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DISTINCTIVE FEATURES OF THE FORMATION AND MIGRATION OF RADIOACTIVE CONTAMINATION IN THE IPUT RIVER AFTER THE ACCIDENT AT THE CHERNOBYL NUCLEAR POWER PLANT

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With the example of the Iput river, studies are performed and based on them an analysis is made of the formation of contamination of elements of a river system by radionuclides ^{137}Cs and ^{90}Sr after the accident at the Chernobyl Nuclear Power Plant. It has been revealed that before the years 1990–1994 the contamination of the river system was mainly formed by the primary fallout of radionuclides on the water surface of the river but after the year 2000 it will be determined only by the ingress of radioactive contaminants with surface flow from a water catchment. The studies have shown that the contamination of the Iput river in the territory of Belarus is substantially influenced by the transfrontier transfer of radionuclides from the territory of Russia. According to our estimates, at the end of 1986, this contribution amounted to 30% for ^{137}Cs and 96% for ^{90}Sr; as of now, it is 86% and 65% for ^{137}Cs and ^{90}Sr, respectively.

To investigate the mechanisms of formation of radioactive contamination of river systems and to reveal the regularities of migration of radioactive contaminants in rivers and of the transfrontier transfer of radionuclides by water based on the data of radioenvironmental monitoring and field investigations carried out by the State Committee for Hydrometeorology of the Republic of Belarus and by the "Taifun" Scientific-Production Association (Russia), we selected the Iput river as a test basin. It flows over the Belarus-Bryansk "spot" with contamination levels of 37 to 2220 kBq/m^2 for ^{137}Cs and of 0.37 to 31.1 kBq/m^2 for ^{90}Sr.

The Iput river is the largest tributary of the Sozh river in both length and water content. It starts in the Klimovichi district of the Mogilev region, flows over the territory of Russia (the Bryansk region), then over the territory of Belarus (the Gomel region), and flows into the Sozh river two kilometers below the town of Gomel (Fig. 1).

The river length is 437 km, and its extension in the territory of Russia is 370 km; the total fall of stream is 84.8 m, and the mean water-surface slope is 0.19%. The twisting coefficient of the river is 2.82.

The Iput river has a well-developed and relatively uniform network; it numbers more than 750 water passages and has six main tributaries, namely, the Voronitsa, Nadva, Voronusa, Unecha, Irzhach, and Vikholka rivers. The river-network density is 0.38 km/km^2. The area of the water catchment is 10,900 km^2 [1].

The annual average discharge of water during many years of observation into the Iput river (the observation station in the town of Dobrush) is 46.0 m^3/sec [1]; in the past decade, the maximum (the year

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TABLE 1. Basic Characteristics of the Iput River System [1, 4, 5]

No. of chamber	Cross section of observation	L, km	F, km^2	$a_0(^{137}Cs)$, kBq/m^2	$a_0(^{90}Sr)$, kBq/m^2	Q_w^*, m^3/sec
1	Krutoyar	170	3930	8.8	0.555	23.6
2	Kozarichi	250	1880	15.8	0.995	31.4
3	Ushcherp’e	300	2290	220.0	3.73	38.8
4	Vyshkov	360	1300	824.0	15.2	43.5
5	Dobrodeevka	370	190	1122.0	11.8	45.3
6	Vylevo-1	392	373	2220.0	31.1	45.5
7	Vylevo-2	394	21	925.0	30.7	–
8	Dobrush-1	402	84	220.0	27.0	–
9	Dobrush-2	403	11	220.0	27.0	–
10	Dobrush-3	405	21	220.0	25.2	46.0

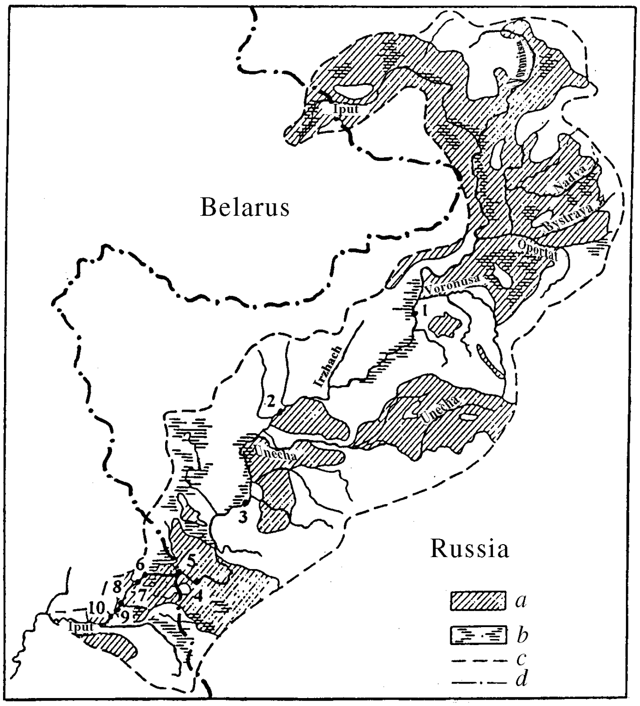

Fig. 1. Map-scheme of disposition of control and calculated cross sections (1 through 10) in the basin of the Iput river: 1) Krutoyar; 2) Kozarichi; 3) Ushcherp’e; 4) Vyshkov; 5) Dobrodeevka; 6) Vylevo-1; 7) Vylevo-2; 8) Dobrush-1; 9) Dobrush-2; 10) Dobrush-3: a) forest; b) bogs, c) water-catchment boundary; d) Russia–Belarus frontier.

1990) and minimum (the year 1989) water discharge in the indicated control cross section was 351 m^3/sec and 5.41 m^3/sec, respectively.

The river is used as a water receiver of the drainage network, for industrial and domestic water supply (the towns of Surozh and Dobrush), and for local timber rafting and fishing. In the town of Dobrush, a water-storage basin is constructed to provide water intake for the Dobrush Paper Mill.

To analyze the formation and migration of radioactive contamination in the Iput river, we have performed computational studies based on a multichamber model of radionuclide migration in the river network [2, 3]. For this purpose, its river network was subdivided into ten control volumes (chambers) of different extension: five chambers embraced the river in the territory of Russia, while the next five chambers embraced it in the territory of Belarus (Fig. 1).

In subdividing the network of the Iput river into chambers, we took into consideration information on the level of ^{137}Cs and ^{90}Sr contamination of its water catchment [4, 5], on the distinctive features of the hydrologic-morphometric characteristics of the river channel [1], and on the layout of the main observation stations along its channel:

(1) in the territory of Russia: the villages of Krutoyar, Kozarichi, Ushcherpie, Vyshkov, and Dobrodeevka;

(2) in the territory of Belarus: Vylevo-1 (the most ^{137}Cs and ^{90}Sr contaminated portion of the water catchment); Dobrush-2 (water-storage basin in the town of Dobrush); Dobrush-3 (terminal control cross section in the town of Dobrush).

Moreover, two calculated control cross sections were introduced in the territory of Belarus, namely, Vylevo-2 on the isoline of the 925 kBq/m^2 ^{137}Cs contamination of the water catchment and the town of Dobrush-1 in front of the water storage basin. The basic information on the levels of contamination of the water-catchment portions and on the hydrologic characteristics of the Iput river obtained from the experimental data and the literature sources [1–7] is given in Table 1.

Since the information on the hydrologic-morphometric parameters of the Iput river channel, the water-erosion characteristics of its water catchment, the sorption properties of soil-grounds of the water catchment, and sediments transported along the river channel is insufficiently exact, even often rough, and in the majority of cases is not available at all, we have performed parametric studies in the initial stage [2].

The parametric studies have also been carried out to reveal the sensitivity of the model to a change in the undetermined parameters which can vary in natural systems within the limits of two orders of magnitude. In the present study, such parameters are the coefficients of distribution of radionuclides in the systems "water–suspensions," "water–bottom sediments," and "water–soil of water catchment"; the turbidity of the wash brought from the water-catchment surface into the river network; the width of the layer of bottom sediments; the groundwater flow. An analysis of the model sensitivity to a change in the parameters indicated has shown that its output parameters respond to the greatest degree to a change in the sorption characteristics of the river medium and of the water catchment. With variation of these characteristics within the range $K_d(^{137}Cs) = 0–100$ m^3/kg; $K_d(^{90}Sr) = 0–10$ m^3/kg, the difference of the radionuclides in concentration in water can reach one to two orders of magnitude [2, 6, 7].

The parametric studies performed were employed in calibration of the parameters of the model and its testing based on the data of radiation monitoring carried out in Russia in 1991–1993 and in Belarus since 1987 up to the present time. In the course of calibration, the initial parameters of the model were chosen for each chamber to satisfy both the actual conditions of functioning of the river system and the agreement of the calculated results and the experimental data. The model parameters were calibrated by the method of successive approximations on the basis of experimental measurements of the concentrations of radionuclides ^{137}Cs and ^{90}Sr in soluble form, on suspensions, and in bottom sediments along the river channel for the years 1987–2000. The values of such parameters as the groundwater flow, the modulus of flow of a solid matter from a water catchment, and so on agree rather well with the literature data for the basin of the Iput and Sozh rivers [8, 9]. The deviations of the annual average calculated concentrations of the radionuclides in water, on suspensions, and in bottom sediments from the measured ones are within the limits of seasonal fluctuations of measurement data in the volumes of the chambers which can be considered to be acceptable for such a class of models [2]. Satisfactory agreement of the experimental data and the calculation results in a wide range of variation of the space-time characteristics ($L > 400$ km, $t = 10$ years) confirms its effectiveness and sufficient adequacy for describing the processes modeled [2].

The monitoring of many years of the radiaton situation on the Iput river, the literature data, and the parametric studies of the model and its calibration have made it possible to determine the basic initial infor-

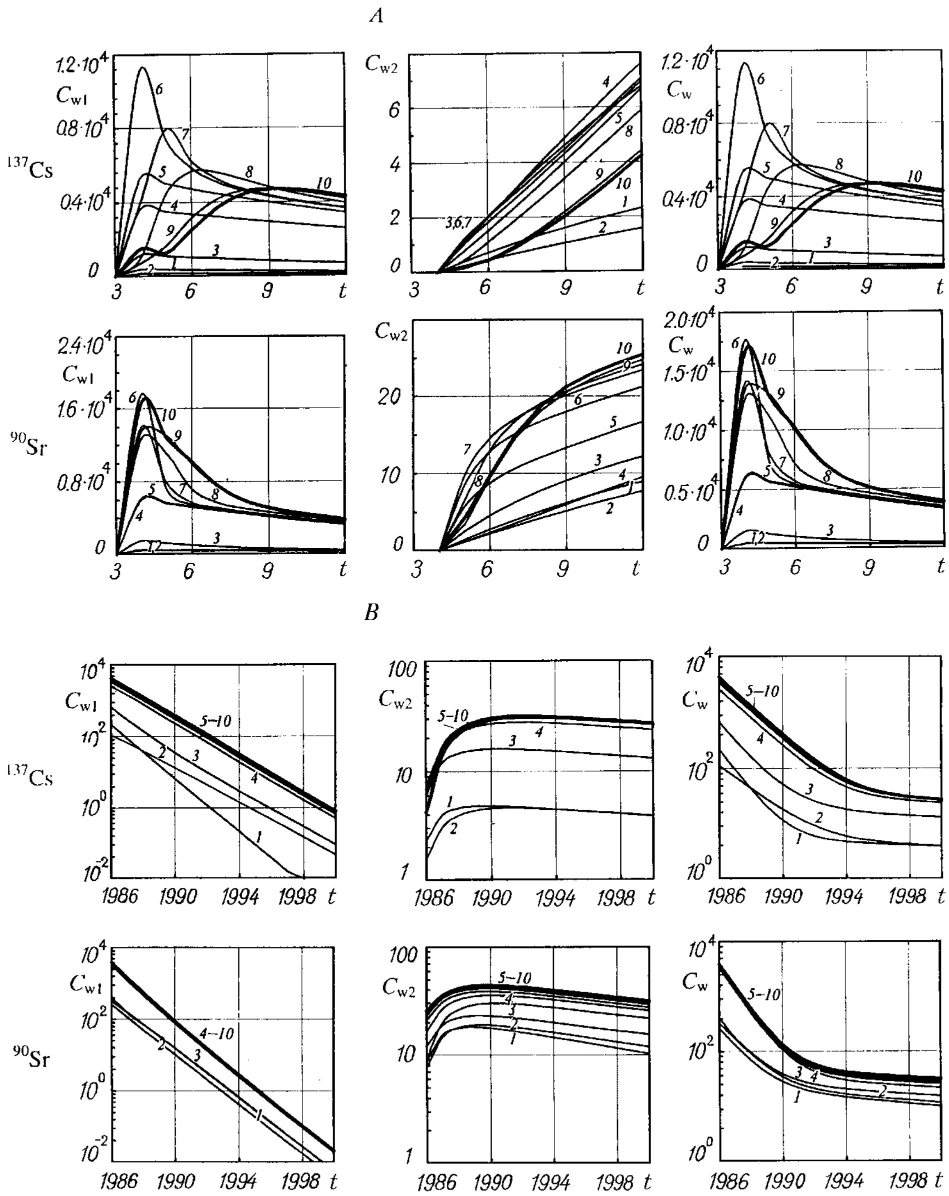

Fig. 2. Formation of contamination of water of the Iput river by radionuclides ^{137}Cs and ^{90}Sr during the year 1986 (*A*, *t*, months) and the years 1986–2000 (*B*, *t*, years) in chambers (1 through 10): [C_{w1}, specific activity of radionuclides in water as a result of their fallout on the water surface of the river; C_{w2}, the same as a result of the ingress of radionuclides with surface flow from the water catchment; C_w, total specific activity of radionuclides in the river water. C_{w1}, C_{w2}, and C_w, Bq/m^3.

mation needed for computational studies of the formation of migration of radioactive contamination of the Iput river.

In the course of computational studies, we have revealed the following features in the formation of contamination of the Iput river by radionuclides ^{137}Cs and ^{90}Sr and in their migration.

(1) The main sources of the ingress of radiactive contaminants into the Iput river were the fallout of radioactive aerosols on the water surface of the river in April–August, 1986 after the Chernobyl accident and the ingress of radionuclides with solid and liquid surface flows from the contaminated water catchment.

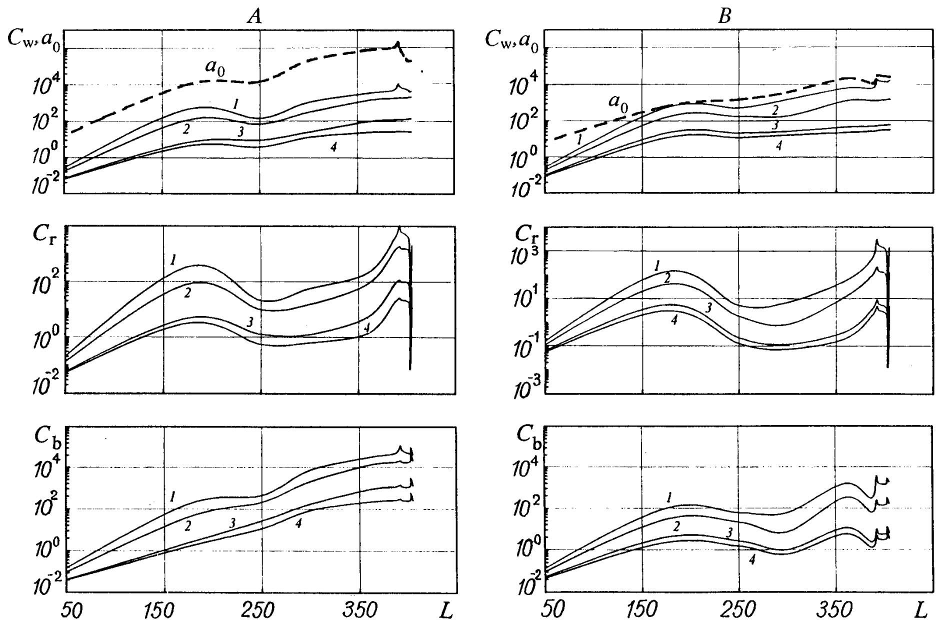

Fig. 3. Variation in the density of contamination of the water catchment by ^{137}Cs (*A*) and ^{90}Sr (*B*) and their specific activities in water-soluble form, on suspensions, and in bottom sediments along the channel of the Iput river: 1) 1986; 2) 1987; 3) 1992; 4) 2000. *L*, km; a_0, Bq/m^2; C_w and C_r, Bq/m^3; C_b, Bq/kg.

(2) The formation of contamination of elements of the river system in 1986 was mainly determined by the fallout of radionuclides on the water surface (Fig. 2*A*). In the years 1987–1994, the influence of the first factor was still substantial, but by the year 2000 radioactive contamination of the river network was found to consist of 99% of the radionuclides brought with surface flow from the water catchment (Fig. 2*B*). Further contamination will entirely depend only on the surface flow from the water-catchment areas.

(3) The calculated and experimental intensities of contamination of water and of suspended and bottom sediments along the river channel correlate with the density of radioactive fallouts on a water-catchment territory of the Iput river, which is indicative of the strong local influence of the acting sources of contamination (Fig. 3).

(4) The formation of contamination of the river medium in the town of Dobrush was substantially influenced, especially in the first period, by the ingress of contaminants from more contaminated higher-lying portions of the river (the village of Vylevo) (Fig. 2*A*). The possibility of such a phenomenon is confirmed by similar events which were observed on the Pripyat river in 1986 [10].

(5) Contamination of the Iput river by radionuclides ^{137}Cs and ^{90}Sr is formed in different ways. Owing to the lower sorption capacity of suspensions and bottom sediments in relation to ^{90}Sr, as compared to ^{137}Cs, their concentrations in elements of the river medium (in water, on suspensions, and in bottom sediments) significantly differ (Fig. 3). Despite the fact that the densities of the fallout of these radionuclides in the basin of the Iput river differ by almost two orders of magnitude, their concentrations in soluble form are close in value. However, on suspended sediments, ^{137}Cs migrates in amounts 5–10-fold larger and with entrained sediments in amounts 10–100 fold larger than ^{90}Sr.

(6) It is known that the velocity of migration of radioactive contaminants in a river system greatly depends on the sorption characteristics of suspended and bottom sediments. As calculations have revealed, with a mean velocity of the water of ~ 0.4 m/sec in the Iput river the velocity of propagation of the ^{90}Sr-contamination front is 112 km/yr, which is almost 100 times slower than water flow but twice as quick as

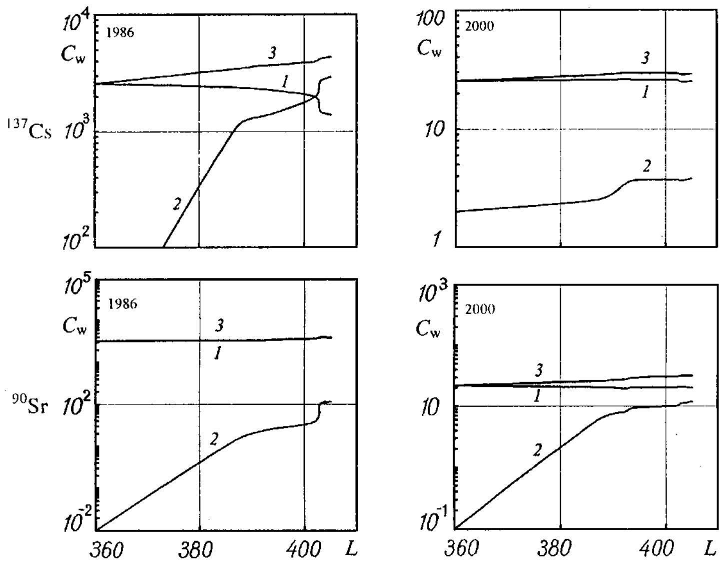

Fig. 4. Influence of the transfrontier transfer of radionuclides ^{137}Cs and ^{90}Sr on the contamination of water in the Iput river in the territory of Belarus in the years 1986 and 2000 as a result of the fallout of radionuclides in the territory of Russia (1); Belarus (2); on the entire water catchment of the Iput river (3). *L*, km; C_w, Bq/m^3.

the transfer of ^{137}Cs along the Iput river channel. The difference in velocities owes to the greater mobility of ^{90}Sr, which is related to smaller values of its distribution coefficients in the systems "water–suspensions" and "water–bottom sediments" [6, 7].

(7) It has been established that the morphometric characteristics of the river channel exert a pronounced influence on the distribution of radioactive contamination between elements of the river medium (water and suspended and bottom sediments). This feature was most pronounced on the ninth portion of the river, i.e., the water-storage basin (the town of Dobrush), in which, due to the processes of sedimentation of finely dispersed fractions, the concentration of radionuclides on suspensions decreased by a factor of approximately 20, while in bottom sediments it increased more than twice as compared to the neighboring portions (Fig. 2). These calculations qualitatively confirm the results of radioactive monitoring carried out by the Center of Radiation Control and Monitoring of the Natural Environment at the State Committee for Hydrometeorology of the Republic of Belarus [11] and reflect the actual properties of the element of a water object, i.e., the water-storage basin, as a trap of radioactive contamination.

(8) The computational studies performed have demonstrated that the formation of contamination of the Iput river in the territory of Belarus substantially depends on the transfer of radionuclides from the territory of Russia through the Belarus–Russia frontier. This is related to the fact that a larger part of the Iput river (~90%) flows over the territory of Russia. Almost 95% of its river flow is formed in this territory (see Table 1). Therefore, the substantial influence of the transfer of radionuclides from the territory of Russia through its frontier with Belarus on the contamination of the Iput river in the territory of Belarus was to be expected. The results of the computational study have shown that in the terminal cross section near the town of Dobrush the maximum concentration of radionuclides in water in the first year after the Chernobyl accident was determined by direct fallout of radioactive aerosols on the water surface of the river in the territory of Belarus. As judged from our estimates, at the end of 1986 the contribution of the transfer of radionuclides from the territory of Russia through the Belarus–Russia frontier amounted to 30% for ^{137}Cs and to ~96% for ^{90}Sr. As of now, 86% of the contamination of the Iput river by ^{137}Cs and 65% by ^{90}Sr enters from the territory of Russia, and despite the much higher density of contamination of the water-catchment area of the Iput

river in the territory of Belarus, the contamination of water in the river is determined mainly by the transfrontier transfer (Fig. 4). In this case, the determining factors are the formation of the basic fraction of river flow in the territory of Russia and the substantially greater accumulation of radionuclides over its water-catchment area: $\sim 1.89 \cdot 10^{12}$ kBq of ^{137}Cs and $\sim 3.85 \cdot 10^{10}$ kBq of ^{90}Sr, while in Belarus $\sim 5.55 \cdot 10^{11}$ and $5.36 \cdot 10^{9}$ kBq, respectively.

The analysis of formation and migration of radioactive contamination in the Iput river makes it possible to refine and improve the system of monitoring of the condition of water objects of Belarus and to develop additional recommendations on protection and optimization of nature- and water management and of re-creation of water objects contaminated by radionuclides.

NOTATION

t, time; L, distance from the source of the river; C_w, C_r, and C_b, specific activity of radionuclides in soluble form, on suspensions, and in bottom sediments of the river system; a_0, initial density of the fallout of radionuclides on the water-catchment surface and on the water surface of the river; F, water-catchment area; Q_w^*, mean-statistical discharge of water; K_d, coefficient of distribution of radionuclides in the systems "water–suspensions," "water–bottom sediments," and "water–soil of water catchment." Subscripts: w, water; r, suspensions; b, bottom sediments; d, distribution; o, initial value; 1, fallout of radionuclides on a water surface; 2, ingress of radionuclides with surface flow from a water-catchment basin.

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