Information Model of Ecological Systems on the Basis of Reliability and Radiocapacity with Application of GIS Technologies

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Abstract. In this paper the model approach based on application of analytical GIS technology for description of radioecological processes in real landscapes was presented. The problem of verification of chamber models on the basis of field data is realized by modeling of ecological risks for ecosystem biota. The thesis presents the results of modeling the process of radionuclide migration along the trophic chain: “soil” - “fodder plants” - “cow” - “milk” - “man”, - in the conditions of Volyn region (cesium-137) using the example of village Galusia.

Keywords: radionuclide migration, population, collective radiation exposure, chamber models, geographical informational systems (GIS).

1 Introduction

System approach to studying ecological objects is necessary condition of current researches in ecology. Wide range of different methods is applied for investigating natural phenomena:

-methods of data collecting by means of different equipment and technical means;

-methods of processing obtained information, its reduction, compression and generalization;

- methods of interpreting obtained actual material.

Complexity and longtermness are peculiarities of modern ecological researches by means of equipment: observations of living organisms and environmental factors on chosen areas of an ecosystem are carried out for sufficiently large time interval. Besides complex observations on stationary areas, global monitoring of ecosystems and the whole biosphere can be fulfilled. Experiments play an important role in ecological investigations.

However, field monitoring cannot be considered as a single approach to ecological processes investigation, and firstly because of limitation of time and hardware possibilities. Modern ecological researches are characterized by more and more application of modeling methods and firstly mathematical methods. The sense of mathematical modeling is construction of simplified, generalized abstract model of the investigated system, and by changing its parameters it is possible to assess and predict its development, make decision for providing its ecological safety [1].

Development of geographical informational systems (GIS) leads to wider application of mathematical-cartographic methods in ecological investigations, which combine cartographic model reflecting spatial differentiation of ecosystem components' states and mathematical model of system's dynamics. The GIS concept itself includes comprehensive possibilities of collecting, integration and analyses of data distributed in space or attached to concrete territory. Due to this GIS-technologies are used successfully in ecological investigations, in particular, for creation of maps of main environmental parameters. Results of modeled pollution calculations can be imposed on natural maps of vegetation, agricultural sites and housing area. It is possible to state with certainty that namely GIS will be one of main branches of application of new informational technologies for solving problems of natural resource management, assessment, prediction and planning of environmental state, providing ecological safety [2].

2 Problem Statement

After accidents on the Chernobyl nuclear power plant and Fucushima-1 mass field researches on levels of radionuclide contamination of natural habitats – atmosphere, soil, plants and animals – began to be conducted. They are extensive investigations which need systematization and formalization by specially developed models and algorithms. Acting means and schemes of environmental monitoring cannot fully reflect dynamics of migration and redistribution of radionuclides in components of ecosystems of different types. Field monitoring is not able "to grasp the immensity" because of time and equipment shortage. It is necessary to include different types of modeling into research, assessment, prognosis and management of ecosystems.

Among methods and means of radionuclides transport modeling the method of chamber models is widespread. Velocities of radionuclides transfer between ecosystem's chambers are understood in two ways: 1) as the part of general reserve of radionuclides in chambers which transfers to conjugate chambers per unit time [1]; 2) as assessment of part of radionuclides in volume or weight unit (m^3, kg, l) of some chamber which is able to transfer into volume or weight unit of a conjugate chamber (for example, soil – plants etc.) [3].

In the article we represent the model approach based on application of analytical GIS technology for description of radioecological processes in real landscapes. The problem of verification of chamber models on the basis of field data is realized by modeling of ecological risks for ecosystem biota [4].

3 Chamber Models in Radioecology

The method of chamber models is used for description of transfer and migration of radionuclides in ecosystems. According to this approach the whole chain of radionuclides transfer is divided into chambers (boxes). In mathematical models interaction between chambers is defined by coefficients of velocities of radionuclides transfer between chambers.

The constant growth of radioactive substances and sources of ionizing radiation use in various industries, medicine, science increases their impact on all components of the natural environment. Therefore, radionuclides that have fallen on the territory of Ukraine as a result of the accident at the Chernobyl nuclear power plant, by trophic chains can form noticeable dose loads for the population of Ukraine.

First of all, these are long-lived radionuclides ^{137}Cs and ^{90}Sr, which constitute the main environmental danger and have a biotic character, since they are analogous to the macroelements K and Ca, which are necessary for the life processes of plants and animals. In Ukraine a fairly systematic and detailed monitoring of contamination of soil, water and food with radionuclidesis carried out. The ^{137}Cs content is measured on human radiation meters (SICh), and then, using the models, the expected dose is calculated for the population of settlements. Analyzing milk monitoring data, an assessment of the so-called passport dose is carried out.

But, except for assessments and monitoring of the current state of environmental safety for settlements of Ukraine, there is an immediate need to calculate the long-term forecast of the radioecological state. Such forecast will make it possible to carry out a choice and substantiation of real countermeasures for the control and management of the environmental safety of contaminated territories of Ukraine and population. Therefore the development of relatively simple mathematical models of the radionuclides distribution and their dynamics on the basis of field investigations is an important and urgent problem of modern ecology. On the one hand, this approach will allow in the future to have a valid model of radioecological safety for each specific settlement. On the other hand, such model, based on the real parameters of the ecosystem will assess the possible environmental risks from other pollutants (heavy metals, herbicides, etc.). We are talking about the formation of generalized parameters of environmental safety and environmental risks that are characteristic of a particular settlement.

In modern ecology and radioecology, enough approaches and models for assessing ecological capacity and radiocapacity for large areas have been developed. At the same time, there is clearly a lack of methods and models necessary for assessing and predicting the state of local ecosystems of specific settlements.

Therefore, the concretization of existing approaches and models is relevant and important task of modern ecology. It is necessary to have a method of operative creating environmental safety models with binding them for specific conditions of any settlement, for the use of which environmentalists do not require complex specialized training. Such approach will allow including into the settlement's environmental passport a valid mathematical model of environmental safety that can be verified by monitoring data. The presence of such a model will allow minimizing the volume and details of monitoring, predict critical situations in this ecosystem. This will set limits on the ecological capacity of the ecosystem and limit excessive anthropogenic pressure on the territory.

The thesis presents the results of modeling the process of radionuclide migration along the trophic chain: “soil” - “fodder plants” - “cow” - “milk” - “man”, - in the conditions of Volyn region (cesium-137) using the example of village Galusia (Figure 1). The parameters are established and the features of this phenomenon are investigated. This makes it possible to have methods and approaches for monitoring, predicting and managing radioecological safety for this local ecosystem and other similar ecosystems [5].

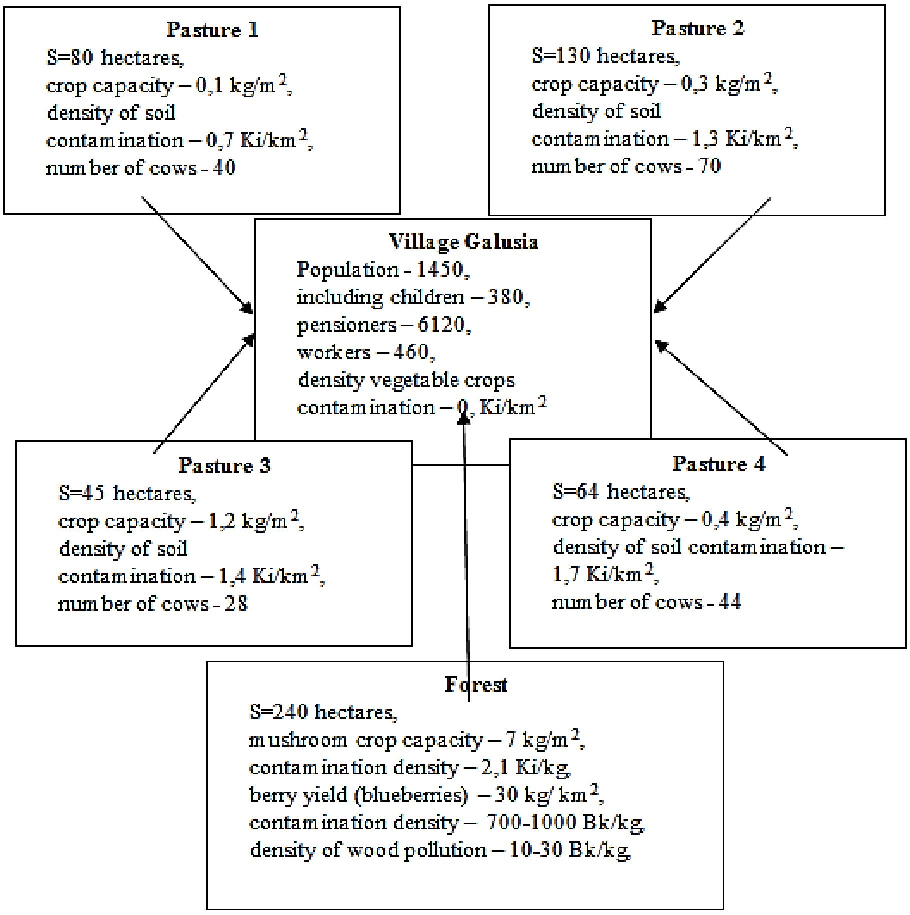

Fig. 1. Diagram of the main components of the ecosystem of village Galusia (Manevich district of Volyn region).

The structured block diagram of the chamber model is shown on Figure 2. The parameters indicated in the diagram (a_{ij}) denote the transfer rates (transition) of radionuclides between the ecosystem chambers and have a dimension: the part of radionuclides transferred between the chambers per one year. The methods and models for calculating the transition between cameras comprise the content of a specially designed and protected declarative package of the utility model.

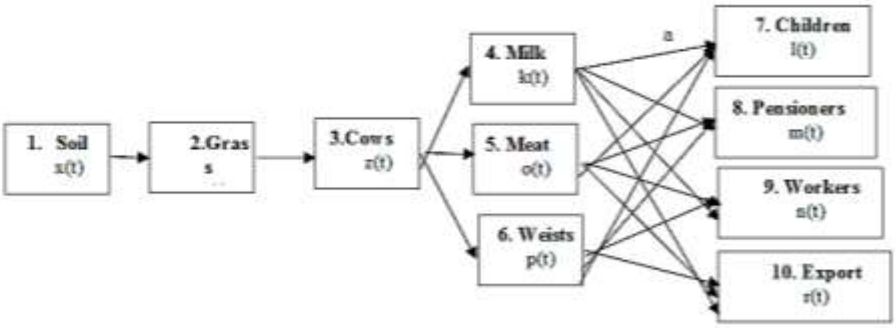

Fig. 2. Structured block diagram of village Galusia

It was found that the main dose-forming components of the agroecosystem Galusia, are the 4 main pastures. These pastures function, in a reliable sense, as a parallel system. According to the theory of reliability [3], the general reliability of this agroecosystem as a system for transporting radionuclides from a pasture to man, can be represented approximately as a sum of the reliability parameters of the pasture blocks.

The chamber model of this agroecosystem can be represented as a system of blocks. It has been established that the radionuclide transport stream from each of the four pastures forms a parallel system. Deliveries of radionuclides from pasture to the population forms a consistent system: "soil" - "grass" - "cow" - "milk" - "meat" - "people". The reliability of such a consistent ecosystem can be represented as a product of the reliability parameters of the component blocks that form the radionuclide transport stream.

According to the chamber model the factor of ecological capacity and radiocapacity of a specific element of the ecosystem and / or landscape (F_j) is determined as:

$$F_j = \frac{\sum a_{ij}}{a_{ij} + \sum a_{ji}}, \tag{1}$$

where $\sum a_{ij}$ is the sum of the rates of pollutants transition from different components of the ecosystem to a specific element of the ecosystem — j -th (according to chamber models), and

$\sum a_{ji}$ is the sum of the rates of pollutants transition from the j-th chamber to other components of the ecosystem associated with it [6].

This factor of ecological capacity and radiocapacity determines the reliability of the radionuclide retention (^{137}Cs tracer) in each component of the system.

On the basis of the expeditionary research, the results of observations and calculations, estimates of the rates of transition between the chambers of the studied agroecosystem were obtained.

For simplicity it is possible to calculate the reliability of the studied agroecosystem with average values of velocity parameters.

According to the data, the calculation of the ^{137}Cs radionuclide transfer to the population of the village was made. This value can be used to calculate the collective dose, using the values of dose rates for ^{137}Cs (2×10^{-8} Sv/Bq). The estimated collective dose is about 1.6 Sv/year. At the same time, the assessment of the average value of the individual dose of people irradiation is about 1,1 mSv/year (at a rate of 1 mSv/year). Assessment of the additive to the collective dose due to the use of forest products is 0.34 man. Sv year, and garden products - 0.2 Sv/year. Then, the total collective dose will be about 2.14 Sv/year, and the individual dose of irradiation for each inhabitant of the village may be 1.4 Sv/year.

Received data allow assessing the reliability of the components of the ecosystem by the formula (1) and, using the consistent nature of the linkage of the individual components in the agroecosystem with the population, receiving the assessment og the reliability of this agroecosystem as a system for transporting radionuclides from pastures to populations. The shown approach can be applied to evaluate the effectiveness of different types of countermeasures [4].

The system type of the radiological research of settlements covers the main links: soils, hay, agricultural animals, milk, forest, people. This type of simulation has been used for different types of ecosystems. Thus, models of transport of radionuclides ^{137}Cs on a typical slope ecosystem, mountain ecosystem, lake ecosystem and cascade of Dnieper water reservoirs have been constructed [1].

4 Analytical GIS Technology in Ecology

Analysis of pollutants behavior in sloped ecosystems, which form the basis of virtually any terrestrial landscape, showed the possibility of describing the distribution and redistribution of radionuclides by radiocapacity theory methods with using chamber models. Our studies have shown that the rate of radionuclide movement in the landscape is determined mainly by several characteristics: steep slope (P_1), cover type (P_2), landscape density (P_3), vertical (P_4) and horizontal (P_5) migration. Rank estimation methods were used to estimate the probabilities of the influence of these landscape indicators on the redistribution of radionuclides. Each of the indicators is evaluated in the range of values from 0 to 1. Because of the independence of the landscape indicators, the overall assessment of the probability of radionuclide migration by the elements of the landscape is defined as a general probability and is calculated by the formula:

$$P = P_1 \times P_2 \times P_3 \times P_4 \times P_5, \qquad (2)$$

Particular problem is represented by real landscapes, when the estimation of the parameters of radioactivity concerns large territories, where system of factors influencing the redistribution of radionuclides by biotic and abiotic components of ecosystems operate. The main factors influencing the radioactivity parameters are determined: slope steepness, type of vegetation of the surface, runoff rate, type of soil, etc. As established from the field studies of the processes of radionuclide motion on sloping systems and soil erosion processes under the action of surface runoff, the drainage intensity dramatically increases with the slope steepness. According to estimates and literary data, with the slope steepness of 1-3o, the probability of discharge per year is 0.01-0.05 from the reserve of the pollutant on this part of the slope, and with a steep slope of 25-30 °, the probability of discharge of radionuclides and other pollutants is tending to 1.

Using the technical capabilities of the ESRI ArcGIS software product, a model-analytic GIS has been developed that allows analyzing and forecasting the migration of pollutants in ecosystems. The mathematical basis of this GIS is the mathematical model of migration of pollutants in ecosystems. The main information components of this model are the physico-chemical and biochemical characteristics of the pollutants, as well as the natural and anthropogenic factors of the environment. Analysis of the initial data allows us to reach the defining blocks of the model - indicators of the rate of discharge and removal of pollutants in ecosystems.

As a result of processing the source data and analyzing it in ArcGIS using the Spatial Analyst and 3D Analyst modules, analytic maps are created which represent indexed raster images that are composed of pixels of a given size. Each of these pixels has a specific digital, index or logical value that it obtains as a result of performing calculations on one of the possible algorithms for interpolating data from the source, raster, or vector information GIS layers.

Due to the implementation of a number of spatial and mathematical calculations with raster information layers, we can obtain a set of necessary raster-index analytic maps with indicators of discharge, take-off and accumulation rates of pollutants for each of the pixels, which, having a given dimension, represent an elementary spatial unit of the terrain. Using the "Bitmap Calculator" component from the arsenal of the Spatial Analyst module, according to the accepted mathematical model, we define the sequence of mathematical operations that will be implemented over the index values of the analytic cards, and also enter the layer with the data on contamination and the number of calculation cycles that simulate the time interval (as rule in 1 year). As a result of these calculations, we get a new index raster layer, depicting projected pollution levels of the territory, which are investigated within a predetermined interval of time.

As a result, we obtained estimation and forecast maps for the selected polygon (Reserve "Lesniki" in Koncha-Zaspa near Kyiv along the river). Fig. 3 shows maps of radio intensity indices of the landscape of the original polygon (on the right) and the structure of its relief (on the left).

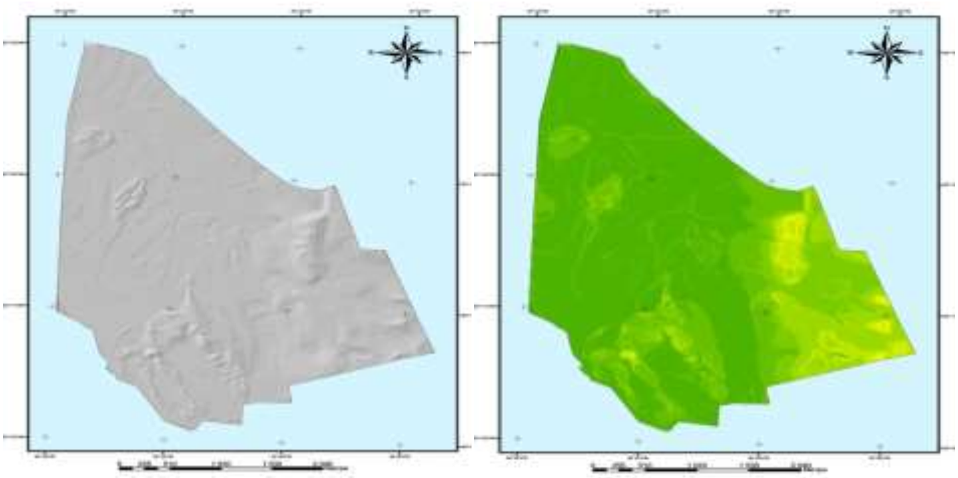

Fig. 3. Real values of radioactivity indicators of the landscape of Lisniki in the Koncha-Zaspa near Kyiv (on the right) and its relief (left)

Using parameters that influence the redistribution of radionuclides in the landscape, maps (Fig. 4) of the initial uniform contamination of the ^{137}Cs landscape (on the left) and map of redistribution of radionuclides based on the parameters 10 years after the accident (right) were constructed. It is evident that a significant redistribution of pollutant is expected in the studied landscape.

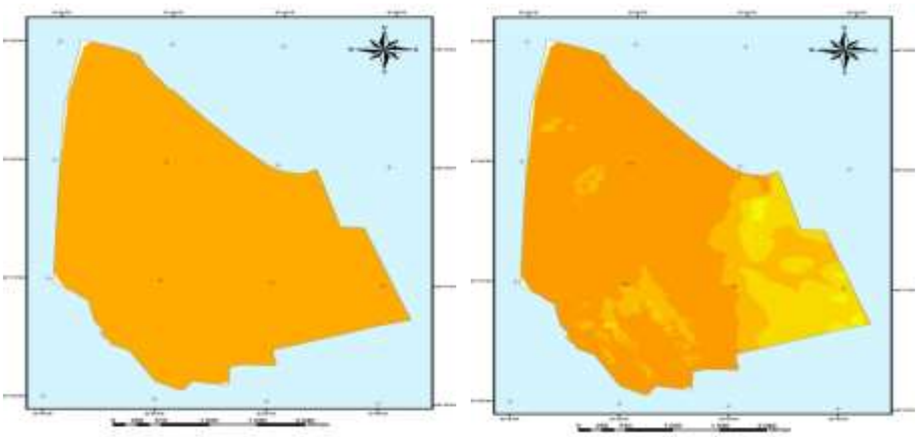

Fig. 4. The uniform distribution of ^{137}Cs radionuclides on the investigated polygon (initial state to the left) and redistribution of radionuclides 10 years after the accident (right).

This process is intensified (Fig. 5) after 20 years of evaluation (left), and 30 years after the accident, the prediction map (right) shows the sharp concentration of radionuclides in the landscapes (darker red paint). In our landscape, it is primarily a swamp [2].

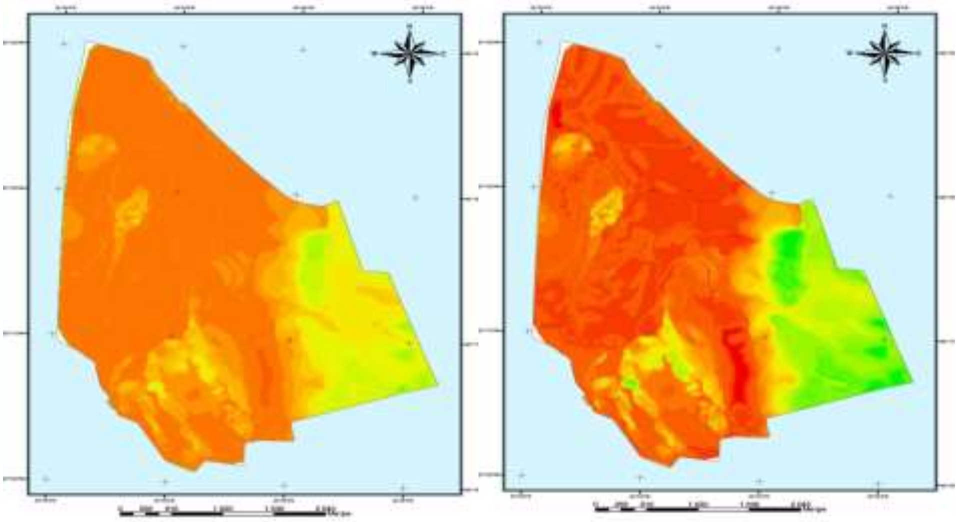

Fig. 5. Forecast of distribution of radionuclides in 20 years (left), and 30 years (right) after the accident

5 Verification of Models by Field Data

The model must meet two requirements:

- reflect those features of the studied object, which act as a subject of research;
- be adequate to the investigated object.

According to these requirements, the process of modeling itself can be divided into four stages: qualitative analysis, mathematical implementation, verification by field data and studying the model.

Within the presented research, chamber models of the real ecosystem have been developed and analyzed for real ecosystem of the village Galusia of the Manevitsky district of the Volyn region affected by the accident at the Chernobyl nuclear power plant. The models take into account all the main streams of ^{137}Cs radionuclides. The block diagram of chamber models contains all the main pasturelands. If necessary, the diagram may include radionuclide streams from forest products (mushrooms and berries), as well as from the use of garden products.

As a result of the simulation, assessments and forecast of the expected contamination of $^{13}7Cs$ radionuclides of human food products (milk, meat) were received, which is reflected in the values of collective dose loads for humans.

According to the simulation results, it was found that in the settlements of the type like Galusia, notable dosage loads were formed not immediately after the accident, but only in 1992-1994. Now, 30 years after the accident at the ChNPP, people accumulate total collective doses of radiation from ^{137}Cs from 40 to 80 people / Sv. In these territories, the large contribution to the collective dose is forest products. For villages of the Gazus type, a marked accumulation of collective dose for the population is characteristic for the population during 30-40 years after the accident, which is ensured by 1% of the stock of ^{137}Cs radionuclides in this ecosystem.

Thus, agroecosystems are an important source of transport of radionuclides from the environment to humans. The greater the radioactivity factor of the entire agroecosystem, the more reliable it is to humans (in understanding the reliability of radionuclide deliveries).

Using the rate of migration, distribution and redistribution of radionuclides of ^{137}Cs in agroecosystem components, as well as the cesium transition rate to all population groups, it is possible to calculate the reliability of this agroecosystem and to estimate the contribution of various components of the agroecosystem in generating dose loads per population.

Depending on the amount of radionuclides that have fallen on the territory, countermeasures can be used, the effectiveness of which depends on many factors (for example, soil type, humidity, rainfall, etc.) and evaluate their utility [6].

6 Conclusions

Application of models and reliability theory to the study of ecological processes in various types of ecosystems is necessary since it allows to assess the basic characteristics and fundamental properties of ecosystems. The proposed method for assessing the reliability of ecosystems can be used to estimate the level of contamination and transitions of other pollutants in different ecosystems.

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