Appendix 4

A Radioecological Model for Thyroid Dose Reconstruction of the Population of Belarus after the Chernobyl Accident

A radioecological model for thyroid dose reconstruction of the population of Belarus after the Chernobyl accident

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Abstract A radioecological model was developed to estimate thyroid exposures of the population of Belarus subsequent to the Chernobyl accident. The input of the model consists of an extensive data set of the ^{137}Cs-activity per unit area deposited during the Chernobyl accident, rainfall data for different regions of Belarus, the ^{131}I/^{137}Cs ratio in the deposit and the start of the grazing period in Belarus in April/May 1986. The output of the model is the age-dependent thyroid exposure due to the intake of ^{131}I with fresh milk. Age-dependent average thyroid doses were assessed for the selected regions of Belarus. The maximum values of thyroid dose were estimated for the inhabitants of the Gomel oblast where the highest deposition was observed among the regions considered in this paper. The lowest doses were estimated for the Vitebsk oblast with the lowest level of depositions. The mean exposures for Grodno oblast and Minsk oblast and for Mogilev oblast and Brest oblast are very similar. The results were compared with estimations of the thyroid exposure that are based on ^{131}I-measurements in human thyroids; the results are in good agreement. The model may be used to assess thyroid exposures in Belarus for areas, where no ^{131}I-measurements are available.

Key words: Chernobyl, Belarus, ^{131}I, Thyroid dose

Introduction

During the Chernobyl accident, large activities of iodine isotopes were released. Due to the predominantly northwest and the northeast wind directions within the first period after the accident, nearly the whole territory of the Republic of Belarus was contaminated with radioactive iodine isotopes. The most important radioiodine isotope was ^{131}I, its deposition varied from 0.2 to 37 MBq/m^2 in five from six Belarus oblasts [1].

Therefore, in the first few months, the thyroid was the most exposed organ. The main exposure pathway was due to intake of fresh milk, whereas the incorporation of iodine due to inhalation was in most cases less important. As a consequence of the contamination, a monitoring programme was initiated, during which the iodine activities in human thyroid were measured for more than 130,000 people. The measurements concentrated on the highly contaminated parts of Gomel and Mogilev regions and in Minsk city [2]. In total about 1.4% of the population of Belarus was monitored. However, not all most of the thyroid measurements are of good quality, as they were made during an extended field monitoring programme under difficult boundary conditions. [3]. Therefore, to complete and to check the consistency of the iodine measurements in thyroids, the iodine transfer to humans is simulated by means of a radioecological model.

This study describes the approaches to estimate the thyroid exposures to different population groups. The model is applied to different population groups in Belarus.

Methodology

Radioecological model

The thyroid exposure for the Belarus population after the Chernobyl accident was due to ingestion and inhalation of short-lived iodine isotopes. The most important pathway of exposure was ingestion of ^{131}I with locally produced foodstuff. Thyroid exposure due to inhalation was important only for small group of people who were evacuated shortly after the accident and for those people who did not consume locally produced food [4]. The scheme of the radioecological model is shown in Fig. 1. The models estimates the thyroid exposure due to the consumption via the pathway pasture-cow-milk. The input parameters are the ^{137}Cs ground deposition, ratio ^{131}I to ^{137}Cs in ground deposition, the amount of rainfall during the rainfall event and yield of pasture grass in April-May 1986.

In the model proposed, the ^{137}Cs activity per unit area is the starting point. The number of measurements of ^{131}I activity per unit area after the Chernobyl accident is very limited, since ^{131}I decayed before detailed and country-wide monitoring programmes could be performed. In many settlements, the ^{131}I deposit to the ground was not measured. For those cases, in [5], the ^{131}I deposition σ_{I-131} to the ground is estimated from the ^{137}Cs-deposition σ_{Cs-137} and the $^{131}I/^{137}Cs$ $R_{I/Cs}$ ratio observed in the various parts of the country:

$$\sigma_{I-131} = \sigma_{Cs-137} \cdot R_{I/Cs} \quad (1)$$

Data for the ^{137}Cs deposition to the ground are available for the whole country, so from these data set the ^{131}I-deposition to soil can be estimated for the whole country by interpolation. The data on the ^{137}Cs-activity per unit area is provided by the Belarus Republic Center of Radiation and Environment Monitoring, the data are decay-corrected to April 1986 for each settlement. All values are corrected for global fallout taking into account ^{137}Cs levels of 2 $kBq \cdot m^{-2}$ [6].

For simplification, it is assumed in the model that the activity was deposited during one single deposition event. The activity deposition onto grass is estimated as a fraction of the total ^{131}I ground deposition, which is intercepted by grass:

$$A_g = \sigma_{I-131} \cdot F_w \quad (2)$$

where F_w is the interception factor that quantifies the activity fraction that is retained initially by the grass.

The activity concentration in grass at time t after deposition is given by:

$$C_g(t) = \frac{A_g}{Y_g} \exp[-(\lambda_w + \lambda_r)t] \quad (3)$$

where Y_g is the yield of grass at time of deposition ($kg \cdot m^{-2}$ fresh mass), λ_w – decrease rate of ^{131}I in grass due to weathering and growth dilution (d^{-1}) and t is the time after deposition (d).

The activity ingested by the cow $A_c(t)$ is calculated from the concentration of activity in the grass and the feeding rate I_g of cow ($kg \cdot d^{-1}$).

$$A_c(t) = C_g(t) \cdot I_g \quad (4)$$

Due to the short half-live of ^{131}I, the consumption of locally produced milk and leafy vegetables are the main potential sources for the daily intake of ^{131}I. However, at this time of the year, only little leafy vegetables are available. Therefore, the intake of milk was considered as the only source for the incorporation of ^{131}I. The activity concentration in milk is calculated by:

$$C_m(T) = TF_m \cdot \int_0^T A_c(t) \cdot \lambda_b \cdot \exp(-(\lambda_b + \lambda_r) \cdot (T - t)) \cdot dt \qquad (5)$$

where $C_m(T)$ is the concentration of activity ($Bq \cdot kg^{-1}$) in milk at time T, TF_m is the transfer factor ($d \cdot kg^{-1}$) for milk, λ_b is – rate representing the biological half-life of ^{131}I in milk (d^{-1}), and λ_r is the radioactive decay rate (d^{-1}).

The intake function of activity for the age group I is defined by the time-dependent concentrations of activity in food and the human consumption rate:

$$I_i(T) = V_{m,i} \cdot C_m(T) \qquad (6)$$

where: $V_{m,i}$ is the consumption rate ($kg \cdot d^{-1}$) of milk of the population group i. The equivalent dose of the thyroid due to ingestion of ^{131}I with contaminated milk for the age group I is estimated by:

$$D_i = DF_i \int_0^T I_i(t) \cdot dt \qquad (7)$$

where D_i is the thyroid dose (Sv), DF_i is age-dependent dose factor for ingestion ($Sv \cdot Bq^{-1}$) for the age-group i and T is the time since deposition (d).

Interception

The quantification of the interception by vegetation is a key point of the assessment of the iodine transfer in the food chains. Unfortunately, the available data of measured ^{131}I activities in soil and grass do not allow a reasonable estimation of the interception fraction. According to Pröhl and Hoffman (1996) [7], the interception depends on various factors as the deposition type (dry or wet), the chemical form and the amount of rainfall and the morphological development of the plant. According to Chamberlain, the interception factor f_d for dry deposits by vegetation can be quantified as:

$$f_d = 1 - \exp(-\mu B) \qquad (8)$$

where B is the dry weight of the vegetation per unit area (kg m^{-2}), and μ is the absorption coefficient (m^2 kg^{-1}). Although the biomass B may vary within a factor of about 2, the variations of the resulting activity concentration in grass is less since the interception increases with the biomass; therefore an average value for the yield of grass at the time of the accident of 0.5 kg/m² (fresh mass) is applied. Assuming a dry matter content of 20 %, the interception for dry deposition is assessed as 0.3.

For this estimation, an absorption coefficient of μ=3.60±0.05 m²/kg has been applied. This value is in the upper range of the absorption coefficient that has been reported for elemental iodine and submicron particles. For iodine vapor on grass, Chamberlain (1970) [8] had measured a value for μ of 2.8±0.14 m²/kg. However, since radioiodine occurs in gaseous as well as in particulate form, the value of 3.6 m²/kg has been applied to avoid an underestimation of the interception of dry deposits.

The interception fraction f_w of wet deposited activity is estimated according to the approach described in radioecological model ECOSYS ([9]), using the same parameter values for the yield of grass.

$$f_w = \frac{7 \cdot \left(1 - \exp(-Y_g \cdot k)\right) \cdot S}{R} \cdot \left(1 - \exp(-\frac{\ln 2}{3 \cdot S} \cdot R)\right) \quad (9)$$

where: Y_g is yield of grass (kg m^{-2} fresh mass) at time of deposition, k is a unitless normalisation factor (k = 1 m^2 kg^{-1}), S is the apparent thickness of a water film that remains on the foliage after a rainfall event (0.1 mm), R is the amount of rainfall during which the activity has been deposited (mm).

However, it is difficult to differentiate between dry and wet deposition. In some parts of the country, the deposition was predominantly dry, in other parts iodine was deposited during both dry and wet deposition processes. It is necessary to take into account both deposition modes appropriately to achieve an integrated approach for estimating the interception fraction. For this purpose the following approach is used.

The interception fraction is estimated as function of the amount of rain. In Fig. 2, the interception fraction for dry deposits is given (full line) according to equation 8. The relationship between rainfall and the interception fraction of wet deposits (equation 9) is represented by the dashed line. For the interception, the total amount of rain is the crucial quantity, whereas the rainfall intensity is of minor importance (Hoffmann et al. 1992) [10]. It can be seen that for low amounts of rain, the interception of wet deposits is very similar to that of dry deposits. With increasing rainfall, for wet deposits, the interception decreases with the amount of rainfall, since only a limited amount of water can be retained on the plant. For mixed deposits, the interception is approximated by a joint curve that is a combination of the interception of dry and wet deposits (dotted line). This function can be interpreted as a combination of the dependences for dry and wet depositions; it is approximated by an exponential function. For dry deposition, the curve meets exactly the interception fraction as in equation 8. For the important range of rainfall from 1-10 mm, the resulting interception is assumed to be higher than the wet deposition curve, since wet deposition is always accompanied by dry deposition which tends to cause higher interception fractions.

Start of grazing

The Chernobyl accident occurred during the start of the grazing season. Since the consumption of fresh milk is the main pathway, the start of the grazing season has a direct influence on the initial contamination of milk and the ingestion dose to the population affected.

According to [11], in the South of Belarus, the grazing period started a few days earlier than in the Northern part. In the Brest and the Southern part of the Gomel oblast, the grazing season started on 25.04.86. With a delay of 1-2 days, the pasture started in Mogilev and Northern part of Gomel oblasts, whereas the 28-29 of April was the start of this period for Minsk and Grodno oblasts. The Vitebsk oblast was delayed by 5 days compared to the Southern parts of republic.

Activity of ^{131}I in grass and milk

For the weathering and growth dilution rate constant, a value of λ_{w+d}=0.069±0.016 d^{-1} was applied that corresponds to a half-life of 10 days [5]. For the biological half-life of iodine in milk in milk, a value of λ_b=0.99 d^{-1} [9] was used. For the milk transfer coefficient the information from different investigations was analyzed and a value of TF_m= $3 \cdot 10^{-3}$ d/kg was chosen for the assessment [5,9]. For the daily intake of grass by cows, an average value for the whole grazing period of pasture I_g=43 kg [11] was chosen.

Milk consumption

There are various estimations for the age-dependent milk consumption which were carried out in many investigations as in first years after accident and retrospectively [12]. The summary of the existing data resulted in the values summarized in table 1. Similar results for inhabitants of Belarus were reported in [5].

These data are in good agreement with the result of surveys of milk consumption, which were carried out in Russia, Smolensk and Briansk regions [13]. The data agree also well with the results of questionnaire carried out in the Chernigov region, Ukraine [14].

Zone division

According to [15] contamination in Belarus started on 26-27 April 1986. For nearly all parts of Belarus, the main deposition can be associated to one single day. The maximum values of ^{131}I activity in daily samples of the deposit to soil were observed on 27-29 of April with the exception of the Vitebsk oblast where the deposition maximum was observed on 30 April/1 May [15, 16].

As discussed above, the deposition mode (dry and/or wet) is important as well. The State Committee on Hydrometeorology of Republic of Belarus performed precipitation measurements from 26.04.86 till 01.05.86 at 50 locations in Belarus. The rain was collected daily in bulk samplers. In Figure 3, the locations with these data are indicated. Furthermore, the locations are given for which the ^{131}I/^{137}Cs ratio was measured by Matveenko et al. (1999) [15] who analyzed the gamma–spectrums of soil samples that were collected and measured in various settlements of the Gomel and Mogilyov oblast in May and June 1986.

Based on the information on the rainfall; the ^{131}I /^{137}Cs-ratio in the deposit and the main day of deposition (day when ^{131}I-activity in daily soil samples reached maximum), Belarus was divided into the parts with the same radioecological conditions (Fig. 4).

Within each zone, the deposition mode, the main day of deposition are the same or at least very similar. In order to check this classification, the ^{137}Cs-deposition was plotted against the amount of rainfall at the day of main deposition for the different regions of Belarus. Although only few data are available, it is obvious that in all parts that the deposition increases with increasing amount of rainfall (Fig. 5-8). The amount of rain is less than 1 mm for the all points from Zone 5. Following, this deposition can be characterized as "dry".

The proposed division of Belarus into 5 zones with similar conditions was also applied for the estimation of the ratio of ^{131}I to ^{137}Cs (Fig. 4). Using information about values of ^{131}I to ^{137}Cs, the ratio available from direct measurements of activity ^{131}I and ^{137}Cs, relationships between $R_{I/Cs}$ and σ_{137} were derived for each zone (Fig. 9-12). In general, the ^{131}I/^{137}Cs-ratio decreases with increasing ^{137}Cs-deposition. The figures contain all available data; however, the number of underlying data is very small, since there are only few locations with complete data sets. The ^{137}Cs–deposition increases in proportion to the amount of rainfall; this means wet deposition becomes more and more important. Dry deposition of elemental iodine is much more effective than dry deposition of particle-bound radionuclides as caesium. However, the deposition of ^{131}I and ^{137}Cs with rain is about equally effective [17].

For zone 5 only very little data are available. The deposition is – compared to the parts of the country - very low. Therefore less monitoring resources were allocated. The few available data indicate low ^{131}I-deposition for this region [15, 18]. Combined with the available ^{137}Cs-activities per unit area, low ^{131}I/^{137}Cs ratios in the 5th zone are achieved that are equivalent to the minimum value of this parameter for Belarus ($R_{I/Cs\ min}$ was applied as 3). This observation is not really consistent with the other parts of the country and is yet not fully understood.

Thyroid dose estimation

The thyroid dose estimation for settlements of Belarus was based on the presented approach (Eqs.1-9). It was assumed that the contamination occurred at the day of the main deposition. Based on initial information from State Committee on Hydrometeorology of Republic of Belarus, the relationships in Figures 5-8 and 9-12 were used to estimate the rainfall and the $^{131}I/^{137}Cs$ -ratio. The maximum values of rain were 5 mm for dry conditions and 16 mm for mixed and wet. The interception factor is estimated accordingly to the rainfall values, using the derived function (Fig. 2) for these cases.

According to the measurements described in [15], the $^{131}I/^{137}Cs$ ratio varies from of 3 to 60 in Belarus [15]; however, as illustrated in Fig. 9-12, the values rarely exceed a value of 20 which is consistent with the observations made in [19]. Evacuation or relocation is only taken into account for settlements within the 30 km–zone. The evacuation occurred in 3 phases: the first phase was till 5.05.86 (51 settlements), the second was till 9 May 1986 (29 settlements); the third was 1.09.86 and did not influence to the thyroid dose assessment [3]. Consumption of locally produced milk by the rural population was assumed, for urban areas the consumption of contaminated milk was interrupted by 06.05.86 according to an officially implemented milk ban [20]. Other possible countermeasures are not taken into account.

The levels of ^{131}I in milk that was consumed by the inhabitants of the cities of Belarus were estimated as average from the surrounding whole oblast. For the assessment of the ^{131}I contamination of milk in Minsk city, the information about the delivery of milk was used (data were estimated from 3 main milk factories on May 1986). Based on the data from 36 suppliers of milk in Minsk, the average value was estimated and applied to estimate thyroid exposures of the population of the city of Minsk.

Results

As a first step, the thyroid exposures normalised to the ^{137}Cs-deposit was estimated and compared against thyroid doses that were assessed for contaminated areas of Ukraine and Russia. The results are summarised in Table 2. Furthermore, thyroid dose estimations are included which were performed for the evacuees of the 30 km-zone. The comparability with the results of evacuees is limited, since the evacuation interrupted the intake of milk that was produced within the 30 km zone. Having in mind this limitation, the thyroid doses per unit ^{137}Cs per unit area of this study agree well with those determined in other studies. The absolute numerical values as well as the age-dependence are similar for all cases.

Based on the model described above, for a number of settlements from different oblast, thyroid exposures were estimated (Table 3). These exposures are compared against assessments that were obtained on the basis of ^{131}I-measurements in human thyroids and assumptions on the time–dependence of the ^{131}I-intake and excretion [24]. The results are presented in Table 3. For the comparison, settlements were selected with more than 10 measurements for this age group from different administrative units (city, town, rural).

Since the age-dependence is similar for all oblast, the comparison is limited to adults. In all settlements selected, more than 10 measurements from this age-group are available [24]. Additionally, the table contains data on the ^{137}Cs deposition and the rainfall. The values for the interception fraction and the $^{131}I/^{137}Cs$ ratio as derived from the relationships in Fig. 2 and Figs. 9-12 respectively are shown as well. For these examples, the mean thyroid doses vary from 0.07-0.57 Gy. The maximum values for thyroid doses are estimated for the inhabitants of the settlements of the Gomel oblast. In this oblast, the highest contamination is found. The lowest thyroid doses are estimated for the Vitebsk oblast with the lowest level of depositions.

The estimates for Grodno and Minsk areas are very similar. The average thyroid dose for the Mogilev oblast is similar to Brest oblast although the ^{137}Cs-deposition is higher in Mogilev. In the Mogilev oblast, there was predominantly wet deposition leading to a relatively higher initial contamination of the plant, whereas in the Brest oblast, the deposition was mixed.

In Table 4, average thyroid doses are estimated for 4 highly contaminated raions (districts) of Belarus. The estimations are based on ^{131}I activity measurements in human thyroids [25] and the results of the present model for 3 age groups (0-7, 7-18, adults). The average for a raion is the calculated as a population-weighted mean of the thyroid exposures received in the settlements. Since the data rainfall are limited to a few locations (Fig. 3), the values for interception and $^{131}I/^{137}Cs$ ratio are estimated on the relationships in Figs. 3, 5-8 and Figs. 9-12 respectively. Again, there is a very good agreement between the thyroid doses estimated by the model described and the assessment that is based on ^{131}I measurements in the thyroid. The largest deviation between both approaches is about 40 %. The mean thyroid exposure for the age-group 0-7 is up to 1.6 Gy; the exposures for adults are a factor of 3-4 lower.

The spatial distribution of the thyroid dose for children aged 0-18 years on raion level is presented in Fig. 13. As the figure indicates, the highest thyroid exposures were received by children from Southern raions of the Gomel oblast and Eastern raions of the Brest oblasts with thyroid doses in the order of 0.5 to1 Gy.

In Fig. 14, the average thyroid doses for the age group 0-18 for all Belarus oblasts and Gomel and Minsk cities. The exposures are calculated as a population-weighted mean of the average thyroid doses in each settlements in 1986 [26]. The mean doses vary by about a factor of 30 between the Southern oblast Gomel and the Northern oblasts as Grodno and Vitebsk.

Uncertainty

Radioecological modelling is inevitably associated with uncertainties, since neither the boundary conditions nor the model parameters are accurately known [27]. For estimating the uncertainty, for the model parameters frequency distribution were estimated and these data were processed by application of Monte-Carlo-techniques for a settlement in the Gomel region with a ^{137}Cs activity per unit area of 0.4 MBq/m^2. The endpoint of this uncertainty analysis is to estimate the 97.5/2.5-percentile ratio of the resulting frequency distribution of the thyroid dose for both infants and adults, if the ^{137}Cs-activity per unit area of a given settlement is known.

The parameters are summarised in Table 5. The uncertainty of the ^{137}Cs-activity per unit area is due to the inhomogeneity of the deposition and possible errors during the measurements. According to the relation in Fig. 5, the $^{131}I/^{137}Cs$-ratio is 10 with a standard deviation of 2 for the assumed ^{137}Cs-activity per unit area. From Fig. 2 and [28], the mean interception factor is approximately 0.15, which varies approximately from 0.05 to 0.25. This uncertainty range is simulated by a normal distribution (0.15±0.03). The distribution of the transfer factor feed-milk is derived according to [29]. The uncertainty of the milk intake is modelled according to table 2.

Table 6 shows the correlations among the parameters that were taken into account. However, the correlations coefficients are partly based on judgement since the data for an exact derivation is too poor. Therefore, the correlation coefficients are assumed to quantify a general trend rather than a well-known relationship between two parameters and the numerical values applied should not be overemphasised. To quantify a weak relationship (e.g. Yield of grass – Feeding rate), a correlation coefficient of 0.5 was assumed, which means that one parameter is determined to a degree of 25 % by the other one. A correlation coefficient of 0.7 was applied, if the relationship is assumed to be moderate; a value of 0.7 corresponds to a coefficient of determination of 50%. If the relationship between two parameters is assumed to be relatively strong, a correlation coefficient of 0.8 is assumed, which corresponds to a coefficient of determination of 64%. The calculations were performed by means of the software package Crystal Ball [30].

In table 7, the uncertainty of the thyroid exposure according to the present model is shown for infants and adults. Due to the underlying distributions of the parameters, the results are close to a log-normal distribution. The model starts from the ^{137}Cs activity per unit area, the uncertainty of the normalised thyroid dose is quantified by the ratio between the 97.5- and 2.5-percentile. Additionally the ratio of the 95- and 5-percentile is given. The estimated 97.5/2.5-percentile ratio is 23 and 27 for infants and adults respectively, the corresponding values for the ratio of the 95/5%-percentile are 11 and 13. The uncertainty for adults is somewhat higher due to the wider range of milk intake (Table 2). The parameter sensitivity declines in the order milk intake, transfer factor feed –milk, interception, $^{131}I/^{137}Cs$ ratio and ^{137}Cs-activity per unit area. Due to the assumed correlations among the last three parameters, their overall sensitivity is relatively little.

Summary and conclusions

In this paper, the thyroid exposure of the population in Belarus is estimated by means of a radioecological model. The input data for the model are:

- The ^{137}Cs-activity per unit area deposited during the Chernobyl accident,
- The relationship between the rainfall and the ^{137}Cs-activity per unit area as well as the $^{131}I/^{137}Cs$ ratio per unit area in different regions of Belarus
- The start of the grazing period in Belarus in April/May 1986

The model estimates the exposure due to the intake of ^{131}I with fresh milk subsequent to the Chernobyl accident. The thyroid exposure due to the intake of milk contaminated with ^{131}I is modelled, taking into account

- The interception of 131I by vegetation in dependence of the rainfall,
- The intake of 131I by grazing cattle, and
- The age-dependent consumption of milk by humans.

The contamination pattern in Belarus is very inhomogeneous. Therefore, the country has been divided into different zones according to start of grazing, ^{137}Cs per unit area, rainfall, and the $^{131}I/^{137}Cs$-ratio.

Based on this approach, age-dependent thyroid exposures normalised to the ^{137}Cs-activity per unit area were estimated. The results compare well with those obtained in studies to reconstruct thyroid exposures in contaminated areas of Ukraine and Russia.

The model has been used to estimate thyroid exposures in different regions of Belarus. The highest doses are estimated for the oblasts Gomel, Brest and Mogilev. In the Southern part of the Gomel oblast, average thyroid doses for the age-group 0-7 years of up to 1.5 Sv are estimated for some raions. In general, the thyroid doses decrease towards the North of Belarus due to the later start of the grazing period and due to the lower deposition. However, the thyroid doses do not necessarily decrease in proportion to the deposited activity, since high activities per unit area were often deposited with rainfall and the fraction of activity intercepted by grass decreases with the amount of rainfall.

The uncertainty of the results was estimated for the Gomel oblast, it is quantified as the ratio of the 95- and the 5-percentile of the resulting distribution of the thyroid dose normalised to the ^{137}Cs-activity per unit area. The uncertainty range is 11 and 13 for infants and adults respectively.

For a number of settlements, the estimated thyroid doses were compared with exposure assessments that were assessed on the basis of ^{131}I measurements in human thyroids. For these settlements, the ratios of the predictions based the radioecological model and on ^{131}I-measurements in human thyroid vary in the range from 0.66 to 2. However, the monitoring programme concentrated on the highly contaminated areas. The good agreement of the model with assessments that are based on thyroid monitoring suggests the applicability of the model to areas where no measurements of ^{131}I in human thyroids were performed.

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List of Tables

Table 1 Age-dependent consumption rates of fresh milk in Belarus

Age (y)	Daily milk intake (l/d)
0 - 1	0.4 ± 0.2
1 - 4	0.4 ± 0.2
5 - 6	0.4 ± 0.2
7 - 12	0.5 ± 0.3
12 - 17	0.5 ± 0.3
18 and adults	0.7 ± 0.4

Table 2 Comparison of the thyroid dose per unit ^{137}Cs per unit area of this study against the results of dose reconstruction in other studies

Region	Normalised thyroid dose (Gy per MBq/m² ^{137}Cs)					Reference
	Age-group					
	1 y	5 y	10 y	15 y	adult	
Settlements with more than 10 measurements (include settlements from 30 km zone)	6.0±6.2	3.6±3.7	2.3±2.4	1.4±1.4	1.5±1.5	This study
Settlements in 30 km zone separately	4.8±2.16	2.8±1.3	2.2±0.8	1.5±0.5	0.9±0.6	This study
30 km zone	5.3	3.2	1.6	1.1	0.8	[21]
Chernigov				2-20		[14]
Zhytomyr (∅ 3 villages)	5-12	3-8	2-5	1.4-4	0.7-2	[22]
Zhytomyr (∅ whole oblast)			3.9±2.8			[22]
Briansk #		0.7±0.2				[13]
Tula #		1.0±0.4				[13]
Kaluga #	2.5-8	1.6-5			0.3-1.1	[23]

predominantly wet deposition

Table 3 Thyroid exposures in selected settlements from different oblast in comparison with doses derived from ^{131}I measurements in the thyroid for adult (settlements with more than 10 measurements)

Oblast	Settlement	Type of settlement	^{137}Cs activity per unit area kBq/m^2	Ratio $^{131}I/^{137}Cs$	Rainfall (mm)	Interception for I-131	Thyroid dose (this model) Gy	Thyroid dose (derived from measurements) Gy	Ratio Model/ measurement
	Minsk						0.018	0.018	1.00
Gomel	Gomel	city	-	-	-	-	0.11	0.07	1.17
Gomel	Narovlia	town	517	11.72	2.9	0.14	0.30	0.22	1.35
Gomel	Vetka	town	751	10.1	4.3	0.11	0.19	0.16	1.22
Gomel	Bragin	town	742	10.1	4.2	0.11	0.29	0.26	1.11
Gomel	Golubovka	rural	223	16.6	1.2	0.27	0.56	0.47	1.19
Gomel	Glazovka	rural	121	8.1	3.8	0.12	0.07	0.10	0.66
Gomel	Palmira	rural	495	11.9	2.8	0.15	0.50	0.46	1.09
Gomel	Udalevka	rural	241	16.0	1.3	0.26	0.55	0.52	1.05
Gomel	Viazhyshe	rural	545	11.5	3.1	0.14	0.49	0.51	0.97
Gomel	Vyshemir	rural	207	17.1	1.1	0.29	0.57	0.79	0.72
Gomel	Bartolomeevka	rural	1490.	7.6	8.6	0.07	0.46	0.45	1.03
Mogilev	Mogilev	city	-	-	-	-	0.02	0.03	1.51
Mogilev	Cherikov	town	227	6.6	7.3	0.08	0.04	0.04	1.02
Mogilev	Pochepy	rural	135	7.8	4.3	0.11	0.07	0.05	1.31
Mogilev	Popovka	rural	297	6.1	9.6	0.06	0.07	0.03	1.97

Table 4 Comparison of thyroid assessed on the basis of ^{131}I measurements in human thyroids and by means of the radioecological model

Raion	Age groups, years	Average thyroid doses, Gy		Ratio
		Based on measurements of ^{131}I activity in thyroid	Model assessments	
Khoiniki	0-7	1.6	1.2	1.3
	7-18	1.0	0.70	1.4
	Adult	0.45	0.32	1.4
Bragin	0-7	1.5	1.1	1,4
	7-18	0.95	0.73	1.3
	Adult	0.40	0.30	1.3
Narovlia	0-7	1.3	1.4	0.92
	7-18	0.97	0.94	1.1
	Adult	0.36	0.36	1
Vetka	0-7	1.6	1.5	1.1
	7-18	1.2	0.98	1.2
	Adult	0.34	0.41	0.82

Table 5 Assumed parameter frequency distributions for the estimation of the thyroid exposure

Parameter	Model value	Type of distribution	Standard deviation	Reference
^{137}Cs activity per unit area (Bq/m²)	1[a]	Log-normal	GSD=1.5	See text
Ratio ^{131}I/^{137}Cs	10	Normal	STD=2	See text
Interception	0.15	Normal	STD=0.03	[28]
Transfer factor milk	0.003	Log-normal	GSD= 1,5	[29]
Feeding rate	43	Triangular	33-53	Judgement
Intake of milk (infants, 0-3 age)	0.4	Normal	STD=0.2	Table 2
Intake of milk (adults)	0.7	Normal	STD=0.4	Table 2
Yield of grass (fresh mass) [b]	0.5	Triangular	0.35-0.65	Judgement

[a]Relative distribution

Table 6 Correlations between parameters

Parameter 1	Parameter 2	Correlation coefficient	Remark
Interception factor	^{137}Cs activity per unit area	- 0.7	137Cs deposition increases with rainfall, Interception decreases with rainfall (eq. 9)
Interception factor	Yield of grass	0.8	Interception factor increase with yield (equation 8 and 9)
^{137}Cs activity per unit area	I/Cs ratio	-0.7	^{137}Cs deposition increases with rainfall,
Feeding rate	Yield of grass	0.5	Within the physiological limits, the feed intake increases with the feed supply

Table 7 Uncertainty for infants and adults, defined as the 97,5/2,5 and the 95/5-percentile

Age	Normalised thyroid dose (Sv per Bq m^{-2} ^{137}Cs)	
group	Ratio 97,5/2,5 percentile	Ratio 95/5 percentile
Infants	23	11
Adult	27	13

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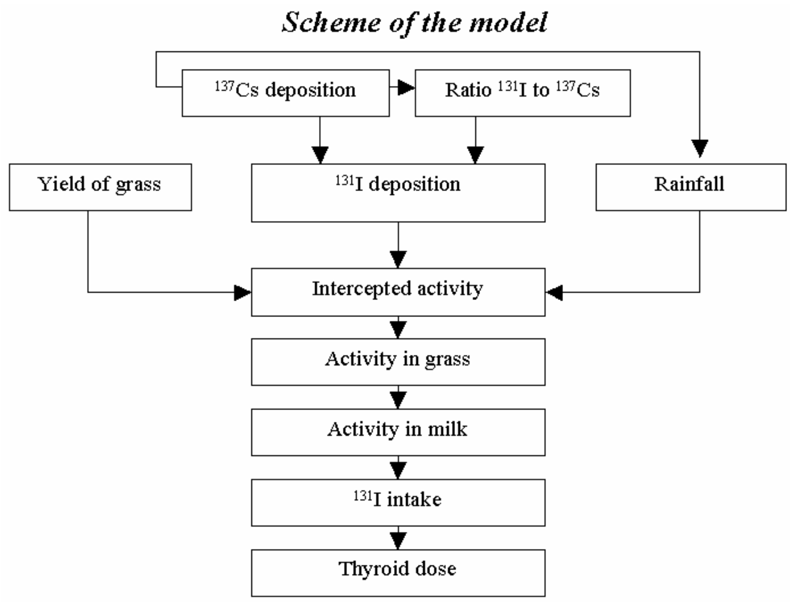

Fig. 1 Scheme of the radioecological model to estimate thyroid doses for Belarus after the Chernobyl accident.

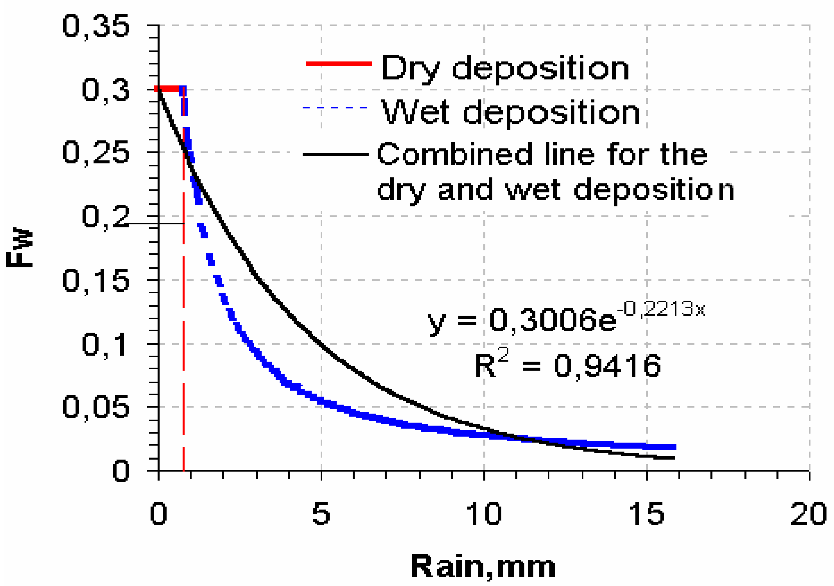

Fig. 2 Function of dependency for interception factor from value of rainfall event.

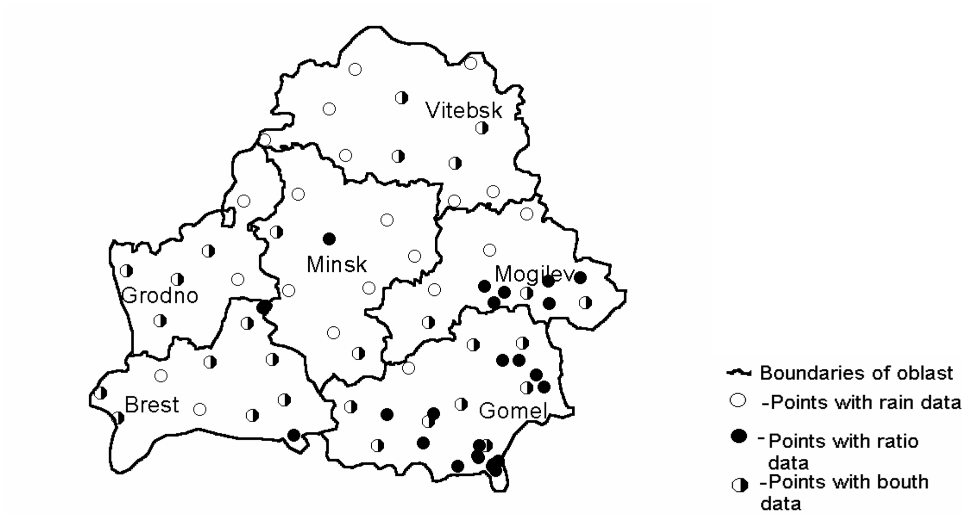

Fig 3 Locations in Belarus with measurements of rainfall and/or data on the ratio ^{131}I to ^{137}Cs for the main day of deposition.

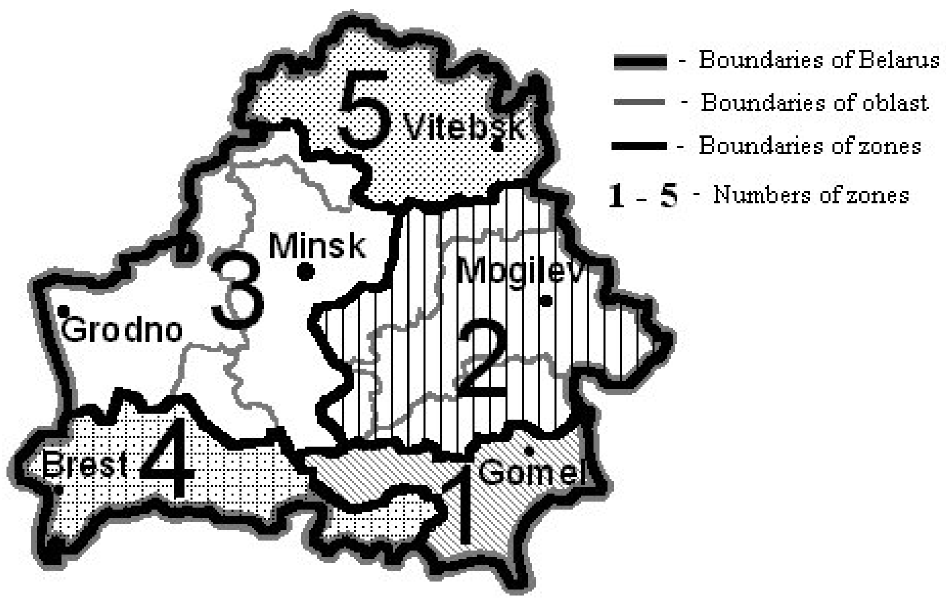

Fig. 4 Areas of Belarus with similar radioecological conditions.

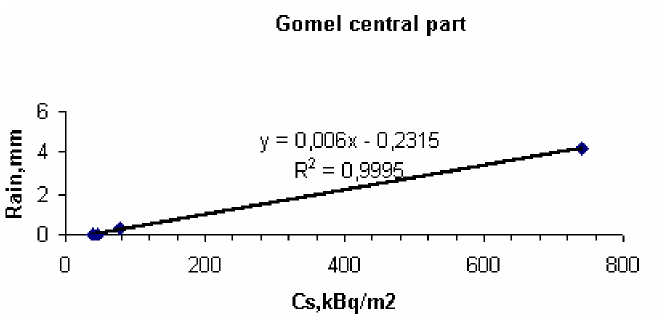

Fig 5 Relation between amount rainfall and ^{137}Cs-activity per unit area for Zone 1.

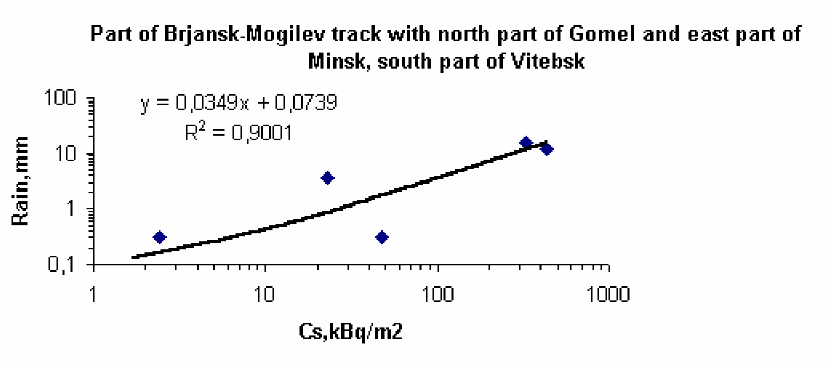

Fig. 6 Relation between amount rainfall and ^{137}Cs-activity per unit area for Zone 2

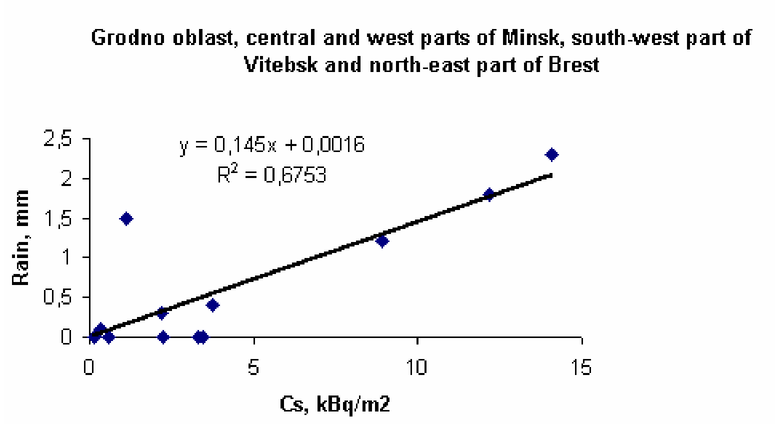

Fig. 7 Relation between amount rainfall and ^{137}Cs-activity per unit area for Zone3

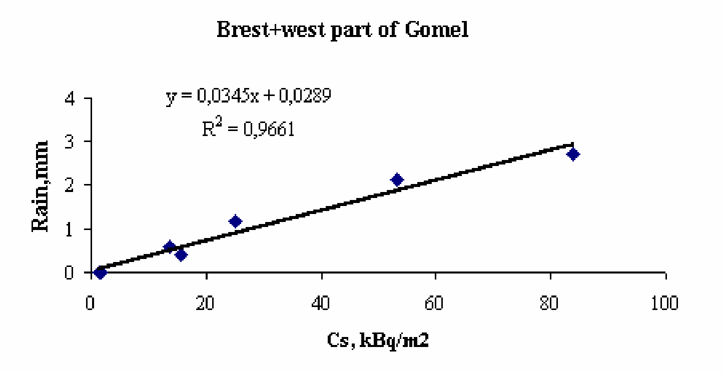

Fig 8 Relation between amount rainfall and [137]Cs-activity per unit area for Zone 4

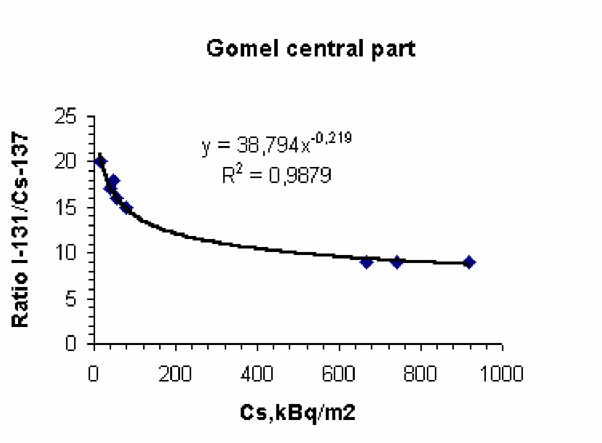

Fig. 9 Dependence between $R_{I/Cs}$ and σ_{137} for Zone 1.

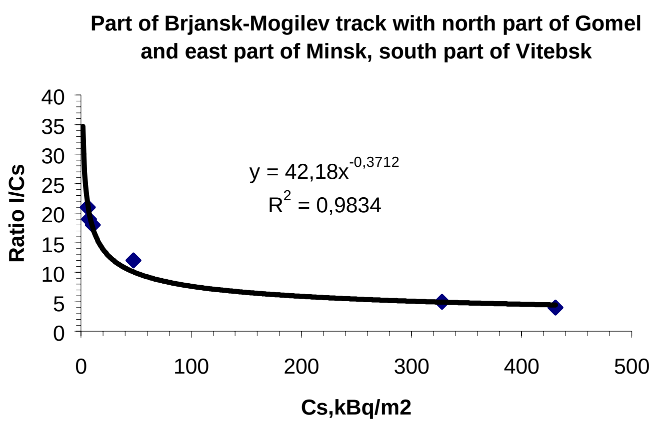

Fig. 10 Dependence between $R_{I/Cs}$ and σ_{137} for Zone 2

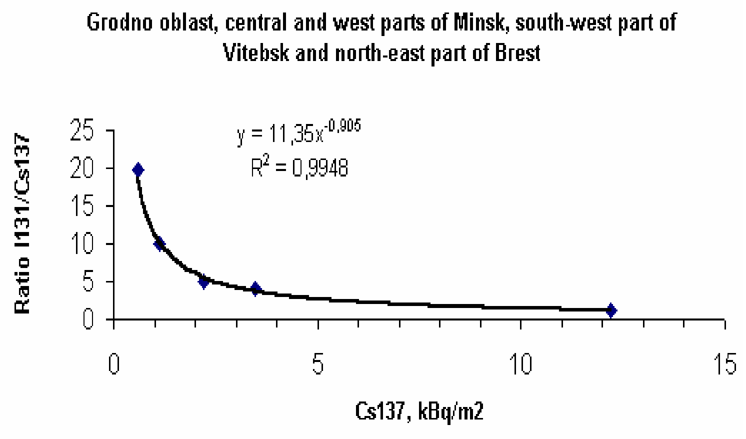

Fig. 11 Dependence between $R_{I/Cs}$ and σ_{137} for Zone 3.

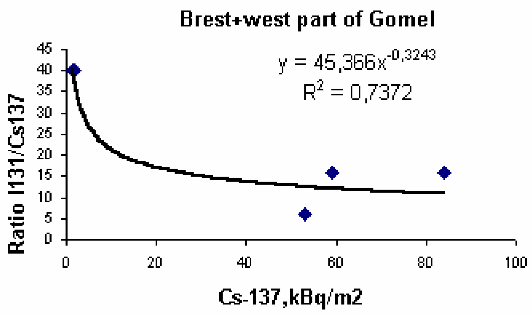

Fig. 12 Relationship between $R_{I/Cs}$ and σ_{137} for Zone 4.

Fig.13 Thyroid dose pattern for children aged 0-18 years

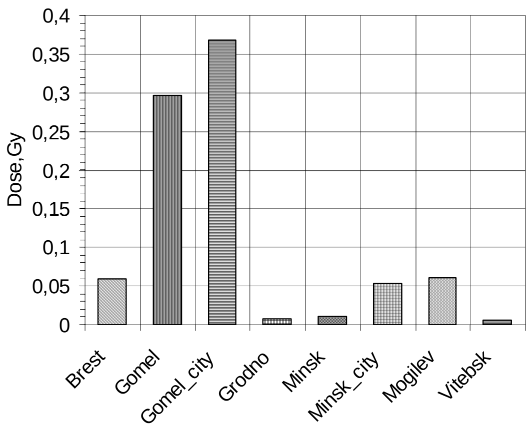

Fig. 14 The average thyroid doses for 0-18 age group for all Belarus oblasts and Gomel and Minsk cities