Nuclear Engineering and Technology xxx (xxxx) xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Geoinformation decision support system for remediation of the ^{137}Cs contaminated agricultural lands after the Chernobyl NPP accident

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ARTICLE INFO

Article history:
Received 12 April 2021
Received in revised form
29 October 2021
Accepted 12 December 2021
Available online xxx

Keywords:
Decision support system
Chernobyl NPP accident
Radioactive contamination
Agricultural products
Risks of exceeding the standard
Remediation technologies

ABSTRACT

Based on GIS technologies, a decision support system (GIDSS) has been developed to remediate agricultural lands in the Bryansk region (Russia) contaminated by ^{137}Cs after the accident at the Chernobyl nuclear power plant. GIDSS is a multilevel system consisting of basic, information and computational layers. GIDSS allows justifying a targeted approach for the remediation of agricultural lands belonging to agricultural enterprises for the production that meets the established radiological requirements for the content of radionuclides. Evaluation of the effectiveness of alternative remediation technologies and the selection of optimal measures were carried out at the level of elementary plots using radiological criteria. The introduction of GIDSS will enable agricultural producers in the south-western districts of the Bryansk region to conduct radiation-safe agro-industrial production in radioactively contaminated areas, which will help improve the socio-economic situation of the region and return it to normal living conditions.

1. Introduction

The Chernobyl nuclear power plant accident in 1986 is the largest in the world nuclear power industry's history. As a result of the accident, not only the countries of the former USSR (Russia - 60.0 thousand km^2, Belarus - 46.0 thousand km^2, Ukraine - 38.2 thousand km^2) were subjected to large-scale radioactive contamination with ^{137}Cs deposition density above 37 kBq m^{-2} (1 Ci km^{-2}), but also some European countries: Sweden, Finland, Austria, Norway, etc. [1]. Agricultural lands occupy a significant area in radioactively contaminated (primarily ^{137}Cs) territories. Thus, in Russia, contaminated agricultural lands amounted to more than 2 million hectares, and the highest levels of soil contamination with this radionuclide (over 1480 kBq m^{-2}) were recorded in the south-western districts of the Bryansk region [2]. Although 35 years have passed since the Chernobyl accident, in several districts of the Bryansk region, the area of radioactively contaminated agricultural land is 245 thousand hectares: 37–185 kBq m^{-2} – ~136,000 ha, 185–555 kBq m^{-2} – ~89,000 ha, 555–1480 kBq m^{-2} – ~20,000 ha. Some of the local agricultural products do not meet the established radiological standards [3]. Agricultural lands in the south-western districts of the Bryansk region with ^{137}Cs soil surface contamination above 1480 kBq m^{-2} (40 Ci km^{-2}) on an area of 17,100 ha (7300 ha of arable land and 9800 ha of pastures) were excluded from agricultural production. According to predicted estimates, the decay of ^{137}Cs to a level of less than 37 kBq m^{-2}, which characterizes “clean” areas, will continue in the most contaminated areas of agricultural land until 2180 [2]. This governs the long-term agricultural production problem on the radioactively contaminated areas of the Southwest of the Bryansk region.

Agriculture on the lands affected by the Chernobyl accident was initially associated with the risk of obtaining crop, fodder, and livestock products that did not meet sanitary regulations and standards for radionuclides' content. From the first months after the accident, various protective and remediation measures were implemented to reduce radioisotopes' accumulation in agricultural products [4]. In the Bryansk region territory, researchers worked out optimal agrochemical and agrotechnical technologies for various types of crop and forage products, taking into account the levels of radioactive contamination and soil properties, including fertility indicators and zonal specifics of agricultural production [5].

Agricultural production under the conditions of large-scale radioactive contamination and the need to justify the most effective ways to reduce the content of radionuclides in agricultural

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https://doi.org/10.1016/j.net.2021.12.017

products (i.e., the selection of protective measures with maximum radiological efficiency at minimum costs) required the development of new approaches and methods for assessing the post-accident situation, as well as the development of software tools for multi-criteria analysis of the effectiveness of alternative remediation technologies. The basic information for such assessments was data on the radionuclides' contamination of agricultural lands. In conditions of heterogeneity (spotting) of radioactive contamination and a variety of agricultural landscapes, leading to uncertainties in solving the problems posed, special software – the decision support system (DSS) - is usually used.

To date, both foreign and Russian scientists have developed a number of GIS projects and decision support systems (DSS) using GIS technologies to assess the consequences of radioactive contamination of territories and their remediation. The largest international project, where specialists from many European and CIS countries took part (1991–2001), was the project to develop the DSS RODOS [6,7]. This system was designed to predict the consequences of accidents at nuclear power plants and manage a post-accident situation, both in acute and long-term periods.

Another system, named RECASS, was designed for information support in dealing with emergencies associated with accidental environmental pollution [8,9]. The main tasks of the system were a collection, processing, systematization and storage of monitoring data, presentation of the analysis results of the pollution state in the controlled area, modelling of the processes of the pollutants' spread in the atmosphere, calculation of average annual individual and collective effective doses of the public considering a typical diet of the population and the number of residents in radioactively contaminated territories. The DSS uses geographic information systems' capabilities and implements models based on different techniques with different promptness.

Several GIS projects were created to eliminate the consequences of the Chernobyl accident in agriculture. The most famous DSS for assessing the aftermath of radioactive contamination of rural areas and their remediation was the applied geographic information system PRANA created in the mid-90s [10] and later transformed into the land use management system DECERN [11]. PRANA includes vector maps, databases of attributive information. It is a set of specialized geographic information systems (GIS) used to calculate collective radiation doses to the public, risks of exceeding standards in products and to optimize countermeasures in agriculture under conditions of radioactive contamination.

Another GIS project was developed to justify the return to the economic turnover of territories temporarily removed from the land use after the Chernobyl accident due to high radioactive contamination levels. The geographic information system includes a library of digital maps for agricultural lands of 22 farms in the south-western districts of the Bryansk region removed from land use: land use types, ^{137}Cs contamination density (5 rounds of a survey from 1988 to 2015), soil maps, humus content, fundamental agrochemical indicators (pH, P_2O_5, K_2O), maps with prognostic assessments of the production possibility of crops, fodder, livestock that meets the standards, with various options for land cultivation (without countermeasures, subject to the application of remediation measures). The created library of digital maps makes it possible to assess the radioecological situation and substantiate the need for remediation measures [12].

Over the years after the Chernobyl accident, the boundaries and names of agricultural enterprises located in radioactively contaminated areas and elementary plots' boundaries have repeatedly changed. Improvement of the approaches to optimizing the remediation processes of radioactively contaminated areas, the development of GIS technologies and the possibilities of map digitalization using space images, varying conditions of agricultural production and changes in the effectiveness of countermeasures lead to the need in developing new, more advanced decision support systems based on GIS. Therefore, the scope of this paper is to present such a GIS-based DSS.

2. Methods

The main task of the DSS is to provide the end-user with a tool for analyzing data and choosing the optimal solution considering a set of influencing factors. DSS implements the collection, storage, presentation of information, and solving information retrieval analysis issues through a database management system (DBMS). In our case, the DSS should support making decisions on the agricultural production on radioactively contaminated areas that meet radiological standards, based on the systematization of data obtained from various sources, including radiation monitoring [3].

Modern GISs have a powerful computing complex for collecting, processing and then displaying spatially coordinated data and related non-spatial information. They also include the capabilities of a DBMS, raster and vector graphics editors and analytical tools, which enables creating a DSS based on them. Such systems are called GIDSS. They allow visual displaying and transforming input information flows into output forms acceptable for decision support. In the current research, a decision support system (GIDSS) prototype was developed based on GIS technologies to remediate radioactively contaminated agricultural lands in 5 south-western districts of the Bryansk region, most affected by the Chernobyl accident. GIDSS was implemented with the Russian language interface in the ArcMap 10.5 environment included in the ArcGIS software. The project's objects are attribute tables for storing information and digital maps for data visualization. ArcMap provides all the processing and data management capabilities when working with large amounts of information. If necessary, the project is open for entering and editing existing information on agricultural lands' properties. All geographic data were normalized to a single coordinate system – WGS-84 [13].

The following data sources were used to create a GIS to support decision-making on the remediation of ^{137}Cs-contaminated agricultural lands in the Bryansk region (Fig. 1):

- cartographic materials (topographic and general geographic maps, maps of administrative-territorial division, cadastral plans, etc.);
- remote sensing data (aerial and ground surveys of the area, etc.);
- data of radioecological monitoring of terrestrial ecosystems and agricultural products;
- statistical data (information on environmental pollution, etc.);
- literature data (reference publications, books, monographs and articles containing information on certain types of geographic objects).

The developed GIDSS is multilevel and is represented by basic, information and calculation layers (Fig. 2). Base layers contain the following information: boundaries and location of agricultural enterprises; topography, including data on settlements, roads, hydrographic network, forests, etc. (Fig. 3). This information is the basis for data binding, reconciliation of information layers, and subsequent analysis.

As the primary material for digitizing the contours of land plots

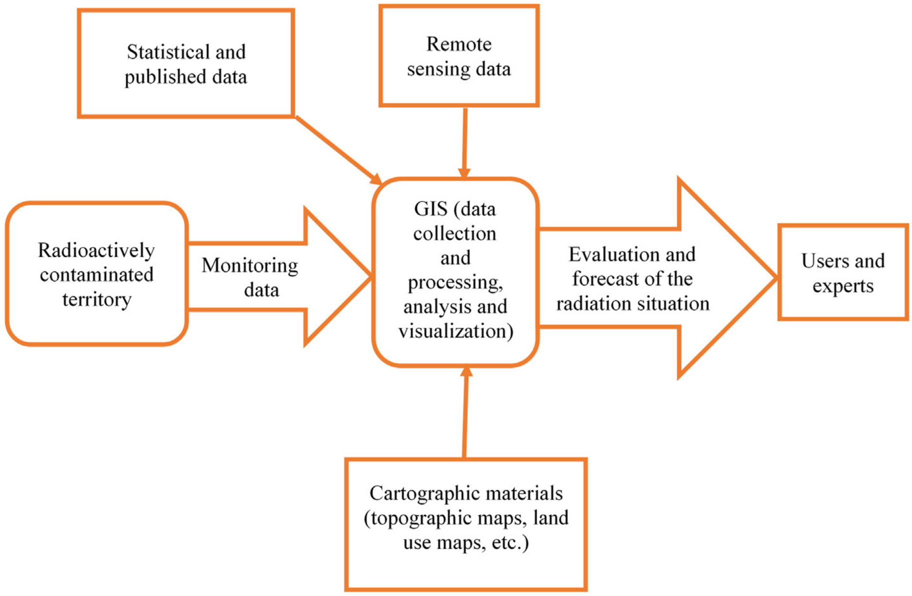

Fig. 1. Conceptual scheme of GIDSS for the remediation of ^{137}Cs-contaminated territories.

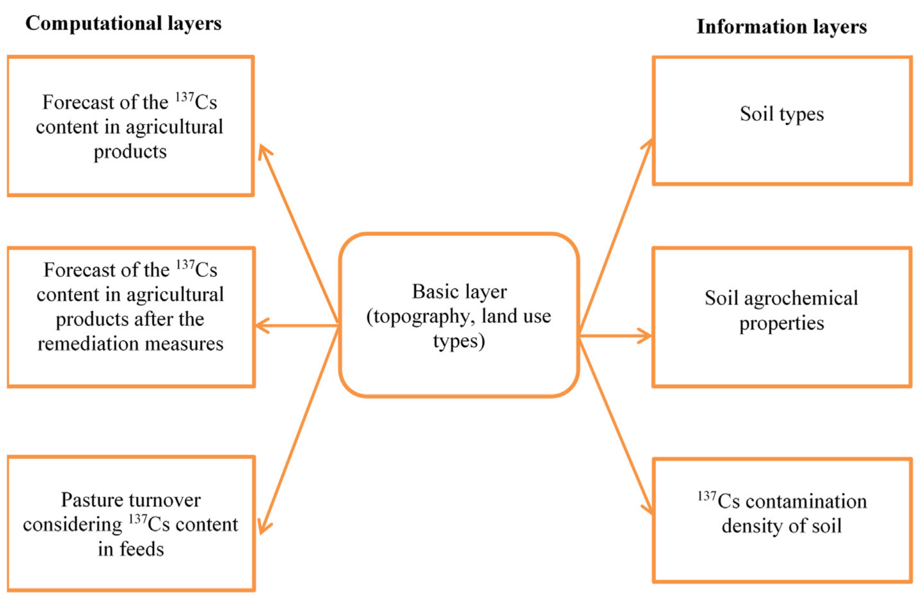

Fig. 2. Structure of GIDSS for the remediation of ^{137}Cs-contaminated agricultural lands.

and the boundaries of agricultural enterprises' land use, we used modern schemes of their on-farm structure and corresponding space images.

The GIDSS information block consists of the following layers:

- *the density of soil* ^{137}*Cs contamination*, including the following ranges: < 37; ≥37 and < 185; ≥185 and < 555; ≥555 and < 1480; ≥1480 kBq m^{-2} (Fig. 4);
- *land-use type*, including settlements, arable land, gardens, pastures, hayfields, fallow lands, forests, shrubs and other lands (Fig. 5);
- *crop rotations structure* (individual in each agricultural enterprise);
- *soil type* (sandy, sandy loam, loam, clay, peaty);
- *soil agrochemical parameters* (pH, P_2O_5, K_2O, Ca, Mg, CEC, humus).

The calculation module uses the collected attributive information about agricultural enterprises to predict radionuclides' content in agricultural products before and after applying the remediation technologies.

The accumulation of radionuclides in crops depends on the density of soil contamination, radionuclide characteristics, the type and properties of soils, and plants' biological characteristics. The measurement error in gamma-spectrometric analysis of the ^{137}Cs activity concentration in the soil of agricultural land and agricultural products did not exceed 15%. Suppose there are no direct measurements on the activity concentrations in agricultural products. In that case, for the calculations, the GIDSS uses the transfer factors (TF) of

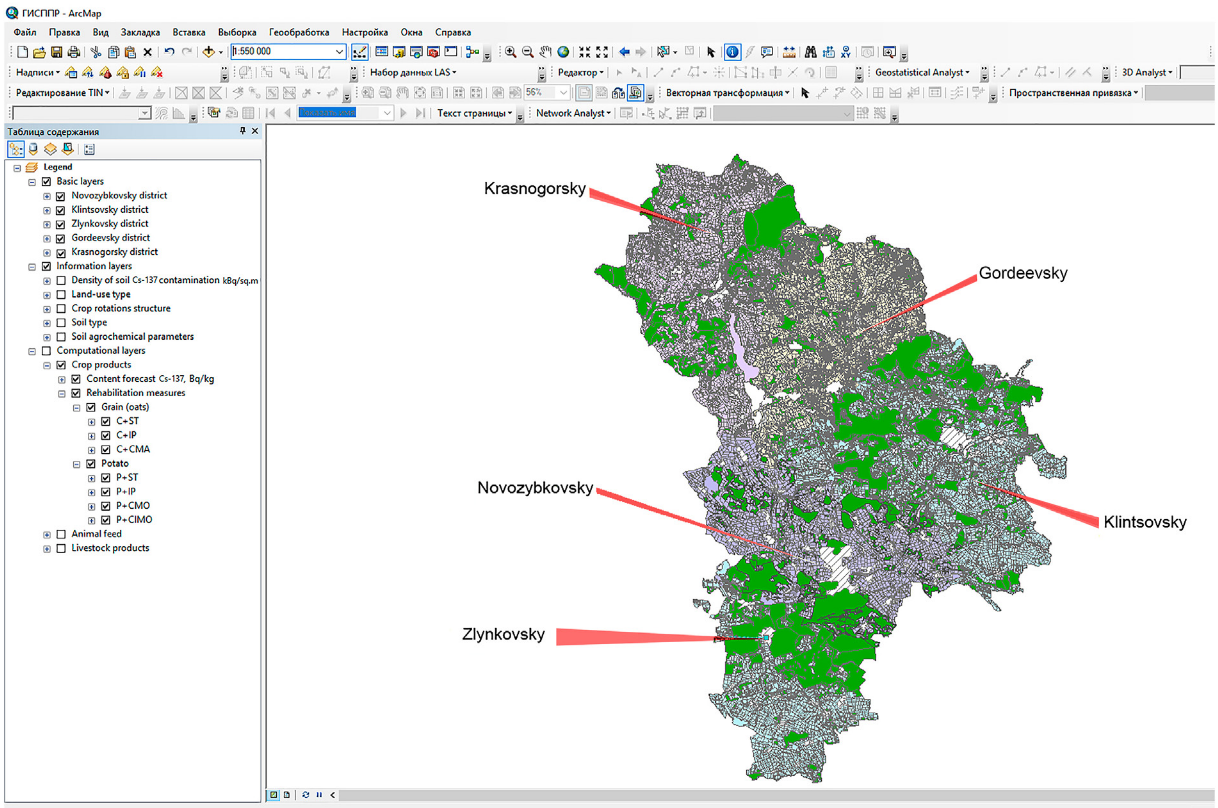

Fig. 3. Basic layers of the GIDSS for the remediation of radioactively contaminated agricultural land in the south-western districts of the Bryansk region.

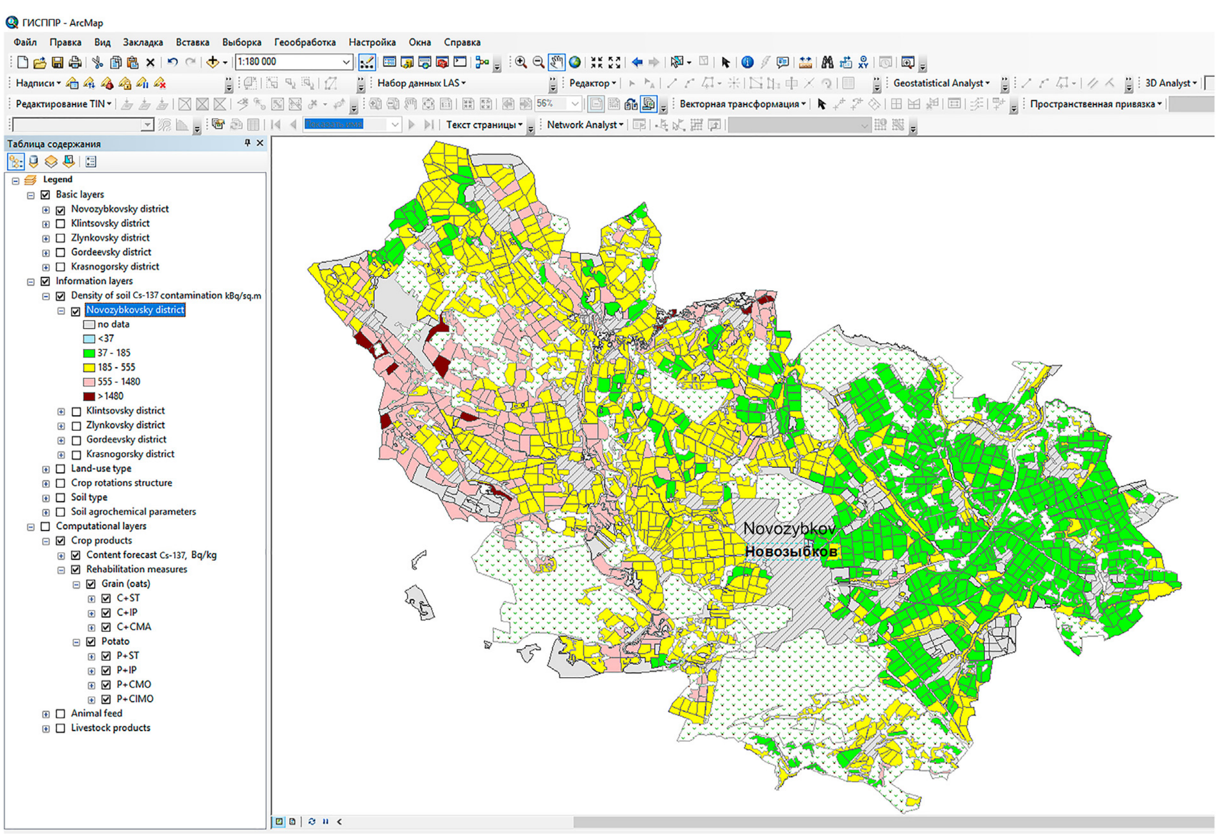

Fig. 4. Mapping in the GISDSS of the layer "Density of ^{137}Cs contamination" of agricultural lands in Novozybkovsky district of Bryansk region.

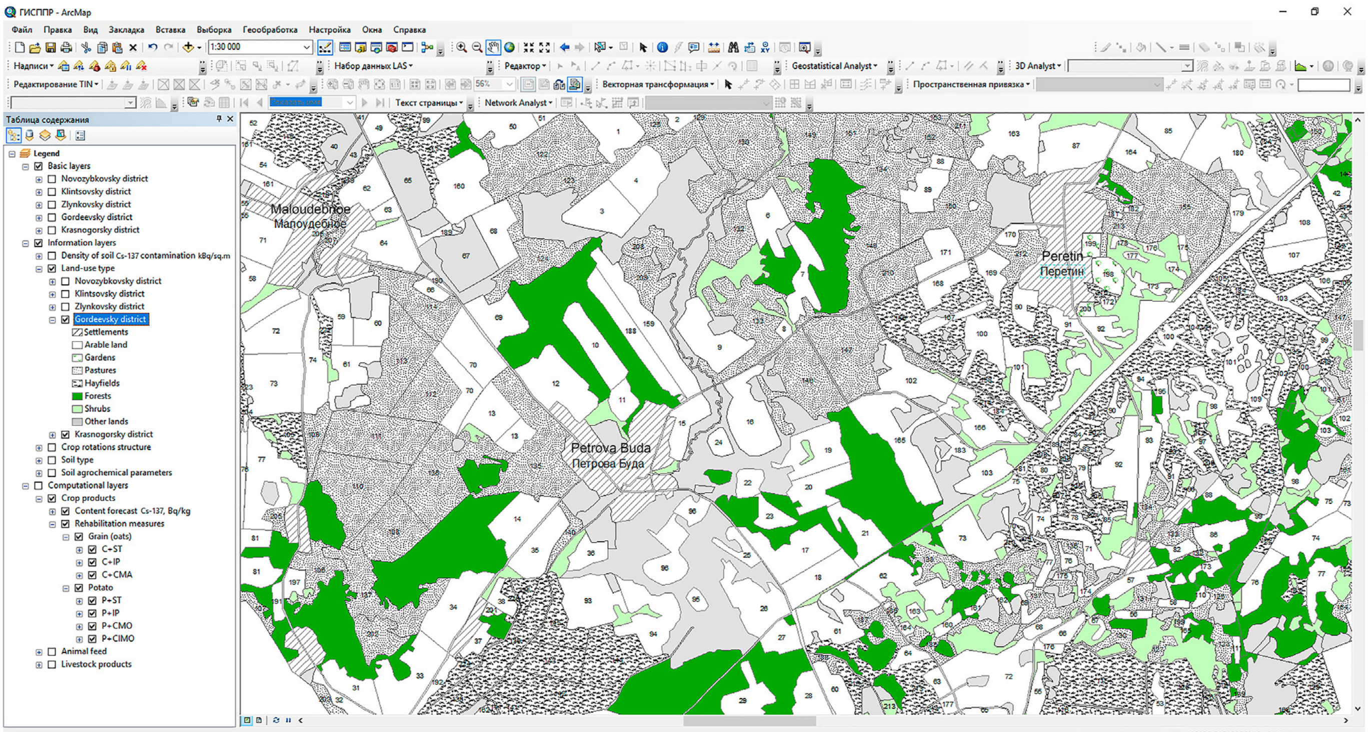

Fig. 5. Mapping in the GISDSS of the layer "Land use type".

^{137}Cs into agricultural plants depending on the soil types, fertility, i.e. provision with exchangeable potassium of soddy-podzolic soils, typical for the Southwest of the Bryansk region [4].

Calculation of ^{137}Cs contamination levels of crop products and animal feed is carried out according to equation (1):

$$C_v = TF_{ag} \times A_s \tag{1}$$

where C_v is an activity concentration of ^{137}Cs in food crops and animal feed (dry matter), Bq kg^{-1};

TF_{ag} is ^{137}Cs aggregated transfer factor into a product, (Bq kg^{-1})/(kBq m^{-2});
A_s is the ^{137}Cs soil surface concentration, kBq m^{-2}.

The maximum permissible soil surface concentration of ^{137}Cs in agricultural lands ($A_{s,lim}$), where it is possible to obtain crop, fodder and livestock products that meet the established radiological standards, is determined in the GIDSS by equation (2):

$$A_{s,lim} = \frac{C_{v,\ lim}}{TF_{ag}} \tag{2}$$

where $C_{v,\ lim}$ is the maximum permissible concentration of ^{137}Cs in food products and feeds for farm animals, Bq kg^{-1} (following the current standards).

The calculation of the predicted concentrations of ^{137}Cs in livestock products (C_{lp}) is performed according to expressions (3) and (4):

$$C_{lp} = A_{diet} \times \frac{TF_f}{100} \tag{3}$$

where A_{diet} is the radionuclide activity ingested with the daily diet, Bq;

TF_f is a radionuclide transfer factor from the feed to 1 kg (L) of product,% kg^{-1} (L^{-1}).

$$A_{diet} = \sum A_i \times m_i \tag{4}$$

where A_i is the actual concentration of the radionuclide in the feed i, Bq kg^{-1};

m_i is the amount of feed i in the diet, kg.

The daily diet for the pasture ("critical") period of grazing, when there is an increased accumulation of radionuclides in livestock products, includes 50 kg of green mass and 1.5 kg of feed grain [14].

In the final results, the model calculations considered the uncertainty in assessing potential ^{137}Cs contamination of agricultural products. The uncertainty is influenced by the variability of the levels of radioactive contamination of arable land and pastures, the radionuclide transfer factors even within one group of soils (the effect of soil acidity, the use of agromeliorants in previous years, and other factors). To minimize the uncertainty in the assessment results, the GIDSS uses ^{137}Cs concentrations in the soil of each elementary plot, transfer factors for the corresponding soil type and the probabilistic (risk) approach. It was considered acceptable if the risk of ^{137}Cs concentration in the final agricultural product exceeding the corresponding standard was less than 5–10%.

Based on predictive estimates of ^{137}Cs activity concentrations in agricultural products, the GIDSS offers the most optimal option for using agrochemical (for arable land) or additional agrotechnical (for grassland) methods from the list of remediation technologies, which includes measures with estimated efficiency parameters (the rate of reduction of the radionuclide content). The reduction factor of remediation measures (f) depends on the soil type, its physical and chemical properties, and agricultural crop kind. The result of applying the technology on a specific agricultural site is described by equation (5):

$$C_{rt} = \frac{C_v}{f} \tag{5}$$

where C_v and C_{rt} are the ^{137}Cs activity concentrations in agricultural products without and with the application of remediation technology.

Optimization of technologies for agricultural land remediation comprised the selection of measures ensuring the receipt of agricultural products that meet the established radiological standards at minimal costs, i.e. the cheapest ones.

Thus, the layers of the calculation block display the following information:

- forecast of ^{137}Cs content in crop production (cereals, potatoes), fodder production (green mass of grasses, hay, haylage, silage) and animal husbandry (milk, meat);
- forecast of ^{137}Cs content in crop, fodder and livestock products after application of remediation technologies;
- pasture-turnover, considering the content of ^{137}Cs in main feed types for each farm with a soil contamination density of over 185 kBq m^{-2}.

The current version of the GIDSS software implements the possibilities of using agrochemical and agrotechnical methods tested in practice, the most effective from the point of view of reducing the transfer of ^{137}Cs to crop (Table 1) and feed products (Table 2).

3. Results and discussion

Maps of the current on-farm structure of 89 agricultural enterprises in 5 south-western districts of the Bryansk region were digitized to create GIDSS. These maps include more than 24 thousand polygons and over 11 thousand plots of agricultural lands (Table 3).

Radiological and agroecological monitoring of agricultural lands in the Bryansk region was carried out by the Center for Chemicalization and Agricultural Radiology "Bryansky" of Russia's Ministry of Agriculture. From the first days after the Chernobyl accident, special attention was paid during monitoring to the region's south-western districts as the most radioactively contaminated. The GIDSS project was developed based on the last rounds of radiological and agrochemical surveys conducted from 2015 to 2018. [3], i.e. according to the most relevant data and detailed characteristics of each elementary plot. In GIDSS, the main indicators of agricultural enterprises (location of farms, fields, elementary plots, soil characteristics, levels of ^{137}Cs contamination, the structure of crop rotations, etc.) are verified with the results of the latest rounds of surveys and with data from the register of radioactively contaminated lands [15].

The GIDSS calculation block visualizes the areas with a high probability of exceeding the radiological standards in agricultural products. For example, an assessment of the possibility of producing hay for cereal grasses in the "Baturovsky" farm in the Krasnogorsk region showed that when using this type of forage for harvesting both hayfields and pastures (perennial grasses), as well as arable lands (annual seeded grasses), on 99 plots with a total area of 1927 ha (59% of all plots), without the use of particular

Table 1
Radioecological efficiency of agrochemical technologies for cereals and potatoes on arable land contaminated with ^{137}Cs, reduction factor.

Brief description of the technology (abbreviation in GIDSS)	Soil group			
	I[a]	II	III	IV
Cereals				
Standard doses of mineral fertilizers – $N_{60}P_{60}K_{60}$ (C + ST)	1.0	1.0	1.0	1.0
Increased doses of potash fertilizers - $N_{60}P_{60}K_{120}$ (C + IP)	1.7	1.5	1.5	2.0
Complex application of mineral fertilizers and agromeliorants - $N_{60}P_{60}K_{120}$ + 3 t ha^{-1} of $CaCO_3$ (C + CMA)	2.4	2.0	–	3.0
Potatoes				
Standard doses of mineral fertilizers – $N_{90}P_{90}K_{90}$ (P + ST)	1.0	1.0	1.0	1.0
Increased doses of potash fertilizers - $N_{90}P_{90}K_{180}$ (P + IP)	1.5	1.5	1.3	2.0
Complex application of mineral and organic fertilizers - $N_{90}P_{90}K_{90}$ + 40 t ha^{-1} of manure (P + CMO)	2.0	2.0	1.7	–
Complex application of mineral and organic fertilizers - $N_{90}P_{90}K_{180}$ + 40 t ha^{-1} of manure (P + CIMO)	2.6	2.3	2.0	–

[a] I – sand; II – loam; III – clay; IV – peat.

Table 2
Radioecological efficiency of agrotechnical and agrochemical methods on hayfields and pastures contaminated with ^{137}Cs, reduction ratio.

Brief description of the technology (abbreviation in GIDSS)	Soil group			
	I[a]	II	III	IV
Surface improvement with standard doses of mineral fertilizers - $N_{60}P_{60}K_{60}$ (SI)	1.3	1.3	1.3	1.3
Surface improvement with liming of acidic soils at a dose of 3 t ha^{-1} $CaCO_3$ (SI + L)	1.5	1.5	–	1.7
Surface improvement using liming and standard doses of mineral fertilizers – 3 t ha^{-1} $CaCO_3$ + $N_{60}P_{60}K_{60}$ (SI + LF)	1.7	1.5	–	2.0
Surface improvement with the use of increased doses of potash fertilizers - $N_{60}P_{60}K_{120}$ (SI + ST)	2.0	1.7	1.5	2.0
Surface improvement with the use of liming and increased doses of potash fertilizers – 3 t ha^{-1} $CaCO_3$ + $N_{60}P_{60}K_{120}$ (SI + IP)	2.5	2.0	–	2.5
Radical improvement with standard doses of mineral fertilizers - $N_{90}P_{90}K_{90}$ (RI)	2.0	2.0	2.0	2.0
Radical improvement with liming of acidic soils at a dose of 3 t ha^{-1} $CaCO_3$ (RI + L)	2.5	2.3	–	3.0
Radical improvement using liming and standard doses of mineral fertilizers – 3 t ha^{-1} $CaCO_3$ + $N_{90}P_{90}K_{90}$ (RI + LF)	3.0	2.5	–	3.5
Radical improvement with the use of increased doses of potash fertilizers - $N_{90}P_{90}K_{180}$ (RI + ST)	3.5	3.0	2.5	4.0
Radical improvement with the use of liming and increased doses of potash fertilizers – 3 t ha^{-1} $CaCO_3$ + $N_{90}P_{90}K_{180}$ (RI + IP)	4.0	3.5	–	4.5
Radical improvement with the use of complex fertilizer Borofosk at a dose of 0.8–1.0 t ha^{-1} (RI + B)	4.5	4.0	–	5.0
Drainage with radical improvement (D + RI)	–	–	–	7.0

[a] I – sand; II – loam; III – clay; IV – peat.

Table 3
Number of polygons digitized in GIDSS in farms of 5 south-western districts of the Bryansk region.

District	Number of enterprises	Area of agricultural lands, thous. ha	Number of elementary plots of agricultural lands	Total number of polygons (all digitized objects)
Gordeevsky	15	54.8	2577	6719
Zlynkovsky	14	32.3	1526	2678
Klintsovsky	23	61.3	2741	6128
Krasnogorsky	18	57.2	2302	5772
Novozybkovsky	19	60.6	1901	2834
Total	89	266.2	11047	24131

technologies, cannot guarantee the receipt of feed meeting the standards (Fig. 6).

As an example, a forecast of ^{137}Cs activity concentration in grain (oats) is presented before and after the use of alternative remediation technologies in the “Kurganovsky” farm of the Krasnogorsk district (Fig. 7). The schematic map shows in red a high risk of exceeding the standard in grain (60 Bq kg^{-1}), green areas show a high probability of oats production that meets the regulatory requirements. In this agricultural enterprise, 51 plots are used for arable land with an average ^{137}Cs contamination density of 572 kBq m^{-2}, with a wide variability of contamination levels from 181 to 1257 kBq m^{-2}.

The GIDSS forecast showed that it is impossible to produce food grain (oats) meeting the standard at 38 plots of the Kurganovsky agricultural complex (Table 4). Application of increased doses of potash fertilizers in a dose of $N_{60}P_{60}K_{120}$ will reduce the transfer of ^{137}Cs from soil to grain, leading to a decrease in the number of areas with the grain standard excess (60 Bq kg^{-1} for ^{137}Cs) to 31. The most effective technology is the complex application of mineral fertilizers and ameliorants – $N_{60}P_{60}K_{120}$ and $CaCO_3$ (at a dose of

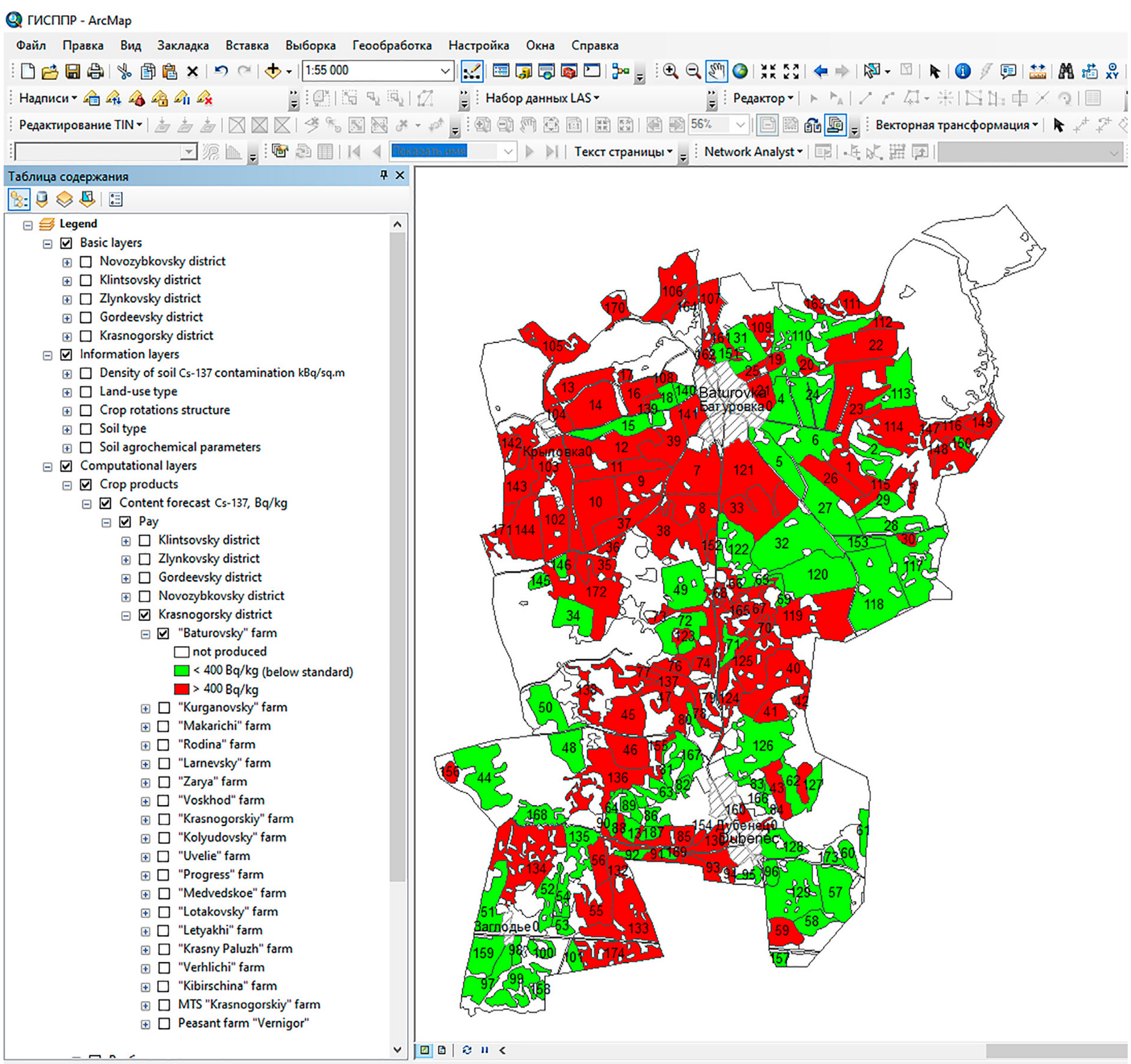

Fig. 6. Mapping in the GISDSS of the ^{137}Cs content forecast in the hay of the "Baturovsky" farm of Krasnogorsk district.

Table 4
Forecast of ^{137}Cs content in grain (oats) during its production on contaminated agricultural lands of the Kurganovskiy agricultural enterprise of Krasnogorsk district before and after the application of remediation technologies.

Grain (oats) production option	^{137}Cs content in grain, Bq kg^{-1}			The fraction of areas exceeding the standard (60 Bq kg^{-1})
	mean	min	max	
Without remediation technologies	103	18	226	0.75
Increased doses of potash fertilizers - $N_{60}P_{60}K_{120}$	69	12	151	0.61
Complex application of agromeliorants - $N_{60}P_{60}K_{120}$ + 3 t ha^{-1} of $CaCO_3$	52	9	113	0.33

3 t ha^{-1}). When using it, the number of areas exceeding the standard in grain would decrease to 16, i.e. more than two times compared to the initial situation, which is a good indicator for the long-term period after the Chernobyl accident. On arable lands, where it is impossible to achieve the production of food grain that meets the standard, farm owners can change the crop to produce forage with less strict requirements for the content of ^{137}Cs (200 Bq kg^{-1}) in grain.

For the territory of the former Semipalatinsk test site in Kazakhstan, an example of a radiation legacy (testing of nuclear weapons), a radioecological monitoring system based on GIS technologies was also developed. The system structure includes databases containing environmental and radiological information; set of radioecological models; software that provides the integration of information resources and the formation of digital maps [16,17]. The radioecological monitoring system of the former Semipalatinsk test site has been used to make managerial decisions on the rational use of land resources and ensure the safe conduct of economic activities. The developed GIS network of radioecological monitoring of the Semipalatinsk test site is focused to a greater extent near the sites where nuclear explosions were carried out (Balapan, Degelen, Atomic Lake, etc.). GIDSS of the Southwest of the Bryansk region presented in this work covers all agricultural lands at the level of elementary plots, making it possible to fully assess the radiation situation on the territory and offer the optimal remediation measures.

4. Conclusions

The developed GIDSS has a large amount of compiled experimental and computational information. The created system makes it possible to assess and visually display the current state of radioactively contaminated agricultural lands and estimate the effectiveness of the implementation of technologies for the remediation of these territories. The GIDSS shows the potential for obtaining agricultural products that meet sanitary, hygienic and veterinary standards and regulations. The work results can be an information base for solving practical problems of planning and managing territories affected by the Chernobyl accident, including the optimization of remediation technologies and the organization of radioecological monitoring of agricultural lands contaminated with radionuclides.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the Russian Science Foundation [grant number 18-19-00016].

The authors would like to thank Dr. Janice E Hudson (Sinclair Community College) for her advice and comments.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2021.12.017.

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