JOURNAL OF ENVIRONMENTAL ENGINEERING
AND LANDSCAPE MANAGEMENT

2008

16(1), 23–29

MODELLING VERTICAL MIGRATION OF ^{137}Cs IN LITHUANIAN SOILS

Donatas Butkus[1], **Marina Konstantinova**[2]

[1]*Dept of Environmental Protection, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania. E-mail: Donatas.Butkus@ap.vgtu.lt*

[2]*Institute of Physics, Nuclear and Environmental Radioactivity Research Laboratory, Savanorių pr. 231, LT-02300 Vilnius, Lithuania*

Submitted 15 Apr. 2007; accepted 21 Nov. 2007

Abstract. ^{137}Cs vertical migration in soil was evaluated using two methods: evaluating migration parameters using the quasi-diffusion model, and modelling vertical migration using VS2DI software package, which is intended for simulating transport of pollution in different types of soil. ^{137}Cs distribution in soil was compared in elevated contamination "spots" in 1992 and 1999–2000. It was determined that ^{137}Cs vertical distribution in soil has two maxima caused by the ^{137}Cs global fallout due to nuclear weapon tests and by the fallout due to the ChNPP accident. ^{137}Cs concentration simulated by VS2DI software package is close to the measured ^{137}Cs concentration, especially to values measured in 1992. This shows that the software is able to simulate ^{137}Cs vertical migration due to a single fallout. The quasi-diffusion model is adequate for description of long-term ^{137}Cs vertical migration, and the results of measurements and calculations agreed within error limits. Parameters of long-term vertical migration of ^{137}Cs in soil, the transfer rate *w* and the diffusion coefficient *D* were found for each region: in the western region of Lithuania (mainly sandy loam) D = 0.12 cm^2/year^{-1}, w = 0,26 cm/year^{-1}, in the southern region of Lithuania (mainly loam) D = 0.13 cm^2/year^{-1}, w = 0.29 cm/year^{-1}, and on the Curonian Spit (mainly fine sand) D = 0.1 cm^2/year^{-1}, w = 0.22 cm/year^{-1}.

Keywords: ^{137}Cs, modelling, vertical migration, ChNPP accident, soil, transfer rate, quasi-diffusion coefficient.

1. Introduction

After the Chernobyl nuclear power plant (ChNPP) accident in 1986, ^{137}Cs is considered as one of key artificial radionuclides in the environment. There were two most important periods of ^{137}Cs contamination of the Lithuanian territory: the first one was during the period of nuclear weapon tests in the atmosphere during 1945–1980, and the second one was after the ChNPP accident in 1986. This radionuclide contaminates environment, forms extra human exposure, and it is a tracer of geochemical and geophysical processes.

After the ChNPP accident Lithuania was directly in the path of contaminated air masses coming from Chernobyl. In 1987, it was determined that ^{137}Cs pollution density ranged from $7.4{\cdot}10^2$ to $3.0{\cdot}10^4$ Bq m^{-2}. The regions of elevated level of ^{137}Cs contamination, called "spots", ranging from square meters to square kilometres were observed (Butkus *et al.* 1994). The largest amount of ^{137}Cs after the ChNPP accident is accumulated in the same areas, where fallout anomalies were registered after nuclear weapon tests (Butkus *et al*. 2001). At present, contamination with ^{137}Cs is evaluated all over the whole territory of Lithuania, but the measurements were performed during different time periods.

Studies of distribution of ^{137}Cs in soils are relevant to the estimation of the density of contamination of soil layers, exposure forecast, determining the penetration depth as well as calculating the rate of natural self-decontamination (Baturin 1997; Израэль *et al.* 1998). The content of ^{137}Cs in soil is mainly influenced by vertical migration, less influenced – by transfer in the groundwater and in the geosphere, even much or far less – migration in plants, and the least – by resuspension with wind (Шестопалов *et al.* 2001). In soil with high moisture content radionuclide migration is significant (Фесенко *et al.* 1997). The major processes of vertical migration are diffusion, convection transfer with the soil liquid, and migration via the roots of plants (Ажабов *et al.* 1999). One of the most important factors is the presence of certain kinds of vegetation, in particular, coniferous trees, the litter of which retains radionuclides for a long time and carries out the role of a specific filter; or some representatives of berries and mosses. So, after the initial fallout radionuclides can hardly get into a soil with moss cover because they are engulfed by mosses and are kept fixed in them for a long time (Hrabovskyy *et al.* 2004).

Models often used for description of ^{137}Cs vertical migration are those with Gaussian or exponential distribution of the radionuclide profile in an undisturbed soil (Фесенко *et al.* 1997; Hrabovskyy *et al.* 2004; Schuller *et al.* 2002; Isaksson, Erlandsson 1998; Barišic *et al.* 1999; Ivanov *et al.* 1997; Rosen *et al.* 1999; Holgye, Maly 2000; Bossew, Kirchner 2004). Some authors use the exponential function of depth and experimentally determined parameters (Schuller *et al.* 2002; Isaksson, Erlandsson 1998). The authors of (Barišic *et al.* 1999) describe ^{137}Cs vertical migration by a logarithmic-polynomial equation, using coefficients which can be found by the least-squares method using the measured cesium activities in the sampled soil compartment. Compartment models are also used, where migration is described by rate equations, and the rate parameters are transfer coefficients which characterize the rate of migration of a radionuclide between the layers (Kanapickas *et al.* 2005). The authors of (Holgye, Maly 2000) use both the compartment model and diffusion model and find the transfer rate ranging from 0.18 cm/year^{-1} to 0.99 cm/year^{-1}. In this work we use the quasi-diffusion model where the main parameters are transfer rate and diffusion coefficient (Baturin 1997; Фесенко *et al.* 1997; Hrabovskyy *et al.* 2004; Ivanov *et al.* 1997; Rosen *et al.* 1999; Bossew, Kirchner 2004). In the Ukrainian soils the diffusion coefficient (D) ranged from 0.06 to 0.69 cm^2/year^{-1}, and the transfer rate (w) ranged from 0.07 to 0.89 cm/year^{-1} (Ivanov *et al.* 1997) as well as the main values were: D = 0.20 cm^2/year^{-1}, and w = 0.55 cm/year^{-1} (Hrabovskyy *et al.* 2004). At the same time in Sweden the transfer rate value ranged from 0.2 cm/year^{-1} to 0.6 cm/year^{-1} (Isaksson, Erlandsson 1998; Rosen *et al.* 1999).

The aim of the present work is to evaluate the long-term vertical radionuclide migration using two methods: quasi-diffusion model for vertical ^{137}Cs migration, and simulation with VS2DI software package. VS2DI is intended for modelling of pollution transport in varied porous media; thus, it can be used for simulation in different soil types.

2. Materials and methods

2.1. Sampling and measurement of ^{137}Cs concentration

In 1999–2000, the soil sampling was repeated in the regions of elevated contamination, ("spots"), where ^{137}Cs concentration was measured after the ChNPP accident: in the southern and western regions and the Curonian Spit (Fig. 1). Each region has a different soil type: the soil in the southern region is mostly clay loam, in the western region it is clay and sandy loam, and in the Curonian Spit it is mostly fine sand.

Soil was sampled in the 0–50 cm depth soil layer, in flat open places with an undisturbed structure of soil, at meadow or glade, not closer than 50 m from trees or shrubbery, and not closer than 100 m from roads. A metal ring with the 14 cm diameter and 5 cm height was driven into the soil, and soil samples were cut with a shovel. Each sample was divided into layers of 2 cm thickness from 0 to 20 cm depth and layers of 5 cm from 20 to 50 cm depth. 3 profiles were sampled in the southern "spot", 4 profiles – in the western "spot", and 8 ones were sampled in the Curonian Spit.

The soil samples were transported to the laboratory in plastic bags, dried and weighed, and their density was determined. The ^{137}Cs activity was determined using a gamma semiconductor Ge(Li) spectrometer with the registration efficiency of 0.26 % in the standard cells: 1 L volume Marinelli vessels. The radionuclide was identified by its radiation energy at 662 keV as well as ^{137}Cs concentration (Bq kg^{-1}) and deposition density (Bq m^{-2}) were evaluated.

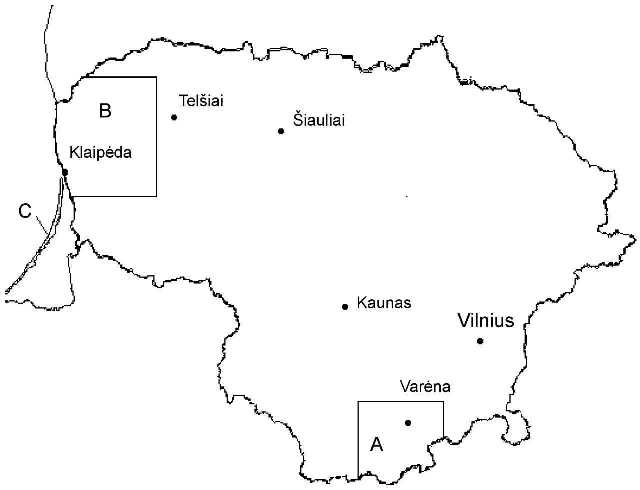


Fig. 1. Regions of elevated contamination in the territory of Lithuania: A – southern "spot", B – western "spot", C – the Curonian Spit "spot"

2.2. Evaluation of ^{137}Cs vertical migration in soil using a quasi-diffusion model

It was accepted that ^{137}Cs vertical migration was diffusion and directional transfer, and the second-order differential equation was solved (Butkus *et al.* 2001; Фесенко *et al.* 1997; Ivanov *et al.* 1997; Holgye, Maly 2000; Bossew, Kirchner 2004):

$$\frac{\partial q(x_1 t)}{\partial t} = D(x_1 t)\frac{\partial^2 q(x_1 t)}{\partial x^2} - w\frac{\partial q(x_1 t)}{\partial t} - \lambda q(x_1 t), \quad (1)$$

where $q(x,t)$ is concentration of ^{137}Cs in soil, Bq m^{-3}; $D(x,t)$ is the quasi-diffusion coefficient, m^2 y^{-1}; λ is a constant of radioactive decay, y^{-1}; w is the transfer rate, m y^{-1}, x is the depth of penetration, m; t is time of migration, y.

This model is applicable if the following simplifications may be applied: the vertical component is probably the dominant one, i.e. the model is purely one-dimensional; the soil is homogeneous; D and w parameters are considered constant over the soil column as well as constant over time; sorption of ^{137}Cs is constant; only mobile form of ^{137}Cs takes part in the process; the parameter D combines two different physical processes, molecular diffusion and hydrodynamic dispersion of the solute, into a single constant (Bossew, Kirchner 2004).

The mostly used solution of this equation, describing a single fallout with initial and boundary conditions, is:

$$q(x,t) = 0, \text{ when } t = 0;$$

$$q(x,t) = 0,\ \partial q(x,t)/\partial x = 0, \text{ when } x \to 0,\ t > 0; \quad (2)$$

$$D\frac{\partial q(x,t)}{\partial x} - wq(x,t) = Q\delta(t), \text{ when } x = 0,\ t \geq 0,$$

where $\delta(t)$ is the delta function; Q is the deposition density, Bq m^{-2}.

The solution of the equation is as follows (Butkus *et al.* 2001; Фесенко *et al.* 1997; Isaksson, Erlandsson 1998; Bossew, Kirchner 2004):

$$q(x,t)=Q\cdot\exp(-\lambda\cdot t)\cdot\left[\begin{array}{l}\dfrac{1}{\sqrt{\pi\cdot D\cdot t}}\cdot\exp\left(-\dfrac{(x-w\cdot t)^2}{4\cdot D\cdot t}\right)-\\ \dfrac{w}{2\cdot D}\exp\left(-\dfrac{w\cdot x}{D}\right)\cdot\left(1-erf\left(\dfrac{x+w\cdot t}{2\cdot\sqrt{D\cdot t}}\right)\right)\end{array}\right], \quad (3)$$

where *erf(x)* is the error distribution function.

However, the present ^{137}Cs contamination of Lithuanian soils is determined not only by deposition after the ChNPP accident. It was accepted that distribution of ^{137}Cs in the studied regions was formed in two stages. The fallout took place during 1945–1963 (global) and in 1986 ("Chernobyl"). Thus, the equation was modified, and the migration of ^{137}Cs was estimated by solving the equation (Butkus, Konstantinova 2003):

$$q(x,t)=Q_1\cdot\exp(-\lambda\cdot t_1)\cdot\left[\begin{array}{l}\dfrac{1}{\sqrt{\pi\cdot D\cdot t_1}}\cdot\exp\left(-\dfrac{(x-w\cdot t_1)^2}{4\cdot D\cdot t_1}\right)\\ -\dfrac{w}{2\cdot D}\exp\left(-\dfrac{w\cdot x}{D}\right)\cdot\left(1-erf\left(\dfrac{x+w\cdot t_1}{2\cdot\sqrt{D\cdot t_1}}\right)\right)\end{array}\right]+$$
$$Q_2\cdot\exp(-\lambda\cdot t_2)\cdot\left[\begin{array}{l}\dfrac{1}{\sqrt{\pi\cdot D\cdot t_2}}\cdot\exp\left(-\dfrac{(x-w\cdot t_2)^2}{4\cdot D\cdot t_2}\right)-\\ \dfrac{w}{2\cdot D}\exp\left(-\dfrac{w\cdot x}{D}\right)\cdot\left(1-erf\left(\dfrac{x+w\cdot t_2}{2\cdot\sqrt{D\cdot t_2}}\right)\right)\end{array}\right], \quad (4)$$

where Q_1 and t_1 are ^{137}Cs deposition density and time after the global fallout, Q_2 and t_2 are ^{137}Cs deposition density and time after the Chernobyl fallout.

2.3. Evaluation of ^{137}Cs vertical migration in soil using VS2DI software package

For the forecast of ^{137}Cs vertical migration the VS2DI software was used. VS2DI is a graphical software package for simulating different pollution transport in saturated porous media. It combines a graphical user interface with a numerical model to create an integrated, window-based modelling environment. Users can specify and change initial information: hydraulic and transport properties, initial and boundary conditions, grid spacing and other model parameters (Table) (Hsieh *et al.* 2000).

We specified the following parameters: geometry and boundaries of the initial polluted region (in our case – the vertical section 10×20 cm); time, mass and depth dimension; initial hydraulic condition (in our case – open vertical section); soil type (in our case – clay loam, sandy loam and fine sand) (Fig. 2) (Lietuvos…1985); relative hydraulic conductivity, porosity, moisture content; decay constant and initial concentration of pollution (in our case – ^{137}Cs), and time of migration (Hsieh *et al.* 2000).

3. Results and discussion

It has been obtained that vertical distribution of ^{137}Cs in all three soil types has two peaks. The first one is in the topsoil layers (in clay loam and sandy loam in the 2–4 cm layer, and in fine sand at the 0–2 cm depth). The second peak was observed at the 6–20 cm depth, depending on the soil type and landscape. We propose that the first increase is the result of the ChNPP accident fallout, and the second one is caused by the global ^{137}Cs fallout as a result of nuclear weapon tests, when ^{137}Cs migrated below the 20 cm depth.

The maximum peak was observed in the western region (sandy loam soil). In western Lithuania, in 1983, the ^{137}Cs surface activity density reached 1040 Bq m^{-2}, and in the territory of Lithuania it was not higher than 780 Bq m^{-2} (Butkus, Konstantinova 2003). In the southern region and the Curonian Spit, before the ChNPP accident, the surface activity density of ^{137}Cs was not very high relative to the western region. Non-identical vertical distribution of ^{137}Cs in the regions could be explained by different physical and chemical parameters depending on the properties of soil. In particular, it may be the soil composition (loam prevails in the southern region, there is loam and sandy loam in the western region, and fine sand on the Curonian Spit), the soil moisture content, or landscape characteristics and vegetation (Шестопалов *et al.* 2001; Hrabovskyy *et al.* 2004; Barišic *et al.* 1999; Holgye, Maly 2000).

As the forest litter retains caesium, the migration rate decreases significantly. On the Curonian Spit, most of the samples were taken in forests covering most of its territory. So, in this "spot" parameters of ^{137}Cs vertical migration are lower than in other regions.

For modelling of the quasi-diffusion coefficient and the transfer rate, Q_1 and Q_2 values were selected for each "spot". Modelled Q_1 and Q_2 values were based on real deposition density values determined in 1979–1984 and in 1992–2000, and they were extrapolated using the values taken in 1963 and in 1986, respectively (Butkus *et al.* 2001). Modelled t_1 and t_2 values represent time after the global fallout (37 y) and time after the Chernobyl fallout (14 y). Consequently, the modelled parameters of the quasi-diffusion coefficient D and the transfer rate w for each region and soil type are as follows: in the western "spot" (mainly sandy loam) $D = 0.12$ cm^2 y^{-1}, $w = 0.26$ cm y^{-1}, in the southern "spot" (mainly loam) $D = 0.13$ cm^2 y^{-1}, $w = 0.29$ cm y^{-1}, and in the Curonian Spit "spot" (fine sand) $D = 0.10$ cm^2 y^{-1}, $w = 0.22$ cm y^{-1} (Butkus, Konstantinova 2003).

These values are within the ranges given in the referred works, determined in the Ukraine and Sweden (Ажабов *et al.* 1999; Isaksson, Erlandsson 1998; Ivanov *et al.* 1997; Rosen *et al.* 1999).

Fig. 3 shows comparison of the results of two modelling methods and the measurement results of ^{137}Cs distribution in 1992. ^{137}Cs concentration at different depths was measured only in the southern "spot" and the Curonian Spit.

Fragment of calculations of VS2DI software

MASS BALANCE SUMMARY FOR TIME STEP 35
PUMPING PERIOD NUMBER 1
TOTAL ELAPSED SIMULATION TIME = 1.700E+01 year

VOLUMETRIC FLOW BALANCE	TOTAL cm **3	TOTAL THIS TIME STEP cm **3	RATE THIS TIME STEP cm **3/year
FLUX INTO DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES	0.00000E+00	0.00000E+00	0.00000E+00
FLUX OUT OF DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES	–8.59969E+06	–2.97984E+03	–2.56621E+03
FLUX INTO DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES	0.00000E+00	0.00000E+00	0.00000E+00
FLUX OUT OF DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES	0.00000E+00	0.00000E+00	0.00000E+00
TOTAL FLUX INTO DOMAIN	0.00000E+00	0.00000E+00	0.00000E+00
TOTAL FLUX OUT OF DOMAIN	–8.59969E+06	–2.97984E+03	–2.56621E+03
EVAPORATION	0.00000E+00	0.00000E+00	0.00000E+00
TRANSPIRATION	0.00000E+00	0.00000E+00	0.00000E+00
TOTAL EVAPOTRANSPIRATION	0.00000E+00	0.00000E+00	0.00000E+00
CHANGE IN FLUID STORED IN DOMAIN	0.00000E+00	0.00000E+00	0.00000E+00
FLUID VOLUME BALANCE	–8.59969E+06	–2.97984E+03	–2.56621E+03
SOLUTE MASS BALANCE	Bq	Bq	Bq /year
FLUX INTO DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES	0.00000E+00	0.00000E+00	0.00000E+00
FLUX OUT OF DOMAIN ACROSS SPECIFIED PRESSURE HEAD BOUNDARIES	–1.80275E+12	–4.19014E+08	–3.60850E+08
FLUX INTO DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES	0.00000E+00	0.00000E+00	0.00000E+00
FLUX OUT OF DOMAIN ACROSS SPECIFIED FLUX BOUNDARIES	0.00000E+00	0.00000E+00	0.00000E+00
DIFFUSIVE/DISPERSIVE FLUX INTO DOMAIN	2.95558E+12	4.20849E+08	3.62430E+08
DIFFUSIVE/DISPERSIVE FLUX OUT OF DOMAIN	0.00000E+00	0.00000E+00	0.00000E+00
TOTAL FLUX INTO DOMAIN	2.95558E+12	4.20849E+08	3.62430E+08
TOTAL FLUX OUT OF DOMAIN	–1.80275E+12	–4.19014E+08	–3.60850E+08
TOTAL EVAPOTRANSPIRATION	0.00000E+00	0.00000E+00	0.00000E+00
FIRST ORDER DECAY	–2.70156E+07	–1.83586E+06	–1.58103E+06
ADSORPTION/ION EXCHANGE	0.00000E+00	0.00000E+00	0.00000E+00
CHANGE IN SOLUTE STORED IN DOMAIN	5.27009E+04	–1.03892E+03	–8.94710E+02
SOLUTE MASS BALANCE	1.15280E+12	–8.28197E-02	–7.13235E-02

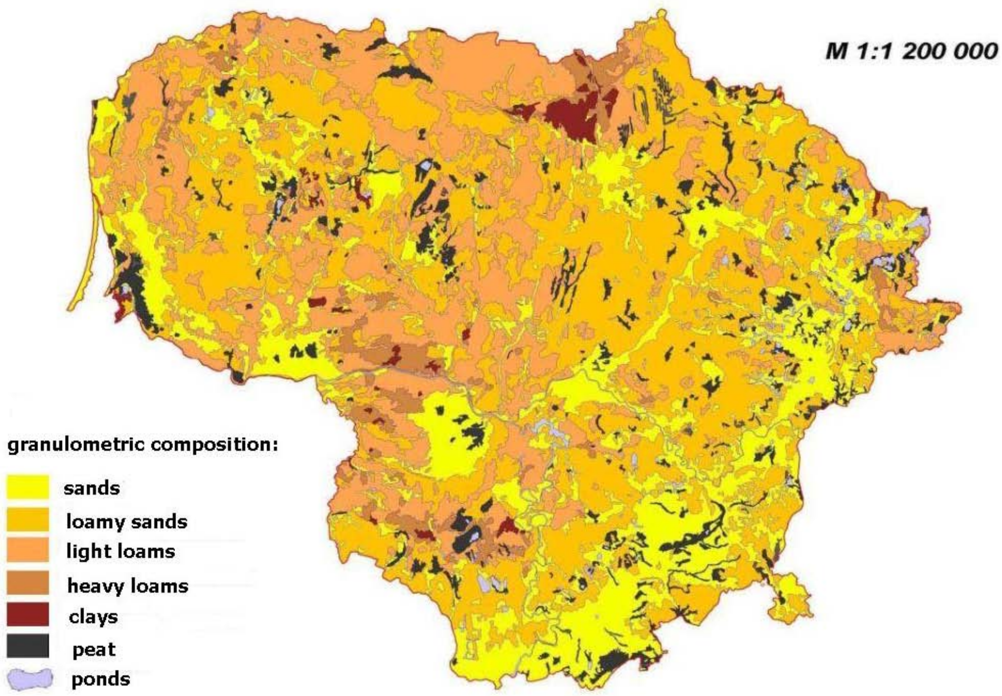
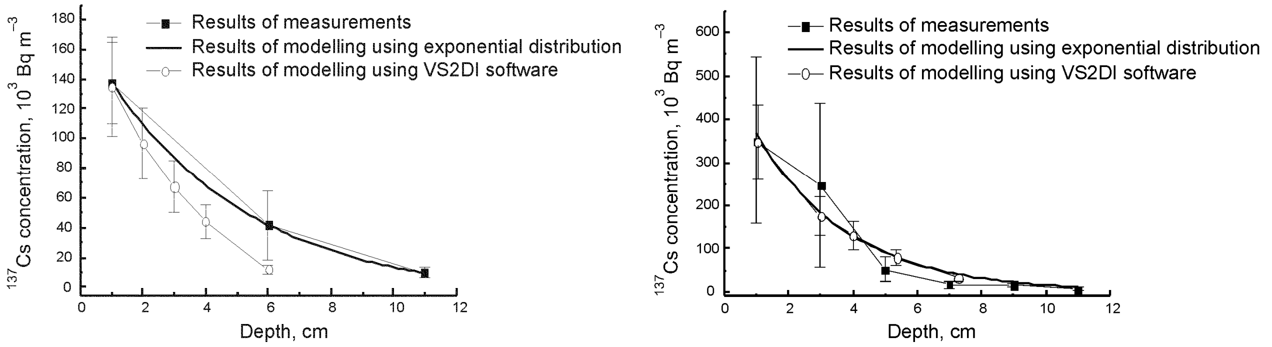
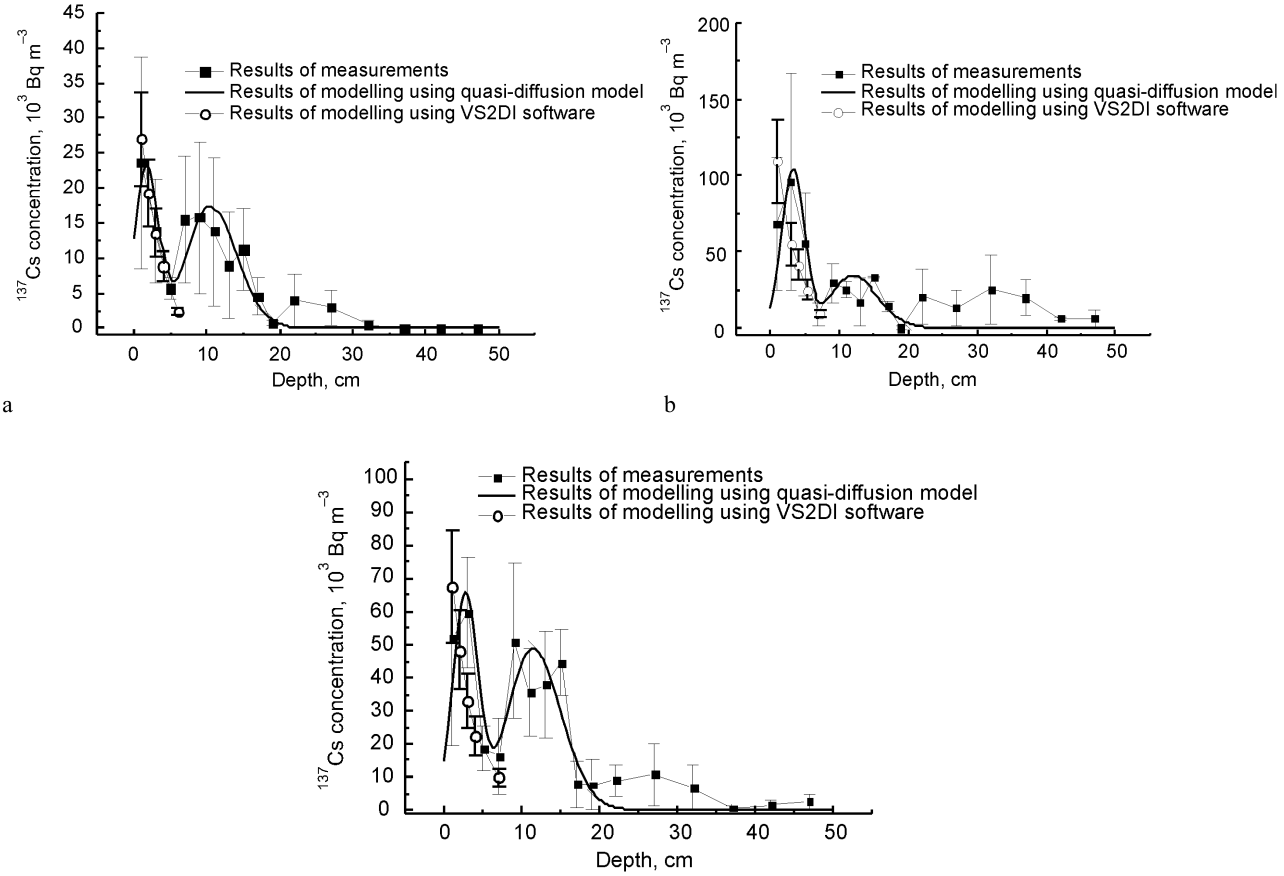


Fig. 2. Map of granulometric composition of Lithuanian soils (Lietuvos... 1985)



a b

Fig. 3. Distribution of ^{137}Cs volume concentration in soil in 1992: a – Curonian Spit "spot", b – southern "spot"



c

Fig. 4. Distribution of ^{137}Cs volume concentration in soil in 1999–2000: a – Curonian Spit "spot", b – southern "spot", c – western "spot"

Comparison of ^{137}Cs concentration measured and modelled using VS2DI software shows (Figs. 3, 4) that this software is good for evaluation of pollution after a short fixed time period. However, the vertical migration of the radionuclide in soil is a complex process which depends on a significant number of natural factors. Besides, multiplex deposition was not taken into account.

In 1992 it was observed that ^{137}Cs vertical distribution was exponential (Lietuvos… 1985). At such a time "Chernobyl" ^{137}Cs was mainly in the first (top) soil layer (0–2 cm), so, exponential approximation was used for description of ^{137}Cs vertical migration.

Fig. 4 shows comparison of the results of two methods of modelling and measurement of ^{137}Cs distribution in 1999–2000. ^{137}Cs concentration in soil profile was measured in the southern, western "spots" and the Curonian Spit "spot".

What can be the causes for some disparity observed between the measured ^{137}Cs concentration in soil and that calculated using both models? Even though the soil used in the experiment was not cultivated, it might be disturbed, for example, by wild animals as well as by worms and insects. Irregularity in the distribution of the radionuclide could result from changes in the soil moisture, irregular drying out of soil and by roots of plants.

Fig. 4 shows that equation (4) is sufficiently adequate for the description of the long-term ^{137}Cs vertical migration, and the results of measurements and calculations coincide within the limits of error.

As we can see, VS2DI software does not give the second peak which appears using measuring and equation (4). The results of modelling and measurement coincide approximately to 7 cm depth. ^{137}Cs vertical migration modelled using VS2DI in the topsoil is close to ^{137}Cs concentration values measured in 1992. However, this program is not adequate for the description of the long-term ^{137}Cs vertical migration (in 1999–2000). Hence, we conclude that VS2DI software can be used for the description of the radionuclide vertical migration only in the case of a single fallout.

4. Conclusions

1. ^{137}Cs vertical distribution in the soil of the studied regions (in three types of soil – clay loam, sandy loam and fine sand) has two peaks: the first one is in topsoil (in clay loam and sandy loam it is from 2 to 4 cm depth, in fine sand – from 0 to 2 cm depth), and the second one is at a depth from 6 to 20 cm, depending upon the soil type or landscape. We suppose that the first one is the result of the ChNPP accident fallout, and the second one is caused by the global ^{137}Cs fallout as a result of nuclear weapon tests, when ^{137}Cs migrated deeper than to 20 cm depth.

2. Variations of ^{137}Cs concentration in time modelled using VS2DI software are close to measured ones, particularly in 1992. This proves suitability of VS2DI software for simulation of ^{137}Cs vertical migration in the case of a single fallout.

3. The quasi-diffusion model is adequate for description of long-term ^{137}Cs vertical migration, and the results of measurements and calculations agreed within the limits of error. The parameters of long-term vertical migration of ^{137}Cs in soil, the transfer rate w and the diffusion coefficient D, were determined for each region: in the western region of Lithuania (mainly sandy loam) they are: $D = 0.12$ cm^2/year^{-1}, $w = 0.26$ cm/year^{-1}; in the southern region of Lithuania (mainly loam) – $D = 0.13$ cm^2/year^{-1}, $w = 0.29$ cm/year^{-1}; on the Curonian Spit (mainly fine sand) – $D = 0.1$ cm^2/year^{-1}, $w = 0.22$ cm/year^{-1}.

References

Barišic, D.; Vertačnik, A.; Lulic, S. 1999. Caesium contamination and vertical distribution in undisturbed soils in Croatia, *Journal of Environmental Radioactivity* 46: 361–374.

Baturin, V. A. 1997. Vertical migration of radionuclides in soil of East-Ural track and its influence on the intensity of outgoing radiation, *Atomic Energy* 82: 44–48.

Bossew, P.; Kirchner, G. 2004. Modelling the vertical distribution of radionuclides in soil. Part 1: the convection-dispersion equation revisited, *Journal of Environmental Radioactivity* 73: 127–150.

Butkus, D.; Morkūnas, G.; Kandrotas, G. 1994. Contamination of territory of Lithuania with cesium-137, *Journal of Ecological Chemistry* 3: 133–138.

Butkus, D.; Lebedytė, M.; Lubytė, G.; Matusevičius, K.; Mažeika, J. 2001. ^{137}Cs and ^{90}Sr in the soils of Lithuania, *Geochemistry International* 39: 719–724.

Butkus, D.; Konstantinova, M. 2003. Studies of long-term vertical migration of ^{137}Cs in soil, *Environmental and Chemical Physics* 25: 75–80.

Holgye, Z.; Maly, M. 2000. Sources, vertical distribution, and migration rates of $^{239,240}Pu$, ^{238}Pu, and ^{137}Cs in grassland soil in three localities of Central Bohemia, *Journal of Environmental Radioactivity* 47: 135–147.

Hrabovskyy, V.; Dzendzelyuk, O.; Katerynchuk, I.; Furgala, Y. 2004. Monitoring of radionuclides contamination of soils in Shatsk National Natural Park (Volyn Region, Ukraine) during 1994–2001, *Journal of Environmental Radioactivity* 72: 25–33.

Hsieh, P. A.; Wingle, W.; Healy, R. W. 2000. *VS2DI – a graphycal software package for simulating fluid flow and solute or energy transport in variably saturated porous media.* U. S. Geological Survey. Water-Resources Investigations Report, 99–4130. Lakewood. 16 p. CO.

Isaksson, M.; Erlandsson, B. 1998. Models for the vertical migration of ^{137}Cs in the ground – a field study, *Journal of Environmental Radioactivity* 41: 163–182.

Ivanov, Y. A.; Lewyckyj, N.; Levchuk, S. E. 1997. Migration of ^{137}Cs and ^{90}Sr from the Chernobyl fallout in Ukrainian, Belarussian and Russian soils, *Journal of Environmental Radioactivity* 35: 1–21.

Kanapickas, A.; Mažeika, J.; Paulaitienė, I.; Baužienė, I. 2005. Influence of physical properties of soil on ^{137}Cs mobility, *Lithuanian Journal of Physics* 45: 65–72.

Lebedytė, M. 2002. *Gama spinduliuotės intensyvumo pažemio ore kaitos Lietuvoje tyrimai*: daktaro disertacija. Vilnius. 103 p.

Lietuvos TSR dirvožemio žemėlapis M 1:300000, RŽPI. Vilnius, 1985. 215 p.

Rosen, K.; Oborn, I.; Lonsjo, H. 1999. Migration of radiocaesium in Shvedish soil profiles after the Chernobyl accident, 1987–1995, *Journal of Environmental Radioactivity* 46: 45–66.

Schuller, P.; Voigt, G.; Handl, J.; Ellies, A.; Oliva, L. 2002. Global weapon's fallout ^{137}Cs in soil and transfer to vegetation in south-central Chile, *Journal of Environmental Radioactivity* 62: 181–193.

Ажабов, А. К.; Мухамедов, А. К.; Потемкин, Г. В. 1999. Вертикальная миграция ^{137}Cs в некоторых почвах Узбекистана, *Атомная энергия* 87: 311–314.

Израэль, Ю. А.; Имшенник, Е. В.; Квасникова, Е. В.; Назаров, И. М.; Ступин, Е. Д. 1998. Долгосрочный прогноз изменения радиоактивного загрязнения территории России цезием-137 после аварии на Чернобыльской атомной электростанции, *Метеорология и гидрология* 4: 5–17.

Фесенко, С. В.; Спиридонов, С. И.; Санжарова, Н. И.; Алексахин, Р. М. 1997. Оценка периодов полуснижения содержания ^{137}Cs в корнеобитаемом слое почв луговых экосистем, *Радиационная биология. Радиоэкология* 37: 267–280.

Шестопалов, В. М.; Кашпаров, В. А.; Иванов, Ю. А.; Богдевич, И. М. 2001. Пути миграции „чернобыльских“ радионуклидов в наземных ландшафтах, в *Международная конференция „15 лет после Чернобыльской катастрофы. Опыт преодоления“.* Киев, Украина, 12–22 апреля 2001. 5 с. CD.

^{137}Cs VERTIKALIOSIOS MIGRACIJOS LIETUVOS DIRVOŽEMIUOSE MODELIAVIMAS

D. Butkus, M. Konstantinova

S a n t r a u k a

^{137}Cs vertikalioji migracija dirvožemyje buvo įvertinta, matuojant jo savitąjį aktyvumą dirvožemyje ir taikant du metodus: radionuklido vertikaliosios migracijos įvertinimas pagal kvazidifuzinį modelį ir jos modeliavimas, naudojant VS2DI kompiuterinę programą, kuri skirta taršos sklidimui įvairių tipų dirvose modeliuoti. ^{137}Cs pasiskirstymas dirvožemyje buvo palygintas su ^{137}Cs didelės užtaršos plotuose („karštose dėmėse“) 1992 ir 1999–2000 m. Buvo nustatyta, kad ^{137}Cs vertikalusis pasiskirstymas turi dvi smailes, pirmoji atsirado dėl ^{137}Cs globalios iškritos, sukeltos branduolinio ginklo bandymais, antroji – dėl Černobylio avarijos iškritos. ^{137}Cs savitasis aktyvumas, sumodeliuotas naudojant VS2DI kompiuterinę programą, yra artimas išmatuotam ^{137}Cs savitajam aktyvumui, ypač išmatuotam 1992 m. Tai rodo, kad ši programa tinka vienkartinės taršos ^{137}Cs vertikaliajai migracijai modeliuoti. Tačiau ilgalaikei ^{137}Cs vertikaliajai migracijai aprašyti labiau tinka kvazidifuzinis modelis, ir jo rezultatai bei matavimo rezultatai sutampa neviršydami paklaidų ribų. Ilgalaikės ^{137}Cs vertikaliosios migracijos dirvožemyje parametrai, kryptingos pernašos greitis w ir kvazidifuzinės pernašos koeficientas D buvo nustatyti kiekviename regione: Vakarų Lietuvos regione (vyrauja priesmėlis) D = 0,12 cm^2/m^{-1}, w = 0,26 cm/m^{-1}, Pietų Lietuvos regione (vyrauja priemolis) D = 0,13 cm^2/m^{-1}, w = 0,29 cm/m^{-1}, o Kuršių nerijoje, kur vyrauja smulkus smėlis, D = 0,1 cm^2/m^{-1}, w = 0,22 cm/m^{-1}.

Reikšminiai žodžiai: ^{137}Cs, modeliavimas, vertikalioji migracija, ČAE avarija, dirvožemis, kryptingos pernašos greitis, kvazidifuzinės pernašos koeficientas.

МОДЕЛИРОВАНИЕ ВЕРТИКАЛЬНОЙ МИГРАЦИИ ^{137}Cs В ПОЧВАХ ЛИТВЫ

Д. Буткус, М. Константинова

Р е з ю м е

Вертикальная миграция ^{137}Cs в почве была исследована при измерении его концентрации в почве, а также при помощи двух методов: оценки параметров миграции с помощью квазидиффузионного метода и с использованием компьютерной программы VS2DI, предназначенной для моделирования переноса загрязнения в различных типах почв. Сравнивается распределение ^{137}Cs в областях повышенной загрязненности („горячих пятнах“) в 1992 г. и 1999–2000 гг. Установлено, что вертикальное распределение ^{137}Cs имеет два максимума, обусловленных глобальным выпадением ^{137}Cs в результате ядерных испытаний и вследствие Чернобыльской аварии. Концентрация ^{137}Cs, смоделированная с помощью программы VS2DI, близка к измеренной, особенно к значениям, измеренным в 1992 г. Это свидетельствует о том, что программа может быть использована для моделирования вертикальной миграции одиночного выпадения ^{137}Cs. Квазидиффузионная модель приемлема для описания долгосрочной вертикальной миграции, причем результаты измерений и вычислений совпадают в пределах погрешности. Были найдены параметры долгосрочной вертикальной миграции ^{137}Cs, направленная скорость переноса w и коэффициент диффузии D для каждого из регионов: в Западной Литве (преобладает супесчаная почва) D = 0.12 см^2 г$^{-1}$, w = 0,26 см г$^{-1}$, в Южной Литве (преобладает суглинок) D = 0.13 см ^{2} г$^{-1}$, w = 0.29 см г$^{-1}$ и на Куршской косе (преобладает мелкий песок) D = 0.1 см^2 г$^{-1}$, w = 0.22 см г$^{-1}$.

Ключевые слова: ^{137}Cs, моделирование, вертикальная миграция, авария на ЧАЭС, почва, направленная скорость переноса, коэффициент диффузии.

Donatas BUTKUS. Dr Habil, Prof, Dept of Environmental Protection, Vilnius Gediminas Technical University (VGTU). Doctor Habil of Science (environmental engineering), VGTU, 1999. Membership: a member of International Academy of Ecological and Life Protection Sciences. Publications: author of more than 200 research papers, co-author of the monograph *Geophysical problems of atmospheric krypton-85* (in Russian and English). Research interests: radioactive gases, self-cleaning of the atmosphere, ionizing radiation; consequences of the Chernobyl accident; environment physical pollution (ionic and non-ionic radiation, noise and vibration).

Marina KONSTANTINOVA. Dr, research worker, Nuclear and Environmental Radioactivity Research Laboratory, Institute of Physics.
Doctor of Physics, Institute of Physics, 2002. Master of Ecology, Vilnius Gediminas Technical University, 1997, Bachelor of Physics, Vilnius University, 1995. Publications: co-author of 22 scientific publications. Research interests: contamination of soil with ^{137}Cs before and after Chernobyl NPP accident, contamination of soil and water with radionuclides in the Ignalina NPP surroundings, vertical and horizontal migration of ^{137}Cs in soil, ^{137}Cs vertical migration parameters, ^{137}Cs soil-to-plant transfer, ^{137}Cs and ^{3}H release from radioactive waste repository and migration with ground water; external equivalent gamma dose rate caused by artificial and natural gamma radionuclides in soil and ^{222}Rn decay products in air.