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GEOINFORMATION MODELLING FOR THE SITING OF INDUSTRIAL SOLAR POWER PLANTS CONSIDERING LANDSLIDE PROCESSES IN MOUNTAINOUS AREAS

The article presents an integrated approach to assessing the suitability of territories for the placement of industrial solar power plants (SPPs) in mountainous conditions, taking into account the spread of landslide processes, which are a key natural constraint for infrastructure development in the Carpathian region. The object of the study is the Kosiv district of the Ivano-Frankivsk region, an area characterised by complex geological structure, increased susceptibility to landslides, and growing investment interest in alternative energy projects. The relevance of the work is determined by the need to account for geodynamic risks in the spatial planning of energy facilities and the insufficient integration of geostatistical methods into project practice. The methodological basis of the study is a combination of geoinformation modelling and geostatistical interpolation tools. Vector analysis of spatial constraints was performed based on buffer modelling around infrastructure facilities, water networks, buildings, and forest areas, making it possible to identify conflict-free zones. Next, morphometric criteria, such as slope angle and exposure, were applied, considering orographic requirements for efficient electricity generation. All criteria were integrated into ModelBuilder, which ensured the reproducibility and automation of the spatial analysis process. A geostatistical risk assessment of landslide processes was implemented by constructing a semivariogram and a spatial autocorrelation model (Moran's I), which revealed a high degree of clustering of hazardous points. Ordinary Kriging and Co-Kriging methods were applied to construct the risk surface, taking into account topographical factors. The results obtained enabled the determination of spatial differentiation of risk within the study area with high interpolation accuracy. The residual validation error (RMSE ≈ 4.47) confirms the model's high quality, and Co-Kriging using relief derivatives (slope and aspect) showed better adaptability to mountainous conditions. At the final stage, a spatial ranking of plots was conducted for areas exceeding 1.5 ha and a geometric shape index of less than 1.8. This ensures the effectiveness of their potential use for the placement of SPPs. The analysis results show that only about 13 % of the suitable areas meet the configuration requirements and have an acceptable level of landslide risk (less than 46 %). Based on integrating the risk map with the array of prepared sites, a summary map of optimal areas for SPPs placement was created, considering technical and natural constraints. The scientific novelty of the study lies in its first-ever full-scale geostatistical assessment of landslide risk in the context of solar energy facility planning in the Ukrainian Carpathians. The practical significance is determined by the possibility of directly applying the results to form-spatial development plans and environmentally safe development of territories. The presented approach can be adapted for other regions, including the Carpathian region as a whole, which is characterised by active geodynamic processes, and can be applied in environmental impact assessments for alternative energy facilities.

Keywords: geoinformation modelling; landslide hazard; solar power plants; geostatistics; spatial analysis; planning and management; the Carpathians.

Introduction

The intensification of renewable energy sources, particularly solar power plants (SPPs), in mountainous regions is accompanied by increased requirements for assessing the territory's engineering-geological and geodynamic conditions. In areas with active gravitational dynamics, such as the Ukrainian Carpathians, landslides are a key component of natural hazards, capable of causing infrastructure damage, affecting hydrological regimes, and land use conditions. Changes in atmospheric precipitation and water balance patterns, characteristic of the current stage of climate transformation, significantly increase the need to assess the spatial stability of slopes within potential sites for renewable energy infrastructure.

Existing approaches to landslide hazard mapping typically rely on heuristic assessments, multifactorial rating analysis, or logistic regression. While these models consider individual morphometric and engineering-geological factors, they only partially reflect the spatial continuity of natural processes and are limited in their ability to interpolate risks outside the observation zone. In this context, geostatistical methods, particularly spatial autocorrelation testing, variogram-based modelling, as well as Ordinary and Co-Kriging interpolation, are gaining significance. These methods have the advantage of formally describing the spatial structure of risk, identifying distribution patterns, and creating high-resolution predictive surfaces.

Over the past decade, spatial modelling of landslide risk has increasingly relied on geostatistical analysis methods. Among the most commonly used approaches are variograms and spatial interpolation techniques, such as Kriging, along with their covariance modifications. These methods have proven effective in identifying patterns of spatial dynamics and in developing predictive models. Several studies have demonstrated the feasibility of employing multidimensional geostatistical methods in hydrogeological and orographically complex regions [Paradeshi et al., 2013; Corominas et al., 2014; Vessia et al., 2020]. These techniques are particularly valuable for mapping landslide-prone areas, where input data is unevenly distributed [Roslee et al., 2012; Nicula et.al, 2017]. Interpolation algorithms based on the functional analysis of dependencies between topographic and geological variables enable the high-precision reproduction of risk structures in previously unexplored areas [Bednarik et al., 2024].

In particular, the works [Chen et al., 2020, Tordesillas et al., 2021] present the results of landslide hazard modelling using Co-Kriging, which incorporates factors such as the topographic index of moisture, slope, and surface orientation. Other studies highlight the benefits of combining spatial interpolation with hotspot analysis, enabling the identification of local risk accumulation centers, even in scenarios with uneven input data coverage [Nava et al., 2022].

At the same time, there is increasing concern regarding the environmental safety of renewable energy projects in areas with complex terrain. It is known that at least 8–9 % of malfunctions at solar farms in mountainous regions are related to geodynamic risks, particularly landslides and related hydrogeomorphological phenomena [Hao et al., 2021; Li et al., 2023]. Despite the availability of thorough regional studies demonstrating the possibilities of integrating GIS and geostatistics within individual projects [Nistor et al., 2018, 2019, Ilovan et.al, 2019, Kumar et al., 2021, Sestras et al., 2021, Bednarik et al., 2024], a systematic methodology covering the entire cycle – from risk mapping to decision-making on the location of SPPs – remains underdeveloped. The application of such approaches is particularly relevant to the Ukrainian Carpathians. This region is geologically unstable, characterized by a significant diversity of landforms, high hydrographic density, and intensified landslide processes [Ivanik et al., 2019; Deputat et al., 2025; Shtohryn et al., 2024]. Using the example of the Kosiv district, which is one of the most vulnerable areas on the left bank of the Prut slope, it is advisable to develop an adapted model for spatial risk assessment and territorial suitability assessment of solar energy facilities.

The Kosiv district, situated in the southeastern part of the Ivano-Frankivsk region, is part of the northeastern fragment of the Outer Eastern Carpathians. The district's territory is characterized by its geological diversity and high morphodynamic activity, resulting from both natural (tectonics, relief, precipitation) and anthropogenic factors. The geological foundation of the district is represented by Palaeogene flysch strata, in particular an alternation of sandstones, siltstones, and claystones, which form an environment with increased structural anisotropy and vulnerability to shear deformations [Kuzmenko et al., 2016].

Active orogenic uplift, which reaches 1–4 mm/year in the Carpathians, maintains steep slopes and deep erosion dissection, intensifying gravitational processes. The region's territory exhibits a pronounced tectonic segmentation, characterized by zones of transverse and longitudinal faults, where landslides are most frequently recorded. Climatic factors further complicate the situation: annual precipitation of 1,000–1,200 mm, with distinct seasons of heavy rain and snowmelt, contributes to the saturation of slopes with moisture and the formation of conditions for landslides and debris flows.

The studied area is affected by seismic vibrations from the Vrancea focus, making geodynamic conditions and endogenous processes significant contributors to landslide occurrences [Sirenko et al., 2020; Hablovska et al., 2023; Hablovskyi et al., 2023; Micu et al., 2023; Ioane et al., 2025; Kendzera et al., 2025; Pronyshyn et al., 2025]. Their analysis is necessary to assess the engineering and geological stability of the territory and plan the safe location of SPPs.

Over the past decade, there has been an active implementation of alternative energy facilities, primarily solar power plants, in the Kosiv district [Kasiyanchuk et al., 2018]. These projects are mainly located on the slopes that were previously used for agriculture, terraced slopes, or inter-river areas with disturbed natural drainage structures. However, in many cases, project decisions are made without a complete assessment of the geomorphological stability of the sites, which is a critical factor in areas prone to landslides.

Main factors affecting geomorphological stability when placing SPPs

The expansion of renewable energy in the Ukrainian Carpathians, particularly through the construction of industrial solar power plants, is taking place in conditions of limited geomorphological stability of the territories. The geological structure, with a predominance of flysch formations, steep slopes, and excessive moisture in the slope systems, creates increased vulnerability to artificial interventions. This section summarises the key mechanisms of destabilisation caused by the placement of RES infrastructure.

Engineering destabilisation of slopes

One of the primary sources of morphological impact is the modification of the natural relief due to the terracing of slopes, the construction of mounting platforms, and the formation of service infrastructure (technical roads, cable trenches, drainage systems). Such interventions cause a disturbance in the gravitational balance, a shift in the direction of runoff, and changes in the distribution of masses on the slope. When using 'cut-and-fill' levelling methods, the risks of instability increase due to the emergence of overloaded embankments or cuts without sufficient engineering reinforcement.

These processes become critical on slopes composed of sandstones and clays with high water saturation, where mechanical disturbances in the structure cause plastic deformations and landslides. Field studies have recorded an increase in local instability, even with slight disturbances to slope equilibrium, under conditions of increased precipitation [Information Report..., 2010].

Changes in the hydrological regime and waterlogging

The presence of infrastructure elements that disrupt natural infiltration (concrete foundations, compacted surfaces, closed drainage systems) forms a new surface runoff structure. The local concentration of water flows, redistribution of deep drainage, and accumulation of moisture in colluvial zones below SPP facilities contribute to increased pore pressure in the soil mass.

Numerous studies, particularly in Central Europe, show that even a 10–20 % increase in soil moisture in the upper horizons can reduce the limit shear strength by 30–50 %, especially in flysch strata [Bednarik et al., 2024]. This effect becomes cascading in mountainous terrain.

Disturbance of soil and vegetation cover

Using heavy equipment to clear land for SPPs causes soil compaction, destruction of the turf layer, and damage to the root systems of stabilising plants.

As a result:

- the ability of soils to retain moisture decreases;
- the proportion of surface runoff increases;
- erosion furrows, gullies, and ravines develop.

These processes are particularly active on unsecured terraced slopes that were previously used for agriculture or have already been disturbed by secondary vegetation [Ivanyshyn et al., 2024].

Systemic effects in cluster placement of SPPs

In cases where several renewable energy facilities form spatial clusters, the cumulative impact exceeds the sum of individual effects. This is primarily due to the gradual destruction of vegetation cover, which plays a crucial role in regulating the hydrological balance of the territory. The loss of root structure and reduction in transpiration lead to a decrease in the ability of ecosystems to retain moisture, contributing to the accumulation of excessive surface runoff. At the same time, a significant part of the catchment area is being compacted due to the movement of machinery, construction work, and the replacement of natural substrate with artificial surfaces. Such interventions not only alter the infiltration properties of soils but also create a new hydromorphological structure at the site. Ultimately, the increase in the overall anthropogenic load on slope systems leads to a loss of their stability, the activation of gravitational processes, and the potential formation of new landslide-prone areas.

The gradual decrease in morphological stability within the local basin creates favourable conditions for activating latent landslide foci. Despite this, current environmental impact assessment standards in Ukraine do not require consideration of geodynamic risks in strategic or detailed planning procedures. This situation creates a critical gap in infrastructure siting in regions of heightened natural vulnerability.

Taking into account the spatial structure of risk at the preliminary analysis stage

An integrated landslide hazard map for the Kosiv district was used in this study to integrate geodynamic information into spatial planning [Kasiyanchuk, 2016]. It summarises morphometric characteristics (slope, exposure, curvature), structural-geological boundaries, the hydrographic network, and existing landslide processes.

This map allows the formation of an array of sites suitable for the placement of SPP facilities, taking into account the landslide factor in advance. It can be used as a fundamental element in the formation of a risk-oriented planning model in mountainous regions (Fig. 1).

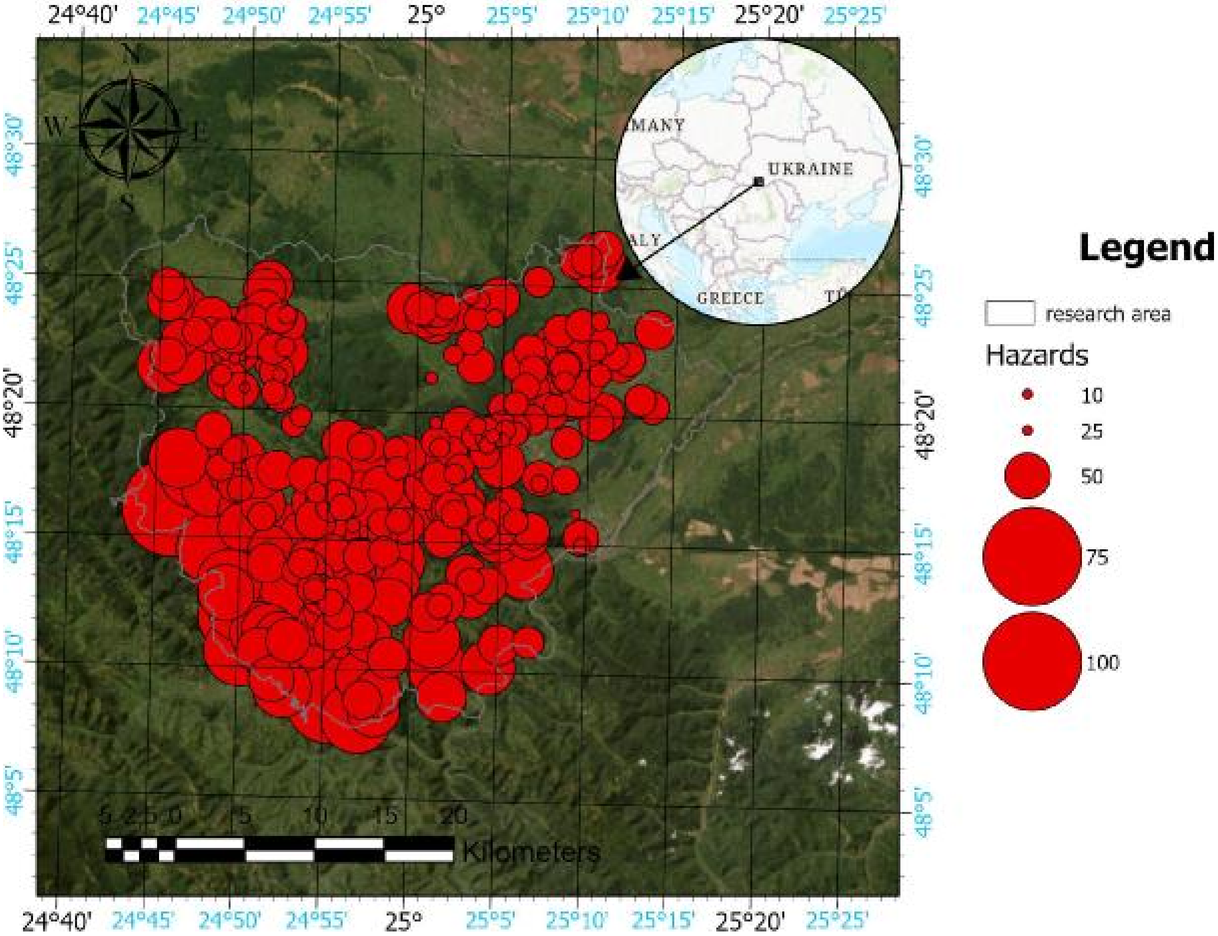

Fig. 1. Map of the probability of ecological and geological risk of landslides in the Kosiv district.

Purpose

The work aims to assess the spatial suitability of territories for the placement of industrial SPPs, considering the landslide hazard, based on geoinformation and geostatistical analysis. The relevance of the study lies in the fact that the placement of renewable energy facilities in landslide-prone mountainous regions, in particular in the Ukrainian Carpathians, is carried out without a proper assessment of the geodynamic vulnerability of the territories, which creates risks of a natural and technogenic nature and requires the integration of spatial analysis methods into planning practice.

Research methodology

The methodology implemented in this study is based on the logic of spatial screening of territories that do not meet the technical, morphological, or environmental criteria for the location of industrial solar power plants within the Kosiv district of the Ivano-Frankivsk region. The primary focus is on developing a suitability model that considers the landslide hazard, a characteristic geodynamic threat to the studied territory.

All operations were performed in ArcGIS Pro, using ModelBuilder tools to ensure process reproducibility. Initially, thematic layers were created to reflect the physical geography of the territory, including a digital elevation model (SRTM, 30m), a hydrographic network, forest boundaries, power lines, and transportation infrastructure. The data were converted to a single coordinate system (UTM Zone 35N). The landslide inventory was compiled for the period 1980–2022, while the SRTM DEM (30 m) reflects the topography around the year 2000. The forest cover data correspond to 2020, and the infrastructure layers were derived from OpenStreetMap in 2021. While there are minor temporal discrepancies between these datasets, these are not expected to significantly impact the modelling outcomes given the relative stability of topographic and infrastructural features during this period.

At the first modelling stage, spatial restrictions were imposed on territories based on buffering objects that were incompatible with the safe or legally permissible location of SPP. A 50 m buffer was applied to buildings in accordance with current regulations on sanitary protection zones [State sanitary rules…, 1996]. Water bodies (rivers and lakes) were restricted by a 50 m buffer following the

Water Code of Ukraine [State sanitary rules…, 1995]. To improve energy efficiency, only those sites located within 30 m of overhead power lines [Rules for the Protection of Electrical Networks, 1997] and 50 m of major roads [DBN V.2.5-56:2014, 2014] were deemed acceptable. Forest areas (50 m) [Zanaga et al., 2021] were completely excluded from further analysis as objects of ecological value. Buffering, polygon merging, and stepwise exclusion were implemented as a block sequence in ModelBuilder.

The second stage was a morphometric assessment of the territory. Based on the digital terrain model, layers of slope, exposure, and surface curvature were constructed. Standard spatial analysis algorithms were used for this purpose. A slope of up to 15° was considered technically acceptable for SPPs design, while areas with greater steepness were considered unstable or economically unfeasible. The exposure data were transformed into a binary mask, selecting areas oriented to the south (315-45°), as well as southeast and southwest, to maximize insolation. Both variables were used for spatial filtering without creating a rating assessment or multifactorial weighting.

Next, using the suitability mask that was created, the remaining areas were converted into polygons. The area of each polygon was calculated to select only those that could accommodate SPP facilities with a capacity of more than 1 MW (from 1.5 hectares). Thus, the model formed a list of geospatially justified sites, excluding insignificant parameters. A separate area of research was the geostatistical assessment of landslide hazard, which is considered a significant constraint in mountainous conditions. A used point database of landslides for the Kosiv district was compiled based on open geological reports and our data. Using spatial statistics tools in ArcGIS Pro, an assessment of global autocorrelation (Moran's I [Moran, 1950]) and local spatial clustering (Getis-Ord Gi*) was performed, which allowed the identification of areas with abnormally high density of landslide events.

In the next stage, an experimental semivariogram was constructed to identify patterns of spatial variability in risk, after which risk interpolation was performed using the Ordinary Kriging method. To increase the density of the spatial sample, a regular grid of points (100×100 m step) was created, using slope and exposure values as secondary variables in the Co-Kriging model.

Research results

Geospatial analysis of areas suitable for the placement of SPPs

One of the key objectives of the study was to develop a spatial model for identifying areas potentially suitable for the deployment of industrial SPPs. To this end, a logical sequence of geoprocessing was implemented in ArcGIS Pro using the ModelBuilder module, which enabled automated implementation of a spatial clipping scenario based on several limiting factors.

ModelBuilder allows you to create a graphical algorithmic data processing scheme that ensures the reproducibility and transparency of the analysis. This study used the tool to sequentially build a spatial incompatibility model (conflict zones) based on current regulatory and environmental constraints.

During the modelling process, buffer zones were formed around objects whose presence is critical for the selection of locations (Fig. 2):

- forests – 50 m (ecological alienation);
- water bodies (rivers, lakes) – 50 m (hydrological protection strip);
- power lines – 30 m (technical regulation zone);
- motorways – 50 m (sanitary protection zone);
- existing buildings – 50 m (buffer zone taking into account safety standards).

After creating the buffers, each layer was merged to form a generalised conflict zone – a combined layer with all spatial restrictions. The next step was to spatially subtract (Erase) this conflict zone from the layer of potentially accessible territories (res_ter), which made it possible to identify areas without direct spatial conflict with critical objects.

The resulting layer was divided into separate polygons using the Multipart to Singlepart tool, which enabled further analysis of each polygon by area, morphometric characteristics, and level of infrastructure accessibility, among other factors.

As a result of implementing the scheme, an array of 4,070 polygons was obtained that met the spatial suitability criteria for the placement of solar power plants (Fig. 2). To analyse their suitability in terms of the scale of implementation of alternative energy projects, a statistical assessment of the polygon areas was carried out. More than 95 % of the polygons have an area of less than 1.5 hectares, which is the lower limit of feasibility for the placement of industrial solar power plants. The average area is only 1.33 hectares, which indicates the fragmentation of the spatial structure of potentially suitable territories.

However, the analysis showed that 660 landfills exceed the 1.5-hectare threshold and can potentially be considered as sites for industrial solar power plants (with a capacity of 1 MW and above).

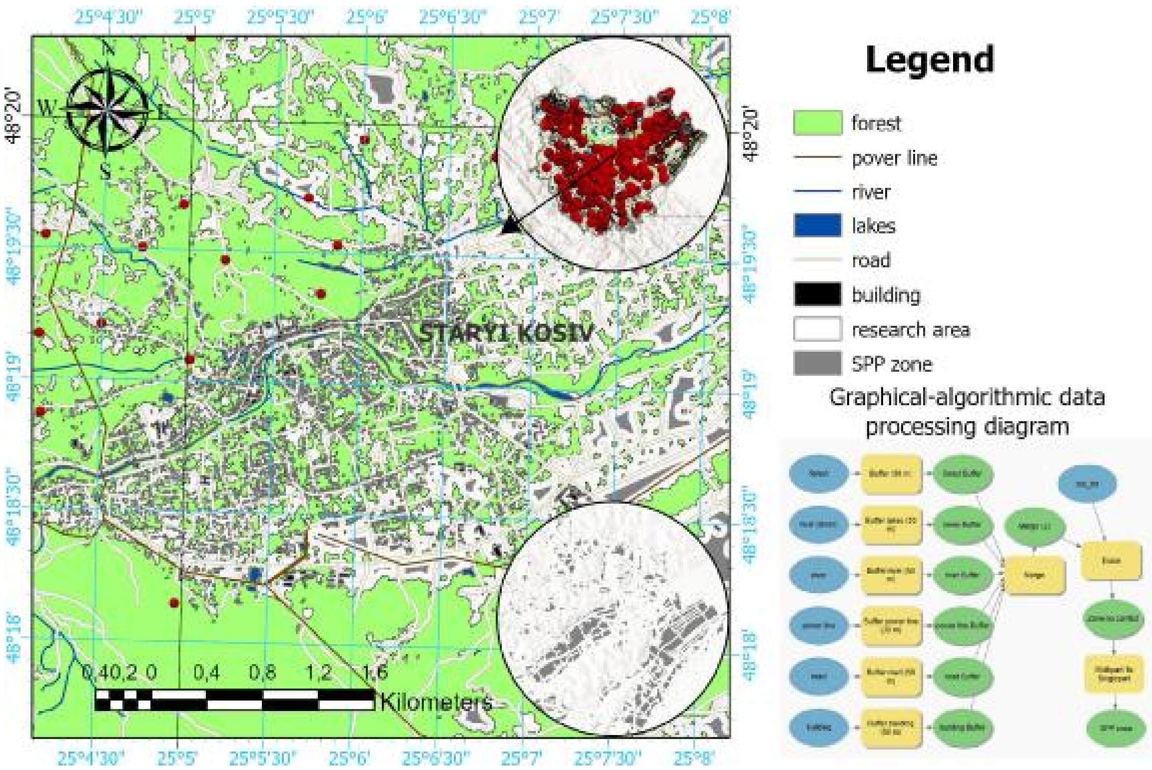

Fig. 2. Geospatial analysis and ModelBuilder data processing scheme for the study area.

Geostatistical modelling of landslide hazard risks

To integrate the risks associated with landslide processes into the suitability model of territories for SPPs, a comprehensive geostatistical analysis of the spatial distribution of landslide hazards was conducted. The spatial database of point data was formed based on the existing map of integral landslide risk. This database enabled the assessment of the autocorrelation structure and allowed for interpolation of risk levels in areas without direct observations.

Spatial autocorrelation (Moran's index)

At the first stage of geostatistical analysis, spatial autocorrelation of landslide risk values within the Kosiv district of the Ukrainian Carpathians was assessed. For this purpose, the Spatial Autocorrelation (Global Moran's I) tool from the Spatial Statistics Tools package in ArcGIS Pro was utilized. A point layer containing the integral landslide risk index values was used as input data.

The inverse distance method with Euclidean metric was chosen to formalise the spatial relationships between objects. The spatial analysis results are presented in the form of a standard graphical report (Fig. 3). The value of Moran's index (Moran's I = 0.439) indicates the presence of moderate positive spatial autocorrelation, which shows a tendency towards risk clustering. The extremely high Z-index (13.34) and the *p*-value of zero demonstrate the high statistical significance of the result. The probability that the observed spatial grouping could have occurred by chance is less than 1 %.

The distribution graph (Fig. 3) shows that the obtained value is on the right side of the normal distribution, corresponding to a significance level of $p < 0.01$. Thus, the detected spatial grouping is not random and is caused by the structural features of the environment being studied.

The results confirmed the hypothesis of stable spatial patterns in the distribution of landslide risks. This provides grounds for using geostatistical interpolation methods, particularly Ordinary Kriging, which allows spatial extrapolation of risks in areas with missing values.For an in-depth analysis of the spatial structure of landslide risks, the Getis-Ord Gi* spatial statistics method was used, which allows identifying so-called "hot spots" and "cold spots" – areas with abnormally high or low risk values that demonstrate spatial cohesion.

The analysis was performed in ArcGIS Pro using the Hot Spot Analysis (Getis-Ord Gi*) tool. The input layer was a set of points with risk attributes obtained at the previous stage. Spatial dependence was determined using the Inverse Distance principle, and the distance for analysis was selected automatically according to the criterion of optimal spatial correlation.

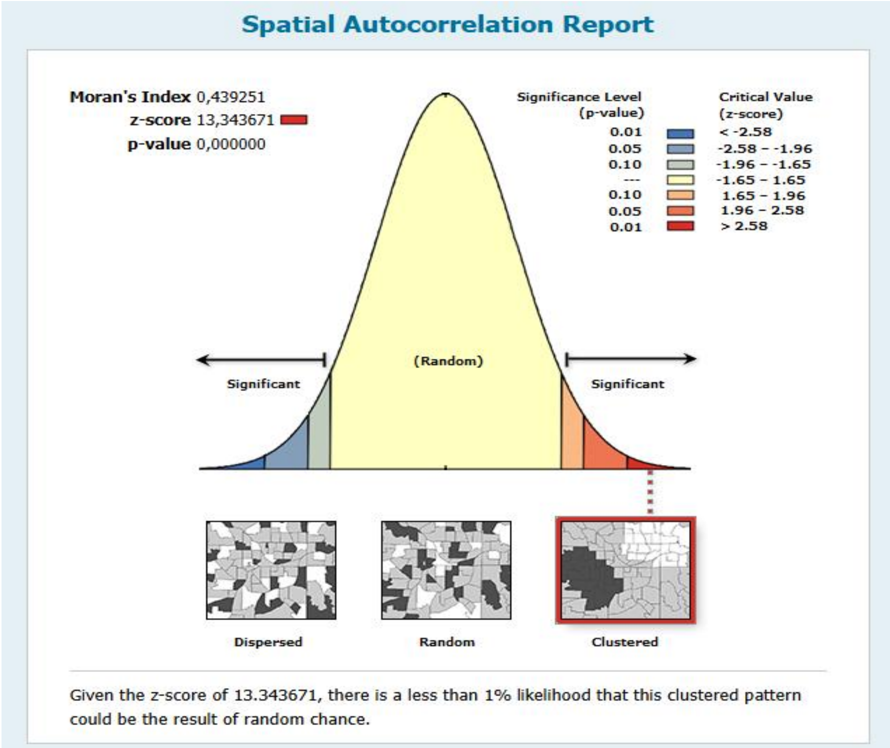

Fig. 3. Autocorrelation graph of landslide risk

Identification of spatial anomalies in landslide risk distribution

Fig. 4 shows a thematic map that displays local statistically significant clusters of risk values:

"Hot spots" are areas with a high risk of landslides, statistically confirmed by cohesion. Identified with confidence levels of 90 %, 95 %, and 99 %, they are mainly concentrated in the southwestern part of the Kosiv district.

Cold Spots are areas with a lower risk, statistically significantly grouped. They are primarily identified in the north-east of the territory, which is characterized by less complex terrain and remoteness from tectonically active zones.

Not Significant are the points without a statistically significant spatial context.

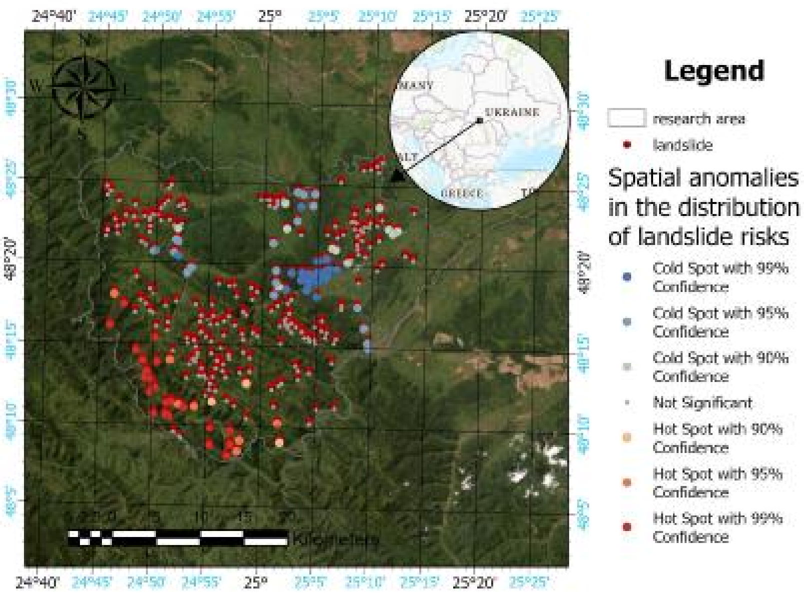

Fig. 4. Map of spatial risk cluster.

Semivariogram and covariance

This analysis enabled the identification of areas requiring increased attention for further geostatistical risk modelling, as well as safer areas potentially suitable for the placement of infrastructure facilities, particularly solar power plants.

The Getis-Ord Gi* method complements the global autocorrelation analysis (Moran's I) by allowing for localised risk zoning. The data obtained is further used to calibrate the interpolation model and can also be incorporated directly into a spatial suitability model for the placement of alternative energy facilities, while considering the risks of landslidesTo examine how landslide risk varies across the mountainous regions of the Kosiv district, we analyzed spatial autocorrelation. This involved using a semivariogram and a covariance model, which helps to evaluate how a spatial phenomenon changes with distance.

An empirical semivariogram based on a set of points with a risk attribute showed a steady increase in dispersion γ(h) with increasing interpoint distance (Fig. 5). The Stable function was used for modelling with the following key parameters:

Nugget: 11.874 – non-random local variations or measurement errors;

Partial Sill: 18.522 – dispersion described by the model;

Range: 7156.8 m – the limit of spatial autocorrelation, beyond which the values are no longer related.

The semivariogram indicates the presence of moderate spatial autocorrelation within a radius of 7 km. This means that landslide risks in certain areas tend to cluster spatially, justifying the use of geostatistical forecasting methods (Fig. 5).

Additionally, covariance modeling was performed to describe the degree of spatial similarity between risk values. The following parameters were obtained in the Spherical model:

Nugget: 20.728 – level of random variation;

Partial Sill: 15.069 – spatially determined part of the variation;

Range: 9661.6 m – limit of spatial dependence preservation.

The covariance graph (Fig. 5) shows a decline in values to zero at a distance of about 9.7 km, which confirms the results of the semivariogram but indicates a slightly wider area of spatial influence. This may be due to the impact of tectonic structures or morphological features of the slopes.

The covariance map (Fig. 5) shows the most outstanding spatial connectivity in the central part of the study area, indicating a zone of high risk probability. Areas with low or negative covariance values are recorded on the periphery, which may result from a decrease in the influence of active landslide processes and heterogeneity of the input data.

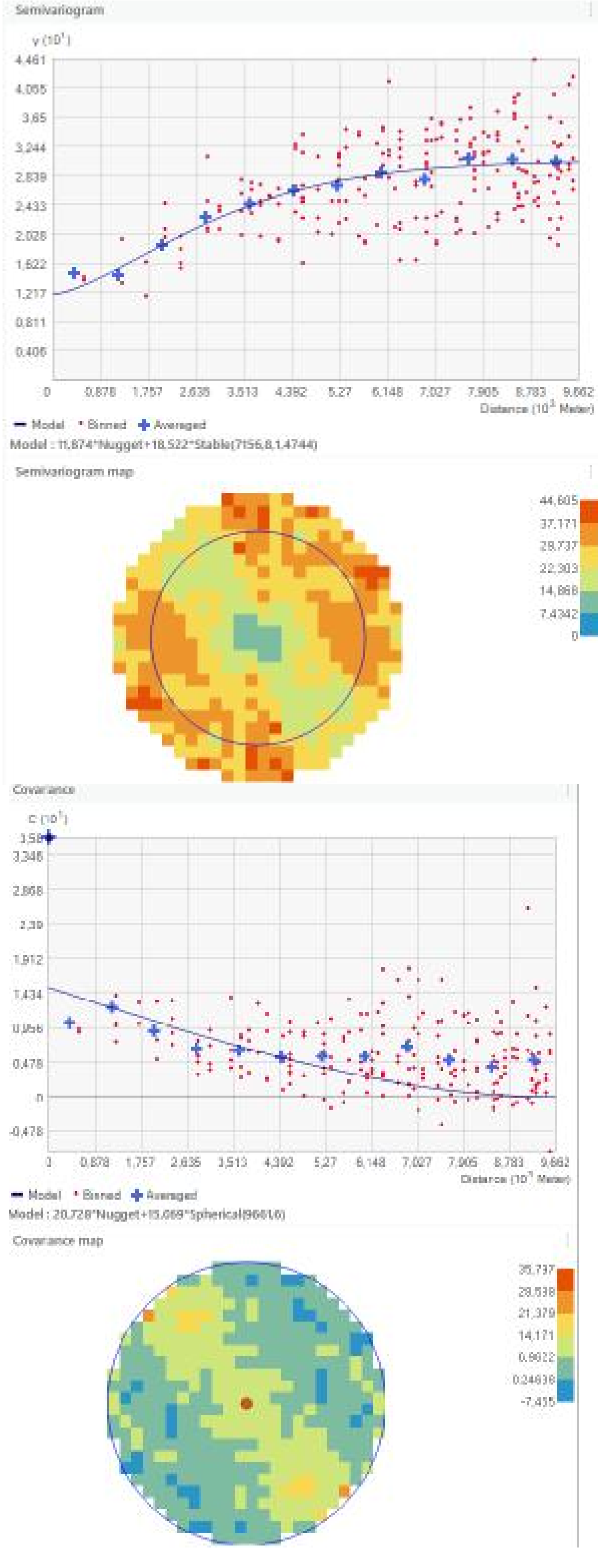

Fig. 5. Spatial autocorrelation using a semivariogram and a covariance model.

Construction of landslide risk forecast maps

Among the theoretical models tested (Stable and Spherical), the Stable model was selected because it most accurately represented the experimental semivariogram, which exhibited a significant 'nugget' effect and a prolonged correlation 'tail'. Additionally, it yielded a smaller prediction error, as indicated by the cross-validation results. The main parameters of the Stable model are as follows: type = 1.0402, number of lags = 12, lag size = 2,398 m, nugget = 11.7–34.5, partial sill = 19.5–50. The search radius was set to 21,475 m, and the standard neighbourhood included 5 maximum and 2 minimum neighbours. The sectorisation was divided into 4 sectors at 45° each.

The correlation and co-regionalisation coefficients (Table 1.) confirm a high level of structural consistency between the risk parameters and the morphometric parameters of the slope. This justifies the use of CoKriging as an effective modelling tool for analyzing the spatial distribution of hazardous processes.

Table 1

Correlation and co-regionalisation coefficients

Variable	Correlation coefficient, r	Co-regionalisation coefficient, γ_{12} h	Interpretation
Hazard – Slope	0.72	0.65	Strong positive correlation
Hazard – Aspect	0.58	0.47	Moderate dependence
Hazard – Elevation	0.49	0.42	Average spatial-structural similarity

Both spatial dependence models confirm the validity of further use of Ordinary Kriging for constructing a predictive risk surface. The obtained parameters (nugget, sill, range) were used to configure the interpolation model and to implement Co-Kriging, where the morphometric parameters of the relief are considered secondary variables (slope, aspect).

Two predictive surfaces were constructed using Ordinary Kriging (OK) and Co-Kriging (CK) methods for spatially interpolating landslide risk. Both models were implemented based on spatial dependence parameters obtained from the results of semivariogram analysis (Fig. 6). For Co-Kriging, additional morphometric variables were considered – slope and aspect.

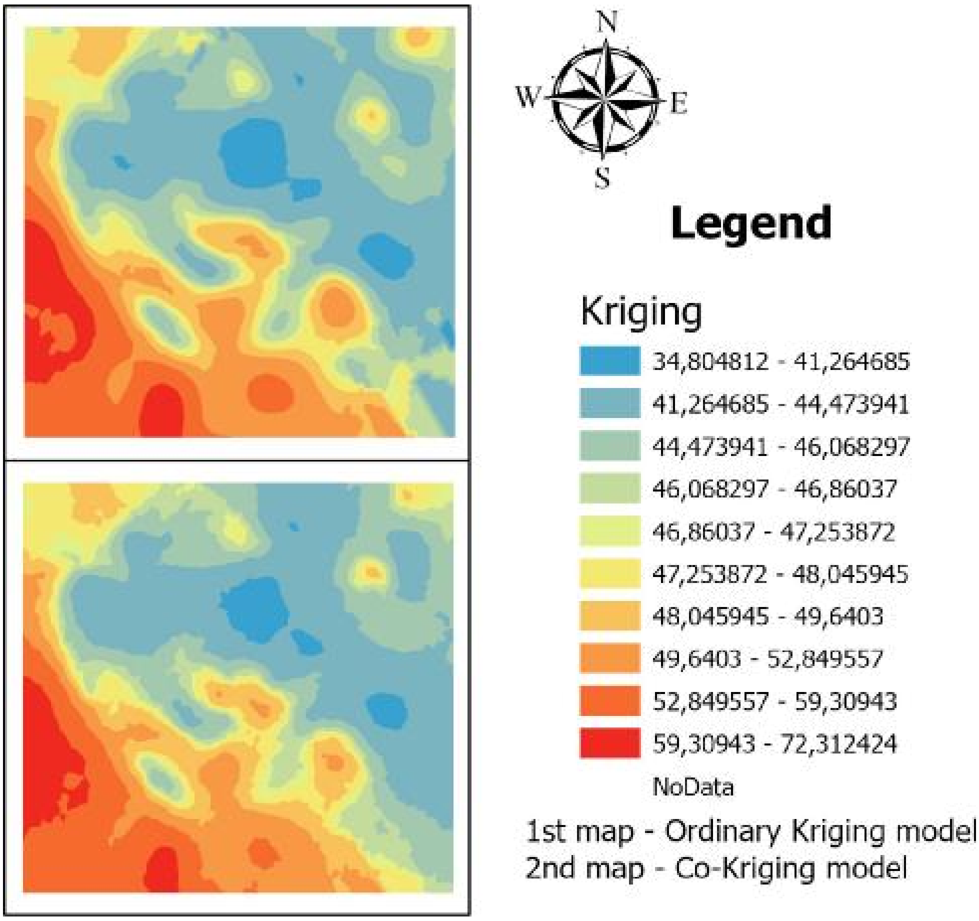

Fig. 6. Landslide risk maps.

The Ordinary Kriging model was based exclusively on risk values determined for point objects with known landslide hazard characteristics. The interpolation map displays a generalized spatial risk field, with clearly defined areas of increased risk in the central and southwestern parts of the study area.

However, the model does not consider the spatial heterogeneity associated with the natural determinants of landslide formation, which may limit the accuracy of the local forecast. To enhance the Co-Kriging model, additional predictors – slope and exposure values – were obtained from a digital terrain model at regular grid points (100 x 100 m). This approach allowed the model to reveal more detailed spatial patterns and local anomalies.

In the Co-Kriging model, high-risk areas (red and orange areas) exhibit clearer boundaries and align more closely with the relief morphology than those identified by the Ordinary Kriging (OK) model. In the northern part of the region, the CK model identifies high-risk areas 'smoothed out' in the OK model, indicating sensitivity to micro-relief. Low-risk areas in the Co-Kriging model are now more distinctly defined, enhancing the accuracy of identifying locations suitable for SPP placement.

As shown in the figure, integrating morphometric indicators into the Co-Kriging model yielded a more spatially refined and detailed forecast map. This map more accurately reflects the potential threats of landslides in mountainous conditions, confirming the feasibility of using joint geostatistical modelling (Co-Kriging) for geoinformation risk analysis in planning infrastructure facilities, such as solar power plants.

Comparison of forecast values with actual data

To confirm the feasibility of using the CoKriging method, we conducted a comparative analysis of the relationships between the variables, as well as an assessment of the improvement to the spatial model relative to traditional Ordinary Kriging. The cross-correlation between hazard values and slope morphometric parameters was found to be r = 0.72 for slope and r = 0.58 for exposure. These results indicate that both parameters play a significant role as secondary predictors. The co-regionalisation coefficient $\gamma_{12}(h)$ shows consistency in risk and slope variations within distances of up to 350 metres, corresponding to the local scale of hydrogeomorphological activity.

Comparing the statistical accuracy indicators showed that applying CoKriging decreased the mean square error (ΔRMSE = −0.48) and the standard deviation of residuals (ΔRMS = −0.11) relative to Ordinary Kriging. This confirms the increased stability of the interpolation surface and the more accurate localisation of areas with increased landslide hazard.

At the final stage of modelling, the reliability of the results was verified using cross-validation. For the Ordinary Kriging model, the key metrics were: the mean value of the residuals (Mean) –0.056, indicating no systematic bias, and the root mean square deviation (RMS) at 4.48, indicating moderate variability in the results. The mean standardised residual was –0.0077, and the standardised root mean square deviation (RMS Standardised) was 1.059, consistent with the expected theoretical distribution of residuals. Cross-validation was performed using a leave-one-out (LOO) strategy, embedded in the Kriging / Co-Kriging workflow. Each observation was removed sequentially while using the remaining data to make a prediction. The resulting standardised RMS of approximately 1.06 suggests that the model's prediction variance is well calibrated, and that the Kriging standard errors provide a realistic estimate of local uncertainty.

A residual error map was constructed for a qualitative analysis of the discrepancies between the measured and modelled values (Fig. 7). It shows that significant deviations are concentrated mainly in the peripheral areas of the study area, where the density of the source points is lower. Visual analysis revealed that the main centres of residual error correspond to areas of complex micro-relief, as well as to fragments where forest areas or anthropogenically transformed territories prevail.

The Standard Error of Prediction raster highlights spatial variability in model confidence; areas exhibiting elevated standard errors indicate zones where the interpolated hazard values are less certain and therefore require caution. In siting decisions, such high-uncertainty areas should be deprioritized for immediate development or be subjected to targeted field investigations and local geotechnical studies before any installation is approved.

In addition, we developed a graph of the distribution of measured and modelled landslide risk values. The peak of the predicted distribution is slightly shifted to the right, indicating a tendency for the model to underestimate the risk in areas with higher actual values. This confirms the usefulness of additional predictors, such as exposure and slope steepness, within the Co-Kriging model.

Thus, the results indicate that the model's quality is satisfactory, especially given the limited number of input observations.

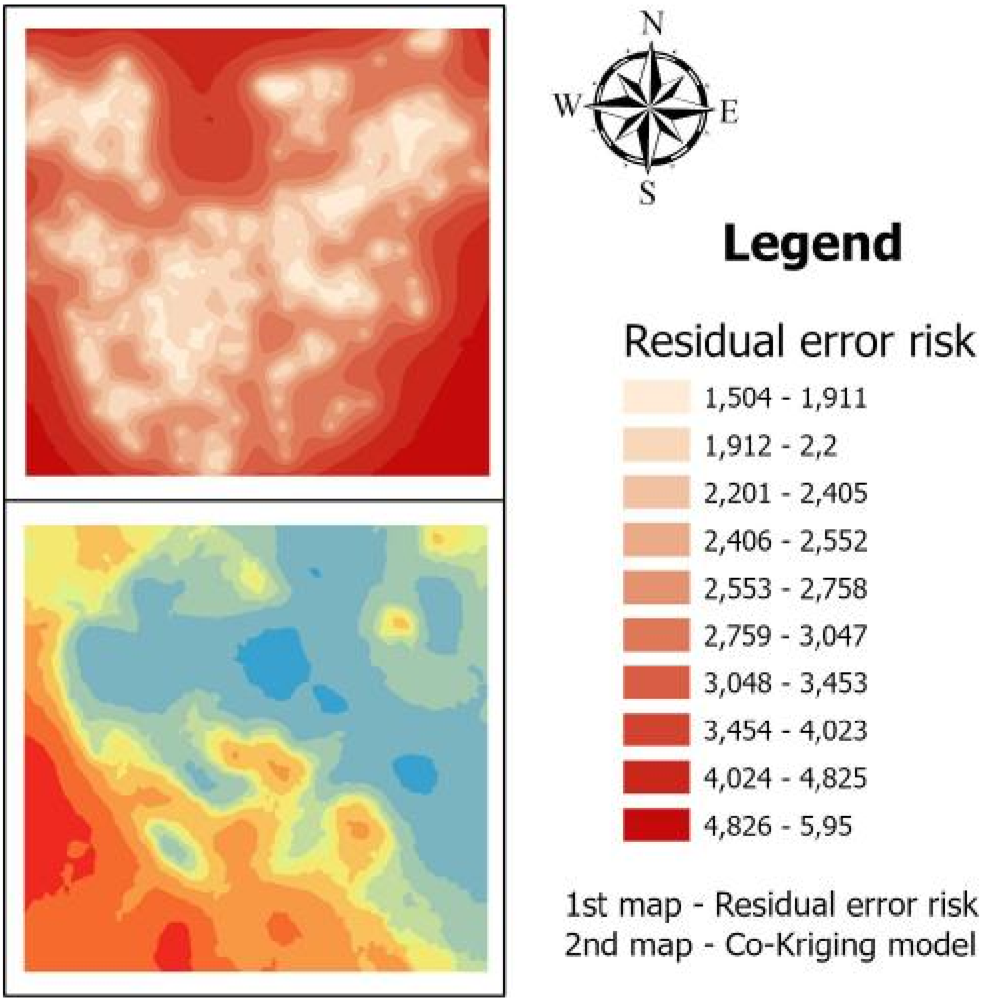

Fig. 7. Map of residual errors.

Spatial-analytical ranking

After completing geostatistical modelling and validation of the interpolation model, a spatial overlay of the risk map was performed on an array of sites that had passed a preliminary geoinformation filter, i.e., that met the requirements for morphometric, infrastructural, and landscape parameters. The vectorized objects obtained from the model, based on ArcGIS ModelBuilder, contained information about the configuration, dimensions, accessibility, and location relative to power lines, roads, water bodies, and natural vegetation.

Geometric constraints were applied to the spatial database to identify suitable sites for industrial solar power plants. The first criterion was an area of at least 1.5 hectares, which corresponds to the typical parameters of a single 1 MW modular solar power plant. Industry technical recommendations suggest that the minimum area for the effective operation of an industrial photovoltaic complex should not only accommodate the solar panels, but also include service pathways, inverter installations, installation and technological areas, as well as the necessary distance to avoid self-shading on complex terrain. In mountainous conditions, such requirements become particularly critical compared to flat terrain.

The second important indicator was the geometric compactness of the site, assessed using the Shape Index. An index value exceeding two often indicates that the site is elongated, fragmented, or non-functional, making it difficult to optimize the placement of modular structures. An upper limit of 1.8 was set as the acceptable value, which allows for the elimination of overly elongated or isolated elements, while still permitting naturally elongated shapes on slopes with a slight elevation difference.

Each site in this sample was assigned an average landslide hazard risk value obtained from the integrated map. This approach enabled the combination of information from two sources: geometrically and functionally suitable areas, and a modelled assessment of potential landslide activity intensity (Fig. 8).

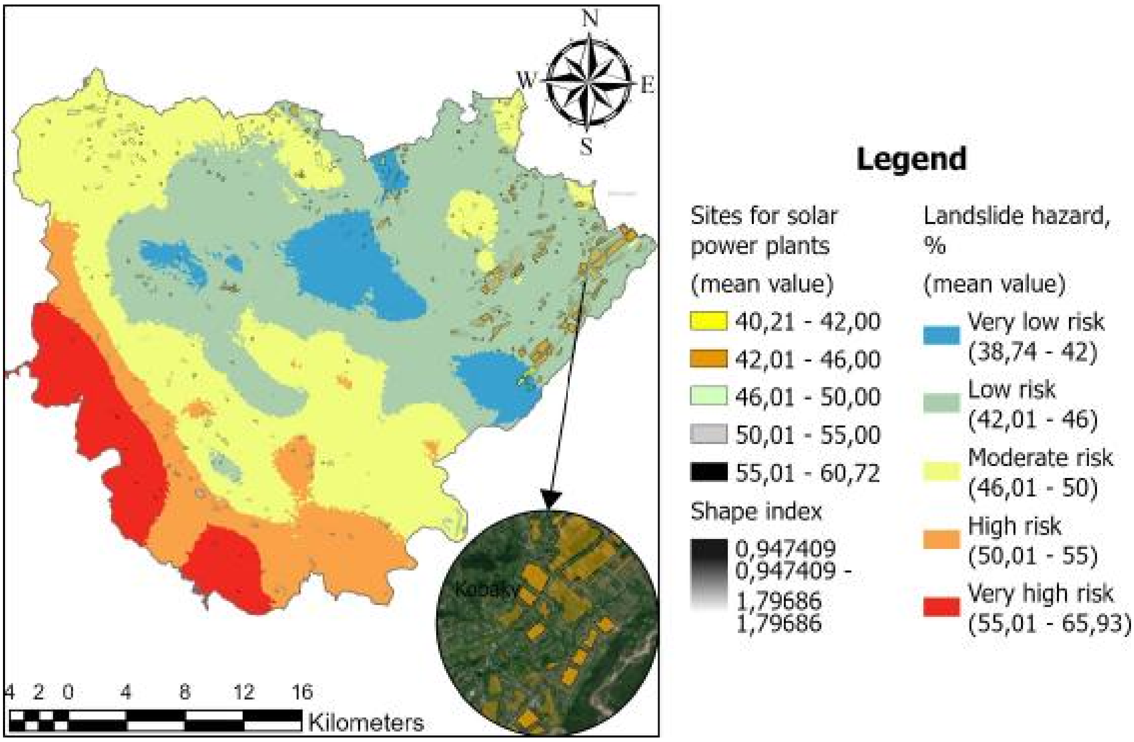

Fig. 8. Integrated spatial suitability model for industrial SES, taking into account the landslide hazard in the Kosiv district.

As a result of the spatial analysis, suitability and landslide hazard maps were integrated, allowing for a multi-factor ranking of territories for the further placement of industrial solar power plants.

In total, 504 sites that meet the spatial, morphometric, and geodynamic conditions for potential SPPs placement were included in the final array. The area of the selected sites ranges from 1.5 to 81.6 hectares, with an average of 6.55 hectares. Considering that industrial solar power plants with a capacity of 1 MW typically require about 1.5 to 2 hectares, the majority of the selected sites offer ample space for technical reserves and buffer zones.

The Shape Index, which indicates geometric compactness, has an average value of 1.40, confirming the predominantly regular morphology of the areas, with no excessive convexities or fragmentation. Particular attention was paid to the distribution of landslide risk. The areas were classified into five categories based on the mean risk values. In the "Very Low" category (less than 45 points), 39.1 % of areas were identified, while another 47.4 % fell into the 'Low' class (45-50 points), accounting for 86.5 % of potentially safe areas. Moderate risk was recorded for only 10.3 % of sites, and high or very high risk was observed in less than 3.2 % of cases.

The risk threshold of 46 % was determined based on an engineering expert assessment derived from practical experience in slope stability analysis in similar geomorphological settings to those of the Carpathians. This criterion reflects the upper limit of acceptable stability conditions for moderately sloping terrain suitable for solar facility placement.

Areas suitable for SPPs with minimal risk and satisfactory geometric parameters (area over 1.5 ha, Shape Index < 1.8) are located mainly in the northern and north-eastern parts of the Kosiv district. Areas with increased risk are primarily confined to the southern macro-slope, where unstable geomorphological conditions are widespread. The generalised map justifies spatial solutions for infrastructure planning in mountainous conditions, considering natural constraints.

Practical significance

The study results provide an analytical basis for the territorial planning of renewable energy facilities in complex geodynamic conditions, contributing to the reduction of risks associated with emergencies and artificial damage. The methodology can be integrated into strategic environmental assessment and land use planning procedures in conditions of landslide hazard.

Scientific novelty

For the first time in the mountainous part of the Ukrainian Carpathians, the Kosiv district, a combination of geoinformation modelling has been implemented to assess the suitability of territories for industrial solar energy production. This assessment incorporates geostatistical evaluation of landslide risks, utilizing Kriging / Co-Kriging interpolation methods. The proposed methodology considers not only morphometric and infrastructural factors, but also the spatial autocorrelation of risks, which allows for greater accuracy in identifying stable areas.

Conclusions

The presented study demonstrated the effectiveness of an integrated approach to spatial suitability analysis for the placement of industrial solar power plants within geodynamically unstable regions. The model integrates geoinformation and geostatistical methods, ensuring both cartographic accuracy and analytical depth when assessing natural risks. At the same time, the results emphasise the need to take into account the full range of geological processes – both endogenous and exogenous – since an isolated analysis of landslide phenomena does not reflect the full complexity of geodynamic threats characteristic of areas with potential SPP locations.

1. A comprehensive multi-stage methodology has been developed that integrates morphometric indicators, spatial constraints, and geostatistical assessment of landslide hazards. This approach enables high-precision and spatially detailed assessments of territories.
2. Vectorisation and buffering of key infrastructure, hydrography features, and natural environment objects were conducted following regulatory and geotechnical requirements. This process helped to exclude areas with potential conflicts and created a positive morphostructural base.
3. The application of ArcGIS ModelBuilder enabled the implementation of an automated geospatial model for site selection. This model considers parameters such as slope, exposure, area, shape, and accessibility, while maintaining a consistent analytical logic throughout all stages.
4. Geostatistical modelling of landslide hazards, based on Ordinary Kriging and Co-Kriging, allowed us to reflect the spatial autocorrelation of risk. This helped identify areas with the most significant potential hazard within the study area, with accuracy confirmed by model validation.
5. The integration of relief derivatives as secondary variables in Co-Kriging interpolation improved the model`s fit to complex orographic conditions. This approach reduced residual errors and enhanced the spatial informativeness of the assessment.
6. Spatial analysis of geometric and risk characteristics showed that of the total number of sites that meet technical and geomorphological requirements (504 units), more than 86 % have a very low or low level of landslide risk (Landslide hazard < 50), with an average value of 46.4. In addition, it was found that most sites have a regular shape (average Shape Index = 1.40), which ensures the efficient use of space for solar modules without the need for complex landscape transformation.
7. The integrated suitability map reflects a synthesis of natural-geographical, morphometric, and risk-oriented factors, forming an analytical basis for territorial decision-making within the Kosiv district.
8. Comparison of the plots with the landslide risk map showed that a significant part of the potentially suitable areas is located within moderate and high risk levels. This requires additional engineering and geological justification before SPP facilities are placed.
9. The proposed model has been found to have high application potential for the formation of local and regional plans for the development of alternative energy, especially within the framework of strategic land use planning in conditions of natural vulnerability.
10. The scientific value of this work lies in the interdisciplinary integration of geoinformation analysis and geostatistical modelling, providing a qualitatively new level of risk formalisation for selecting areas for industrial development, especially in mountainous landscapes with increased landslide activity.

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ГЕОІНФОРМАЦІЙНЕ МОДЕЛЮВАННЯ ЗОН ДЛЯ РОЗМІЩЕННЯ ПРОМИСЛОВИХ СОНЯЧНИХ ЕЛЕКТРОСТАНЦІЙ З УРАХУВАННЯМ ЗСУВНИХ ПРОЦЕСІВ У ГІРСЬКИХ УМОВАХ

У статті висвітлено інтегрований підхід до просторової оцінки придатності територій для розміщення промислових сонячних електростанцій (СЕС) у гірських умовах із врахуванням поширення зсувних процесів, які є одними з ключових природних обмежень для інфраструктурного розвитку в Карпатському регіоні. Об’єктом дослідження Косівський район Івано-Франківської області – територія, що характеризується складною геологічною будовою, підвищеною схильністю до зсувів і зростанням інвестиційного інтересу до проєктів альтернативної енергетики. Актуальність роботи зумовлена потребою у врахуванні геодинамічних ризиків під час просторового планування енергетичних об’єктів та недостатньою інтеграцією геостатистичних методів у проєктну практику. Методологічна основа дослідження – поєднання інструментів геоінформаційного моделювання та геостатистичної інтерполяції. Векторний аналіз просторових обмежень здійснено на основі буферного моделювання навколо об’єктів інфраструктури, гідромережі, забудови та лісових масивів, що дозволило виділити зони без конфліктів. Далі застосовано морфометричні критерії – кут нахилу схилу та експозицію – з урахуванням орографічних вимог для ефективної генерації електроенергії. Усі критерії інтегровано в ModelBuilder, що забезпечило відтворюваність і автоматизацію процесу просторового аналізу. Геостатистичну оцінку ризику зсувних процесів реалізовано із побудовою семіваріограми та моделі просторової автокореляції (Moran’s I), що виявила високий ступінь кластеризації небезпечних точок. Для побудови поверхні ризику застосовано методи Ordinary Kriging та Co-Kriging з урахуванням топографічних факторів. Отримані результати дали змогу визначити просторову диференціацію ризику у межах території дослідження з високою точністю інтерполяції. Залишкова помилка валідації (RMSE ≈ 4,47) засвідчує високу якість моделі, а Co-Kriging з використанням похідних рельєфу (slope та aspect) краще адаптується до умов гірської місцевості. На завершальному етапі здійснено просторове ранжування ділянок площею понад 1,5 га з геометричним індексом форми нижче ніж 1,8, що забезпечує ефективність їхнього потенційного використання для розміщення СЕС. Результати аналізу свідчать, що лише близько 13 % придатних за площею ділянок відповідають вимогам до конфігурації та мають допустимий рівень зсувного ризику (менше ніж 46 %). На основі інтеграції карти ризиків з масивом підготовлених ділянок створено підсумкову карту оптимальних зон розміщення СЕС, яка враховує як технічні, так і природні обмеження. Наукова новизна дослідження полягає у вперше реалізованій повномасштабній геостатистичній оцінці ризику зсувів у контексті планування об’єктів сонячної енергетики в умовах Українських Карпат. Практична значущість визначається можливістю безпосереднього застосування результатів для формування планів просторового розвитку та екологічно безпечного освоєння територій. Підхід може бути адаптований для інших регіонів (Карпатського регіону) з активними геодинамічними процесами та використаний під час оцінювання впливу на довкілля для об’єктів альтернативної енергетики.

Ключові слова: геоінформаційне моделювання, зсувна небезпека, сонячні електростанції, геостатистика, просторовий аналіз, планування та управління, Карпати.

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