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Investigation of the Transfer Radioactive Contamination from the Chernobyl Zone and its Impact on Radiation in the Environment

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ABSTRACT

The study examined the consequences of a forest fire in a radioactively polluted area in the Chernobyl accident zone, namely the transfer of radioactive substances as well as their impact on the environment and radiation situation. The purpose of the study was to develop a mathematical model of the transfer of radioactive substances and a methodology for integrated assessment of the ability of an ecosystem to retain deposited radionuclides. The research methodology is based on existing proven mathematical methods and models, such as the turbulent diffusion model, the Gaussian static model, and the hierarchy analysis method (Thomas L. Saaty method). Models were obtained for the formation of a radioactive smoke cloud and its migration in the atmospheric air, the spread of radioactive aerosols and gas components, taking into account convection, turbulent exchange, humidity, wind strength and direction over the combustion zone. The processes of blowing and fluttering in the wind by the wind as the horizontal migration perturbers of radioisotopes represent a new, still insufficiently studied area of research. Integral indicators for assessing the ability of the natural components of the forest complex to reliably accumulate and retain the radioisotopes that have settled have been determined. It was revealed that the priority factors of impact on the environment and the degree of radioactive contamination are the activity and directions of migration of combustion products, which constitute radioactive contamination.

Keywords: radiation capacity, polluted areas, forest fires, radioactive spread, environmental safety.

INTRODUCTION

The global situation of forest fires on the planet is becoming problematic. Climate change suggests that fire activity will increase in temperate regions. This will greatly impact ecosystems, such as peatlands and forests. To date, there have been no complete studies on the background distribution, causes and laws of the spread of fires in such ecosystems in these regions, especially in Europe [Kirkland et al., 2023]. Given the difficulty of predicting the spread of forest fires, researchers are increasingly turning their attention to modelling these processes in three-dimensional scenarios, taking into account environmental factors [Meng et al., 2023; Sydorenko et al., 2022;

Wu et al., 2022; Zhao et al., 2023]. The next logical step is to analyse the consequences of forest fires in radiation-contaminated areas [Yeremenko et al., 2021] and the radiation impact on humans and the environment [Dolchinkov and Karaivanova-Dolchinkova, 2016; Dolchinkov, 2017]. Understanding the physical processes of the spread of radiation pollution as a result of forest fires, precisely on the basis of mathematical modelling [Sydorenko et al., 2022; Evangeliou and Eckhardt, 2020; Evangeliou et al., 2016], is an adequate and rational basis for assessing the impact of this process on the ecological system and humans. This enables to fully talk about the methods of recreation in the areas damaged by forest fires and environmental consequences in radioactively contaminated areas [Saha et al., 2023; Schüle et al., 2023].

The problem of horizontal migration of radioisotopes that have settled in soils should also be taken seriously. Such a physical phenomenon as deflation contributes to contamination or compaction of radiation contamination on the adjacent territories. Here, it is necessary to take into account the multifactorial nature of migration, namely: direction, intensity, dynamic characteristics of atmospheric flows, the tendency of the soil to deflate and the protection degree from the wind effects, etc. In addition, the secondary radioisotope contamination risk of areas associated with the soil pollution power, the activity of radionuclides per unit mass of ash and the wind erosion impact should be taken into account. Determining the level of radionuclide migration due to atmospheric phenomena can be assessed through the deflation module. The calculation of this element must have a mathematical description of the model for predicting the transfer of radionuclides in the air after a forest fire. The main parameters in this deflation model should be: radioactivity, intensity and maximum wind speed, and more.

The most adequate results of studying the process of distribution of radioactive pollutants are obtained when mathematical models are supplemented with the results of field research. Examples include studies of the identification of transport, deposition, exposure to radionuclides [Evangeliou and Eckhardt, 2020; Evangeliou et al., 2016] and chemical pollutants released after forest fires. The works [Evangeliou and Eckhardt, 2020; Evangeliou et al., 2016] assess the releases of previously fallen radionuclides from forest fires in the extremely polluted area, study their dispersion and impact on the population as well as the impact of these fires on the EU countries. Formation of a radioactive cloud and its migration in the atmospheric air during a forest fire as a result of mathematical and computer modelling is described in [Vambol et al., 2022]. Here, convection, turbulent exchange, humidity, wind strength and direction over the combustion zone were taken into account, and the obtained modelling results were compared with experimental measurements of 137 Cs concentrations in the air during a forest fire. In [Liu et al., 2023], a Lagrangian chemical transport model was presented to simulate the transport and chemical transformations of boreal forest fire plumes within several hours after their release.

An overall assessment of the studies examining the impact of the spread of radiation pollutants during and after a forest fire shows that the authors consider mathematical modelling of only individual problems. Isolating a separate area of research, namely the migration of radionuclides in forest ecosystems after a forest fire, may become a priority. Forecasting based on modelling of the secondary transfer of one of the main dose-forming radionuclides 137 Cs, forecasting changes in the radioecological state of the territory during and after a forest fire is an urgent task. The mathematical model, in this case, must combine the radioisotopes spread in the air, take into account the phenomenon of deflation as horizontal migration perturbers, as well as the ability of the ecosystem to retain deposited radionuclides in the contaminated area. For this purpose, a scientific methodological approach should be used, which, using a new integral indicator, satisfies the conditions for the complexity of solving this difficulty. As a result, the results of mathematical modelling in combination with known experimental data should make it possible to assess the level of radionuclide migration after a fire in a forest ecosystem.

The goal of this paper was to develop a mathematical model of the transfer of radioactive substances after a forest fire and a methodology for integrated assessment of the ability of the ecosystem in a contaminated area to retain fallen radionuclides. To achieve these goal, the following tasks were solved:

1. Determination of a physical and substantiation of a mathematical model of the transfer of radioactive substances after a forest fire;
2. Consideration of the secondary transfer of one of the main dose-forming radionuclides, 137 Cs, using a mathematical model as an

expression of the relationship between key parameters of processes of blowing and fluttering in the wind by the wind namely, the maximum possible wind speed and radioactivity, etc.;
3. Use of computer modelling for a smoke plume generating and scattering and the precipitation of radioactive particles as combustion products from it;
4. Assessment of the ability of forest ecosystem elements to firmly retain fallen radionuclides after a forest fire;
5. Analysis of the process of spreading radioactive contamination of 137 Cs to a forest ecosystem was conducted based on the proposed mathematical model, and the results were compared with full-scale field studies.

MATERIALS AND METHODS

To develop a universal approach to constructing a mathematical model of various ecosystems, a block hierarchical structure was proposed. In describing the forest ecosystem, the decomposition method was used as a variation of the hierarchy analysis method (Thomas L. Saaty). Descriptions of the process of distribution of radionuclides after a forest fire in the air were carried out using a turbulent diffusion model and a Gaussian static model. To determine the potency and direction of the radioactive combustion products migration, a deflationary approach was applied. The mathematical description of the spread of radioactive contamination of territories in an ecosystem is a system of linear differential equations of the first order with constant coefficients. The results of statistical method, were used as data from field research and monitoring of forest ecosystems of the 30 km Chernobyl nuclear power plant zone.

Mathematical modelling

On the basis of an understanding of the probabilistic character of the forest fires physical processes in contaminated areas and the complexity of mathematical modelling of the secondary transfer of one of the main dose-forming radionuclides, 137 Cs, it was proposed to distinguish two stages of this phenomenon. At the first stage, it is necessary to simulate the release of radioactive combustion products during a forest fire onto the ecosystem territory. The calculation results of the first stage will become the initial data for the second stage, at which the process of migration of the radioactive pollutant 137 Cs in the ecosystem will be modelled. At this stage, it is important to determine an integral assessment of the ability of ecosystems to firmly retain fallen radionuclides.

The authors proposed to use such a concept as the radiation capacity of an ecosystem (relative value in percentage), which allows assessing the main integral characteristics of ecosystems. Radiation capacity determines the proportion of radionuclides that can be firmly contained in the ecosystem (for a year or longer) and must take into account the following parameters:
1. The forest ecosystem type (coniferous, mixed, deciduous);
2. Biomass reserves of forest ecosystems depending on age characteristics;
3. The radionuclide flow parameters from the territory of the forest ecosystem, depending on the average surface slope;
4. Parameters of mobility and solubility of radionuclides in accordance with the type of radionuclide contamination. For example, for the 30 kilometre zone of the Chernobyl nuclear power plant, these can be predominantly fuel particles, condensation components and water-soluble radionuclides;
5. The radionuclide contamination level and their area.

Such indicators are sufficient to calculate what fraction of radionuclides will accumulate in the forest phytobiomass on the surface, and what fraction can enter watercourses from the catchment area with surface run-off.

Modelling a radioactive smoke cloud during a forest fire

The physical nature of the formation of radioactive smoke contamination during a forest fire is conveniently presented in Figure 1, which shows the main zones and stages of the fire. In this diagram, arrows show the spread of contamination. Red indicates high-temperature components, blue indicates the formation of a radioactive smoke cloud with a moderate temperature, and purple indicates a temperature close to ambient temperature.

Taking into account the physical factors and their interrelationships presented in Figure 1, the initial data necessary for modelling smoke radiation pollution can be formed. To evaluate of the radiation contamination degree during a forest fire, it is necessary to know as initial data:

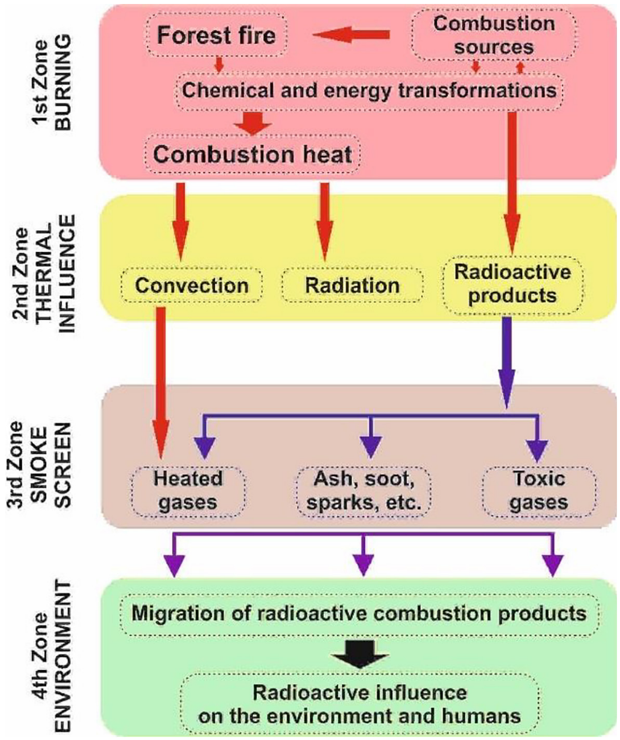

Figure 1. Formation of a radioactive smoke cloud during a forest fire and the impact of radiation on the environment

- Location and conditions of the forest fire;
- The planted forests type and their nuclear pollution;
- Fire intensity and duration;
- The forest fire;
- The process of fire;
- The radioactive aerosols' presence in the combustion products;
- The radioactive combustion products' migration process to the environment;
- The zone of radioactivity distribution taking into account wind direction.

When modelling the emissions of radioactive combustion products during a forest fire, it is proposed to consider a number of independent problems that are interconnected by the step-by-step phases of their occurrence and spread. In the first phase, the transition of radioactive combustion products into the environment occurs through a smoke cloud. In the second phase, the plume of the smoke cloud moves along the surface of the earth. In the third phase (considerable distance from the fire source), a small amount of radiation pollutants remains in the smoke plume due to their "dry" deposition and dispersion.

The distribution process of radioactive combustion products in the atmosphere can be described by various dynamic models. However, to calculate rapidly occurring combustion processes from various foci, physically improved and mathematically adequate models must be applied. To calculate the concentration of radioactive combustion products in the atmosphere, taking into account the variable power of combustion sources and the time of their action, various equations are used [Azarov, 2001].

The main ones are the turbulent diffusion' mathematical expressions for radioactive pollutants filling into the atmosphere as a result of fires with coordinates (x, y, z) located in unlimited space, at constant wind speed and turbulent diffusion coefficients [Azarov, 1998]:

$$\frac{dC}{dt} = k_x \frac{d^2C}{dx^2} + k_y \frac{d^2C}{dy^2} + k_z \frac{d^2C}{dz^2} - \sum_{i=1}^{3} V_i \frac{dC_i}{dx_i}$$

$-\infty < x, y, z < \infty$; (1)

$t > 0$;

$C(0, 0, \Delta h_{ef}, 0) = Q/\Delta W$,

where: $C(x, y, z, t)$ – the radioactive combustion products content per unit volume of atmospheric air depending on time and space coordinates; k_x, k_y, k_z – the turbulent diffusion coefficients for radioactive combustion products in the atmospheric surface layer; V_x, V_y – the wind speed projections on the coordinate axes; V_z – the velocities sum of the radioactive combustion products gravitational settling and the smoke cloud movement in the vertical direction; Q – total activity of α-, β-, γ-radionuclides released into the atmosphere; ΔW – volume of radioactive combustion products released into the environment; Δh_{ef} – the height of the rise of the smoke cloud relative to the surface of the earth.

To calculate the concentration of radioactive combustion products in the atmosphere according to the Green's function properties, the following entry can be used:

$$C(x, y, z) = \int_0^{T} P(\tau) \cdot G(x, y, z, t)\, \partial\tau; \quad (2)$$

$$T = \begin{Bmatrix} t_n, & \text{if } t > t_n \\ t, & \text{if } t \le t_n \end{Bmatrix}$$

The power of a source of release of radioactive combustion products can be determined as the ratio of the total quantity of pollutants diffusing into the atmosphere during the fire outbreak activity:

$$P_t = \frac{Q}{t_n} \quad (3)$$

For a continuous release $P(t)$ = const, one can use formula (2) provided that $t_n \to \infty$, $t \to \infty$, but then the integration will be taken analytically.

Radioactive contaminant concentration $\overline{C_n}$ at each space coordinate $\overline{X_j} = (x^j, y^j, z^j)$ $\overline{X_j} = (x^j, y^j, z^j)$"provided" activity n fire foci and the emission source power – Pj, each having coordinates $\overline{L_j} = (l_1^j, l_2^j, l_3^j)$ is determined by the dependence:

$$\overline{C_n}(\overline{X_j}, \overline{L_j}) = \sum_{j=1}^{N} C(P_j, \overline{X_j}, \overline{L_j}) \quad (4)$$

Formula (4) should be used to calculate the process of distribution of radioactive combustion products from several fires with a complex shape. In addition to this, the concentration fields of radioactive pollutants in the atmosphere, which are formed from fire sources in an area, linear or volumetric can be determined by calculation. The smoke cloud height can be determined using the following mathematical notation:

$$\Delta h_{ef} = \vartheta_i \cdot M^{1/3} \cdot X^{2/3} \cdot U^{-1} \quad (5)$$

where ξi – the transition coefficient for the i-th stability of the atmosphere; M – power of the heat source; X – vertical width of the smoke plume; U – wind speed at the mixing smoke cloud height.

The distance from the smoke cloud release point to the fallout place of radioactive pollutants is determined by the following formula:

$$L = \varepsilon_1 \cdot M^{3/5} \cdot U^{-1} \quad (6)$$

where: ε_1 – transition coefficient for the i-th stability of the atmosphere.

Modelling the spread of radioactive contamination in an ecosystem

To assess the radiation contamination of forest ecosystems after a fire, it is very important to understand what basic elements the ecosystem consists of and how they interact with each other. Interaction between elements of the system is the possibility of transfer of radionuclides from one area (element of the ecosystem) to another. To describe the interaction of all components, it is most convenient to use the decomposition method, similar to the method of hierarchy analysis (Thomas L. Saaty's method). The mutual connection between adjacent subsystems is described by analogy with the finite element method used in mechanics. In this case, the final conditions on the boundary of the previous element are the initial conditions for the subsequent element.

In a general setting, it is necessary to consider the forest ecosystem and the adjacent territories. At the same time, following the principle of priority of the source of impact of a forest fire, the following elements are highlighted: forest (1); forest edge (2); meadow (3); terrace (4); floodplain of a reservoir (river) (5); body of water (river) (6); biota (7); bottom sediments (8); person (9).

The formation of subsystems is carried out taking into account general characteristic features (biological, hydrological, etc.) and thus three subsystems are distinguished (Figure 2): forest, biological and hydraulic subsystems. The forest subsystem consists of such elements as: forest (1), forest edge (2) and meadow (3). In the biological subsystem: terrace (4), biota (7) and humans (9). The hydro subsystem is presented as a set: the floodplain of a reservoir (5); reservoir (6) and bottom sediments (8). The mutual influence and interactions of elements within the boundaries of a subsystem in an ecosystem are shown in Figure 3.

The proposed architecture is flexible and universal in terms of adding/excluding ecosystem elements. For example, by completing eliminating one of the subsystems, the logic of interaction of the remaining elements is not violated. This approach is very important from the point of view

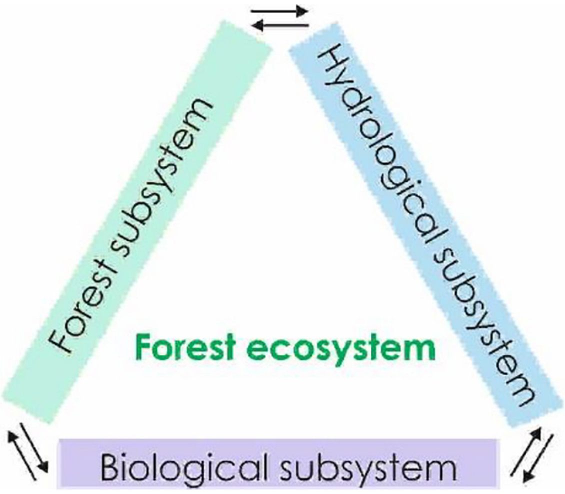

Figure 2. Enlarged structure of the forest ecosystem

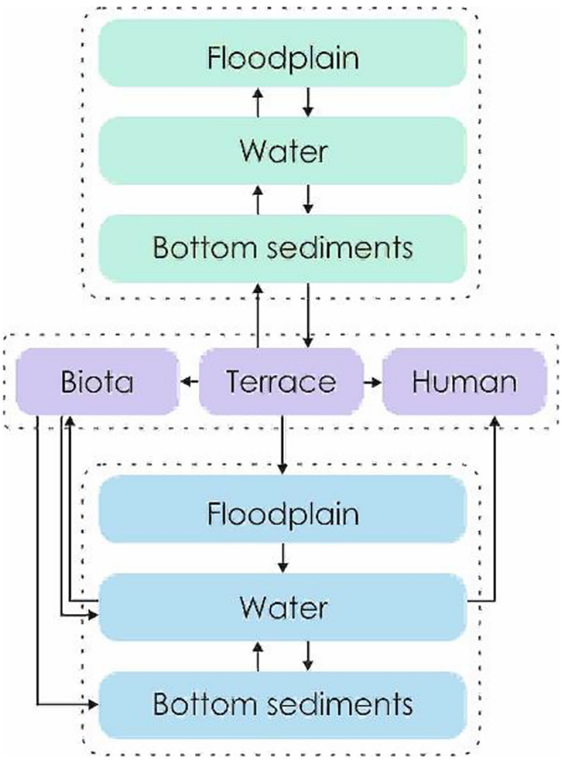

Figure 3. Scheme of forest ecosystem elements

of the flexibility of the process of mathematical modelling of assessing the radiation capacity of forest ecosystems after forest fires.

To mathematically describe the spread of 137 Cs radioactive contamination in an ecosystem, it is most convenient to use differential equations. A system of first-order linear differential equations with constant coefficients quite adequately describes the process under consideration. A similar approach was proposed in [Groza and Matvieieva, 2019] for assessing radioecological processes and the reliability of pollution on ecosystems, but they used a system of three differential equations in which the sought values were for the forest-stream-river elements.

In the conducted study, considering a generalized approach that allows taking into account any number of elements in the ecosystem was proposed. The number of differential equations in this system corresponds to the number of elements of the forest ecosystem. In this case, the mathematical notation looks quite compact, which makes it very convenient for further modelling:

$$\frac{dx(t)}{dt} = Ax(t) \tag{7}$$

where: $x(t) = \{x_1(t), x_2(t),..., x_n(t)\}$ – a vector of unknowns with components characterizing the level of radioactive contamination (Bq) in the elements of the ecosystem; n – number of elements of the forest ecosystem; t – time in decades (10 years); A – matrix of constant coefficients of radioactive decay and sequential transfer of pollution from one element of the forest ecosystem to another. The elements of this matrix a_{ij} are determined on the basis of field studies and depend on geological, biological, meteorological and other parameters.

RESULTS AND DISCUSSION

To assess the radiation capacity of forest ecosystems after forest fires, it is enough to determine the number of ecosystem elements. For example, in the absence of a hydraulic subsystem, there is a mathematical model consisting of six first-order differential equations with unknown specific activity coefficients of radionuclides xi (i = 1...6), forest (1); forest edge (2); meadow (3); terrace (4); biota (5); person (6).

To study the stability of the system of differential equations, a typical slope forest ecosystem was chosen, consisting of nine components: forest λ_i = -0.6 (1); forest edge λ_i = -1.3 (2); meadow λ_i = -1.8 (3); terrace λ_i = -6.3 (4); floodplain of a reservoir (river) λ_i = -3.3 (5); body of water (river) λ_i = -12.86 (6); biota λ_i = 1.39 (7); bottom sediments λ_i = -1.35 (8); forest λ_i = -1.3 (9) (Figure 3). The characteristic polynomial λ_i, (i – one of the nine forest ecosystem components) of matrix A has only negative real roots.

This result indicates the stability of the zero solution of the system with respect to the perturbation of the initial conditions (Lyapunov stability) and the asymptotic stability of the system, that is, it can be argued that $y_i(t) \xrightarrow[t\to\infty]{} 0$; (i = 1, 2…,8).

Smoke plume propagation, and radioactive particles fall out

On the basis of the equations of impulse, mass and the air flow energy and the number of particles in the smoke plume, a three-dimensional model of the smoke plume propagation and the radioactive particles formed from it was developed. The ordinary differential equations system for the speed of air flow along the jet axis, its overheating relative to the ambient temperature, the smoke jet radius, and the concentration of radioactive combustion products in the smoke plume has been solved numerically. Each layer was treated as a separate, independent source of radioactive combustion products. In this case, the concentration of radioactive particles in the atmosphere at different distances from the release site was calculated. Statistical data on temperature and wind fields obtained from radiosonde data were used as input information for the modelling. A forest fire in the Chernobyl zone with a circular area with a radius of 100 meters and a duration of the convective stage of the fire of 1 hour was taken as the initial one. The minimum height of the jet lift was between 2000 and 2500 m and depended on the wind speed profile in the boundary layer and its stratification. As a result, data were obtained for the concentration of 137 Cs at a forest pollution density of up to 37 kBq/m^2 and a relative amount of activity rising into the atmospheric air equal to 7%. Figure 4 shows the dynamics of the formation and movement of a smoke cloud during a forest fire [Vambol et al., 2021].

The heated smoke cloud from radioactive combustion products, which rose into the atmosphere through the action of Archimedean force, was investigated. This cloud moved upward at a speed of no more than 10 m/s. The volatile particles of radioactive combustion products had a complex morphology and chemical inclusions with a density between 3 and 10 mg/cm^3. Particle size varied over a wide sizes range between 0.1 and 100 μm. At the same time, their aerodynamic diameter varied between 30 and 50 μm. The overall result of radioactive contamination of the area depended on time, which depended on meteorological

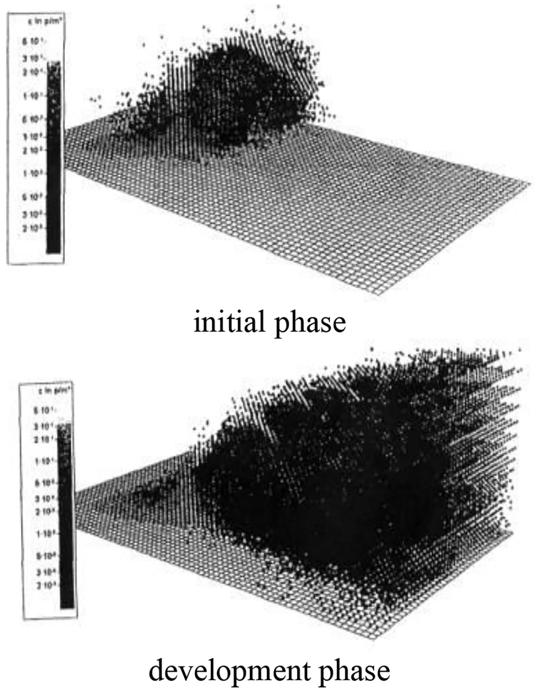

Figure 4. Dynamics of formation and movement of a smoke cloud in space [Vambol et al., 2021]

parameters and distance to the forest fire source (Figure 5) [Vambol et al., 2021].

The main result of the study should be considered the proposed associated mathematical models of the distribution of radionuclides after a fire, both in the atmosphere and in the forest ecosystem.

The significance and originality of the results lie in the systematic approach to studying the issue of radioactive contamination transfer. Models were obtained for the formation of a radioactive smoke cloud and its migration in the atmospheric air, the spread of radioactive aerosols and gas components, taking into account convection, turbulent exchange, humidity, wind strength and direction over the combustion zone. The processes of blowing and fluttering in the wind by the wind as the horizontal migration perturbers of radioisotopes represent a new, still insufficiently studied area of research. In this regard, it seems appropriate to develop an effective methodology for assessing these processes (which are collectively called deflation) that will serve as an indispensable tool for conducting expert assessment of the radiation situation in the area under study. The proposed radiation capacity of an ecosystem as an integral indicator is the most universal characteristic, which in percentage equivalents shows the share of radionuclides entering the forest ecosystem. A mathematical approach based on a system

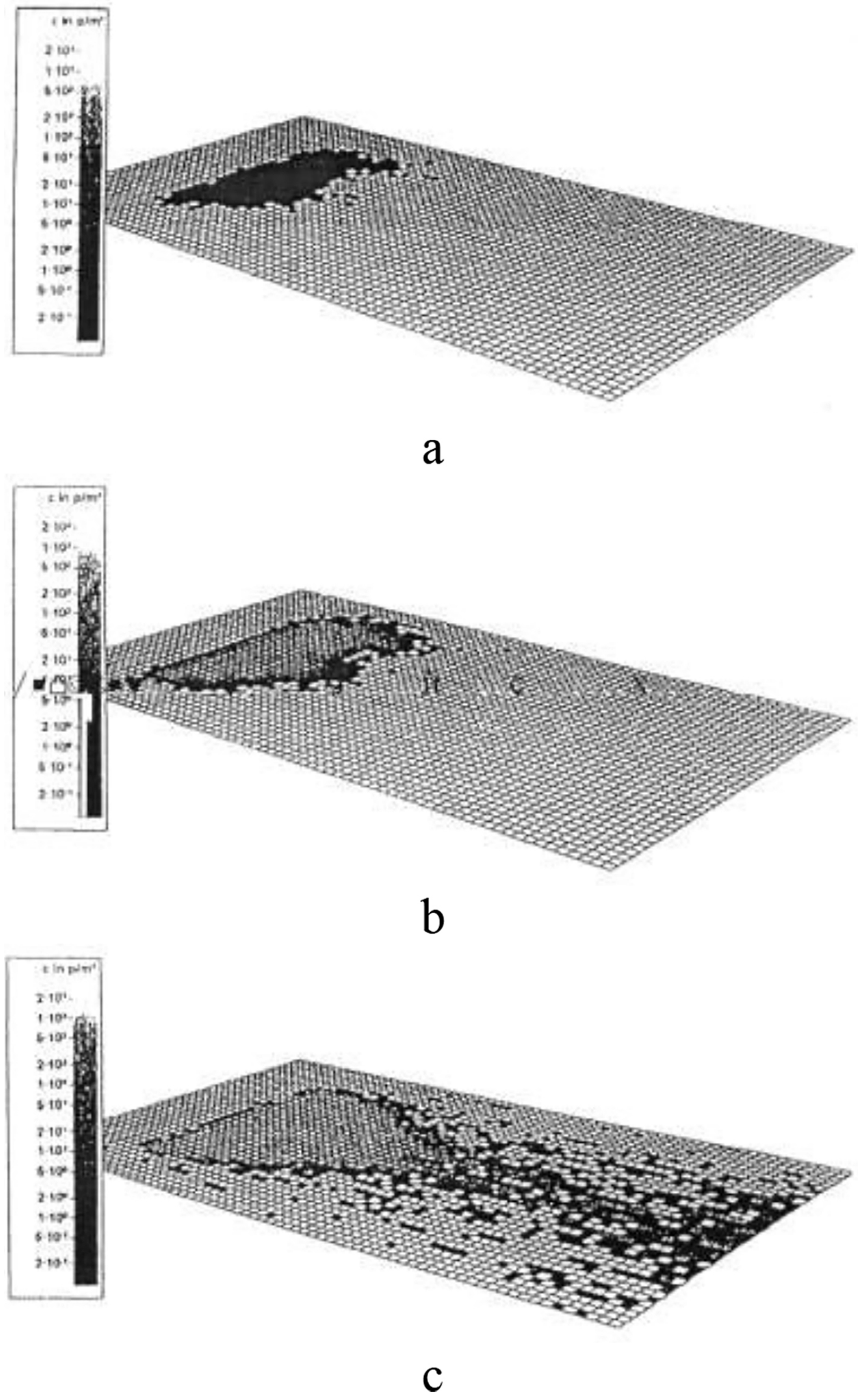

Figure 5. Dynamics of the volatile particles density changes that are formed from radioactive combustion products and settle. Smoke plume trace [Vambol et al., 2021]: a – t_1 = 30 min.; b – $t_{2\,0}$= 120 min.; c – t_3 = 210 min

of first-order differential equations with constant coefficients taking into account the transition coefficients of radionuclides c and their radioactive decay makes it possible to simulate the processes of migration of radionuclides in forest ecosystems and calculate the radiation capacity for various variants of the territory.

Radionuclide distribution forecast in the forest ecosystem

A typical slope forest ecosystem was studied: forest (1); forest edge (2); meadow (3); terrace (4); floodplain of a reservoir (river) (5); body of water (river) (6); biota (7); bottom sediments (8);

person (9). The interaction between elements was determined using the transfer coefficients of radionuclides from one element to another per unit of time (one year). For example, a12 is the coefficient of transition of radionuclides from the forest elementary (1) to the forest edge elementary (2). The coefficients were selected based on field studies and depend on the nature of the cover (forest, grass, etc.), slope, soil type (chernozem, sod-podzolic, gray-forest), runoff volume, air temperature, wind direction and strength, as well as others meteorological parameters.

The parameters of phytobiomass in forest ecosystems are important. A general assessment of phytobiomass reserves in forest ecosystems is given in Table 1. After the Chernobyl accident and at the beginning of the recovery period, most of the radionuclides (82–92%) were in the forest litter, and only 8–12% in the top layer of soil. At the same time, almost 94–99% of radionuclides in the soil are concentrated in a thin upper layer 0–5 cm thick. On the basis of authors' own data and the data from the Ministry of Forestry of Ukraine, an estimate was made of the average accumulation of 137 Cs radionuclides in phytomass, which is $2.6 \cdot 10^{-9}$ Ci/kg for soil containing 1 Ci/km^2 of radionuclides for a coniferous forest and $7.0 \cdot 10^{-9}$ Ci/kg for a mixed forest. These data make it possible to approximately estimate the content of radionuclides in the phytomass of forest ecosystems. Using these data and the values of transition coefficients (TC) in the soil-plant system, it is possible to calculate the expected content of radionuclides in the phytomass formed over an area of 1 km^2 at a radioactivity level at 137 Cs of 1 Ci/km^2 (Table 1).

It has been established that the percentage of the annual surface run-off of radionuclides in a forest with a slope of 1–2 degrees does not exceed 0.2% per year of the stock of radionuclides on the site. For an area with a slope of 3–4 degrees, this value is estimated at 0.5%, and for steeper slopes (6–8 degrees) – at 1%. These conservative marks were taken for the first approximate calculations. In the future, these parameters should be clarified by field measurements.

Parameters of the system of differential equations that are responsible for the migration of 137 Cs radionuclide in the ecosystem:

1. a_{12} – parameter that characterizes the rate of the transition of the 137 Cs radionuclide from the forest element (1) to the forest edge element (2). Long-term monitoring data was used, which showed that a forest can lose from 1 to 5% of the radionuclide reserve per year;
2. a_{23} – parameter characterizing the rate of transition of the 137 Cs radionuclide from the forest edge element (2) to the element; meadow (3). It has been established that 137 Cs is transferred from the edge of the meadows in an amount of 5–15% of the reserve at the edge. An increase in this parameter is associated with a different nature of the coverage, steepness of the slope, and the nature of the run-off;
3. a_{34} – parameter characterizing the rate of transition of the 137 Cs radionuclide from the meadow element (3) to the terrace element (4). The meadow is a zone of anthropogenic influence (animal grazing) and has a relatively weak cover (grass), so the share of 137 Cs transfer will be from 10 to 20% of the total stock in the meadows;
4. a_{45} – parameter characterizing the rate of transition of 137Cs from the terrace element (4) to the floodplain element of the reservoir (5). The agricultural terrace where radionuclides arrive is a zone of active agricultural activity, so the transfer of radionuclides to the floodplain will be somewhat greater and will range from 10 to 30% of the reserve on the terrace;
5. a_{49} – parameter characterizing the rate of the transition of 137 Cs from the terrace element (4) to the human element (9). People actively use products from the agricultural terrace for grazing and feeding livestock and nutrition. It is known that on agricultural lands, the loss of 137 Cs can range from 20 to 60% of the reserve on an agricultural terrace.

Taking into account the transition coefficients of radionuclides, corrected for their radioactive decay, the system of nine simple first-order differential equations with constant coefficients looks like this:

Table 1. Phytomass reserves and radionuclide content in forest ecosystems

Forest type	Young		Middle-aged		Mature	
	Phytomass reserves, t/km^2 dry weight	Radionuclide content, Curie	Phytomass reserves, t/km^2 dry weight	Radionuclide content, Curie	Phytomass reserves, t/km^2 dry weight	Radionuclide content, Curie
Pine	15000	0.04	23 000	0.06	25 000	0.065
Mixed	22000	0.15	32 000	0.22	38 000	0.27

$$
\begin{aligned}
\frac{dx_1}{dt} &= -0.06x_1(t). \\
\frac{dx_2}{dt} &= 0.03x_1(t) - 0.13x_2(t). \\
\frac{dx_3}{dt} &= 0.10x_2(t) - 0.18x_3(t). \\
\frac{dx_4}{dt} &= 0.15x_3(t) - 0.63x_4(t). \\
\frac{dx_5}{dt} &= 0.20x_4(t) - 0.33x_5(t). \\
\frac{dx_6}{dt} &= 0.30x_5(t) + 0.05x_7(t) + 0.07x_8(t) - 1.23x_6(t). \\
\frac{dx_7}{dt} &= 0.50x_6(t) - 0.13x_7(t). \\
\frac{dx_8}{dt} &= 0.05x_7(t) + 0.60x_6(t) - 0.10x_8(t). \\
\frac{dx_9}{dt} &= 0.40x_4(t) + 0.10x_6(t) + 0.03x_9(t).
\end{aligned} \tag{8}
$$

where: variables x_i are dynamic specific activities of radionuclides in ecosystem elements: forest (1); forest edge (2); meadow (3); terrace (4); floodplain of a reservoir (river) (5); body of water (river) (6); biota (7); bottom sediments (8); person (9); t – time.

Using mathematical apparatus to solve the system of differential Equations 8, the results of the distribution of radionuclides were obtained, which are presented graphically in Figure 6.

In a particular case, to analyse the influence of radiation pollution on the biological forms, it is convenient to isolate the biological subsystem. In this situation, the mathematical model (8) is simplified and reduced to a system of three equations:

$$
\begin{cases}
\dfrac{dx_1}{dt} = -0.63x_1(t). \\
\dfrac{dx_2}{dt} = -0.13x_2(t) \\
\dfrac{dx_3}{dt} = 0.40x_1(t) + 0.03x_3(t).
\end{cases} \tag{9}
$$

Next, using a similar mathematical algorithm for solving the system of differential Equations 9, a graphical representation of the forecast of the distribution of radionuclides is obtained (Figure 7).

Obviously, as a result of a forest fire, when the litter and turf are completely burned out, one can expect a significant increase in the rate of migration and surface run-off of radionuclides.

Comparison of the obtained results with field research data

Figure 8 shows the results of a comparison of data obtained by modelling and experimental

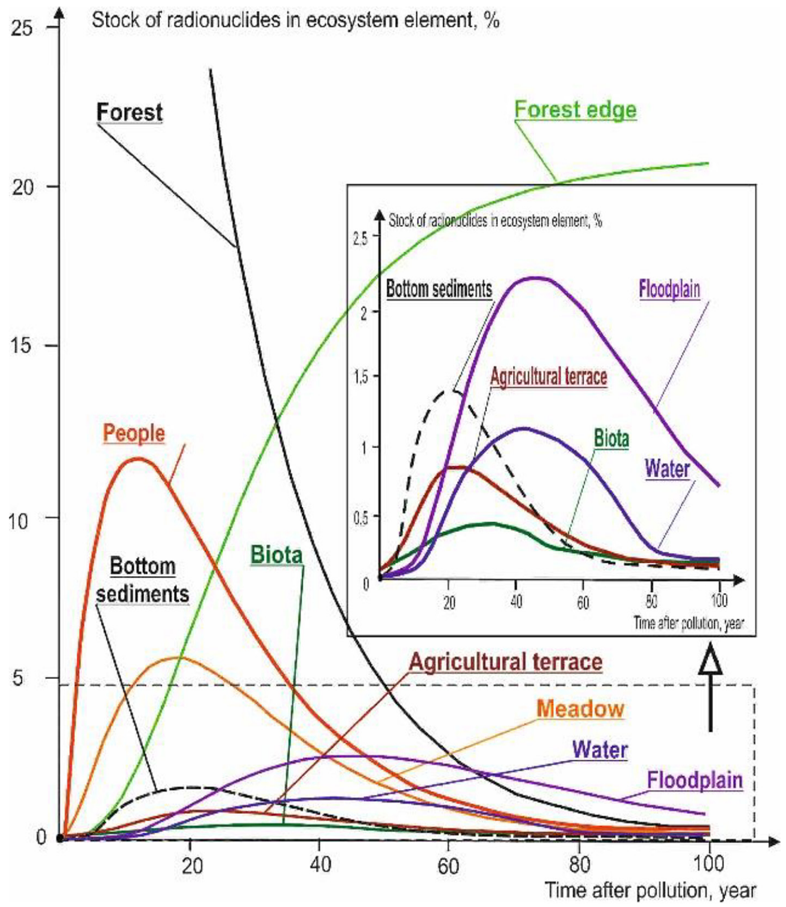

Figure 6. The radionuclides distribution in the forest ecosystem in % over time

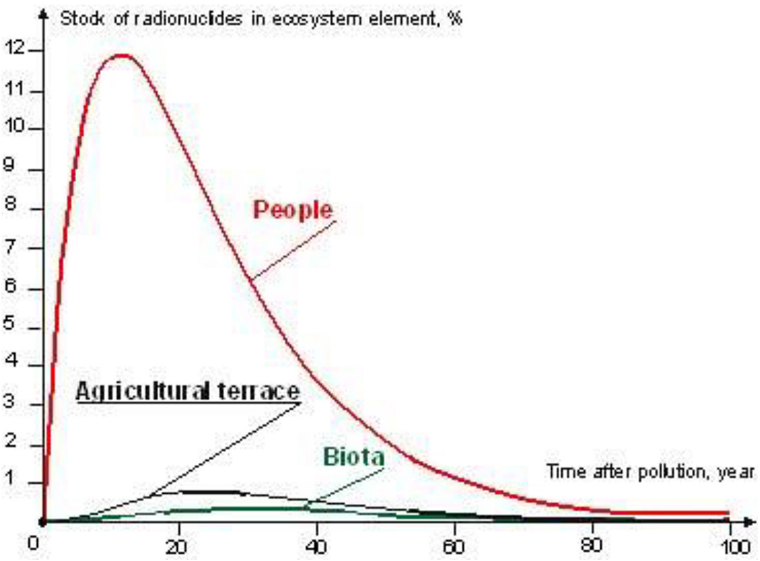

Figure 7. Forecast of radionuclide distribution in the biological subsystem

measurements of 137 Cs concentrations in the air and the density of deposition on the soil surface P during a forest fire in the summer of 1992 in the Exclusion Zone [Vambol et al., 2021]. The developed algorithm and software were adapted taking into account the obtained field experimental data. Also, by comparing field experimental data with modelling results, the reliability of these results was checked.

The field results showed (Figure 8) that the error in the spatiotemporal distribution of 137 Cs concentrations in the atmospheric air and the density of its deposition on the surface of the earth does not exceed 30%. This discrepancy in the data obtained can be explained by the fact that smoke particles had a complex morphological and physicochemical composition with a density from 3 to 10 mg/cm^3, and their spectrum varied in a wide range from 0.1 to 100 μm with different aerodynamic diameters from 30 to 50 microns.

According to these data over 15 years, the total volume of migration for various scenarios is 1.5–7.4% of the stock in the forest ecosystem. On the basis of these values, one should not expect a significant spread of radionuclides from forest ecosystems. The sufficiently high radiation capacity of these territories on small slopes contributes to low migration of radionuclides, and at significant angles of surface inclination it is necessary to evaluate the total run-off of radionuclides and evaluate the paths of further migration on the landscape as a whole (Table 2). Negative flow

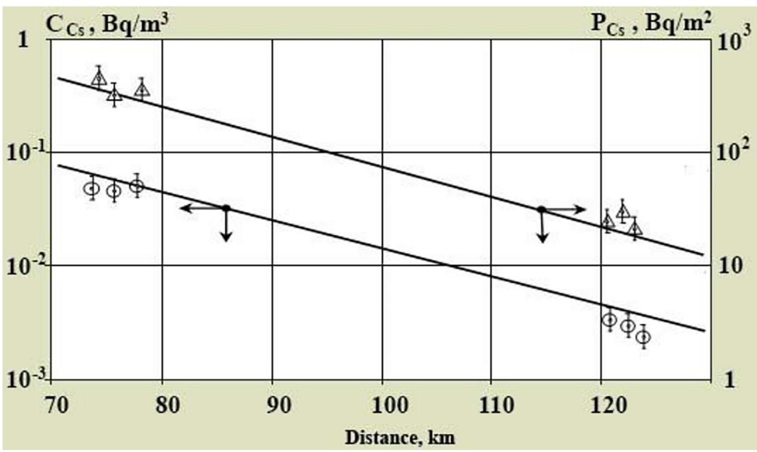

Figure 8. Results of comparison of numerical modelling data and experimentally measured concentrations of 137 Cs radioisotope fallout [Vambol et al., 2021]

zones, where radionuclides are strongly retained, are also considered as an option. Therefore, a radical situation with the migration of radionuclides is only possible as a result of an external influence, such as a fire.

The data from cartographic studies made it possible to generate tables of planes of different types of forests, taking into account slope angles for different values of radionuclide contamination. On this basis, the amount of radionuclides that can migrate at different levels of radionuclide contamination was calculated, which makes it possible to estimate the total radiation capacity of forest ecosystems in the 30 – kilometer Chernobyl NPP zone (Table 3).

According to field studies of the burned forest areas of the 30 – kilometer zone of the Chernobyl Nuclear Power Plant, the amount of radionuclide migration on slopes after a fire increases by at least 10 times and, therefore, the percentage of transfer on different slopes should also be increased 10 times. This makes it possible to realistically assess the migration of radionuclides from forest ecosystems on different slopes, taking into account the calculated probability of fires. Table 4 presents the calculation results for three levels of radionuclide contamination at 137 Cs: 5–15, 15–40 and more than 40 Ci/km^2. Thus, the total migration of radionuclides from forest ecosystems in the 30 kilometre zone of the Chernobyl Nuclear Power Plant, taking into account a probable fire, may increase by 136 Ci over a period of 20–30 years.

Following further reasoning, it is necessary to assess the total impact of possible fires on the radiation capacity of forest ecosystems. Table 5 presents the data on the total annual migration of radionuclides from forest ecosystems with different levels of pollution under normal conditions and taking into account a possible fire. The

Table 2. The magnitude of the radionuclide migration from the forest biocoenosis and radiation capacity for various variants of the slope of the territory. (area 1 km^2, activity 10 Ci/km^2)

Year	Coniferous forest, Ci			Mixed forest, Ci		
	1–2	2–4	4–8	1–2	2–4	4–8
1986	0.005	0.02	0.03	0.012	0.03	0.06
1987	0.012	0.03	0.06	0.016	0.04	0.08
1990	0.35	0.76	0.4	0.6	0.9	0.3
1995	0.27	0.43	0.1	0.4	0.7	0.2
1999	0.15	0.39	0.1	0.3	0.5	0.15
2001	0.1	0.25	0.1	0.2	0.3	0.1
Total over 15 years	0.15	0.35	0.7	0.16	0.37	0.74
Radiation capacity, %	98.5	96.5	93.0	98.4	96.3	92.6

Table 3. Assessment of the total migration of radionuclides (Ci) from forest ecosystems of the 30 kilometre Chernobyl NPP zone with different levels of contamination

Parameters	Contamination, Ci		
	1–2	2–4	4–8
Total supply, Ci	5630	8700	34 600
Migration, Ci	104.3	108.2	526.8
Radiation capacity, %	98.2	98.8	98.5

Table 4. Total migration of radionuclides from forest ecosystems in case of fire

Contamination, Ci/km^2	Slope after fire, Ci				
	0–1	1–2	2–4	4–8	Sum
5–15	0	5.0	43.4	–	48.4
15–40	0	5.8	9.7	–	15.5
More than 40	0	50.4	4.8	16.6	71.8

Table 5. Annual migration of radionuclides from forest ecosystems

Parameters	Contamination, Ci			
	5–15	15–40	More than 40	Sum
Total inventory, Ci	5630	8700	34600	
Migration under normal conditions, Ci	104.3	108.2	526.8	739.3
Radiation capacity under normal conditions, %	98.2	98.8	98.5	
Migration in case of fire, Ci	152.7	123.7	598.6	875.0
Radiation capacity taking into account probable fire, %	97.3	98.6	98.3	

Table 6. Forecast of the reliability of a typical slope ecosystem at different levels of radionuclide contamination (137 Cs) of the upper part (forest)

Pollution level	10 Ci/km^2	50 Ci/km^2	100 Ci/km^2
Forest	0.934	0.671	0.342
Forest edge	1	1	1
Meadow, 6%	0.999	0.997	0.993
Agricultural terrace, 1.4%	0.9998	0.999	0.998
Floodplain of a reservoir (lake), 0.82%	1	0.9994	0.999
Biota of bottom sediments of a reservoir (lake), 1.16%	0.95	0.748	0.496
Overall ecosystem reliability	0.886	0.5	0.168

average radiation capacity without fires is about 98.5%, and when fires are taken into account, it decreases to 98.1%.

An assessment of the actual processes of surface run-off of radionuclides was carried out in May 1994 by means of layer-by-layer sampling of soil in a burnt forest near the village. Kupovatoe (30 kilometre zone of the Chernobyl nuclear power plant). There was an intense fire in 1992. The results of gamma spectrometric analysis of the soil showed that on the second part of the slope, there was a significant accumulation of radionuclides (more than 2.5 times). This indicates the possibility of intensifying run-off processes after a fire (Table 6).

In general, the results of mathematical modelling of the process of propagation of 137 Cs radionuclide contamination in a forest ecosystem and the results of field research are comparable. It can be concluded that for almost all elements, there is a gradual increase and accumulation of radionuclide with the achievement of peak values and a subsequent decrease in content.

The results for individual elements of the ecosystem should also be specified. The forest element (1) is characterized by a smooth discharge of 137 Cs radionuclides almost along an exponential curve with a negative power exponent. For the human element (9), the maximum accumulation of radionuclides is 22% of the supply throughout the entire ecosystem, which determines the dose load on the population of people using this ecosystem. The main component of the human dose is the agricultural terrace (4), where agricultural products are grown.

CONCLUSIONS

A mathematical approach based on a system of first-order differential equations with constant coefficients taking into account the transition coefficients of radionuclides and their radioactive decay was possible to simulate the processes of migration of radionuclides in forest ecosystems and calculate the radiation capacity for various variants of the territory. The obtained results of the radionuclide transfer model after a fire in a forest area, as well as experimental evidence on the deflation power coefficient, enabled to evaluate the radioactive contamination value of the atmosphere.

In particular, the results from the study included:

- the processes of propagation of radioactive aerosols and gas components, taking into account convection, turbulent exchange, humidity, wind strength and direction over the combustion zone;

- In the presented three-dimensional model, the equations of impulse used, and the smoke plume propagation as well as the particles precipitation of radioactive combustion products from it;
- The radiation capacity of the ecosystem was proposed as an integral indicator, which in percentage equivalent shows the share of radionuclides entering the forest ecosystem;
- The mathematical model was confirmed, by the agreement of the calculated data with the results of full-scale field research.
- The meteorological conditions influenced the release and dispersion of radioactively contaminated combustion products into the atmosphere – contributed to a change in the time of cloud formation by 1.5 times; the height of the rise of the smoke cloud by 2 times and a change in the nuclide composition of the emission by 10%.

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