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Preventive radioecological assessment of territory for optimization of monitoring and countermeasures after radiation accidents

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ABSTRACT

A methodology of a preventive radioecological assessment of the territory has been developed for optimizing post-emergency monitoring and countermeasure implementation in an event of a severe radiation accident. Approaches and main stages of integrated radioecological zoning of the territory are described. An algorithm for the assessment of the potential radioecological criticality (sensitivity) of the area is presented. The proposed approach is validated using data of the dosimetric passportization in Ukraine after the Chernobyl accident for the test site settlements.

1. Introduction

After all of the severe accidents that have occurred in the nuclear industry - Kyshtym (1957, USSR), Windscale (1957, Great Britain), Chernobyl (1986, USSR), and Fukushima (2011, Japan) - large, densely populated territories with intensive agriculture became contaminated (Burnazyan, 1990; Bakurov et al., 1997; Aleksakhin et al., 2001; Teverovsky and Ternovsky, 2005; Environmental, 2005; Wakeford, 2007; Steinhauser et al., 2014; MEXT, 2014). These accidents are recognized as communal agricultural ones. A study of their consequences showed that the radioactive contamination of a territory and associated doses of human exposure are determined not only by the characteristics of the release from the emergency source and the current meteorological conditions but are also largely dependent on environmental conditions in the contaminated area (Fedorov et al., 1973; Aarkrog, 1979; Prister et al., 2003; Aleksakhin et al., 2006; Prister, 2008; Fesenko et al., 1997; Kobayashi et al., 2012).

The impact of environmental factors on the response of the environment to radioactive contamination was outlined by Aarkrog (1979). He introduced the concept of radioecological sensitivity to characterize the radioecological properties of environmental samples in a study of the consequences of global fallout of ^{137}Cs and ^{90}Sr in Denmark and the Faroe Islands. The aggregated transfer factor expressed in Ci kg^{-1} per mCi km^{-2} was used as a quantitative measure of radioecological sensitivity. Later, Howard et al. (2002) identified four quantities for quantifying radioecological sensitivity, including transfer factors, radionuclide fluxes, individual exposure of humans and the action load.

After the Chernobyl accident, the concept of radiological sensitivity (or 'vulnerability' in some works) was discussed widely (Howard, 2000) and applied to explain the spatial variability of humans' radiation doses due to consumption of contaminated food. Gillett et al. (2001) showed that the presence of the radioecologically sensitive (vulnerable) regions in England and Wales, where the highest exposures could have occurred after the Chernobyl accident, does not necessarily correspond to the most contaminated areas. The concept of radioecological sensitivity was used to identify areas where high individual or collective doses to man and biota occurred in the SAVE project (Howard et al., 1999) for Western Europe, the RESTORE project (Van der Perk et al., 2000) for Ukraine, the AMAP (Strand et al., 1997) and AVAIL (Borghuis et al., 2002) programs for Arctic ecosystems, the SENSIB project (Mercat-Rommens et al., 2007) for France and others. Geographical Information Systems (GIS) facilitated the radioecological sensitivity analyses, linking the prognostic radionuclide migration models with databases of the spatially varying model input parameters (Dubois et al., 2004). Working Group 8 of the IAEA's EMRAS II Program (IAEA, 2013) proposed the concept of environmental sensitivity for different environments, corresponding with a set of ecological factors for each environment, and noted that environmental sensitivity will differ in short or medium-term scenarios related to the development of a radiation accident.

In Ukraine after the Chernobyl accident the radiation dose of the population in the settlements in the Rivne and Volyn regions (the territory of Ukrainian Polissya) for soil ^{137}Cs contamination levels of

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37–111 kBq m^{-2} (1–3 Ci km^{-2}) was up to 10 times higher (on average) in comparison with settlements with a contamination density of 111–555 kBq m^{-2} (3–15 Ci km^{-2}) near the 30-km Chernobyl Exclusion Zone (Prister, 2008; Radioecological, 2011). In 1986 the territory contamination density was used as the main criterion of danger, and the role of environmental factors was not taken into account. As a result, the ^{137}Cs contamination of milk and meat significantly exceeded national standards even in officially "safe" areas due to the abnormally high ^{137}Cs transfer factor in the "soil-plant-milk" chain in these areas. Unfortunately, agricultural countermeasures on these the most radioecological sensitive soils actually began only since 1988.

The spatial heterogeneity of landscape characteristics (relief, soil type, and vegetation type) and land use conditions can lead to significant variability in the radioactive contamination of agricultural production and the associated doses of internal exposure to the population. However, despite the experience gained, the dose rate of external irradiation and soil contamination density are still used as the main factors to assess the radiation situation, without due regard for soil properties and landscape features, although the dose of the internal exposure of the population at equal contamination density of soil of different quality can vary by up to two orders of magnitude (IAEA, 2005; IAEA, 2010a).

For the first assessments and the operational forecast of the radiation situation in the event of a nuclear accident, a number of decision support systems (DSS) have been developed to date. They include NARAC (USA), ARGOS, RODOS (EU), RECASS (Russia) and WSPEEDI (Japan), among others. These systems can predict the radiation situation using different models of radionuclide migration at a point with given coordinates without a comprehensive consideration of the spatial distribution of environmental factors such as the landscape features of the territory, soil type, land use, etc. (Sugiyama et al., 2014; Hoe et al., 2009; Ehrhardt, 1997; Shershakov and Trakhtengerts, 1996; Nakanishi et al., 2011). Models of radionuclide migration in various media (atmospheric transport and deposition, migration in soil and food chains) use different sets of input data on the ecological properties of the territory, which are not always consistent. The information collected in an "Environmental Impact Assessment" (EIA) report during a nuclear power plant operation period mainly consists of an overview and compilation data for a 30-km area only and does not contain input data required for computational models (Directive, 2003; IAEA, 2014). In addition, the area of radioactive contamination in severe accidents significantly exceeds the size of the NPP observation zone established in the EIA. After the accidents in Kyshtym, Chernobyl and Fukushima, the period of formation of databases of cartographic, statistical and other information, which are necessary for a detailed assessment of the radiation situation, lasted from six months to several years after the accident. During this period, the greater part of the population exposure dose for life has already occurred (Prister, 2008; Likhtarev, 1997).

An assessment of the radioecological properties (landscape characteristics and land use conditions) ***of the agrosphere has not been singled out as one of the main tasks of preventive and post-accident monitoring.*** In the event of a severe nuclear plant accident, ***information from existing radiation monitoring systems of the environment is not sufficient to control the formation of doses and apply adequate countermeasures in the agrosphere across the entire radioactive trace in a timely manner***.

Experience in reducing the consequences of severe accidents has shown that radiation monitoring, an assessment of the state of individual environments, agricultural product quality control, and a system of countermeasures are planned and implemented without taking into account the inhomogeneity of ecological properties of the contaminated territory and the spatial and temporal harmonization of available data. As a result, the data of control and monitoring are difficult to combine in space and time. This reduces the efficiency of information use and increases the uncertainty of assessments and planning of countermeasures in contaminated areas (Prister, 2007; Radioecological, 2011; Prister et al., 2016a). This is especially true when internal irradiation contributes significantly to the total radiation dose of the population.

To increase the efficiency of protecting the population and agricultural production from the consequences of a severe accident, it is proposed that a pre-emergency assessment of radioecological properties of the territory of probable contamination be conducted, including the collection and analysis of information necessary to forecast and assess the radiation situation under different accident scenarios. To optimize the post-emergency monitoring volume and obtain radioecological parameters representative of specific elements of the contaminated area, a methodology is proposed for preventive (prior to the accident) radioecological zoning of the territory and the formation of a database of the properties of the selected areas, with a quantitative assessment of their radioecological sensitivity (a possible contribution to the formation of a population dose) in terms of the radioecological criticality index of an area. Such information is the basis for prompt prediction and assessment of the radiation situation and the development of a countermeasure program.

1.1. Study object and methods

A portion of the western radioactive trace of the Chernobyl accident, formed in the territory of the Ukrainian Polissya, was selected as a test site to develop the radioecological monitoring methodology. The site includes the northern parts of the Chernihiv, Kyiv, Zhytomyr, Rivne and Volyn regions of Ukraine (Fig. 1). The site length in the western direction from the Chernobyl NPP is approximately 360 km, and the area is approximately 37 thousand km^2.

Because decisions on monitoring and countermeasures are made at various spatial levels, an analysis of the territory radioecological properties should be made at three scales: state level - for the territory of the country; regional level - for several administrative regions; and local level - for the district, settlement and farm. Specific information is necessary for all of these scales (Table 1).

In accordance with the requirements for the input data of the scales considered (Table 1), the following initial vector maps from the Web portal http://www.diva-gis.org/gdata and the National Atlas of Ukraine (http://www.isgeo.com.ua) were used in this work:

- **river basins** with hydrographic zoning for 1: 200,000 scale (Lev et al., 2017);
- **relief** (point objects) obtained by converting the raster data of the SRTM (Shuttle radar topographic mission) project (http://srtm.csi.cgiar.org) with a resolution of 900 H 600 m or 90 H 60 m using ArcGIS tools;
- **soils** from the National Atlas of Ukraine;
- **vegetation cover** obtained by converting the raster data of the EU project "GLC2000 global dataset" (http://forobs.jrc.ec.europa.eu/products/glc2000/data_access.php) using the "LCCS" (Land Cover Classification Scheme) terminology and ArcGIS tools.

The initial data were processed and calculated for the cells of three regular grids of state, regional and local scales. This enables us to conduct, using the principle of "telescoping", a preventive assessment of the territory, containing step-by-step, detailed information on the environmental parameters at the level of elementary plots (a farm or a field). The procedure for creating a basic grid-map included:

- grouping soils by radioecological properties and assigning a soil type to the grid cell which occupies the maximum area within it,
- construction of a grid-map of the underlying surface types based on the GLC2000 data and a 2 × 2 km grid,
- construction of a grid-map of the basins using the hydrographic network map (tributaries of 2nd and 3rd orders, the basin area is not less than 2000 km^2) and the terrain from the SRTM project data for