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Original Contribution

GEOGRAPHIC INFORMATION SYSTEMS AS A TOOL FOR SPATIAL RISK ASSESSMENT AND SUSTAINABLE TERRITORIAL MANAGEMENT

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Abstract: *The paper examines the application of geographic information systems (GIS) as a tool for spatial risk assessment and for supporting sustainable territorial management. The relevance of the topic stems from the growing need to analyze risk not only as a theoretical or statistical category, but also as a phenomenon with a clear spatial manifestation, related to specific territories, population, infrastructure, natural resources, and socio-economic activities. The study clarifies the relationship between the main components of risk - hazard, exposure, vulnerability, consequences, and response capacity - and the capabilities of GIS for their spatial representation and integrated analysis. Main GIS-based methods for risk assessment and risk mapping are discussed, including spatial overlay, buffer analysis, proximity analysis, terrain analysis, multi-criteria evaluation, thematic mapping, and scenario modeling. The importance of GIS as a decision support system in prevention, territorial planning, disaster management, critical infrastructure protection, and resource prioritization is emphasized. The main thesis is that geographic information systems transform risk from an abstract management category into spatially visible, measurable, and actionable information necessary for sustainable and evidence-based territorial management.*

Key words: *Geographic information systems, Spatial risk assessment, Risk management, Sustainable territorial management, Spatial analysis, Risk mapping, Vulnerability, Exposure, Disasters, Decision support systems.*

1. Introduction

Contemporary territorial management takes place under conditions of increasing uncertainty caused by natural, climatic, environmental, infrastructural, technological, and socio-economic factors. The growing frequency and intensity of adverse natural phenomena, urbanization, the development of critical infrastructure, and society's increasing dependence on complex technical and information systems impose new requirements on the processes of

risk assessment, management, and reduction. In this context, risk should be considered not only as the possibility of an adverse event occurring, but also as a management category related to the effect of uncertainty on the objectives of a given system, organization, or territorial community [9, 15, 23].

Risk management involves the identification of hazards, analysis of probability and possible consequences, assessment of vulnerability and exposure, selection of appropriate risk treatment measures, and subsequent monitoring. This process is particularly important in disasters, accidents, and crisis situations, where decisions often have to be made under conditions of limited time, incomplete information, and a highly dynamic environment. Effective management requires sufficient, reliable, and timely information to support the rational allocation of resources, coordination among institutions, and the selection of sustainable management [5, 9, 23].

A significant characteristic of risk is its spatial dimension. Hazards arise or manifest themselves in specific territories; vulnerable objects are spatially located; exposure has geographic parameters; and consequences affect specific settlements, infrastructure elements, agricultural areas, natural resources, economic assets, and social communities. This means that risk assessment cannot be comprehensive without spatial analysis of the factors that shape risk and without visual representation of the zones in which it manifests itself with different levels of intensity [4, 14, 24].

Geographic information systems provide an appropriate environment for addressing this problem. They enable the collection, storage, processing, analysis, and visualization of spatial and attribute data related to hazards, exposure, vulnerability, critical infrastructure, response resources, and possible consequences. Unlike traditional information systems, GIS allows the integration of heterogeneous data within a unified geographic framework, thereby creating conditions for multidimensional analysis of complex processes and phenomena [3, 8, 18].

Previous studies have examined the application of GIS in various fields, the capabilities of real-time GIS for monitoring and security, and the role of GIS in the management of natural disasters and crisis situations [5, 6, 7, 8]. The present paper builds on these studies by focusing on the relationship between risk theory and the capabilities of GIS for spatial assessment, risk mapping, and support for sustainable management decisions.

In this context, the present study examines GIS as a tool for linking spatial analysis, risk assessment, and the process of making sustainable management decisions.

The aim of the paper is to justify the application of geographic information systems as a tool for spatial risk assessment and for supporting sustainable management decisions in territorial management.

To achieve this aim, the following research tasks are set:

- To clarify the theoretical basis of risk, risk assessment, and risk management by examining the main concepts related to hazard, vulnerability, exposure, consequences, acceptable risk, and monitoring.
- To present the role of GIS as a tool for the spatial representation of risk through the integration of data on hazards, exposed elements, vulnerable territories, critical infrastructure, and response resources.
- To examine main GIS-based methods for risk assessment and risk mapping, including spatial overlay, buffer analysis, proximity analysis, terrain analysis, multi-criteria evaluation, thematic mapping, and scenario modeling.
- To substantiate the significance of GIS as a decision support system for sustainable management decisions related to prevention, territorial planning, disaster management, critical infrastructure protection, resource prioritization, and enhancing territorial resilience.

2. Exposition

Theoretical basis: risk, assessment, and management

Risk is a multifaceted category used in various scientific fields, including security, economics, ecology, engineering sciences, disaster management, territorial planning, and the management of complex social systems. Regardless of the specific field of application, risk is associated with uncertainty, the possibility of deviation from the expected course of development, and the probability of adverse consequences. In contemporary scientific and management literature, risk is increasingly viewed not merely as a potential hazard or loss, but as the effect of uncertainty on the objectives of a given system, organization, or management process [9, 15].

An essential feature of risk is that it arises under conditions of uncertainty. Uncertainty may stem from incomplete, inaccurate, or contradictory information, dynamic natural and social processes, resource limitations, technological changes, or the inability to foresee all environmental factors in advance. In this sense, risk is not only the result of a specific adverse event, but also a management problem related to the need for decision-making under incomplete information and the possibility of different future scenarios [1, 9].

When building GIS, non-deterministic approaches can also be used, which allow working with incomplete and inaccurate information, detecting contradictions in input data, and gradually refining models as more reliable information becomes available [16].

In a narrower sense, risk is often defined through the probability of an event occurring and the severity of its potential consequences. Such an approach is typical of technical, engineering, and organizational systems, where risk can be assessed through quantitative or qualitative indicators. In a broader management sense, risk can be viewed as a probable adverse deviation from a desired or expected outcome as a result of the variability and non-deterministic nature of environmental factors. This approach is particularly important in the management of territories, natural resources, infrastructure, and settlements, where the consequences of an event may simultaneously affect people, material assets, the environment, and socio-economic development [9, 21].

Risk analysis requires a clear distinction between the concepts of hazard, risk, vulnerability, exposure, consequences, risk factors, and risk situation. A hazard can be viewed as a source of potential harm or as an objective possibility of adverse impact. Risk, on the other hand, includes the probability that this hazard will materialize and lead to specific consequences. Therefore, a hazard in itself is not equivalent to risk; it becomes a risk when exposed and vulnerable elements, systems, or population groups are present [9, 15].

The basic relationship between these components is presented in Fig. 1.

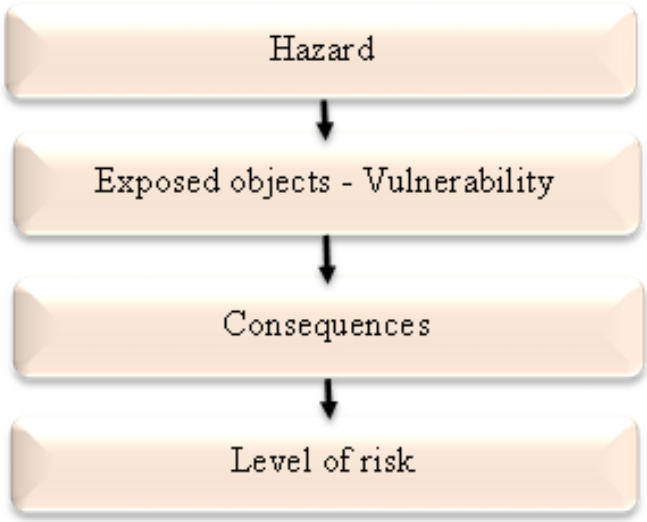


Fig. 1. Main components of risk [9, 15, 23]

Vulnerability is one of the key elements in risk assessment. It expresses the degree to which a given system, territory, infrastructure, or community is susceptible to the adverse impact of a specific hazard. The same hazard may lead to different consequences depending on the characteristics of the affected territory, population density, the condition of infrastructure, the presence of protective facilities, institutional preparedness, and response capacity. Therefore, risk should be analyzed not only through the probability of an event occurring, but also through the degree of vulnerability, the scale of exposure, and the severity of potential consequences [4, 9].

Exposure complements risk analysis, as it indicates which people, elements, resources, territories, or systems are located within the impact zone of a given hazard. In the case of natural disasters, accidents, or environmental threats, exposed elements may include settlements, transport and energy infrastructure, agricultural land, water resources, industrial facilities, protected areas, or critical infrastructure. The greater the concentration of valuable and vulnerable elements in a given territory, the more significant the consequences may be if the risk materializes [14, 23].

Risk assessment is a systematic process of identifying hazards, analyzing the probability of their manifestation, determining potential consequences, and assessing the tolerability or acceptability of risk. It has not only an analytical but also a practical function, as it provides a basis for making management decisions. Risk assessment makes it possible to determine which risks are priorities, which territories are most threatened, what resources are needed, and what measures should be taken to limit, reduce, or control risk [9, 15].

The risk assessment process usually includes several interrelated activities: hazard identification, determination of risk factors, analysis of probability and consequences, evaluation of the level of risk, and determination of the necessary risk treatment measures. This process may be quantitative when sufficient data and measurable indicators are available, or qualitative and expert-based when information is incomplete, uncertain, or difficult to measure. In territorial, environmental, and crisis situations, it is often necessary to combine quantitative data, expert assessments, scenarios, and spatial analyses [1, 9].

Risk management builds upon risk assessment by incorporating a set of principles, methods, actions, and control mechanisms aimed at reducing the probability of adverse events, limiting their consequences, and enhancing the resilience of affected systems. In this sense, risk management is not limited to one-time identification and assessment, but is a

continuous process that includes planning, implementation of measures, monitoring, control, and updating of decisions in response to a changing environment [9, 15]. The generalized logic of the risk management process is presented in Fig. 2.

The concept of acceptable risk occupies a particularly important place in this process. In practice, it is not always possible to completely eliminate risk, especially when natural hazards, climatic processes, technical infrastructure, or complex social systems are involved. Therefore, management decisions are often aimed at achieving a level of risk that is tolerable in relation to specific objectives, resources, regulatory requirements, public expectations, and available response capacity. This implies choosing between different strategies, such as risk avoidance, reduction, sharing, transfer, or acceptance [9, 21].

In disasters, accidents, and crisis situations, risk management becomes particularly significant, as decisions are often made under conditions of limited time, incomplete information, and a high degree of uncertainty. In such cases, risk is not merely a theoretical category, but a practical management problem related to the protection of human life and health, preservation of the environment, safeguarding of infrastructure, and ensuring the continuity of essential societal functions. Effective management requires timely information, institutional coordination, assessment of possible scenarios, and rational allocation of resources.

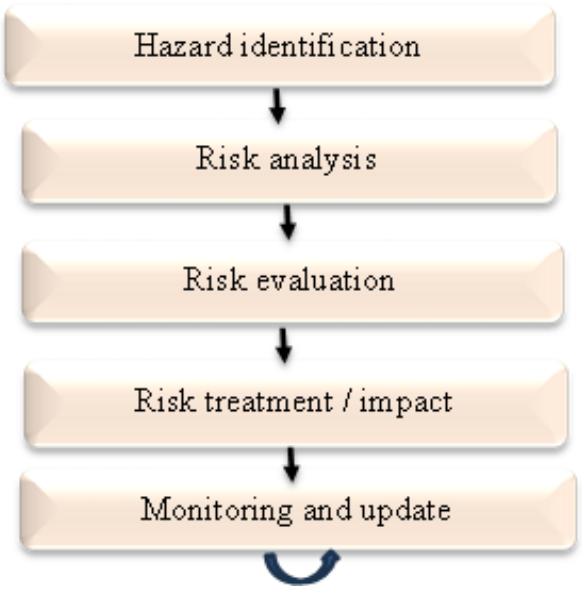


Fig. 2. Generalized risk management cycle [9, 15]

From the perspective of the present study, it is particularly important that risk has a clearly expressed spatial dimension. Hazards arise or manifest themselves in a specific territory; vulnerable elements are spatially located; exposure has specific geographic parameters; and consequences affect specific settlements, infrastructure elements, agricultural land, natural resources, or economic assets. This means that risk management requires not only quantitative and qualitative assessment, but also spatial representation of risk factors and their interrelations [4, 24].

Consequently, the theoretical framework of risk, assessment, and management provides a basis for using geographic information systems as a tool for spatial assessment. Through GIS, hazards, vulnerable elements, exposure, response resources, and potential consequences can be represented as spatial layers and analyzed in an integrated manner. In this way, risk is

transformed from an abstract management category into specific, visualized, and territorially grounded information necessary for sustainable territorial management.

GIS as a tool for the spatial representation of risk

Since risk manifests itself in a specific territorial environment, its study requires tools that allow the spatial linking of data on hazards, vulnerable elements, exposed territories, and response resources. Geographic information systems provide such an analytical environment, as they enable the collection, storage, processing, analysis, and visualization of spatial and attribute data. By linking information to a specific location, GIS makes it possible to examine spatial relationships between natural, infrastructural, social, and economic factors involved in the formation of risk [3, 8, 18].

Unlike traditional information systems, which often present data mainly in tabular or descriptive form, GIS allows data to be organized into spatial layers. Each layer may represent a specific component of the risk environment, such as natural hazards, terrain, the hydrographic network, land use, settlements, transport infrastructure, critical infrastructure, protected areas, demographic characteristics, or response resources. In this way, GIS creates an opportunity to examine heterogeneous data within a unified spatial framework [3, 18].

An example logic for representing risk through GIS layers is shown in Fig. 3.

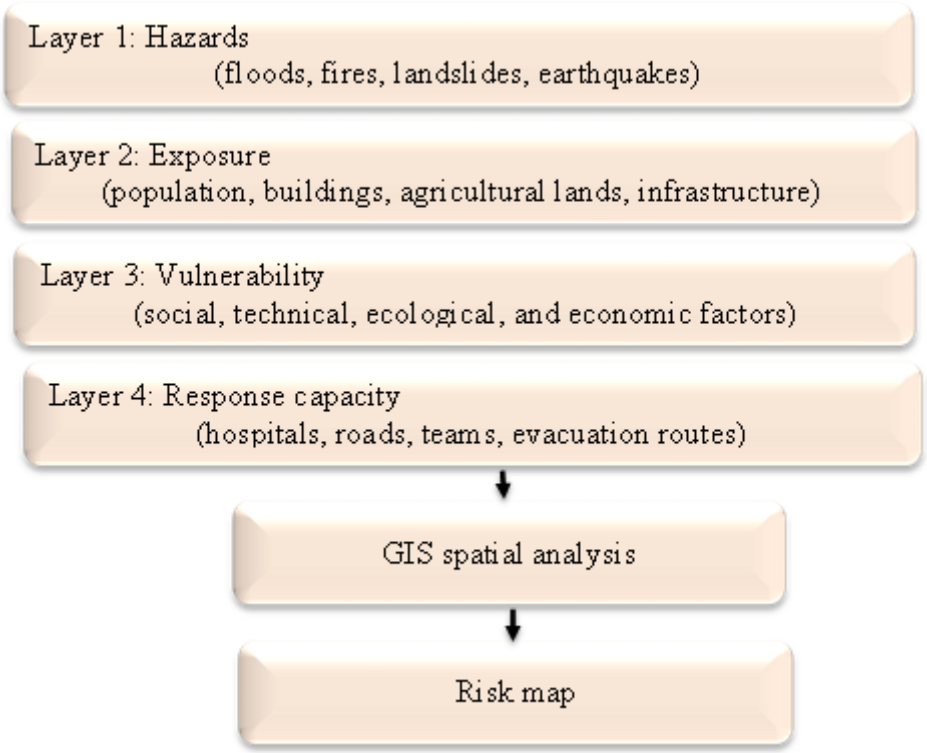


Fig. 3. Spatial representation of risk through GIS layers [5, 18, 19]

Within spatial risk assessment, risk can be represented through the integrated consideration of several main components: hazard, exposure, vulnerability, potential consequences, and response capacity. A hazard may be visualized through maps of floods, landslides, fires, earthquakes, extreme temperatures, industrial accidents, or other adverse events. Exposure indicates which people, elements, resources, or territories fall within the impact zone. Vulnerability characterizes the degree to which these elements may be affected,

while consequences reflect the potential damage to the population, infrastructure, environment, and economic activities [4, 9, 21].

This approach allows risk to be viewed not only as an abstract probability, but also as a spatially determined phenomenon. For example, flood risk is not limited to the probability of a rise in water level, but also depends on which settlements, roads, agricultural land, industrial sites, or critical infrastructure elements are located within the potentially threatened zone. Similarly, forest fire risk depends not only on meteorological conditions and combustible material, but also on proximity to settlements, transport accessibility, response capabilities, and the sensitivity of affected ecosystems.

The spatial representation of risk through GIS is also essential for distinguishing between different levels of risk within a territory. Through mapping, zones with low, medium, or high levels of risk can be identified, as well as critical points where several adverse factors overlap. Such areas may include territories with a high probability of natural hazards, significant population concentration, insufficient infrastructure provision, and limited response capacity. Thus, GIS supports the prioritization of territories where preventive or corrective measures need to be undertaken.

A particularly important advantage of GIS is the ability to integrate data from various sources. Depending on the nature of the risk, these may include cadastral and topographic data, satellite imagery, remote sensing data, meteorological and hydrological observations, statistical information, sensor data, GPS devices, IoT platforms, institutional databases, or field observations. This integration enables the construction of a more complete and up-to-date picture of the risk environment, which is especially important in dynamic processes and crisis situations [5, 8, 11].

In the context of disasters, accidents, and crisis situations, GIS is important primarily as an environment for the spatial integration of data on hazards, affected territories, vulnerable elements, and potential consequences. Through the integrated presentation of these data, impact zones, critical points, and territories with increased exposure can be outlined. In this way, GIS supports the transition from a general description of risk to its specific spatial localization and visual representation.

Real-time GIS further expands this functionality by enabling the dynamic updating of spatial information. Data from sensors, meteorological stations, cameras, GPS devices, drones, satellite systems, and IoT platforms can be integrated into a GIS environment and provide current information on developing processes. This is particularly applicable to the monitoring of floods, fires, transport incidents, environmental pollution, the movement of people and resources, and the observation of critical infrastructure.

From the perspective of sustainable territorial management, the spatial representation of risk through GIS has not only an analytical but also a communication function. Maps and spatial models make complex information more understandable for experts, institutions, local authorities, stakeholders, and the public. This facilitates the discussion of alternatives, the justification of management decisions, and the raising of awareness regarding potential threats and necessary preventive measures.

Another important aspect is the ability of GIS to support scenario-based analysis. Through spatial modeling, different development scenarios for a given risk situation can be examined, such as the spread of a fire, the extent of a flood zone, possible evacuation routes, the accessibility of emergency teams, or the impact on infrastructure elements. This allows preliminary planning of measures and assessment of potential consequences under different conditions [19, 24].

Therefore, GIS can be regarded as a tool that translates the main components of risk into a spatially measurable and visually understandable form. Hazards are represented as

impact zones; exposure as the location of affected people, elements, and resources; vulnerability as a spatial characteristic of sensitivity to impact; consequences as the expected scale of damage; and response capacity as the availability and accessibility of resources for prevention, response, and recovery.

Thus, GIS should not be viewed solely as a mapping tool, but as an analytical and management environment for the spatial representation of risk. Through GIS, risk becomes visible, comparable, and territorially grounded, creating prerequisites for more accurate assessment, better planning, and more effective decision-making. This forms a logical transition to the next stage of the study: the examination of specific GIS-based methods for risk assessment and risk mapping.

GIS-based methods for risk assessment and mapping

GIS-based risk assessment relies on the integrated use of spatial data, thematic layers, analytical procedures, and cartographic models through which the different components of risk can be identified, compared, and visualized. The main advantage of this approach is that it allows risk to be represented not only as a numerical value or expert assessment, but also as a spatially distributed phenomenon related to specific territories, elements, infrastructure, and population [3, 9, 18]. Fig. 4. presents a summarized sequence of GIS-based risk assessment.

The first stage in GIS-based assessment is the collection, structuring, and pre-processing of spatial data. Depending on the nature of the risk being studied, topographic maps, digital elevation models, cadastral data, satellite imagery, remote sensing data, meteorological and hydrological observations, statistical data, and information on land use, infrastructure, population, and critical infrastructure elements may be used. The quality, accuracy, timeliness, and compatibility of these data are essential, as errors or gaps in the source information may lead to inaccurate risk assessment [7, 11, 24].



Fig. 4. Generalized sequence of GIS-based risk assessment [19, 20, 24]

The next stage is the construction of thematic layers representing individual risk factors. For example, in flood risk assessment, layers related to terrain, slope, drainage network, distance to river courses, land use, precipitation, settlements, and infrastructure elements may be included. For landslide risk, layers related to geological structure, slope, slope aspect, rainfall, soil cover, road infrastructure, and anthropogenic impact may be used. For forest fire risk, vegetation, temperature, humidity, wind, accessibility, proximity to settlements, and human activity may be included [14, 24].

One of the main GIS methods for risk assessment is spatial overlay. Through this method, different thematic layers are combined in order to identify territories where adverse factors accumulate. For example, an area with a high probability of flooding, high population density, and the presence of critical infrastructure may be identified as a territory with an elevated level of risk. Spatial overlay makes it possible to highlight spatial relationships that are difficult to establish solely through tabular or descriptive data [3, 20].

Another important method is buffer analysis, which is used to determine zones of influence around specific elements or phenomena. It can be applied to outline risk zones around riverbeds, industrial sites, transport corridors, power lines, dams, fire-prone areas, or other sources of potential hazard. Buffer analysis is particularly useful in the initial identification of territories that fall within a potential impact zone and require further assessment or monitoring [3, 18].

Related to this is proximity and accessibility analysis, which allows the assessment of the spatial location of elements in relation to risk sources or response resources. This type of analysis can be used, for example, to examine how close settlements are to a risk zone, how far emergency teams are from potentially affected territories, which roads provide the fastest access to critical infrastructure elements, and what evacuation options are available. This method is important for planning prevention, response, and recovery activities [5, 18].

In the assessment of natural risks, morphometric and terrain analyses based on digital elevation models (DEM) are frequently used. Through these analyses, slope, aspect, elevation, watersheds, flow directions, accumulation zones, and other terrain characteristics can be determined. These indicators are especially important in the analysis of floods, erosion, landslides, avalanches, and other processes in which terrain has a significant influence on the emergence and development of the hazard [3, 24].

Multi-criteria evaluation (MCE) plays a significant role in GIS-based risk assessment. It allows the simultaneous consideration of multiple factors that have different weights in the formation of risk. Each criterion can be represented as a separate spatial layer, after which the layers are normalized, weighted, and combined into a generalized assessment. For example, when assessing the vulnerability of a territory to flooding, slope, distance to water bodies, land use, population density, type of infrastructure, and historical data on previous events may be included. The multi-criteria approach is particularly suitable for complex management decisions where risk cannot be explained by a single factor alone [19, 20].

Within the framework of multi-criteria analysis, the Analytic Hierarchy Process (AHP) can also be applied. It allows the relative weight of individual criteria to be determined through expert evaluation and pairwise comparison. This method is applicable when sufficient quantitative data are lacking, but expert ranking of factors according to their importance for risk formation is possible. In a GIS environment, AHP can be used to create suitability, vulnerability, or risk maps by combining weighted spatial layers [19, 22].

Classification and categorization of territories by risk level also form an important group of methods. After the risk factors are combined, the resulting values can be grouped into classes, such as low, moderate, high, and very high risk. This creates maps that allow rapid visual differentiation of priority zones for intervention. Such maps are particularly

useful for local authorities, civil protection institutions, planning bodies, and experts who must make decisions regarding preventive measures, investments, restrictive regimes, or emergency planning [22, 24].

Thematic mapping is another fundamental tool in the process of risk representation. Through thematic mapping, the results of the analysis are transformed into maps showing the spatial distribution of hazards, vulnerability, exposure, and risk levels. Maps may be static, when they present the situation at a specific moment, or dynamic, when they are updated with real-time data. In this sense, mapping is not merely visualization, but part of the analytical process, as it supports the interpretation, comparison, and communication of results [6, 18].

When sufficient data are available, methods for spatial modeling and scenario assessment can also be used. They make it possible to simulate the potential development of a given adverse event and assess its possible extent. For example, flood zones at different water levels, the spread of a forest fire under different meteorological conditions, the accessibility of emergency teams in the case of blocked infrastructure, or the impact of an industrial accident on nearby settlements can be modeled. Such scenarios support not only risk assessment, but also advance planning of crisis response actions.

Remote sensing data are also of particular importance, as they expand the possibilities for risk monitoring and assessment. Satellite imagery, drones, and other remote sensing sources allow the observation of changes in land cover, vegetation, water bodies, urbanized areas, and disaster-affected zones. By integrating such data into a GIS environment, trends can be identified, anomalies can be detected, and the development of risk processes can be tracked over time.

GIS-based methods can be used both for preliminary assessment and prevention and for response and recovery after an event occurs. In the preventive phase, they support the identification of risk zones and the planning of measures. During a crisis situation, they enable the tracking of event dynamics, coordination of resources, and selection of appropriate routes. In the recovery phase, they support damage assessment, prioritization of recovery activities, and updating of future prevention plans.

The result of applying these methods is the creation of risk maps that present the territorial distribution of different risk levels. These maps can be used as tools for expert analysis, institutional coordination, territorial planning, public information, and management decision-making. They support the transition from a general description of risk to the specific spatial determination of zones where preventive, protective, or recovery actions are required.

In summary, GIS-based methods for risk assessment and risk mapping provide an opportunity for the systematic integration of data, analysis of spatial relationships, and visual presentation of results. Through spatial overlay, buffer analysis, proximity analysis, terrain analysis, multi-criteria evaluation, thematic mapping, and scenario modeling, risk can be represented as a specific and manageable territorial characteristic. This creates a basis for moving to the next aspect of the study: the use of GIS as a tool for supporting sustainable management decisions.

GIS as a decision support system for sustainable management decisions

The application of GIS in risk assessment is not limited to hazard mapping and the visualization of risk zones. Modern geographic information systems can be regarded as spatial decision support systems because they integrate data, analytical methods, modeling, visualization, and the possibility of comparing different management alternatives. In this sense, GIS not only shows where risk is located, but also supports the selection of measures to be undertaken, the allocation of resources, and the prioritization of territories.

Sustainable territorial management requires decisions that simultaneously take into account natural, environmental, infrastructural, social, and economic factors. Such decisions can rarely be based on a single indicator or an isolated expert assessment. An environment is needed in which different types of data can be integrated, analyzed, and presented in a way that allows comparison between risks, resources, vulnerabilities, and potential consequences. GIS provides precisely such an environment, as it enables the combination of spatial and attribute data within a unified analytical framework. Fig. 5. presents GIS as a system for supporting sustainable management decisions.

In the risk management process, GIS supports decision-making at several levels. At the strategic level, the system can be used to identify priority territories for investment, prevention, and long-term planning. At the tactical level, GIS supports the selection of specific measures, such as the construction of protective infrastructure, changes in land use, restrictions on construction in risk zones, determination of evacuation routes, or deployment of response resources. At the operational level, GIS provides up-to-date information on the current situation, the location of resources, the accessibility of affected territories, and the development of risk processes in real time.

In disaster and crisis management, GIS performs the function of a spatial decision support system. By integrating information on affected territories, accessible routes, critical infrastructure, available resources, and the locations of response teams, GIS supports the formation of a common operational picture. This is important in all phases of management: prevention, preparedness, response, and recovery. In the prevention phase, GIS supports the identification of risk zones and the planning of measures; in the preparedness phase, the development of evacuation routes and the deployment of resources; during the response phase, the coordination of actions and access to affected territories; and during recovery, damage assessment and the prioritization of recovery activities.

As a decision support system, GIS is also essential for resource prioritization. In crisis situations, resources are usually limited, including equipment, personnel, transport, financial means, time, and institutional capacity. Through spatial analysis, it is possible to determine which zones are most threatened, where the highest concentration of population or critical infrastructure is located, which routes are most suitable for access, and which interventions can lead to the greatest reduction in risk. This allows decisions to be more well-founded, transparent, and defensible.



Fig. 5. GIS as a decision support system for sustainable management decisions [5, 18, 19]

important area is the use of GIS in sustainable territorial and infrastructure planning. Risk maps can be used to identify zones unsuitable for construction, to plan transport and energy infrastructure, to manage water resources, to protect agricultural land, and to support environmental protection. When spatial risk assessment is integrated into the planning process, management decisions can be directed not only toward response after an event has occurred, but also toward the long-term reduction of vulnerability and the enhancement of territorial resilience [14, 19, 23].

GIS also supports the management of critical infrastructure. Through the spatial representation of energy, transport, water supply, communication, and public facilities, it is possible to analyze their exposure to various hazards, their interdependencies, and the potential cascading effects in the event of damage or disruption. In the context of security and crisis management, real-time GIS can be used for monitoring strategic facilities, analyzing risks, assessing security, tracking transport routes, and coordinating actions during incidents [6, 10].

A significant advantage of GIS is its capacity for scenario modeling and comparison of alternatives. For example, in the case of flood risk, different water levels and their impact on settlements, roads, and infrastructure can be modeled. For forest fires, scenarios related to different wind directions, terrain accessibility, and the location of firefighting resources can be compared. In urban planning, options for expanding urbanized areas can be assessed in relation to risk zones, transport accessibility, and environmental constraints. In this way, GIS supports not only the description of the current state, but also the selection among possible future decisions [19, 24].

The development of real-time GIS, big data, IoT, 5G, cloud technologies, and artificial intelligence further strengthens the role of these systems in decision-making. Data can be collected from multiple sources, processed dynamically, and used for forecasting, early warning, and the automated detection of spatial patterns. A previous study indicates that the integration of AI and machine learning into GIS enables automatic pattern recognition,

analysis of large datasets, and forecasting of events such as floods, fires, environmental disasters, or transport disruptions [7, 13, 17].

However, the use of GIS as a decision support system for sustainable management decisions requires overcoming a number of limitations. These include the quality and currency of data, compatibility between different information systems, lack of standardized formats, shortage of qualified specialists, the need for reliable technical infrastructure, and issues related to the security and privacy of geospatial data. In real-time systems, latency, communication reliability, and infrastructure resilience under extreme conditions are also of particular importance.

It is particularly important that GIS-based decisions are not perceived as entirely automated or technically neutral. GIS supports the expert and management process, but it does not replace the need for professional judgment, institutional responsibility, regulatory frameworks, and public legitimacy. Spatial models and maps are tools for better information and improved awareness, but management decisions should also take into account social, economic, ethical, and political factors. This is especially important in relation to measures affecting population, property, infrastructure investments, or restrictions on the use of territories [15, 21, 23].

From a communication perspective, GIS facilitates the presentation of complex information to different stakeholder groups. Maps, interactive dashboards, spatial models, and visualizations allow experts, local authorities, institutions, and citizens to better understand the territorial distribution of risk, the rationale behind certain management decisions, and the need for preventive measures. This increases the transparency of the process and creates better conditions for coordination, participation, and public support.

Application of GIS in spatial modeling and optimization of production environments

The capabilities of GIS for spatial analysis, data integration, and decision support can also be considered in the context of production environments. Production processes are carried out within a specifically organized space in which different types of equipment, work zones, and supporting infrastructure are located, and where the movement of material resources, finished products, and people takes place. Representing these elements as spatially located and functionally connected objects makes it possible to analyze their relative position, technological routes, and the relationships between the individual stages of the production process [12, 25].

The application of GIS in such an environment creates an opportunity to integrate different types of data into a unified spatial model and to use them for comparison between different organizational alternatives. In the assessment process, it is possible to simultaneously take into account the distances between successive technological operations, the accessibility of equipment, the safety of work zones, the use of available space, and the location of supporting infrastructure. In this context, multi-criteria analysis can support the selection of an appropriate spatial solution through the integrated consideration of technological, spatial, and safety-related factors [2, 12].

Such an approach can also be applied in the development of experimental production environments that include successive stages of workpiece preparation, subsequent mechanical processing and finishing operations, geometric control, and testing of product surfaces. The spatial modeling of these activities creates an opportunity to analyze technological routes and the interaction between the individual functional zones. In this way, GIS can be regarded not only as a means of visualizing the production environment, but also as a tool for supporting the analysis and optimization of its spatial and functional organization.

In summary, GIS can be regarded as a key tool for supporting sustainable management decisions because it transforms spatial data into analytical and actionable information. Through data integration, risk assessment, mapping, scenario modeling, and visualization, the system supports the identification of priority zones, optimization of resources, planning of preventive measures, crisis response, and recovery after adverse events. Thus, GIS creates a link between scientific analysis, expert assessment, and practical territorial management.

3. Conclusion

The analysis carried out shows that geographic information systems can be regarded as an effective tool for spatial risk assessment, as they allow the integrated representation and analysis of hazards, exposure, vulnerability, critical infrastructure, response resources, and potential consequences. In this way, risk is interpreted not only as a probability or expert assessment, but also as a territorially manifested phenomenon that can be localized, visualized, compared, and managed.

A major advantage of the GIS-based approach is the ability to integrate heterogeneous data and apply spatial analysis methods, including layer overlay, buffer analysis, proximity analysis, multi-criteria evaluation, thematic mapping, and scenario modeling. Through these methods, risk zones can be identified, different levels of risk can be distinguished, and territories requiring preventive, protective, or recovery actions can be determined.

The role of GIS is especially significant in disasters, accidents, and crisis situations, where management decisions are made under time constraints, incomplete information, and a dynamically changing environment. Under these conditions, GIS supports the development of a common operational picture, institutional coordination, resource prioritization, the definition of access and evacuation routes, damage assessment, and the prioritization of recovery activities. The development of real-time GIS, remote sensing, IoT, cloud technologies, artificial intelligence, and machine learning further expands the capabilities for monitoring, early warning, and forecasting risk processes.

From the perspective of sustainable territorial management, GIS is important not only as a technical mapping tool, but also as a decision support system. Spatial risk assessment provides a basis for justifying decisions related to territorial planning, critical infrastructure protection, natural resource management, restrictions on activities in risk zones, investment prioritization, and enhancing the resilience of communities and infrastructure systems.

In summary, GIS can be regarded as a key tool for supporting sustainable management decisions because it transforms spatial data into analytical and actionable information. Through data integration, risk assessment, mapping, scenario modeling, and visualization, the system supports the identification of priority zones, resource optimization, the planning of preventive measures, crisis response, and recovery after adverse events. The capabilities for spatial analysis and multi-criteria evaluation further extend the application of GIS to production and experimental environments, where the system can support the analysis of spatial organization and the interaction between individual functional zones. Thus, GIS creates a link between scientific analysis, expert assessment, and the practical management and optimization of various types of spatially organized systems.

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