current velocity meter according to an established standard scheme. This device can measure velocities in the range from 0.03 to 5.0 m/s. Before using it in the field, the current velocity meter was verified in a specialized laboratory, where the relative basic error of this device did not exceed the permissible limits of ±5% over the entire range of velocity measurements.

2.3. Laboratory Tests

The determination of the specific radioactivity of ^{137}Cs in soils and bottom sediment samples was carried out in laboratory conditions at the Makkaveyev Research Laboratory for Soil Erosion and Channel Processes (Lomonosov Moscow State University, Moscow, Russia); the person in charge was Senior Researcher, Dr. M.M. Ivanov. The samples were dried to a dry state at 105 °C, crushed, and sieved through a sieve with a mesh diameter of 1 mm. The content of ^{137}Cs in the samples prepared for analysis was measured using a coaxial germanium gamma spectrometer (Gamma-spectrometric complex SKS-07P(09P)_G_R (Moscow, Russia)) with an accuracy of about ±15%. The concentration of ^{137}Cs was calculated as a specific value per mass of a dry soil or bottom sediment sample (Bq/kg). Before carrying out measurements of ^{137}Cs activity, at least once a day, the parameters of the energy calibration of the spectrometer were refined and verified using the control source included in the spectrometer package. To do this, the autocalibration option is selected in the SpectraLine (SpectraLine 1.7 family) software package, which automatically refines the parameters of the energy calibration based on the results of processing the measured spectrum and compares the estimated activity of the radioisotope of the control source with the certified values. Then, in automatic mode, the spectrometer background control procedure is carried out, which is necessary to carry out background control after a specified time.

The granulometric compositions of soils and bottom sediments, as well as the content of total organic matter in them, were determined in the biogeochemical laboratory in the Institute of Ecology and Subsoil Use Problems of the Academy of Sciences of the Republic of Tatarstan under the supervision of the head of the laboratory, Dr. D.V. Ivanov. The granulometric composition was analyzed using the pipette method according to [59].

In each sample, the content of clay (particle size less than 5 µm), silt (5–50 µm), and sand (50–1000 µm) was determined. The content of total organic matter in the selected soil and bottom sediment samples was determined via dry ashing at a temperature of 550 °C according to [60]. At the initial stage, the weighed portions of soils and bottom sediments were measured with an accuracy of 1 ± 0.002 g; then, they were placed in crucibles, sent to a muffle furnace that was heated to a temperature of 105 °C, and dried to a constant weight for one hour. After that, the crucibles with samples were reweighed to determine the hygroscopic water (in %) for recalculating the ashing results to dry matter. Then, the sample was ached at 550 °C for four hours to a constant weight, and the relative content of total organic matter in the sample was determined.

In the above-mentioned laboratory, the concentration of suspended particles in the selected water samples (15–18 April 2023) was determined by filtering the sample through a 35 mm FMAC-0.45 membrane filter (cellulose acetate, pore size 0.45 μm). The water sample was pre-shaken and poured into filtration cuvettes. The operation was repeated three times, and the final result was the arithmetic mean of three determinations. Then, they were dried and weighed on an analytical scale with an accuracy of 0.0001 g.

2.4. Statistical Data Processing

Statistical data processing was performed in the XLSTAT 2016.02.28451 software application for Microsoft Excel. The determination of average values, standard deviation, and standard error of the mean was carried out using the descriptive statistics block. To assess the statistical significance of trends, the Mann–Kendall test was used. The magnitude of the linear relationship was determined using Pearson's correlation coefficient.

3. Results and Discussion

3.1. Intra-Basin Redistribution of ^{137}Cs

A summary of the results of the analysis of samples taken in the basins of the two studied rivers revealed a general trend in the redistribution of cesium-137. Despite the significant loss of this radionuclide (natural decay) in soils after the Chernobyl accident in 1986 and atmospheric nuclear weapons testing since the 1950s, its maximum concentration, in general, remains on the near-water-divide surfaces of the basins, under the canopy of mature, mainly forest, vegetation. With an average level of specific activity in near-water-divide soils of approximately 54 Bq/kg, the highest concentration of this radioisotope (up to 78–83 Bq/kg) is characteristic of the western part of the two basins, and the lowest (23–36 Bq/kg) is on the eastern watershed of the Morkvashinka River basin (see Figure 2). This is apparently due to regional features of ^{137}Cs fallout (primarily of Chernobyl origin) from the atmosphere via precipitation; since the soil samples were taken only to a depth of 10 cm, the concentration of caesium-137 in them mainly reflects its Chernobyl trace after 1986.

In the direction from the soils of near-water-divide surfaces to the bottom sediments of beaver ponds of the Morkvashka and Morkvashinka rivers, there is a general decrease in the specific activity of ^{137}Cs, reaching in the latter average values of no more than 6 Bq/kg (Table 2). Only in three separate ponds (two located in the Morkvashinka River and one in the Morkvashka River) do these values reach 17–18 Bq/kg. Thus, the concentration of radiocesium-137 in the bottom sediments of beaver ponds is almost an order of magnitude less than, at the current time, in soils on near-water-divide surfaces unaffected by erosion processes.

The described general spatial features of ^{137}Cs redistribution in bottom sediments of beaver ponds of the studied rivers in the context of their basins are quite expected. In the first years after the accident at the Chernobyl Nuclear Power Plant in 1986 and nuclear tests in the atmosphere, the principal mass of ^{137}Cs that fell due to atmospheric precipitation was washed away together with the organo–mineral mass of the soil during its erosion via the surface runoff of meltwater and rainwater. These processes were most active and large-scale on arable lands of river basins, especially in conditions of sloping relief. To the least extent, erosion processes affected permanently or long-term grassed and forested slopes. In one of the fragments of which one sample of the surface soil layer was taken, the content of ^{137}Cs turned out to be close to the average value of the specific activity of this radionuclide in the soils of the near-water-divide surface forests of the river basins.

Table 2. Specific activity of ^{137}Cs within different landform elements in the Morkvashinka and Morkvashka river basins (Pre-Volga Region of the Republic of Tatarstan).

Landform Elements		N	$\bar{A}$	σ	m
Riverbed	Lower reaches	20	5.4	2.47	0.6
	Middle reaches	13	6.1	3.47	0.9
	Upper reaches	6	6.9	2.26	0.9
	In total	39	5.8	2.80	0.5
High floodplain		2	8.9	1.39	0.9
Lowest terrace		2	17.9	0.94	0.7
Valley slope		1	45.2	–	–
Near-water-divide surface		6	53.5	23.40	23.4
In total		50	12.9	18.08	2.6

Notes: N is the number of samples; $\bar{A}$ is the average value of the specific activity of ^{137}Cs in samples (Bq/kg); σ is the standard deviation (Bq/kg); m is the standard error of the mean (Bq/kg).

The last few decades in the European part of Russia have been characterized by a significant reduction in the area of cropland after the collapse of the USSR at the very end of 1991 [61–66]; although among all the administrative regions of European Russia, the Republic of Tatarstan, together with the Belgorod Oblast, was affected by these processes to the least extent [65]. All this was reflected in a significant reduction in the area of erosion-prone lands (especially after the mid-1990s) and a reduction in the load of sediment into the river network [67]. Along with progressive climate change in recent decades (increasing air temperatures, decreasing depth of soil freezing, etc.), these processes also led, in addition to a reduction in the rate of gully and soil erosion, to a decrease in the intra-annual unevenness of water flow in small rivers due to a greater redistribution of surface runoff into underground runoff. The increase in the natural regulation of river runoff favored, among other circumstances, beaver expansion in the region in the 2000s.

The sediments accumulated at the bottoms of beaver ponds (in the deepest places of the channels under large beaver ponds, they sometimes reach a thickness of 2 m or more), and the comparatively low specific activity of ^{137}Cs reflect their formation in already significantly changed climatic and landscape conditions in the catchments of the studied rivers of recent decades. These sediments lie directly on the weakly rounded, predominantly boulder-rubble alluvium and are not underlain by earlier facies of mass channel accumulation of finely dispersed alluvium. Their absence, for example, is visible in the deepened rocky channels in those sections of the Morkvashinka River that were not affected by beaver activity. Almost twofold and even threefold greater specific activity of ^{137}Cs in the soils of the floodplain and the lowest terrace of the Morkvashinka River relative to that in the bottom sediments of its beaver ponds reflect the conditions of less natural regulation (large intra-annual variability) of the runoff in the era of the greatest distribution of cultivated land and erosion processes in the region (the period of the USSR, before 1991). It was at that time that the floodplains (sometimes the lowest terraces) of the rivers were regularly flooded by mid-flood waters, with the corresponding accumulation of sediments and radionuclides contained in them. At present, these processes are extremely rare.

It was also found that the average concentration of cesium in the bottom sediments of beaver ponds in the smaller Morkvashka River (8.1 Bq/kg) is one and a half times higher than in the ponds of the larger Morkvashinka River (5.3 Bq/kg). Whether this is some kind of coincidence related to the sampling of bottom sediments is difficult to say now, given the circumstances that the annual water flow in the Morkvashka River is four times lower than in the Morkvashinka River, with a smaller proportion of cropland and a channel slope that is twice as steep (Table 1). This issue requires a separate detailed study on a larger number of rivers to obtain more reliable statistical results.

3.2. Distribution of ^{137}Cs Along Rivers

Against the background of the above-mentioned basin-wide trend, we also identified a weak trend of decreasing specific activity of ^{137}Cs in the bottom sediments of beaver ponds downstream of the rivers (Table 2, Figure 4). This is more noticeable for the longest Morkvashinka River than for the Morkvashka River; however, in both cases, this trend, according to the results of the Mann–Kendall test, is statistically insignificant.

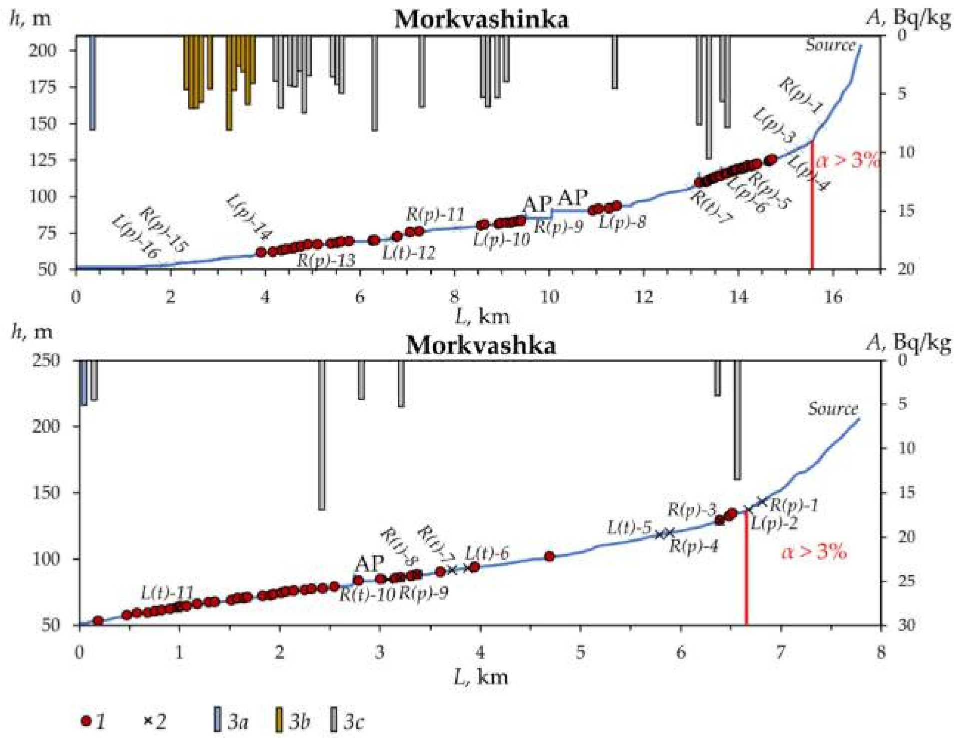

Figure 4. Changes in the specific activity of ^{137}Cs (A) in the bottom sediments of beaver ponds along the Morkvashinka and Morkvashka rivers (Pre-Volga Region of the Republic of Tatarstan). L is the horizontal distance; h is the absolute elevation; $R(\ldots)$ and $L(\ldots)$ are the right and left tributaries of the rivers, respectively, with their numbering (p and t are permanent and temporary watercourses); α is the average slope of the channel; AP is an anthropogenic pond; *1* is the location of beaver dams; *2* is the location of the mouths of the tributaries; *3a* is the sediments in the mouths of the Morkvashinka and Morkvashka rivers in the backwater zone of the Kuybyshev Reservoir (for comparison); *3b* is the sediments in the ponds (mostly drained) without dams, presumably of beaver origin; *3c* is the sediments in the flooded ponds.

Despite this, the question arises about the reasons for such a trend. Since the concentration of ^{137}Cs in dispersion masses is most closely related to their granulometric composition and organic matter content [11,12,14,68], we carried out a correlation analysis of the change in the specific activity of ^{137}Cs in the bottom sediments of beaver ponds along the rivers depending on the change in their granulometric composition and organic matter content. In Figure 5, these changes were visualized using the example of the longest Morkvashinka River. As in the case of ^{137}Cs, changes in the granulometric composition of bottom sediments in its three main fractions along the river do not have statistically significant trends.

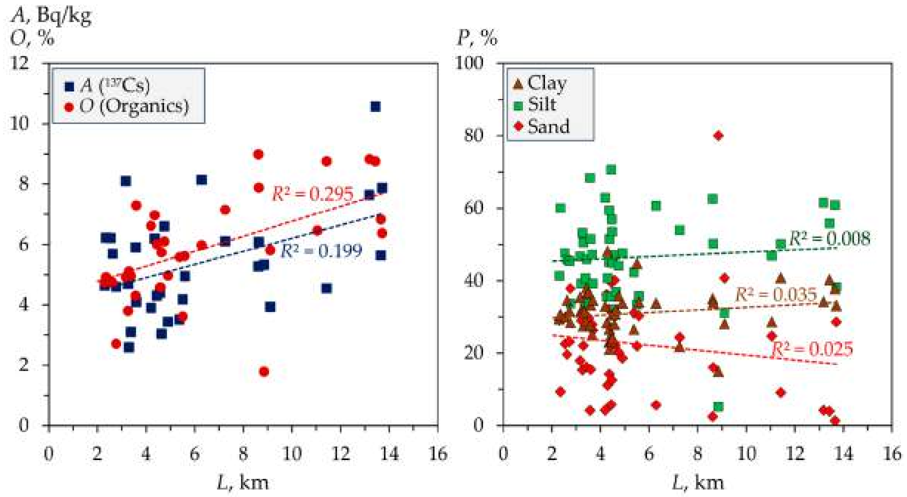

Figure 5. Changes in the specific activity of ^{137}Cs (A), total organic matter content (O), and granulometric composition (P) in bottom sediments (near-surface layers) of beaver ponds along the Morkvashinka River. L is the distance along the river from its mouth (see Figure 4); R^2 is the linear trend approximation coefficient (dashed line).

As shown in Table 3, none of the three main granulometric fractions of bottom sediments show a statistically significant relationship with changes in ^{137}Cs ($p > 0.05$). In the upper reaches of the studied rivers, the relationship between changes in ^{137}Cs and changes in the content of the clay fraction is very close to being statistically significant ($p = 0.077$). On the other hand, the spatial variability of ^{137}Cs in beaver pond sediments along the river shows a good correlation with the variability of organic matter content; this correlation is again the greatest in the upper reaches of the two rivers. In the middle reaches of the rivers, no statistical significance of this correlation was found.

Table 3. Results of the correlation (Pearson's correlation coefficient—r) of the specific activity of ^{137}Cs with the granulometric composition and organic matter of soils and bottom sediments in the Morkvashinka and Morkvashka river basins (Pre-Volga Region of the Republic of Tatarstan).

Landform Element		Coefficient	Granulometry			Organic Matter
			Sand	Silt	Clay	
Riverbed	Lower reaches	r	–0.01	0.14	–0.29	**0.64**
		p	0.972	0.571	0.212	0.002
	Middle reaches	r	0.19	–0.06	–0.34	0.22
		p	0.606	0.859	0.343	0.540
	Upper reaches	r	–0.64	0.55	0.76	**0.82**
		p	0.169	0.261	0.077	0.044
Riverbed as a whole		r	0.08	0.02	–0.23	**0.45**
		p	0.653	0.926	0.202	0.011
Near-water-divide surface		r	0.31	–0.17	–0.03	–0.31
		p	0.617	0.782	0.958	0.616
In total		r	–0.03	0.10	–0.12	**0.46**
		p	0.876	0.538	0.463	0.003

Note: p—statistical significance of the correlation coefficient r (statistically significant correlation coefficient is highlighted in bold).

The decrease in the content of organic matter and the specific activity of ^{137}Cs in the sediments of beaver ponds downstream of the rivers is most likely associated with the peculiarities of the influx of washed-out soil materials from the surface of the interfluves. The maximum average slopes and the largest share of arable lands are noted in the subbasins of the upper reaches of the Morkvashka River and the upper reaches of the left bank of the Morkvashinka River (see Figure 2); It is favorable for soil erosion processes. Another reason may be the peculiarity of the input of organic matter directly into beaver ponds from riparian vegetation. If along the Morkvashka River, the multi-species stand of trees (the autumn litter which partially directly enters the surface of the ponds) is more or less evenly distributed in density along this river than along the Morkvashinka River; it exhibits a relative peak in density mainly along the upper section of its bed. Consequently, this could be reflected, on average for the two rivers, in a greater mass of organic matter in the ponds of the upper reaches of the two rivers (in total). Moreover, in the upper reaches of the rivers, beaver ponds are, as a rule, smaller in size [57,58]. In this regard, even with an equal density of litter per unit of pond surface, the concentration of litter organic matter averaged over its bottom is higher in small ponds (i.e., mainly in the upper reaches of the rivers) than in large ponds (in the middle and lower reaches of the rivers).

It is well known that finely dispersed particles, especially clay minerals, adsorb ^{137}Cs well [69–71] in their interlayer spaces and on chipped surfaces. In contrast to clays, organic matter poorly adsorbs cesium, despite its high specific surface area, and even inhibits the adsorption of the radionuclide in certain areas of clay minerals. This inhibition generally increases the availability of cesium-137 for subsequent transport into deep soil layers and rivers via leaching processes [72,73]. Other researchers have noted that ^{137}Cs is well absorbed by plants due to its strong chemical similarity to potassium ions, which are involved in numerous metabolic processes [74,75]. For example, high concentrations of ^{137}Cs were found [76] in fallen tree leaves collected from the banks of rivers in the area of the Fukushima Daiichi Nuclear Power Plant (Japan) in the autumn of 2013; moreover, the concentrations of radiocesium were comparable or even exceeded those found in the bottom sediments of this area. Therefore, in late summer and early autumn, the bulk of ^{137}Cs in bottom sediments and suspended sediments moves together with organic matter [68]. All these issues require separate and detailed study, which is beyond the scope of this work.

Considering the role of the hydrological factor in the noted statistically insignificant trend of decreasing radiocesium concentration in the bottom sediments of beaver ponds downstream of the studied rivers, it is ambiguous. Due to the lack of any hydrological monitoring within the basins of the two rivers, in mid-April 2023, we carried out one-time measurements of their water discharges and sediment loads; however, these measurements covered only the very end of the spring snowmelt flood phase and better reflect the beginning of the low-water phase of the rivers (Figure 6).

As can be seen from Figure 6, both water discharges and suspended sediment loads showed a statistically significant increase downstream of the rivers, which reflected an increase in the volume of groundwater flow feeding the rivers in this direction, as well as an increase in the mass of riverbed erosion products. From a hydrological point of view, these increasing trends in water discharge and suspended sediment load during the low-water period cannot explain the trend in decreasing ^{137}Cs concentrations in the bottom sediments of beaver ponds downstream of the rivers under study. We do not have any quantitative monitoring data on changes in water discharges and sediment loads during the periods of snowmelt and rainfall in the basins of the two rivers. It is obvious that during these periods, water discharges also increase downstream. The situation is more complicated with changes in sediment load. As was shown in [77], in river basins with a significant share of cropland, the sediment load of rivers tends to decrease downstream due to the increased accumulation of sediments, primarily in the upper links of the fluvial network. This occurs precisely during periods of snowmelt and rainfall where the bulk of the annual sediment runoff of rivers is formed. In this context, the influence of the hydrological factor (a reduction in sediment loads downstream of the rivers) on the decrease in the concentration of cesium in the bottom sediments of beaver ponds downstream of the studied rivers could have occurred during periods of soil erosion in the river basins (periods of snowmelt and rainfall). This issue requires further research.

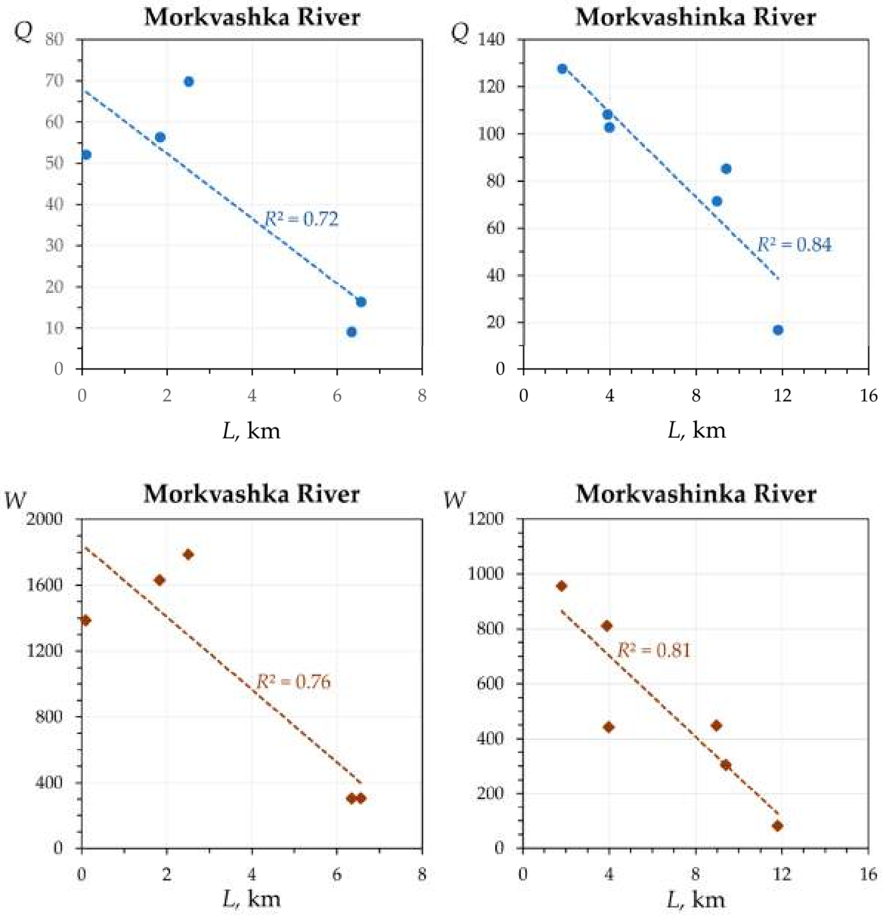

Figure 6. Changes in water discharges (*Q*, L/s) and suspended sediment loads (*W*, mg/s) along the Morkvashka (18 April 2023) and Morkvashinka (15 April 2023) rivers. *L* is the distance along the river from its mouth (see Figure 4); R^2 is the linear trend approximation coefficient (dashed line).

3.3. Distribution of ^{137}Cs in Sediment Thickness

The bottom sediments uncovered via a soil drill at the bottom of one of the dried-up beaver ponds (about 36 m long) in the lower reaches of the Morkvashinka River (in the deepened part of the section of the riverbed where the pond was formed) showed that their accumulation took place in three stages, which correspond to three main sedimentary layers (Figure 7). These layers differ morphologically (in color and density).

The two lower layers (layers II and III) with approximately equal thickness formed about 83% of the entire accumulated thickness of exposed sediments. These two layers are characterized by an absolute predominance (more than 50%) of fine-grained fractions and the minimum proportion of sand (no more than 15%), which is almost three times less than in upper layer I. On the other hand, the lower sediment layer (layer III), which is lighter, contains the least amount of organic matter (no more than 4%) compared to the two overlying sediment layers (about 7–8%), which together formed about 56% of the total thickness of sediments accumulated in the pond.

Thus, in the short sedimentation history of the pond, the following trend can be identified in the roughest approximation: in the early stages, the predominant accumulation of finely dispersed materials with a relatively low organic content was replaced by the accumulation of relatively coarser materials with a relatively higher (almost twice as much) organic content. As for the vertical distribution of the ^{137}Cs concentration in the indicated sediment layers, it has the highest values (more than 6 Bq/kg) in the two upper layers (with a maximum in layer II, almost 8 Bq/kg), in which the total content of organic matter is also the highest (with a maximum, again, in layer II, about 8%). In other words, the highest concentration of ^{137}Cs is confined to the layer (layer II) composed of the finest dispersed material with the highest content of organic matter.

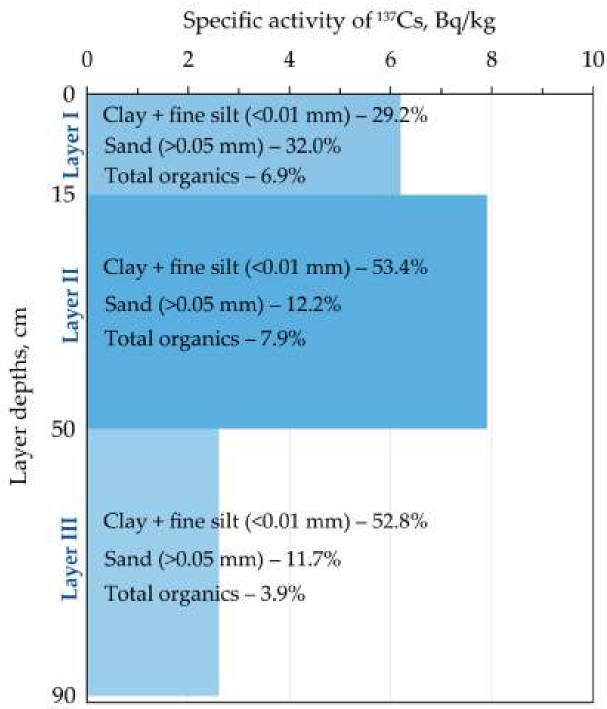

Figure 7. Changes in the average specific activity of ^{137}Cs, particle size distribution, and total organic content in three morphologically distinct layers of bottom sediments in one of the beaver ponds (dried up at the fieldwork) in the lower reaches of the Morkvashinka River. *Note:* layer III lies directly on the surface of the river's carbonate rubble alluvium.

The issue of the time and rate of accumulation of the entire specified thickness of sediments in the beaver pond is solved relatively simply. In the Morkvashinka River, beavers were not noted until 2009 at the latest (personal testimony of the first authors of this article), at least in that part of the river where the bottom sediments described above were uncovered, although their settlement in the region as a whole was already recorded at that time. Therefore, theoretically, it can be considered that the colonization of the Morkvashinka River system by beavers could have begun in 2010–2011. This is supported by surveys of residents (oral reports). This means that the exposed sediment layer with a thickness of 90 cm could have accumulated from 2010 to 2022 (the year of fieldwork) at an average rate of 7.5 cm per year. In general, the volumes and rates of sedimentation of organo–mineral deposits in beaver ponds depend on both the morphometric characteristics of the ponds themselves and the environmental features of their catchments. For example, Butler and Malanson [37,78] estimated the sediment accumulation rate from 2 to 39 cm per year in some ponds in Montana (USA). In Oregon (USA), in the first years of the existence of beaver ponds in this state, the sedimentation rate was up to 47 cm per year, but after 6 years, it decreased to 0.075 cm per year [79]. In Germany, the average sedimentation rate in beaver ponds was 6 cm per year [80].

The issue of the periodization and rates of accumulation of individual layers of the bottom sediment layer is more complicated since, as was said earlier, during the specified period, neither we nor anyone else conducted instrumental hydrological and sedimentation studies in the basin of this river. For this reconstruction, we used data from the nearest hydrological station in the village of Pestretsy on the Myosha River, located in the Western Pre-Kama Region of the Republic of Tatarstan and 51 km east of the lower reaches of the Morkvashinka River, taking into account the relative identity of the climatic and landscape conditions in the basins of these two rivers. Some hydrological data (https://gmvo.skniivh.ru/, accessed on 12 November 2024) on the flood runoff of water and suspended sediment (snowmelt-induced floods account for the predominant share of the annual water discharge and suspended sediment load of the rivers of the study region) of the Myosha River near the village of Pestretsy in the period from 2008 to 2022 are visualized in Figure 8.

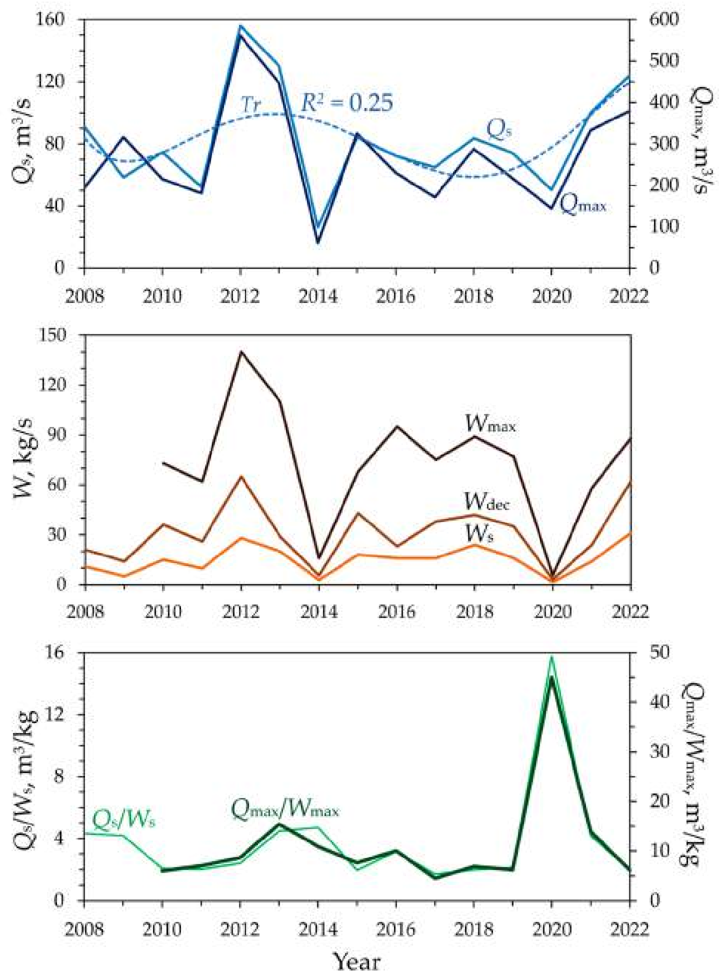

Figure 8. Changes in some parameters of flood water discharge and suspended (+bedload) sediment load of the Myosha River at Pestretsy (Western Pre-Kama Region, Republic of Tatarstan) in 2008–2022. Q is the water discharge (Q_s is the highest monthly average of the year; Q_{max} is the annual maximum); W is the suspended (+bedload) sediment load (W_s is the highest monthly average of the year; W_{dec} is the highest ten-day average in the month with the highest sediment load of the year; W_{max} is the annual maximum); R^2 is the approximation coefficient of the 5-degree polynomial trend line (*Tr*).

According to Figure 8, three periods with the highest average values in the suspended sediment load were distinguished in the Myosha River: 2010–2013, 2015–2019, and 2021–2022. The sediment load was minimal in 2014 and 2020. Considering the above-mentioned climatic and landscape similarities between the territorially adjacent basins of the Myosha and Morkvashinka rivers, one can assume similar long-term dynamics of sediment load in the latter river, which could be accompanied by proportional dynamics of sedimentation rates in its beaver ponds. Therefore, it can also be assumed that the above three layers in the beaver pond we studied could have been formed mainly in 2010–2013, 2015–2019, and 2021–2022, with corresponding sedimentation rates of 10.0, 7.0, and 7.5 cm per year. In other words, the pond filling rates at the early stage of its existence were 25–30% higher than at later stages. We do not exclude that the upper part of layer II (see Figure 7) could have been partially eroded in 2020, according to the hydrological event of the spring snowmelt-induced flood in that year (see Figure 8), where the volumes of water runoff relative to the unit mass of transported sediments (the ratio Q_c/W_c in Figure 8) and, consequently, the erosive force of the river flow were extremely high relative to the entire period from 2010 to 2022. This event could also have caused the accumulation of coarser material formed due to the erosion of the riverbanks (floodplain and the lowest terrace of the river), which resulted in a general "coarsening" of the sediment of the upper layer (layer III; see Figure 7). As for the content of ^{137}Cs (in total, ^{137}Cs is of both Chernobyl and so-called "bomb" origin) in the entire studied sediment layer of the beaver pond, its main mass (about 80%, according to a rough estimate, considering the concentration and thickness of the layer), most likely accumulated in 2015–2022, i.e., in the second half of the sedimentation history of this pond. The history of migration of this radionuclide into rivers, accumulated in bottom sediments from different sources of entry, is complex and requires a separate study.

Despite the noted vague trends of decreasing sediment accumulation rate and increasing total organic matter and the specific activity of ^{137}Cs in the beaver pond from 2010 to 2022, explaining the reasons for the separation of three sediment layers requires the use of a large amount of information: periodic data on the intensity of snowmelt and runoff, soil freezing depth, crop rotations, distribution of erosion washout areas, composition of organic matter, etc. As in the case of changes along the rivers, the relationship between changes in radiocesium and organic matter is mainly due to a single erosive process of their entry from the soils of the interfluves into the ponds. On the other hand, a part of the total organic matter could also enter the pond bottom directly during the decomposition of the bottom-riparian grassy plants and algae inhabiting it, as the development of which in the pond required some time (the maximum development after 2015). These issues also require a separate study.

4. Conclusions

Our results show that the bottom sediments of beaver ponds in small rivers of the study region are accumulators of artificial radioisotopes, in particular cesium-137. The concentration of these artificial radioisotopes is directly proportional and, in general, statistically significantly correlates with the content of organic matter in these sediments. The concentration of organic matter in ponds, in turn, is associated not only with the scale and intensity of the processes of accumulation of products of erosive denudation of soils in interfluves (primarily on arable land) but also with the direct entry of dead organic matter to the bottom of the ponds themselves and in their riparian zone. No statistically significant effect of the granulometric composition of bottom sediments on changes in the concentration of ^{137}Cs in them was revealed, at least according to the results of the work in the two rivers we studied.

The research also shows that the average concentration of cesium-137 in the bottom sediments of beaver ponds is many times (on average, almost an order of magnitude) less than its average content in the soils of near-water-divide surfaces of the interfluves of the studied rivers that are not affected by the processes of their erosive washout. These soil concentrations of ^{137}Cs represent conditionally background levels (taking into account the half-life of the radioisotope), reflecting their regional level after atmospheric fallout following global nuclear weapons tests and, above all, the Chernobyl accident in 1986. However, it should be noted that the indicated ratio of radiocesium concentrations in soils and bottom sediments is valid only relative to modern beaver ponds formed in the last one and a half to two decades. Their bottom sediments, thickness, layered structure, and composition reflect the already significantly transformed landscape and climatic conditions of this agriculturally developed region of the forest-steppe zone of the Middle Volga region.

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Appendix A

Figure A1. An example of a section of the dried-up riverbed of the lower reaches of the Morkvashinka River, composed of weakly rounded rubble alluvium, during the low-water period (July–September) in 2022.

Figure A2. One of the dried-up beaver ponds with characteristic fine-grained bottom sediments in the lower reaches of the Morkvashinka River during the low-water period (July–September) in 2022.

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