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PREDICTION OF MIGRATION OF RADIONUCLIDES IN THE IPUT RIVER BASIN

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Based on the multichamber model, prediction evaluations of the transfer of ^{137}*Cs and* ^{90}*Sr in the Iput river for 100 years after the Chernobyl accident have been performed. In the course of investigation, the indicated time range was subdivided into three periods: the first period covered April–December of 1986 (retrospective evaluation), the second period embraced the years 1987–2000, and the third period covered the years 2000–2080 (long-term prediction). The prediction evaluations of migration of radioactive contaminants in the Iput river have shown that over the course of a century the concentrations of* ^{137}*Cs in the Iput river network will decrease nearly 3000 times and the concentrations of* ^{90}*Sr will decrease 10,000 times. However the levels of contamination of the river systems by these radionuclides will remain rather high.*

Heavy radioactive contamination of the territory of Belarus after the Chernobyl accident, the necessity of solving the problems of elimination of its consequences, and the natural limitedness of observation networks have stimulated the development of mathematical models which are suitable for prediction of the removal of contaminants to the channel network of river basins and their transfer by water.

To perform expert-prediction evaluations of the transfer of radionuclides along the river channel, we have proposed a quasistationary multichamber model for different conditions of ingress of radioactive contaminants into the river network [1]. The model was calibrated and verified based on the data of radiation monitoring of many years and field investigations carried out by the Center of Radiation Control and Monitoring of the State Committee for Hydrometeorology of the Republic of Belarus and the Taifun Science and Production Association (Russia) in the Iput river [2, 3]. This made it possible to quite correctly investigate and give prediction evaluations of a change in the radiation situation along the Iput river channel over the course of 100 years after the accident at the Chernobyl Nuclear Power Plant.

In the course of investigation, the network of the Iput river was subdivided into 10 control volumes (Fig. 1) with allowance for the degree of ^{137}Cs and ^{90}Sr contamination of its water catchment and for the layout of the main observation stations along its channel [2, 4], while the indicated time range was subdivided into three periods:

(1) April–December, 1986, i.e., the most dynamic period of change of the radiation situation in water bodies after the accident at the Chernobyl Nuclear Power Plant [5–7];

(2) 1987–2000 (end of the century), i.e., the time of stabilization of the radiation situation in the river system;

(3) 2000–2080, i.e., the period of the expected radiation situation in the network of the Iput river in the future.

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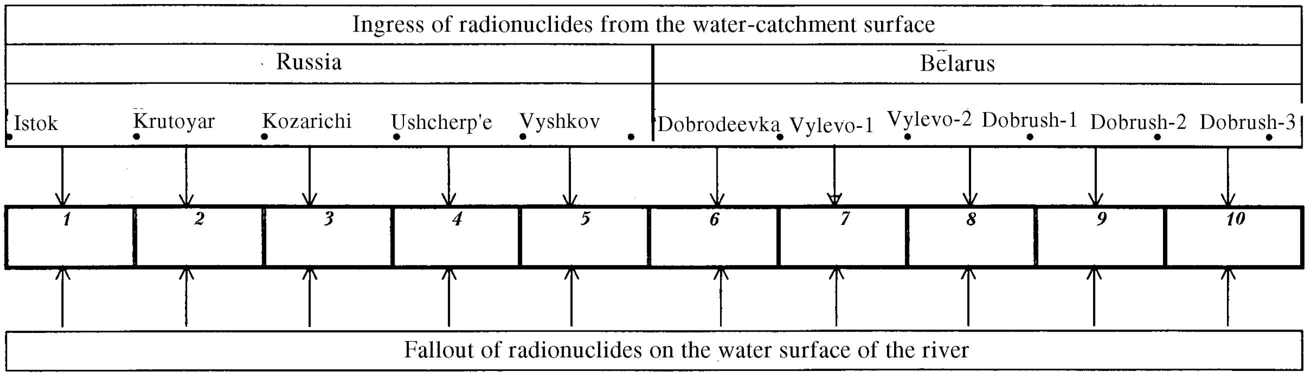

Fig. 1. Scheme of subdivision of the Iput river channel into chambers and of the ingress of radioactive contaminants into the river network (Dobrush-1, in front of the water storage, Dobrush-2, water storage, Dobrush-3, terminal cross section): 1–10) chambers.

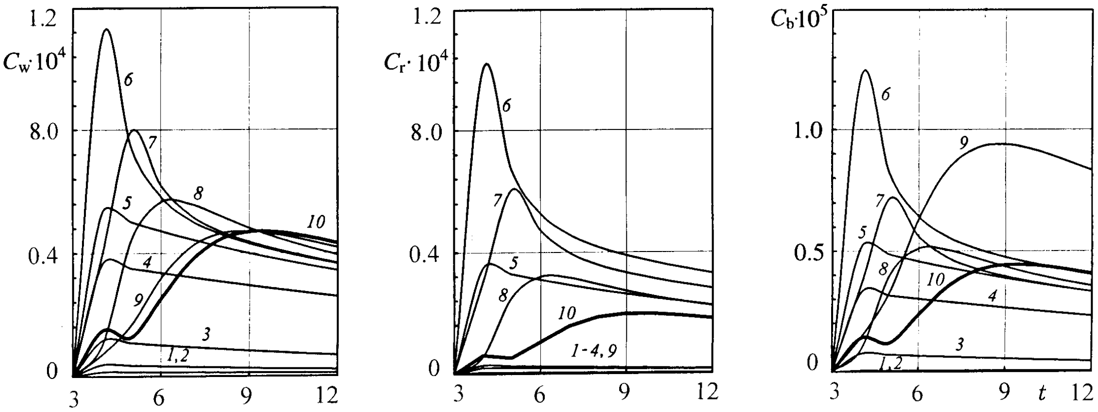

Fig. 2. Retrospective evaluations of the variation in the concentration of ^{137}Cs during the year 1986 in water (C_w), on suspensions (C_r), and on bottom sediments (C_b) in the Iput river in chambers (1–10). t, months; C_w and C_r, Bq/m^3; C_b, Bq/kg.

Retrospective Evaluation of the Radiation Situation on the Iput River in 1986. The analysis of the data of radiation monitoring on the Iput river [8, 9] shows that the observations of the radiation situation in this water body in the first year after the accident at the Chernobyl Nuclear Power Plant were carried out incidentally. The model used in the present investigation makes it possible to evaluate the levels of ^{137}Cs and ^{90}Sr contamination of the river system in this postaccident period, which is of prime importance for reconstruction of the dose loads on the population.

Taking into account the distinctive features of the dynamic development of the radiation situation in water bodies in the period in question [5–7], we evaluated the radioactive contamination of the Iput river system by ^{137}Cs during the year 1986 per month beginning with April 1986.

The results of retrospective evaluations of a variation in the concentrations of ^{137}Cs in water and on suspended and bottom sediments during the year 1986 in chambers are presented in Fig. 2. The analysis of the calculated dependences (see Fig. 2) shows that the maximum concentrations of ^{137}Cs in water and on suspended and bottom sediments in this period are $C_{w\,\max} = 1.1 \cdot 10^4$ Bq/m^3, $C_{r\,\max} = 1.0 \cdot 10^4$ Bq/m^3, and $C_{b\,\max} = 1.2 \cdot 10^5$ Bq/kg respectively and relate to the initial arrival of radioactive aerosols at the water surface of the Iput river in the village of Vylevo (No. 6), where the density of the fallout of ^{137}Cs was maximum (2220 kBq/m^2). We should note the presence of the extremum concentrations in the elements of the river system in all the chambers

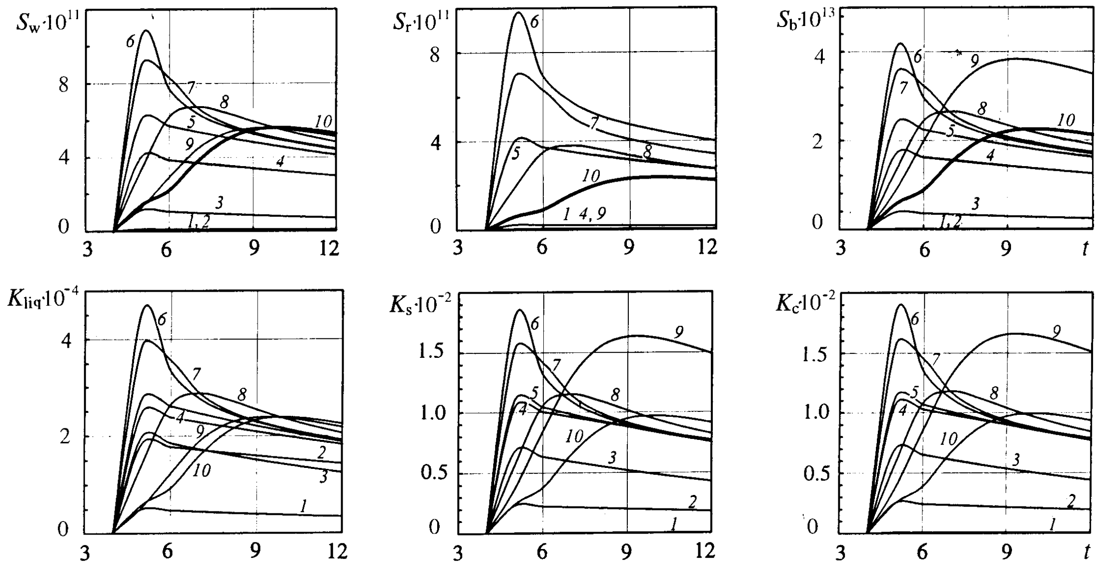

Fig. 3. Retrospective evaluations of the monthly runoff of ^{137}Cs in water (S_w), on suspensions (S_r), and with bottom sediments (S_b) and the change in its coefficients of liquid (K_{liq}), solid (K_s), and total (K_{tot}) runoff in the Iput river in 1986 in chambers (1–10). t, months; S_w, S_r, and S_b, Bq/month; K_{liq}, K_s, and K_{tot}, 1/month.

in April–May, 1986; the values of these concentrations are determined by the density of the fallout of ^{137}Cs on the water surface of the river [4].

In the terminal cross section (the town of Dobrush, No. 10), one could have observed two maximum levels of ^{137}Cs contamination of water and suspended and bottom sediments during the year 1986 (Fig. 2). The first maximum relates to the arrival of radioactive contamination in April–May, 1986 at the surface of the portion of the river from the dam to the terminal cross section in Dobrush. A second concentration maximum higher than the first one appeared in September–October of the same year, which is associated with the lag of the front of contamination brought to the river network from more contaminated higher-lying portions of the water catchment (the village of Vylevo). Analogous phenomena were observed in 1986 on the Pripyat river [7]. By the end of 1986, one could have observed the following maximum concentrations of ^{137}Cs: $C_w = 4.3 \cdot 10^3$ Bq/m^3 in water in the terminal cross section of Dobrush (No. 10), $C_r = 3.6 \cdot 10^3$ Bq/m^3 on suspensions in Vylevo (No. 6), and $C_b = 8.3 \cdot 10^4$ Bq/kg in bottom sediments of the water storage (No. 9).

Figure 3 gives the retrospective evaluations of the monthly runoff and of the runoff coefficients of ^{137}Cs during the year 1986 in water-soluble form and with suspended and entrained sediments in chambers. The form of these dependences virtually follows the concentration profile of ^{137}Cs in time and in chambers. According to our evaluation, the largest runoff of the radionuclides would have been in Vylevo (No. 6): $S_w = 1.06 \cdot 10^{12}$ Bq/month in water-soluble form, $S_r = 9.6 \cdot 10^{11}$ Bq/month with suspended sediments, and $S_b = 4.1 \cdot 10^{13}$ Bq/month with entrained sediments. At the end of the period under study, the largest runoff of ^{137}Cs was evaluated: $S_w = 5.13 \cdot 10^{11}$ Bq/month in water in the terminal cross section (No. 10), $S_r = 4 \cdot 10^{11}$ Bq/month on suspensions in Vylevo (No. 6), and $S_b = 3.5 \cdot 10^{13}$ Bq/month with entrained sediments in the water storage (No. 9).

The analysis of the values of the runoff of ^{137}Cs has shown that its monthly value with entrained sediments would have been almost 40 times higher than its amount in the water-soluble state. The calculations demonstrate that it was precisely the entrained sediments that determined the total runoff of ^{137}Cs in the control cross sections. Since there are no experimental data in support of this fact, it is necessary to carry out additional field investigations of the transfer of ^{137}Cs by entrained sediments.

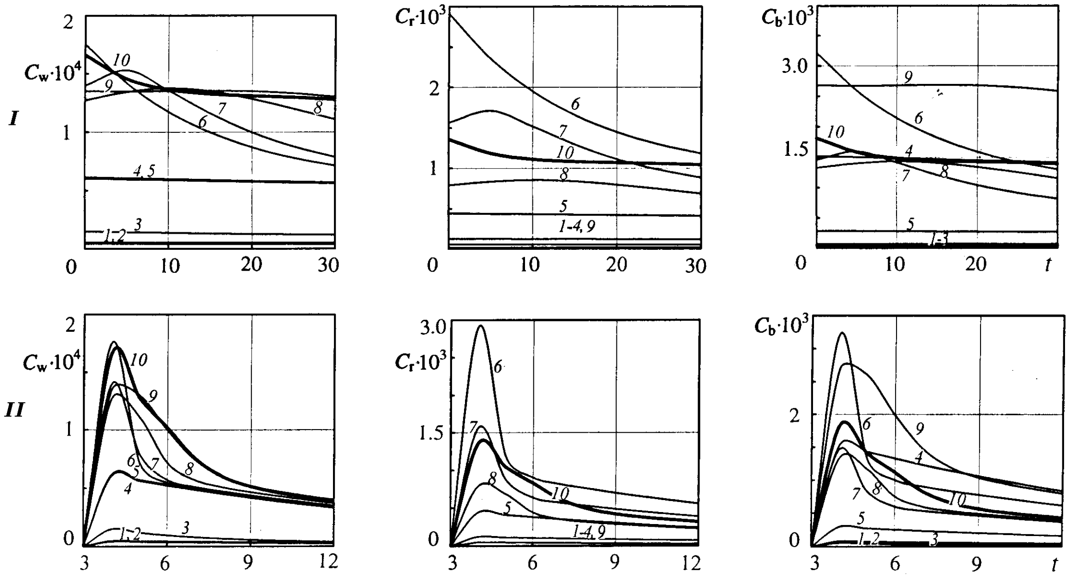

Fig. 4. Retrospective evaluations of the variation in the daily (I) and monthly (II) concentrations of ^{90}Sr during the year 1986 in water (C_w), on suspensions (C_r), and on bottom sediments (C_b) in the Iput river in chambers (1–10). t, days and months; C_w and C_r, Bq/m^3; C_b, Bq/kg.

The changes (Fig. 3) in the coefficients of liquid, solid, and total runoff of ^{137}Cs during the year 1986 show that the solid runoff involving the transfer of the radionuclides by the solid particles of suspended and entrained sediments was determining in the total coefficient in this period. The maximum coefficients of runoff in chamber Nos. 1–7 fall in April–May; in chamber Nos. 8–10, the maximum gradually shifts to September–October. The highest values of the runoff coefficients could have been observed in April–May in Vylevo (No. 6) (the coefficient of liquid runoff $K_{\text{liq max}} = 4.6 \cdot 10^{-4}$ 1/month and the coefficient of solid runoff $K_{\text{s max}} = 1.8 \cdot 10^{-2}$ 1/month). At the end of the period under study, one could have observed the highest values of the coefficient of liquid runoff in the terminal cross section ($K_{\text{liq}} = 2.2 \cdot 10^{-4}$ 1/month) and those of the coefficient of solid runoff in chamber No. 9 ($K_s = 1.5 \cdot 10^{-2}$ 1/month).

Retrospective evaluations of the transfer of ^{90}Sr in the Iput river were performed for May per day and then per month up to the end of the year 1986. Contamination of the river network in this period occurred mainly by the primary fallout of radioactive aerosols on the water surface of the river.

The results of evaluating the variation in the concentrations of ^{90}Sr in water, on suspensions, and in bottom sediments along the Iput river channel are presented in Fig. 4. The analysis of the calculated dependences shows that in the first month after the accident at the Chernobyl Nuclear Power Plant the concentrations of ^{90}Sr in water could have been higher than the values of the permissible concentration (PC) ($C_{\text{w PC}}(^{90}\text{Sr}) = 1.48 \cdot 10^4$ Bq/m^3) in the Iput river in the territory of Belarus (Fig. 4): $C_{\text{w max}} = 1.8 \cdot 10^4$ Bq/m^3 (Belarus, Vylevo-1, No. 6) and $C_{\text{w max}} = 1.66 \cdot 10^4$ Bq/m^3 (Belarus, Dobrush, No. 10). The jump in the variation of the concentrations of ^{90}Sr in water in the territory of Belarus near Vylevo is associated with the presence of a "spot" on this portion of the river basin. In Vylevo (No. 7), in Dobrush-1 (No. 8), and in Dobrush-2 (No. 9), one could have observed higher concentrations of ^{90}Sr in water in the second, third, and fourth five-day periods after the accident respectively. This is associated with the conditions of lag of the radioactive contamination of higher-than-average concentration from water-catchment portions where the higher density of the fallout of ^{90}Sr was observed [4].

The highest concentrations of ^{90}Sr on suspensions and in bottom sediments would have been in the first days after the accident in Vylevo-1 (No. 6), while in the bottom sediments of the water storage (No. 9) the concentrations of this radionuclide would have been the highest as compared to the remaining control volumes virtually throughout the year 1986 (Fig. 4). This is associated with a sharp change in the hydrodynamic charac-

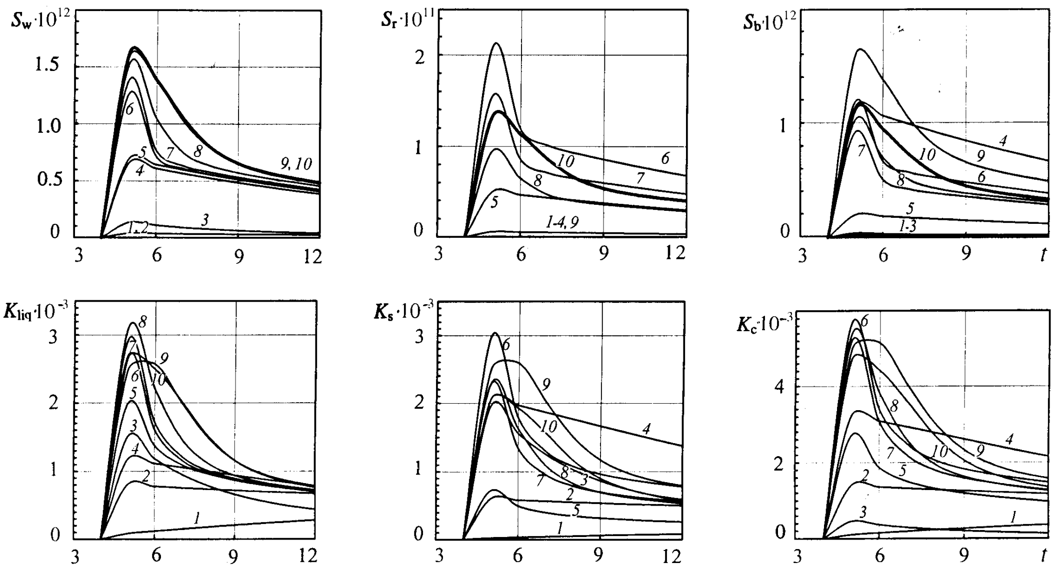

Fig. 5. Retrospective evaluations of the monthly runoff of ^{90}Sr in water (S_w), on suspensions (S_r), and with bottom sediments (S_b) and the change in its coefficients of liquid (K_{liq}), solid (K_s), and total (K_{tot}) runoff in the Iput river in 1986 in chambers (1–10). t, months; S_w, S_r, and S_b, Bq/month; K_{liq}, K_s, and K_{tot}, 1/month.

teristics of this portion of the Iput river channel, namely, with a decrease in the velocity of the flow in the water storage and hence the sedimentation of finely divided fractions.

By the end of the year 1986, higher-than-average concentrations of ^{90}Sr could have been observed in the water of the water storage (No. 9) ($4 \cdot 10^3$ Bq/m^3), on suspensions in Vylevo-1 (No. 6) (555 Bq/m^3), and in bottom sediments of the water storage (No. 9) (800 Bq/kg). Comparison of these values to the analogous concentrations of ^{137}Cs shows that because of the low sorption ability the concentrations of ^{90}Sr are an order of magnitude lower than the concentrations of ^{137}Cs on suspensions and in bottom sediments and are comparable in water.

Figure 5 gives the retrospective evaluations of the monthly runoff and of the runoff coefficients of ^{90}Sr during the year 1986 in water-soluble form and with suspended and entrained sediments along the river channel. The analysis of the calculations shows the presence of the larger-than-average runoff of ^{90}Sr with water and transported sediments in May 1986 throughout the channel of the Iput river. According to our evaluations, the largest runoff of the radionuclides could have been observed in water in the terminal cross section of Dobrush (No. 10) ($S_w = 1.63 \cdot 10^{12}$ Bq/month), with suspended sediments in Vylevo-1 (No. 6) ($S_r = 2.1 \cdot 10^{11}$ Bq/month), and with entrained sediments in Dobrush-2 (No. 9) ($S_b = 1.6 \cdot 10^{12}$ Bq/month). At the end of the period under study, the runoff of ^{90}Sr would have been the largest: $S_w = 4.94 \cdot 10^{11}$ Bq/month with the water of the water storage (No. 9), $S_r = 6.8 \cdot 10^{10}$ Bq/month with suspended sediments in Vylevo (No. 6), and $S_b = 6.75 \cdot 10^{11}$ Bq/month with entrained sediments in the village of Vyshkov. During eight months, the monthly runoff of ^{90}Sr decreased nearly threefold.

Analysis of the values of the runoff demonstrates that the removal of ^{90}Sr in the water-soluble state is comparable to the values of its removal with entrained sediments and is nearly tenfold higher than its removal on suspended particles. This is the main distinction between the transfer of ^{90}Sr and ^{137}Cs [2]. For ^{137}Cs, the fraction of the removal with transported sediments amounted to ~90% of its total runoff.

The calculations show that the highest values of the runoff coefficient of ^{90}Sr would have been in the first month after the accident; one could have observed the coefficient of liquid runoff in the water storage (No. 9) $K_{liq} = 0.31 \cdot 10^{-2}$ 1/month and the coefficient of solid runoff in Vylevo (No. 6) $K_s = 0.30 \cdot 10^{-2}$ 1/month (Fig. 5). By the end of the year 1986, one could have observed the highest values of the coefficient of liquid runoff in the

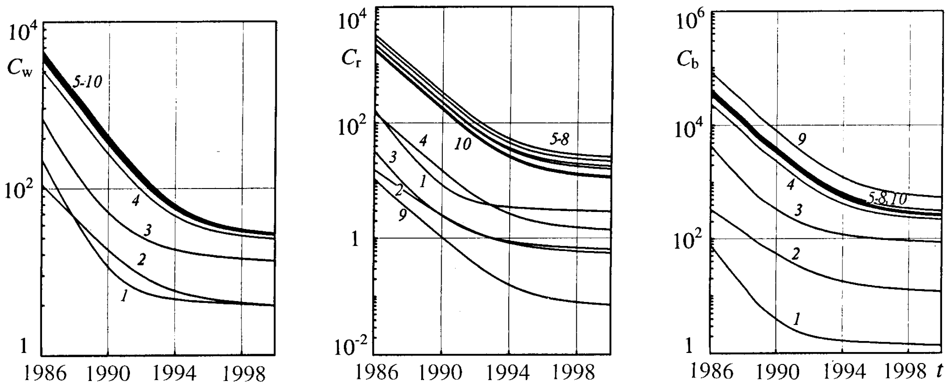

Fig. 6. Variation in the concentrations of ^{137}Cs in water (C_w), on suspensions (C_r), and in bottom sediments (C_b) in the Iput river in 1986–2000 in chambers (1–10). t, years; C_w and C_r, Bq/m^3; C_b, Bq/kg.

water storage (No. 9) $K_{liq} = 0.78 \cdot 10^{-3}$ 1/month and of the coefficient of solid runoff (in the village of Vyshkov, No. 4) $K_s = 0.14 \cdot 10^{-2}$ 1/month.

It is necessary to note that the results of the evaluations performed should be considered to be qualitative since the model used takes no account of the kinetics of interaction of radionuclides in the systems "water–suspensions," "water–bottom sediments," and "water–soil of water catchment"; this kinetics was significant precisely in the first year after the accident when the radionuclides were not yet fixed on solid particles [7]. As the parametric studies have shown, taking account of this fact in this period could have led to a substantial increase in the concentrations of the radionuclides in water and their runoff in the water-soluble state [2].

Evaluation of the Dynamics of the Radiation Situation on the Iput River in the Years 1987–2000. The period of 1987–2000 represents the years of active monitoring of the radiation state of the Iput river in Belarus (the Center of Radiation Control and Monitoring of the Natural Environment at the State Committee for Hydrometeorology of the Republic of Belarus) and partially in Russia in the years 1991–1993 (the Taifun Science and Production Association). In this period, primary attention was paid to observations of the content of ^{137}Cs in water, the contamination of bottom sediments along the river channel was studied to a lesser extent, and the transfer of radioactive contaminants by suspended and entrained sediments was studied inadequately. Unfortunately, monitoring of the content of ^{90}Sr in the river was begun only in 1990.

Evaluations of the change in the radiation situation on the Iput river in these years demonstrate a monotonic decrease in the concentrations of the radionuclides in water, on suspensions, and in bottom sediments with time; the rate of decrease of their values at the beginning of the period is higher than in 2000.

The results of calculating the variation in the concentrations of ^{137}Cs along the river channel during the years 1986–2000 are presented in Fig. 6. According to our evaluations, the concentrations of ^{137}Cs in the elements of the river system decreased on the average by a factor of ~100 in this period. In 2000, one expected the following highest concentrations of ^{137}Cs: $C_w = 28.3$ Bq/m^3 and $C_r = 25.6$ Bq/m^3 in water and on suspensions in the village of Vylevo (No. 6) and $C_b = 545.0$ Bq/kg in bottom sediments of the water storage (No. 9). In the terminal cross section (No. 10), these concentrations are somewhat lower: $C_w = 28.0$ Bq/m^3, $C_r = 11.6$ Bq/m^3, and $C_b = 261.0$ Bq/kg. The influence of the morphology of the channel had the largest effect on the characteristics of contamination of the water storage (No. 9). Just as in the retrospective evaluations, this portion of the channel is characterized by the lowest concentrations of ^{137}Cs on suspensions and by the highest concentrations in bottom sediments (Fig. 6).

The annual removal of ^{137}Cs during the period under study also decreased by nearly two orders of magnitude (Fig. 7). Its removals in water-soluble form and on suspensions differ on the average by a factor of 2.5 in value, but as compared to the removal with entrained sediments they are nearly 40 times smaller than the latter. In 2000, the following values of the largest removal of ^{137}Cs were expected: $S_w = 4.2 \cdot 10^{10}$ Bq/yr and S_r =

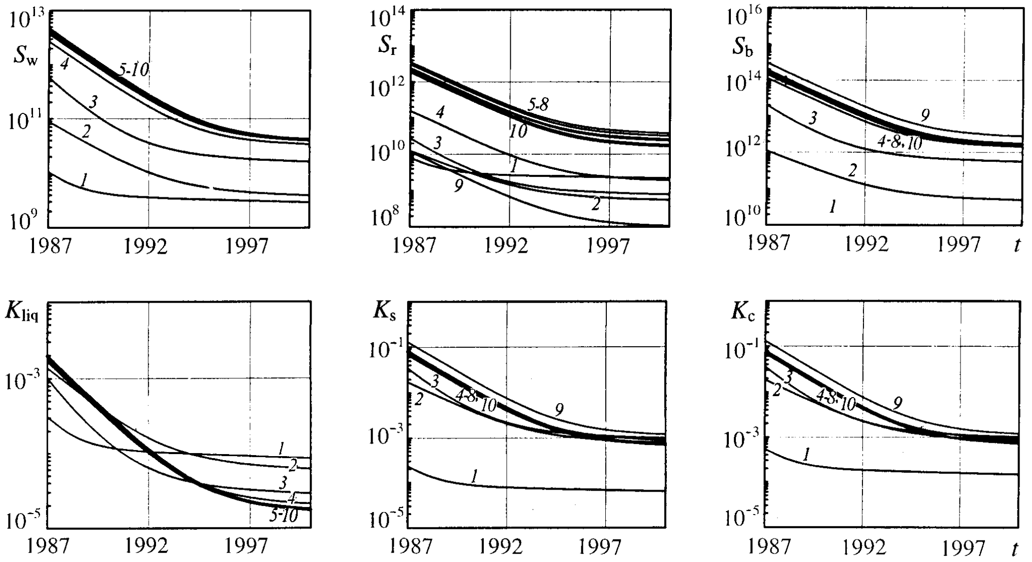

Fig. 7. Change in the annual removal of ^{137}Cs in water (S_w), on suspensions (S_r), and with entrained sediments (S_b) and in its coefficients of liquid (K_{liq}), solid (K_s), and total (K_{tot}) runoff in the Iput river during the years 1986–2000 in chambers (1–10). t, years; S_w, S_r, and S_b, Bq/yr; K_{liq}, K_s, and K_{tot}, 1/yr.

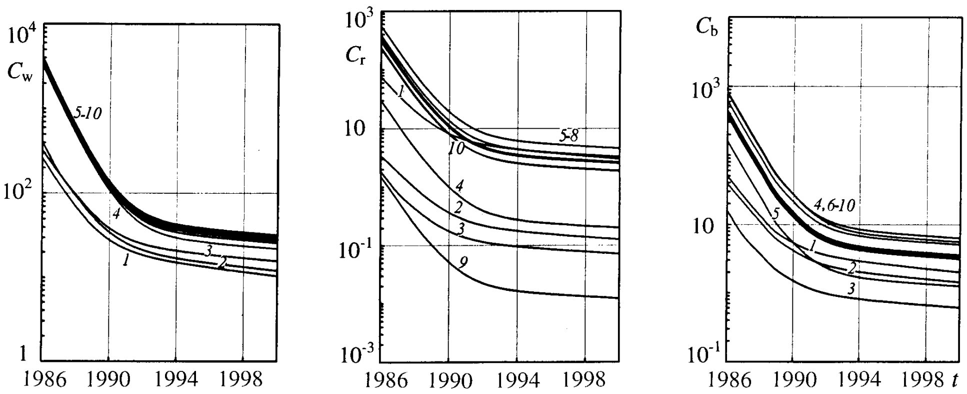

Fig. 8. Variation in the concentrations of ^{90}Sr in water (C_w), on suspensions (C_r), and in bottom sediments (C_b) in the Iput river during the years 1986–2000 in chambers (1–10). t, years; C_w and C_r, Bq/m^3; C_b, Bq/kg.

$3.7 \cdot 10^{10}$ Bq/yr with water and on suspensions in Vylevo (No. 6) and $S_b = 2.8 \cdot 10^{12}$ Bq/yr with entrained sediments in Dobrush-2. In the terminal cross section of Dobrush, these quantities (in 2000) were $S_w = 4.1 \cdot 10^{10}$ Bq/yr, $S_r = 1.7 \cdot 10^{10}$ Bq/yr, and $S_b = 1.66 \cdot 10^{12}$ Bq/yr.

According to our evaluations, during the years 1987–2000 the coefficient of liquid runoff of ^{137}Cs in the terminal cross section changed within $0.2 \cdot 10^{-2}$– $0.17 \cdot 10^{-4}$ 1/yr (Fig. 7). The coefficient of solid runoff characterizing the runoff of ^{137}Cs with transported sediments was $0.8 \cdot 10^{-1}$–$0.7 \cdot 10^{-3}$ 1/yr in the period under study, which is almost 40 times higher than the coefficient of liquid runoff. In 2000, one expected the following highest values of the coefficients of runoff of ^{137}Cs: $K_{liq} = 8.5 \cdot 10^{-5}$ 1/yr for liquid runoff in the village of Krutoyar and $K_s = 1.2 \cdot 10^{-3}$ 1/yr for solid runoff in Dobrush-2 (No. 9).

Evaluations of ^{90}Sr contamination of the Iput river in this period have shown that in 2000 the highest expected concentrations of this radionuclide were $C_w = 31.5$ Bq/m^3 in the terminal cross section of Dobrush

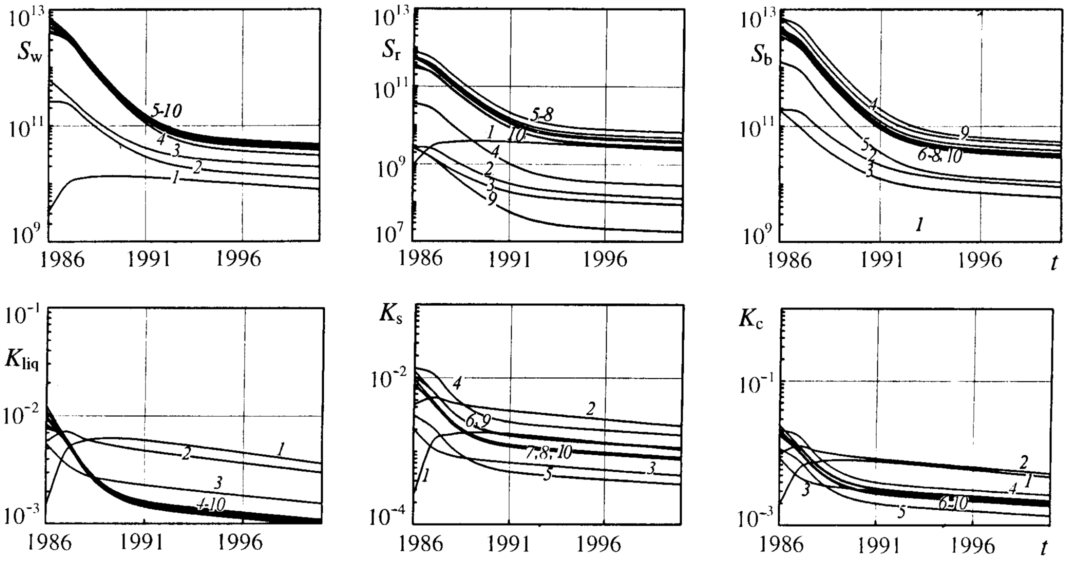

Fig. 9. Change in the annual removal of ^{90}Sr in water (S_w), on suspensions (S_r), and with entrained sediments (S_b) and in its coefficients of liquid (K_{liq}), solid (K_s), and total (K_{tot}) runoff in the Iput river during the years 1986–2000 in chambers (1–10). t, years; S_w, S_r, and S_b, Bq/yr; K_{liq}, K_s, and K_{tot}, 1/yr.

(No. 10), C_r = 4.6 Bq/m^3 on suspended sediments of Vylevo (No. 6), and C_b = 6.3 Bq/kg in bottom sediments in the water storage of Dobrush (No. 9). As the computational studies have shown, the concentrations of ^{90}Sr in the elements of the river system decreased on the average by a factor of 50 in the period from 1987 to 2000.

The annual removal of ^{90}Sr during the period under study decreased nearly 80 times (Fig. 9). In the water-soluble state, it is an order of magnitude higher than on suspensions but, unlike ^{137}Cs, is comparable to the removal of ^{90}Sr with entrained sediments. In 2000, the following highest values of the removal of ^{90}Sr were expected: $S_w = 4.67 \cdot 10^{10}$ Bq/yr with water of the water storage (No. 9), $S_b = 5.4 \cdot 10^{10}$ Bq/yr with entrained sediments in the village of Vyshkov, and $S_r = 4.8 \cdot 10^9$ Bq/yr with suspended sediments in Vylevo (No. 7). It was assumed that the removal of ^{90}Sr in the terminal cross section in Dobrush in 2000 would be $S_w = 4.67 \cdot 10^{10}$ Bq/yr in water-soluble form, $S_r = 3.81 \cdot 10^9$ Bq/yr on suspensions, and $S_b = 3.2 \cdot 10^{10}$ Bq/yr with entrained sediments.

The coefficients of liquid and solid runoff of ^{90}Sr during the years 1987–2000 are characterized by their slight (nearly twofold) change in the first chambers in the presence of an extremum in 1987–1989 and a nearly tenfold change on the last portions of the river (chamber Nos. 5–10) (Fig. 9). The coefficients of liquid and solid runoffs of ^{90}Sr are comparable in value, but the coefficient of liquid runoff is nearly 200 times higher than the analogous factor for ^{137}Cs. In 2000, the highest values of the runoff coefficients were expected to be $K_{liq} = 0.364 \cdot 10^{-2}$ 1/yr for liquid runoff in the village of Krutoyar (No. 1) and $K_s = 0.224 \cdot 10^{-2}$ 1/yr for solid runoff in the village of Kozarichi (No. 2) (Russia).

Thus, during the years 1987–2000, the radiation situation is characterized by a gradual decrease in the levels of contamination of water and transported sediments. A decrease in the rate of change of all the characteristics that determine the transfer of radionuclides in the river network is noted by the year 2000.

Long-Term Prediction of a Change in the Radiation Situation on the Iput River. The prediction has been performed up to the year 2080. A characteristic feature of the period in question is that within the framework of the assumptions made the contamination of the river system in this period will be determined only by the ingress of radionuclides with surface liquid and solid runoffs from the water catchment.

The results of the evaluations of the long-term prediction of a change in the radiation situation on the Iput river during the years 2000–2080 are presented in Figs. 10–13. According to the prediction performed, a

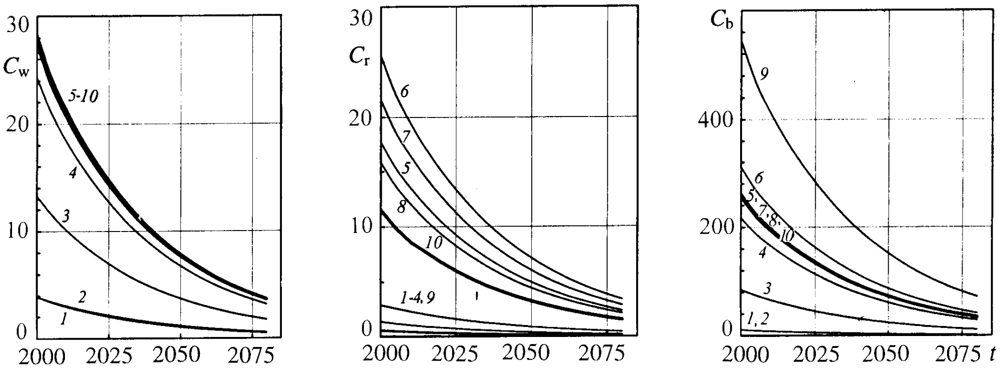

Fig. 10. Long-term prediction of variation in the concentration of ^{137}Cs in water (C_w), on suspensions (C_r), and in bottom sediments (C_b) in the Iput river in chambers (1–10) up to the year 2080. t, years; C_w and C_r, Bq/m^3; C_b, Bq/kg.

gradual decrease within one order of magnitude, on the average, in the concentrations of the radionuclides in water, on suspensions, and in bottom sediments will occur in this time.

The analysis of the prediction evaluations of migration of ^{137}Cs in the Iput river in this period has shown that in the terminal cross section of Dobrush (No. 10), the concentration levels of ^{137}Cs will vary during this time within the following ranges: C_w = 2.8–3.6 Bq/m^3, C_r = 11.6–1.5 Bq/m^3, and C_b = 26.1–34.3 Bq/kg (Fig. 10). It is assumed that in 2080 the highest values of the concentrations of ^{137}Cs will be C_w = 3.7 Bq/m^3 and C_r = 3.4 Bq/m^3 in soluble form and on suspensions in Vylevo (No. 6) and C_b = 72.0 Bq/kg in bottom sediments in the water storage (No. 9). As the evaluations show, the concentrations of ^{137}Cs on suspensions and in bottom sediments in the terminal chamber of Dobrush can be somewhat lower than in three to four chambers lying higher. This necessitates additional monitoring of the water medium on the Vylevo–Dobrush portion.

The removal of ^{137}Cs in dissolved form, on suspensions, and by entrained sediments and the corresponding runoff coefficients are normalized to five years due to the small annual change in these quantities. During the years 2000–2080, the value of the removal of ^{137}Cs in the terminal cross section (No. 10) will decrease from $1.9 \cdot 10^{11}$ to $2.8 \cdot 10^{10}$ Bq/5 yrs (in dissolved form), from $7.8 \cdot 10^{10}$ to $1.2 \cdot 10^{10}$ Bq/5 yrs (with suspended sediments), and from $7.5 \cdot 10^{12}$ to $1.0 \cdot 10^{12}$ Bq/5 yrs (with entrained sediments) (Fig. 11). It should be noted that the removal of ^{137}Cs on suspended sediments in the terminal chamber of Dobrush will be smaller than in chamber Nos. 6–8. The largest removal of the radionuclides will be with entrained sediments: it can be nearly 40 times larger than the removal of ^{137}Cs in dissolved form. In 2080, one can expect the maximum values of the removal $S_w = 2.86 \cdot 10^{10}$ Bq/5 yrs and $S_r = 2.6 \cdot 10^{10}$ Bq/5 yrs in dissolved form and on suspensions in Vylevo (No. 6) and $S_b = 1.9 \cdot 10^{12}$ Bq/5 yrs with entrained sediments in the water storage (No. 9).

The analysis of the calculated dependences of the runoff coefficients of ^{137}Cs in the long-term prediction notes a gradual decrease within one order of magnitude (Fig. 11). In the forthcoming period of time, the values of the runoff coefficients in the terminal chamber will decrease from $0.8 \cdot 10^{-4}$ to $0.2 \cdot 10^{-4}$ 1/5 yrs for liquid runoff and from $0.32 \cdot 10^{-2}$ to $0.5 \cdot 10^{-3}$ 1/5 yrs for solid runoff. In 2080, one can expect the following maximum coefficients of runoff: $K_{liq} = 0.67 \cdot 10^{-4}$ 1/5 yrs for liquid runoff in the village of Krutoyar (No. 1) and $K_s = 0.72 \cdot 10^{-3}$ 1/5 yrs for solid runoff in Dobrush-2 (No. 9) (Russia). Just as in the previous periods, the solid runoff with suspended and entrained sediments will be determining in the formation of the total runoff of ^{137}Cs.

During the years 2000–2080, the concentration levels of ^{90}Sr in the terminal cross section of Dobrush will decrease, i.e., C_w = 25.0–1.8 Bq/m^3, C_r = 2.0–0.15 Bq/m^3, and C_b = 3.0–0.2 Bq/m^3 (Fig. 12). In the year 2080, the highest expected values of the concentration of ^{90}Sr will be C_w = 1.8 Bq/m^3 in water in the terminal cross section of Dobrush (No. 10), C_r = 0.26 Bq/m^3 on suspensions in Vylevo (No. 6), and C_b = 0.35 Bq/kg in bottom sediments in the water storage (No. 9). As the evaluations show, the concentrations of ^{90}Sr on suspen-

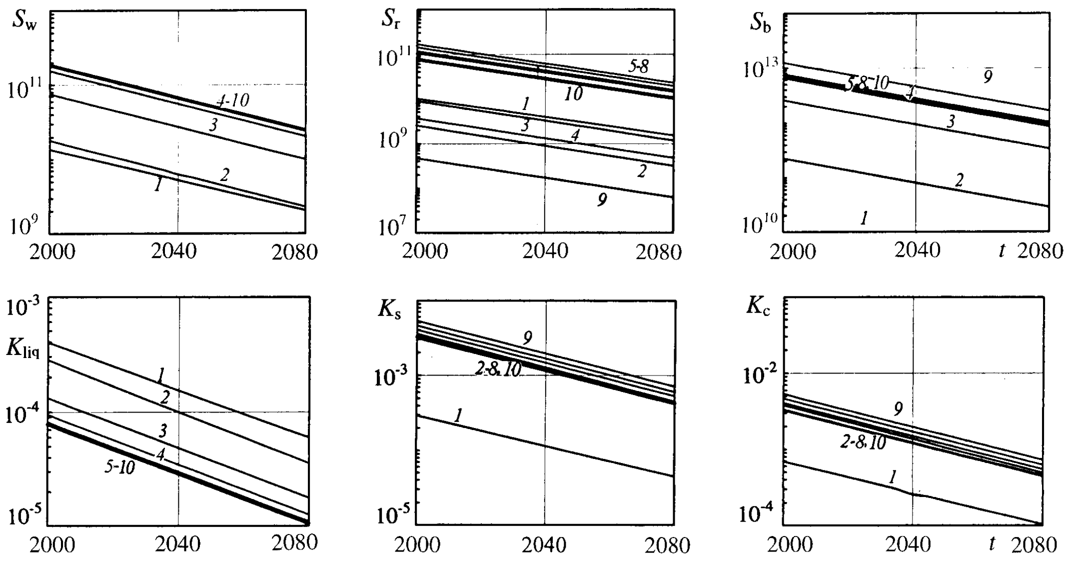

Fig. 11. Long-term prediction of the removal of ^{137}Cs in water (S_w), on suspensions (S_r), and with entrained sediments (S_b) and of its coefficients of liquid in the (K_{liq}), solid (K_s), and total (K_{tot}) runoff in the Iput river in chambers (1–10) up to the year 2080. t, years; S_w, S_r, and S_b, Bq/5 yrs; K_{liq}, K_s, and K_{tot}, 1/5 yrs.

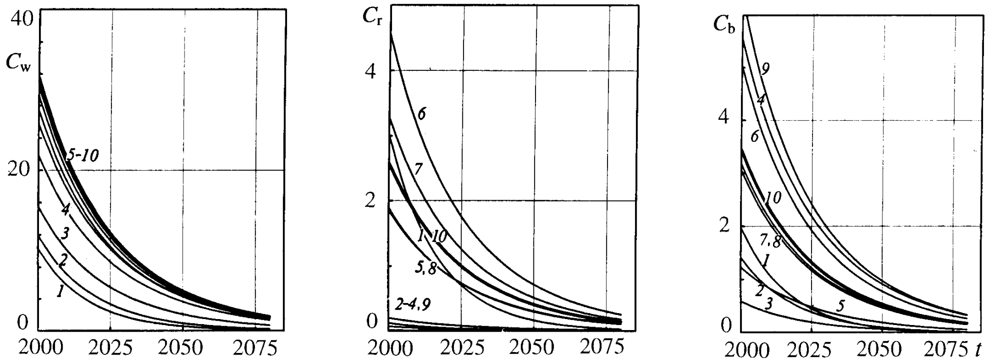

Fig. 12. Long-term prediction of variation in the concentration of ^{90}Sr in water (C_w), on suspensions (C_r), and in bottom sediments (C_b) in the Iput river in chambers (1–10) up to the year 2080. t, years; C_w and C_r, Bq/m^3; C_b, Bq/kg.

sions and in bottom sediments will be nearly five times lower than in water and in the case of the terminal chamber (No. 10) they will be lower than in the upper-lying chambers. The concentrations of ^{90}Sr in water will be comparable to the concentrations of ^{137}Cs, while on suspensions and in bottom sediments they will be nearly 10 and 200 times, respectively, lower than the concentrations of ^{137}Cs.

The prediction evaluations show that in the terminal cross section (No. 10), the removal of ^{90}Sr on suspended sediments will be smaller than in chamber No. 6 and chamber No. 7. The removals in dissolved form and with entrained sediments will be comparable in value and their relation will vary toward higher or lower values depending on the morphology of the channel. The removal on suspended sediments along the river channel can differ within two orders of magnitude from the removal in dissolved form (Fig. 13). During the years 2000–2080, the value of the removal of ^{90}Sr in the terminal cross section of Dobrush (No. 10) will decrease from $2.1{\cdot}10^{10}$ to $1.2{\cdot}10^{10}$ Bq/5 yrs (in dissolved form), from $1.7{\cdot}10^{10}$ to $9.7 \cdot 10^{8}$ Bq/5 yrs (on suspensions), and from $1.4{\cdot}10^{11}$ to $8.0{\cdot}10^{9}$ Bq/5 yrs (with entrained sediments) (Fig. 13). In 2080, the expected maxi-

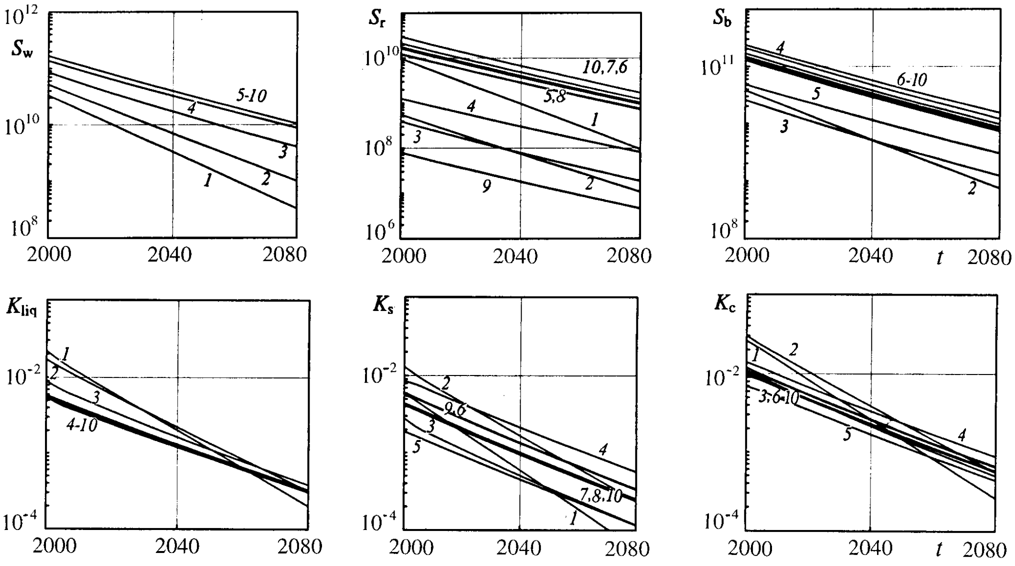

Fig. 13. Long-term prediction of the removal of ^{90}Sr in water (S_w), on suspensions (S_r), and with entrained sediments (S_b) and of its coefficients of liquid (K_{liq}), solid (K_s), and total (K_{tot}) runoff in the Iput river in chambers (1–10) up to the year 2080. t, years; S_w, S_r, and S_b, Bq/5 yrs; K_{liq}, K_s, and K_{tot}, 1/5 yrs.

mum value of the removal of ^{90}Sr can be $S_w = 1.2\cdot10^{10}$ Bq/5 yrs in water in the terminal cross section (No. 10), $S_r = 1.7\cdot10^{9}$ Bq/5 yrs on suspensions in Vylevo (No. 6), and $S_b = 1.5\cdot10^{10}$ Bq/5 yrs with entrained sediments in the village of Vyshkov (No. 4) (Russia).

The analysis of the calculated dependences of the runoff coefficients of ^{90}Sr also shows their gradual decrease within one to two orders of magnitude (Fig. 13). A distinctive feature of prediction evaluations for the years 2000–2080 is that the coefficients of liquid and solid runoffs of ^{90}Sr in the first four chambers (Russia) will be higher than in the subsequent (lying lower along the river channel) chambers, which is also characteristic of ^{137}Cs. This is most probably due to the conditions of formation of the contamination of the river medium in this time interval which will be determined by the runoff from the surface of the water catchment where the total contamination of the first portions is larger than the contamination of all the remaining portions [4].

In these years, the values of the runoff coefficients of ^{90}Sr in the terminal chamber will decrease from $0.48\cdot10^{-2}$ to $0.27\cdot10^{-3}$ 1/5 yrs for liquid runoff and from $0.37\cdot10^{-2}$ to $0.21\cdot10^{-3}$ 1/5 yrs for solid runoff. In 2080, the largest expected coefficients of runoff can be $K_{liq} = 0.32\cdot10^{-3}$ 1/5 yrs for liquid runoff in the village of Ushcherp'e (No. 3) and $K_s = 0.48\cdot10^{-3}$ 1/5 yrs for solid runoff in the village of Vyshkov (Russia). As is seen, the values of the coefficients of solid and liquid runoff of ^{90}Sr are comparable and nearly two orders of magnitude higher than the values of the coefficient of liquid runoff of ^{137}Cs, which distinguishes the behavior of ^{90}Sr from the behavior of ^{137}Cs in the Iput river basin.

The evaluations of the migration of ^{137}Cs and ^{90}Sr in the Iput river network performed in retrospective (1986) and for the period of 1987–2000, and also the long-term evaluations up to the year 2080, have shown that over the corse of a century the concentrations of ^{137}Cs in the elements of the Iput river system will decrease nearly 3000 times, while the concentrations of ^{90}Sr will decrease 10,000 times. This will occur because of the removal of the radionuclides by river flow (runoff), the decrease in their content in the water catchment owing to radioactive decay and surface runoff, and burying of the radionuclides deeper into the soil layer of the water catchment owing to their vertical migration.

Thus, the model used in the present investigation has enabled us to quite adequately describe the migration processes of radionuclides in a river basin and with the example of the Iput river predict a change in the radiation situation over the course of a century. It is expedient to continue analogous experimental and computational investigations of other contaminated water bodies of Belarus with the aim of optimizing the general system of radiation monitoring of Belarus, carrying out measures on safe water management, and evaluating the dose loads received by the population living on contaminated water-catchment areas.

NOTATION

t, time; C_w, C_r, and C_b, concentrations of the radionuclides in dissolved form, on suspensions, and in bottom sediments respectively; S_w, S_r, and S_b, removal of the radionuclides in dissolved form and on suspended and entrained sediments respectively; K_{liq}, K_s, and K_{tot}, coefficients of liquid, solid, and total runoffs of the radionuclides respectively; PC, permissible concentration of the radionuclide in drinking water for the population. Subscripts: w, water; r, suspensions, b, bottom sediments; liq, liquid; s, solid; tot, total.

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