https://doi.org/10.46813/2026-165-181

METHODOLOGICAL PRINCIPLES FOR THE FORMATION OF A REFERENCE SPATIAL FIELD OF GAMMA RADIATION EQUIVALENT DOSE RATE FOR REMOTE RADIATION MONITORING

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The article proposes a methodological approach to the spatial reconstruction of the gamma radiation equivalent dose rate (EDR) field based on discrete surface radiation monitoring data. This study is motivated by the spatial irregularity of the surface observation network operated by the Ukrainian Hydrometeorological Center of the State Emergency Service of Ukraine) and the need to form a spatially continuous information field for further integration with remote and model data in the radiation monitoring system of atmospheric air. Geoinformation methods Inverse Distance Weighting (IDW) and Ordinary Kriging were used to reconstruct the spatial distribution of EDR. The application of different interpolation methods has been found to form distinct spatial representations of the same set of surface observations: IDW better preserves local features and spatial contrasts, while Ordinary Kriging provides a more smoothed field taking into account spatial autocorrelation. The feasibility of using the reconstructed EDR field as a reference information layer for subsequent comparison with remote sensing, meteorological, and model data has been substantiated.

PACS: 93.85.+q; 92.60.Sz

INTRODUCTION

Modern radiation monitoring systems are based on the use of multi-level sources of information, among which surface observation stations, including automated ones, means of remote sensing of the Earth, unmanned aerial vehicles (UAVs), meteorological observations and mathematical modeling of atmospheric processes [1–3] occupy an important place. For the operational assessment of the radiation state of atmospheric air, the possibility of combining these sources in a single space-time information environment is of particular importance.

Ukraine has accumulated significant experience in surface radiation monitoring, particularly regarding the measurement of the gamma radiation equivalent dose rate (EDR) [4]. However, the spatially uneven distribution of monitoring stations results in the discrete nature of the data obtained. While surface stations provide actual measurements at specific coordinates, they do not offer a direct picture of the spatial distribution of the parameter in question between the monitoring points. Indeed, the limited spatial coverage of surface observation networks is identified as one of the challenges facing modern radiation monitoring.

In previous studies by the authors [5–9], the use of satellite technologies, remote sensing and mathematical modeling for the development of the radiation monitoring system of atmospheric air in Ukraine was substantiated. A general algorithm is proposed, which involves obtaining remote data, collecting ground information, its preliminary processing and validation, integrating data sources, modeling the atmospheric transfer of radioactive substances, forming radiation situation maps for further support of management decisions at the level of state authorities.

However, for the practical implementation of such an approach, it is necessary to solve a separate methodological task, which consists in the transition from discrete values of ground measurements to a spatially continuous representation of the radiation field and suitable for further comparison with other spatio-temporal information layers.

The authors of the study propose one way to address this task, namely the application of geospatial interpolation methods [10]. At the same time, it is worth noting that different methods can reproduce local heterogeneity, extreme values and the general spatial structure of the radiation field in different ways. Therefore, the choice of interpolation method should not be based only on the visual analysis of maps, but requires methodical and quantitative justification.

The purpose of this study is to substantiate a methodical approach to the formation of a reference spatial field of the EDR for the reconstruction of the γ-background field based on surface observations by distributing the EDR and its comparative assessment by IDW and Ordinary Kriging methods.

The idea of the study is that the method of spatial interpolation significantly affects the nature of the reconstructed EDR field, and the justified choice of the IDW (Inverse Distance Weighting) or Ordinary Kriging method should be carried out based on the results of a

quantitative assessment of the accuracy of reproduction of surface measurements. At the same time, IDW and Ordinary Kriging can form different spatial reconstructions of the same field, and the choice of method should be determined not only by the visual characteristics of the maps, but also by the accuracy assessment.

The main source of operational information about the spatio-temporal change of the external radiation field is surface radiation monitoring stations equipped with automated or stationary means of measuring gamma radiation. At such points, depending on the type of equipment, continuous or periodic registration of the EDR is carried out.

It is this type of information that is the most representative, because it is directly related to the task that is being solved in this study, since the discrete ground values of EDR are the initial data for further spatial interpolation.

International practice of IAEA [11] has confirmed the importance of these measurements. It should be noted that the European Radiological Data Exchange Platform (EURDEP) [12] provides the exchange of radiation monitoring data, among which the main operational indicator is the EDR. The hourly average values of EDR obtained from thousands of observation points are presented in public access on the EURDEP online map [12].

First of all, it is advisable to note that the measured value of the EDR is an integral characteristic of the external radiation field at the observation station, which is formed by the combined contribution of natural and anthropogenic sources of ionizing radiation, including long-lived radionuclides left after past radiation events.

The authors note that the EDR is considered as a characteristic of the external radiation field, and not as a direct assessment of the concentration of radionuclides in atmospheric air. In turn, the information basis of integrated radiation monitoring may include direct radiometric and spectrometric measurements, remote observation data, meteorological data and mathematical modeling results.

THEORETICAL AND METHODOLOGICAL PRINCIPLES OF THE FORMATION OF A REFERENCE SPATIAL POWER FIELD OF THE EDR

In this study, as the basis of information support for radiation monitoring, we use actual data of surface measurements at the observation posts of the Ukrainian Hydrometeorological Center of the State Emergency Service of Ukraine of the EDR for the period from May 22 to June 5, 2026 [4]. Observation stations provide time series of the EDR values and characterize the radiation state in specific spatial coordinates. At the same time, for territorial analysis, it is necessary to obtain an assessment of the spatial distribution of the indicator not only in the locations of the stations, but also between them.

In previous studies by the authors [5–9], it is proposed to use a methodical approach, according to which it is necessary to integrate automated surface observation stations, satellite platforms, UAVs and mathematical models into a single system of remote radiation monitoring and, accordingly, in a single information and analytical environment. At the same time, surface data is one of the basic sources of information, which must undergo preliminary processing and validation before integration with other data.

Within the scope of this study, it is proposed to distinguish a separate methodological stage, which consists in the formation of the reference spatial field of the EDR. The authors of the study under the reference spatial field the EDR understand a spatially continuous estimate of the rate distribution of the equivalent dose, obtained by interpolation of discrete surface measurements, which is used as a reference information layer for further comparison with remote and model data.

In this case, the term “reference spatial field of EDR” characterizes not the absolute accuracy of the obtained values, but rather their reference function within the radiation monitoring information system. The interpolated field is formed directly on the basis of actual surface measurements and can be used as a basic spatial layer for further comparison with other sources of environmental information.

At the same time, the reference spatial field is not the result of remote measurement and should not be interpreted as the actually measured value of the EDR at each point of the territory. The values between the observation points are calculated and depend on the spatial structure of the initial data and the selected interpolation method using GIS technologies.

Spatial reconstruction in this study by the authors means obtaining a spatially continuous estimate of the EDR field based on discrete values of surface observations using spatial interpolation methods. In this context, interpolation is not the ultimate goal of the study, but an intermediate procedure for moving from a discrete network of observations to a spatial information field.

The generated field can be used as one component of an integrated remote radiation monitoring system alongside satellite, meteorological and model data. This approach is in line with the concept proposed earlier by the authors of the consistent integration of terrestrial and remote sources of information [5–9].

RESEARCH METHODS

The authors of the study carried out spatial modeling, which was performed using GIS technology tools and directly the Quantum GIS software complex [10]. To ensure a correct comparison, the results of interpolation were used using the cross-validation procedure according to the relevant criteria of mathematical statistics. It is the combination of cartographic and quantitative comparison that allows us to assess not only the nature of the spatial structure, but also the accuracy of reproduction of surface observations.

As it was noted, the data of surface observations of the EDR at the radiation monitoring stations in Ukraine [4] were used for the study. Data for May 26, 2026 were used to compare spatial interpolation methods. This date is chosen as a representative time slice for detailed comparison of spatial patterns. Two methods have been applied to form the spatial field, including IDW and Ordinary Kriging [10].

The IDW method is based on the assumption that the effect of observation items on the estimation of an unknown value decreases as the distance to that item increases. At the same time, the Ordinary Kriging method is based on the use of spatial autocorrelation of the studied indicator and taking into account the variogram.

RESULTS OF COMPARISON OF METHODS BASED ON CONSTRUCTED MAPS

The spatial location of operating surface the EDR observation stations is shown in Fig. 1. Their spatial location, the data of which will be used in the future to build an interpolation surface.



Fig. 1. Spatial location of surface monitoring stations measuring the EDR used to construct interpolation surfaces [4]

Using the data of surface observations of the EDR of radiation monitoring of Ukraine for May 26, 2026 and the application of IDW and Ordinary Kriging methods, two spatial models of the distribution of the EDR were constructed, which are presented in Figs. 2 and 3.

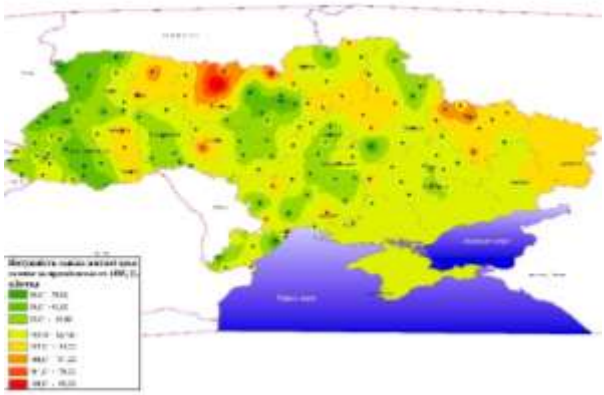


Fig. 2. Spatial distribution of the EDR obtained using the IDW method

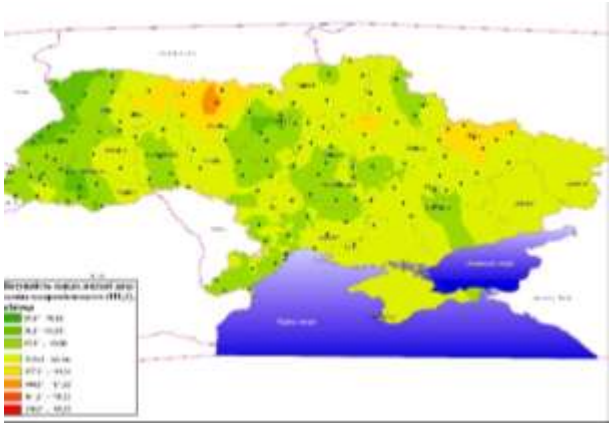


Fig. 3. Spatial distribution of the EDR obtained using the Ordinary Kriging method

A comparison of the resulting maps shows that both methods reproduce the general spatial heterogeneity of the EDR field, yet they are characterized by varying degrees of spatial anomaly localization.

IDW is characterized by a more pronounced preservation of local maxima.

On the maps of Figs. 2 and 3, regions of elevated values directly related to individual points of surface observation are observed. A particularly pronounced local maximum is observed in the Zhytomyr region. This nature of the spatial structure is a consequence of the direct dependence of the weight of the observation on the distance to the evaluation point. As a result of the comparison, unlike IDW, Ordinary Kriging forms a more smoothed field. Local maximum persist, but their spatial boundaries become wider and less contrasting. Spatial transitions between zones of different values are smoother, which corresponds to the geostatistical nature of the method.

FORMATION OF THE REFERENCE SPATIO-TEMPORAL FIELD EDR AND THE RESULT FOR REMOTE RADIATION MONITORING

A cartographic comparison demonstrates that the methods differ in their ability to reproduce the local heterogeneity of the surface radiation field.

For a more detailed study on the choice of method, the authors considered the possibilities of using two interpolation methods, namely IDW and Ordinary Kriging.

Previously, the optimal variogram model was selected for the Ordinary Kriging method. For this purpose, interpolation maps using different models of variograms, the application of which is provided in Quantum GIS [10], were constructed using the Ordinary Kriging method. For each model, interpolation values at the monitoring stations were selected on the maps (see Figs. 2 and 3), which were further used to calculate the three interpolation quality criteria: root mean square deviation (RMSD), mean absolute deviation (MAD) and mean deviation (MD). The results of the calculations are given in the Table 1.

Table 1

Quality criteria for interpolation by the Ordinary Kriging method for different variogram models

Variogram model	Criteria		
	RMSD	MAD	MD
Circular	14.9	11.25	-0.14
Exponential	11.6	8.77	-0.04
Gaussian	15.8	11.90	-0.15
Linear	15.1	11.39	-0.14
Spherical	15.6	11.78	-0.18

As can be seen from the calculation results shown in Table 1, by all criteria the minimum deviations of the interpolation values from the actual ones were observed for the exponential model. For this model, unlike the others, the value of the MD was very close to 0, suggesting that the estimate using the exponential model is unbiased. Therefore, in the future, only the exponential model was used in calculations.

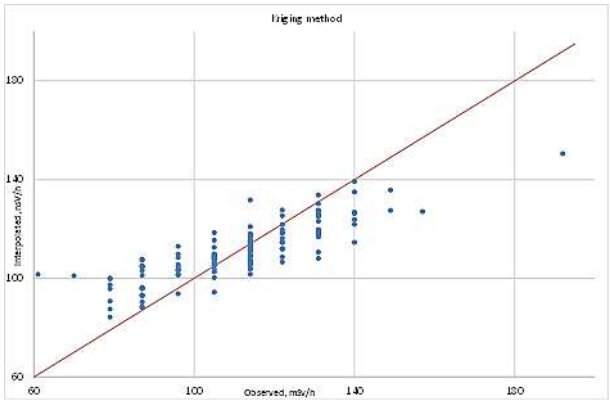
To justify the choice of the optimal research method, a cartographic comparison of the IDW and Ordinary Kriging methods was performed. The comparison was performed according to the criteria of the indicators of RMSD, MAD and MD, the results of the calculations of which are given in the Table 2.

Table 2

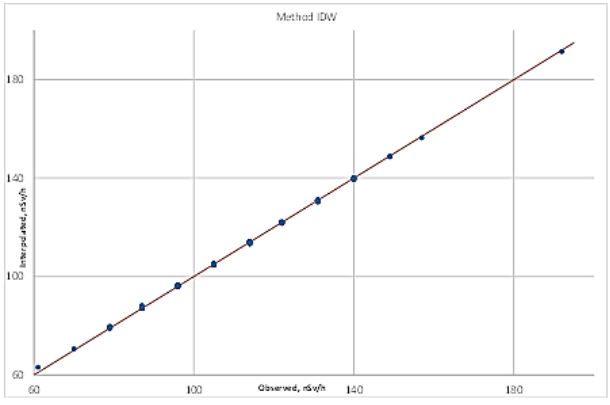
Comparison of Ordinary Kriging and IDW methods by interpolation quality criteria

Criteria	Method	
	Ordinary Kriging	IDW
RMSD	11.6	0.33
MAD	8.77	0.20
MD	-0.04	0.02

As can be seen from the calculation results shown in Table 2, for all the studied criteria, minimum deviations of the interpolation values from the actual ones were observed for the IDW method. Additionally, scatter plots showing the correspondence between interpolated and observed values were constructed (Fig. 4).



a



b

Fig. 4. Scatter plots comparing interpolated values with observed values for the Ordinary Kriging method (a) and the IDW method (b)

As can be seen from the diagrams above, the application of the Ordinary Kriging method, unlike the IDW method, leads to an underestimation of the observed data in the high value range and their overestimation in the low value range. Considering that the high values of the EDR at the ground monitoring stations in Korosten city and Chernobyl city is not an accidental deviation, the constructed diagrams also indicate that the IDW method in our study is more suitable for further research.

Thus, the results of the comparison of the two methods indicate that, although the Ordinary Kriging method is more scientifically based, in our study, the purpose of which was indicated at the beginning of the study, it is advisable to apply the IDW method.

It is advisable to pay special attention to zones where increased values are maintained for several consecutive dates. This allows short-term local features to be separated from more stable spatial patterns.

At the same time, the interpolated spatiotemporal field should be regarded as a reference reconstruction of surface data rather than as a directly measured spatiotemporal characteristic of the radiation situation.

RESULTS OF THE FORMED FIELD FOR REMOTE RADIATION MONITORING

The formation of the reference spatial field of the γ-background is a separate information stage for the further development of the concept of remote radiation monitoring. Its main function is the spatial generalization of surface observations and the preparation of an information layer that can be integrated with other data sources.

In previous studies [5–9], the authors proposed an architecture of remote radiation monitoring, which provides for the integration of surface stations, satellite platforms, UAVs and mathematical models of atmospheric transfer of the radioactive cloud. This study shows that the formed reference field of EDR can be considered as an intermediate spatial information layer between the surface network and other data sources. Currently, the authors propose an improved scheme of information layers of various data sources, which is presented in Fig. 5.

Surface stations
↓
the EDR
↓
IDW/Ordinary Kriging spatial interpolation
↓
spatial field
↓
control of spatio-temporal heterogeneity of the radiation field
↓
detection of changes or zones of increase in the EDR
↓
integration with remote, meteorological and digital data
↓
comprehensive assessment of the radiation state

Fig. 5. Improved scheme of information layers of various data sources

Additional information layers may include atmospheric satellite characteristics, meteorological parameters, fire information, a digital terrain model, and the results of modeling the atmospheric transfer of radioactive substances.

It is important that satellite data should not be considered as a direct analogue of surface measurements of the EDR. They characterize other physical parameters of the atmosphere and the earth's surface and therefore should be used as additional independent information components. This principle corresponds to the concept of integration of surface and remote data sources previously proposed by the authors.

In the future, the reference field can be used for:

- spatial comparison of surface and remote observations;
- detection of spatial anomalies;
- analysis of the dynamics of the radiation state;
- validation and calibration of models (advection-diffusion [13], atmospheric air quality prediction and modelling with chemical (WRF-Chem) [14], chemical transport model (CHIMERE) [15]);
- integration with meteorological data;
- analysis of the impact of emergency events, in particular fires;
- formation of information support for mathematical modeling of the transfer of radioactive substances.

Thus, the field formed is not the end product of remote monitoring, but serves the function of a basic spatial information layer necessary for the further integration of heterogeneous data sources. This makes it possible to specify the general algorithm of remote radiation monitoring proposed earlier by the authors, supplementing the stage of preliminary processing and data integration with the procedure of spatial reconstruction of the surface radiation field. This further development of the methodological approach is important given that the issue of integrating surface radiation data with remote data and mathematical models remains insufficiently explored.

CONCLUSIONS

The authors of the study, based on ground measurements of the EDR, formed a spatially continuous reference field, according to which it is advisable to compare other information layers, substantiated the importance of forming a spatially continuous representation of the EDR field, as a separate methodical stage of creating an information basis for remote radiation monitoring of atmospheric air.

It is proposed to use the concept of the reference spatial field of the γ-background to visualize the spatial reconstruction of surface radiation observations, which performs the function of a reference information layer for further integration of heterogeneous data sources.

A comparison of IDW and Ordinary Kriging methods for forming the spatial field of the γ-background was carried out. IDW has been found to be characterized by a more pronounced preservation of local spatial heterogeneity and local maximum, while Ordinary Kriging forms a more smoothed spatial field.

The spatio-temporal field generated provides an information basis for further integration of surface radiation observations with satellite, meteorological, geoinformation and model data.

It is emphasized that the formed field characterizes the spatial distribution of EDR and is not a direct assessment of the volumetric activity of radionuclides in atmospheric air.

The methodological approach proposed by the authors develops the concept of remote radiation monitoring previously formed by the authors [5–9] by detailing the stage of spatial transformation of discrete surface observations into a reference information layer.

Further research should aim to integrate the generated reference field with remote sensing data, meteorological characteristics and atmospheric transport patterns of radionuclides.

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Article received 22.09.2026

МЕТОДИЧНІ ЗАСАДИ ФОРМУВАННЯ ОПОРНОГО ПРОСТОРОВОГО ПОЛЯ ПОТУЖНОСТІ ЕКВІВАЛЕНТНОЇ ДОЗИ ГАММА-ВИПРОМІНЮВАННЯ ДЛЯ ДИСТАНЦІЙНОГО РАДІАЦІЙНОГО МОНІТОРИНГУ

Г.В. Хабарова, Г.Д. Коваленко, С.В. Барбашев, В.В. Брук, С.Ю. Карандашова

Запропоновано методичний підхід до просторової реконструкції поля потужності еквівалентної дози (ПЕД) гамма-випромінювання за дискретними даними наземного радіаційного моніторингу. Дане дослідження зумовлене просторовою нерівномірністю мережі наземних пунктів спостереження УкрГМЦ ДСНС України та необхідністю формування просторово безперервного інформаційного поля для подальшої інтеграції з дистанційними та модельними даними в системі радіаційного моніторингу атмосферного повітря. Для реконструкції просторового розподілу ПЕД гамма-випромінювання використано геоінформаційні методи Inverse Distance Weighting (IDW) та Ordinary Kriging. Встановлено, що застосування різних методів інтерполяції формує відмінні просторові представлення одного й того самого набору наземних спостережень: IDW краще зберігає локальні особливості та просторові контрасти, тоді як Ordinary Kriging забезпечує більш згладжене поле з урахуванням просторової автокореляції. Обґрунтовано доцільність використання реконструйованого поля ПЕД γ-випромінювання як опорного інформаційного шару для подальшого зіставлення з дистанційними, метеорологічними та модельними даними.