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IMPACT OF URBAN LAND ON THE RISKS OF KARST PROCESSES IN THE NPP LOCATION AREA (ON THE EXAMPLE OF RIVNE NPP)

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The aim of the article is to assess the impact of urbanized areas on the risk of developing karst processes in the area of nuclear power plant location and on the safety of the plant (using the example of the Rivne nuclear power plant). Karst features in the area around the Rivne nuclear power plant were visualized using GIS methods. Systematization of karst hazards was carried out with regard to their impact on the structural integrity and safety of the long-term operation of the Rivne nuclear power plant. The impact of urbanized areas on the geological environment was assessed, and a correlation was established between urbanization factors and the activation of karst-suffusion processes. It is shown that urbanization can contribute to the emergence of karst manifestations and, as a result, to threaten to the safety of NNP. Approaches aimed at improving the assessment of karst hazards, monitoring of the main factors of their activation, and managing urbanized areas to increase the safety of nuclear power plants were proposed.

INTRODUCTION

The radiation safety of the power plant personnel, the population, and the environment depends on the reliable functioning of the nuclear power plant (NPP) and its ability to withstand external hazards. External hazards can be caused by natural or anthropogenic phenomena. Such impacts become more dangerous when they synergistically amplify each other.

Safety standards of the International Atomic Energy Agency for the protection of people and the environment, SSR-1: “Site Evaluation for Nuclear Installations. Specific Safety Requirements” [1] establish requirements that are included in national regulations for environmental and radiation safety. The requirements are based on the evaluation of sites for nuclear installations in terms of external hazards of natural and anthropogenic origin (Requirement 6 [1]), with the aim of ensuring the safety of nuclear power plants. The provision of a comprehensive and coordinated set of safety requirements includes the assessment of natural and technological external hazards, the combined effects of which are evaluated over the entire life cycle of the installation (Requirement 7 [1]), taking into account changes in hazardous processes over time and their consequences (Requirement 19 [1]). External hazards include geotechnical and geological hazards (Requirement 22 [1]), such as slope instability, extreme meteorological conditions and phenomena, the impact on soil and groundwater of seismic loading, the possibility of sinkhole formation, subsidence or surface uplift [2]. The possibility of reducing soil density and altering underground materials at the site, which could affect the safety of the nuclear installation, should be evaluated by appropriate seismic hazard parameters and geotechnical properties of the subsurface, using recognized methods of field and laboratory testing in combination with analytical methods of hazard assessment

Compliance with the above requirements requires the study of factors that activate dangerous geodynamic processes within the controlled territory (sanitary protection zone, observation zone), among which karst is the most influential [3–5].

Karst landscape is a destabilizing factor for the reliability of building foundations, and can pose significant risks to the structural integrity of NPP. The presence of karst rocks creates significant hazards for the safety of nuclear power plants, especially in urbanized areas where human activity can exacerbate the effects of karst processes [6]. In Ukraine, where four nuclear power plants are located, karst hazards highlight the need for comprehensive geoecological monitoring of the surrounding environment in the areas of their placement. Such monitoring is the basis for assessing the risks of accidents resulting from interrelated natural-urban-technogenic factors.

The aim of this article is to differentiate and evaluate the karst risks in the area of NPP locations, which may affect their safe operation (using the example of the Rivne nuclear power plant), and to determine the impact of urbanized areas on the development of karst processes

1. METHODOLOGY AND RESEARCH OBJECTS

1.1. GEOLOGICAL ENVIRONMENT STATUS IN THE AREA OF THE RIVNE NPP LOCATION

The following research results are related to the territory of the 30-km zone around the Rivne Nuclear Power Plant (RNPP), located in the northwestern part of Ukraine on the border of Rivne and Volyn regions. The total area of the 30-km zone is 2826 km^2, with 1658 km^2 in Rivne region and 1168 km^2 in Volyn region.

In Rivne region, the prevailing rocks are those prone to karstification, namely limestone and chalk. Karst systems are extremely complex in their hydrogeological properties and are among the most vulnerable systems in the world. Karst is a particular type of landscape formed by the dissolution of soluble rocks [6]. Karst deformations can occur in the form of caves, sinkholes, funnels, subsidence, etc., which can cause damage to structures and buildings. The territory of Volyn region (20.2 km^2) is practically entirely represented by rocks capable of karstification [7], with an area of open karst of 2.3 km^2 and covered karst of 9.64 km^2. The number of karst manifestations in 2020 amounted to 2016 cases. In Rivne region (20.1 km^2), the area of distribution of karst rocks is 17.15 km^2, with an area of open karst of 0.85 km^2 and covered karst of 10.20 km^2 (Fig. 1). The number of karst manifestations in 2020 amounted to 747 cases [7].

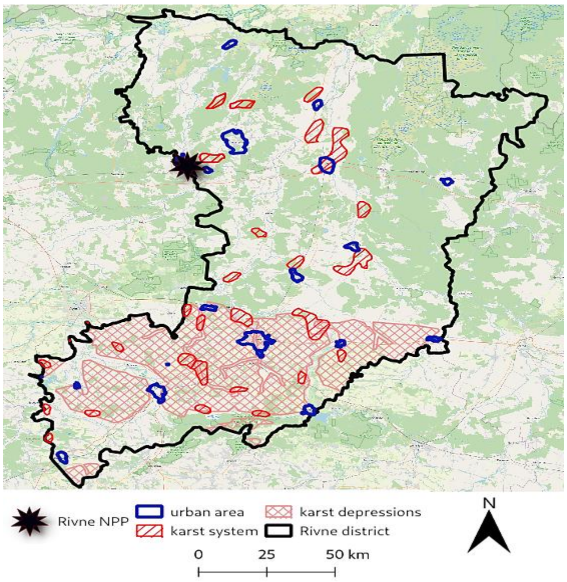

Fig. 1. The map of the Rivne region with zones of karst rocks and karst sinkhole areas (data visualization [8] by the authors)

The location of the Rivne Nuclear Power Plant belongs to the landscape region of the Volyno-Podilskaya Plate, Galician-Volyn Depression, and the Polissya Karst region (VI-A) [7], which contains underground karst formations such as expanded fissures, channels, zones of sinkholes, disintegration and dissolution, as well as the development of caves and collapse-sedimentary funnels.

1.2. METHODOLOGY OF THE STUDY

In the work, a method of visualizing data from geological monitoring was applied, for which indicators of the activation of dangerous exogenous geological processes (DEGP) from the data array of the annual reports of the State Institution "Geoinform" for the period 2010–2021 [7] were combined, and similar data for 2001 were obtained from source [9]. The results of visualizing the areas of active karst and karst depressions based on data presented on the Geodata platform [8] were also used.

The data were visualized using the QGIS program [10]. The parameters of visualization were determined using the "Open Field Calculator" tool [11]. The territories under consideration were visualized based on open data from OpenStreetMap [12].

The authors structured the complex and multifactorial aspects of urbanization in previous studies using indicators of population density and the proportion of the total area of urban settlements to the total area of the region [13]. The latter indicator is associated with the area of impermeable surface in the urbanized area, establishing its connection with dangerous geological processes.

2. RESULTS AND DISCUSSION

2.1. EVALUATION OF GEOLOGICAL AND GEOTECHNICAL HAZARDS IN THE AREA OF THE RIVNE NPP

The site of the Rivne Nuclear Power Plant (NPP) is located in complex engineering-geological conditions of fractured karstic Cretaceous rocks. Karst manifestations, including a karstic collapse (3 m in diameter, 2.5 m in depth), were detected during the construction of the first three blocks of the station.

To structurally strengthen the foundation and reduce the impact of suffusion-karst processes on the stability of the main structures of the Rivne NPP (foundations of buildings and structures of blocks No. 1, 2, 3), cementation of the chalk layer and the contact zone of basalts was carried out by injection. Additionly, strengthening of Cretaceous soils (Quaternary and Paleogene) with drill-injection pipes was used. The cementation method made it possible to grout large cracks and voids in the Cretaceous layer and, in general, reduce the permeability of the soil. In addition, hydro-isolation of water-bearing networks and structures was strengthened, and activities were taken to reduce the penetration of technical water into the soil. The main structures of Block №4 were built on piles that are supported by basalts, which fully cut through the layer affected by karst processes, ensuring their reliable operation.

Regular monitoring of soil and groundwater on the territory of the Rivne NPP is carried out [14]. The results of such monitoring indicate that as of 2018, the geological environment of the site corresponds to the geotechnical properties of the soils in the foundations of buildings and structures of blocks № 1, 2, 3.

However, it is necessary to take into account all aspects of the influence of natural-anthropogenic conditions within the radius of karst hazards in developing predictive characteristics of the engineering-geological conditions of the industrial site. Furthermore, according to Requirement 10 of the IAEA Safety Standards for the Protection of People and the Environment SSR-1 [1], it is important to track the spatial and temporal dynamics of hazardous processes.

During the operation of NPP, geological, hydrogeological, and hydrogeochemical conditions are affected in the locations where their buildings are situated. For example, disturbances in the hydrological regime can cause flooding of territories due to the rise of groundwater levels by 10 m or more [15]. Such processes can sharply intensify the intensity of suffosion-karst processes.

It is also necessary to take into account the impact of mechanical loading on the geological foundation of the plant structures. Changes in the structure of rocks, their physical-mechanical, and hydro-physical properties occur due to the influence of loading, moistening, heating, and other factors. Thus, the probability of karst manifestations that lead to settling of buildings, tilt of foundations, and consequently to the disruption of the safe operation conditions of the NPP increases.

During the operation of NPP, a large number of different radionuclides are formed, which in the event of emergencies can be released into the surrounding environment in different forms and contaminate the territories surrounding the plant.

Thus, prolonged operation of NPP, even without violating operational requirements and regulations, leads to the activation of hazardous exogenous karst processes in surrounding areas. Identification of formed sinkholes, subsidence, fissures, which directly or indirectly affect the safety of the site, is an element of Requirement 22 [1] for assessing geotechnical hazards and Safety Standards No. NS-G-3.6 [2] of the International Atomic Energy Agency (IAEA).

According to the available monitoring data [14, 16], the karstological situation is considered controlled, as there have been no manifestations of suffosion-karst processes on the surface of the ground in the vicinity of the production site blocks № 1, 2, 3, 4 since 1983, and Block № 4 structures are based on basalts. However, during the environmental impact assessment of the production site of the Rivne NPP (Book 1 [17]), geological conditions, including the condition of karst rocks, were not taken into account among the natural factors affecting the nuclear power plant.

As for obtaining monitoring data on the activation of hazardous exogenous geological processes [7], no surveys of karst relief have been conducted in the monitoring areas located within the influence zone on the nuclear power plant structures (Fig. 2), during the last five years. This is in contrast to the data [7, 9] indicating that the area of open karst sinkholes and subsidence manifestations in the Rivne region has increased by more than 10 km^2 over the last 20 years.

This trend requires an improved and effective strategy for managing karst risks. This should include identifying potential hazards, assessing the vulnerability of the karst-covered area, and implementing activities to mitigate these risks.

The total area of active karst in the area surrounding the station within a radius of 30 km is 69 km^2 (see Fig. 2). The areas are located to the northeast of the station. According to GIS data [7, 8], there are three areas of karst and sinkhole rocks adjacent to the station. Area 1 has a total area of 20 km^2, of which 10 km^2 are directly within the 30 km karst zone. Area 2 covers 22 km^2, of which only 1 km^2 is within the 30 km zone. Area 3, with an area of 27 km^2, is located 5.36 km from the center of the nuclear power plant.

The authors of this article have used a territorial hazard index of karst formation, which was previously determined in [18], as the ratio of the karst system area to the area of the considered district (in this case, the 30-km zone around the NPP). This calculated index of territorial impact determines the potential maximum risk of karst process activation within the aforementioned limits. Territorial indicators of karst hazard, calculated using the methodology [20], have been determined for the 30-km zone and are as follows: for area 1 – $Rt_1 = 3.5 \cdot 10^{-3}$; for area 2 – $Rt_2 = 0.36 \cdot 10^{-3}$; and for area 3 – $Rt_3 = 9.6 \cdot 10^{-3}$.

It is obvious that site 3 directly affects the safety of the NPP structures. The impact of sites 1 and 2 will depend on the hydrogeological and geochemical characteristics of the area, the direction of geochemical migration of elements and infiltration and groundwater flow, their level of occurrence, and other landscape features.

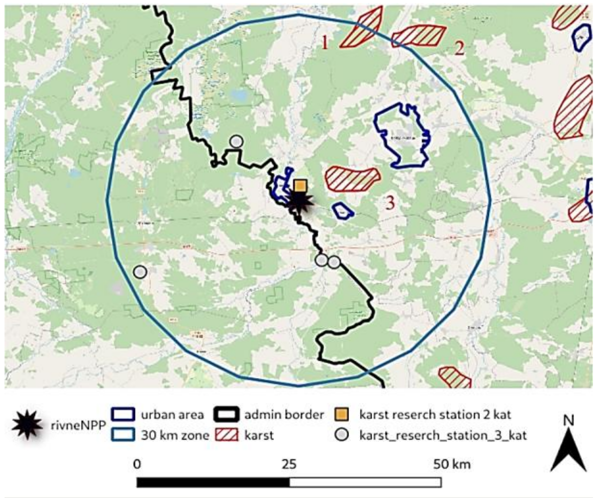

Fig. 2. A map of the 30-km zone of the Rivne Nuclear Power Plant (RNPP) with areas where karst-subsidence rocks are located

The karst danger is considered in terms of specific types of threats that can be posed to structures and affect the conditions of operation of the nuclear power plant. Based on various methods of vulnerability assessment of nuclear power plants in areas prone to karst manifestations [3–5, 19], we propose the following differentiation of the most significant types of karst risk for the safety of structures and the NPP site with the surrounding area:

1. Risk for the industrial site of the RNPP – determines the potential geological danger for the industrial site and the 30-km observation zone:

1.1. Caused by the formation of karst voids, softening of rocks, and subsidence ($R_{1.1}$);

1.2. Caused by the mechanical pressure of the nuclear power plant structures and the creation of underground karst deformations ($R_{1.2}$);

1.3. Caused by the erosion of infiltration waters into karst rocks and the formation of karst water ($R_{1.3}$);

2. Risk for the safe and long-term operation of the nuclear power plant – determines the probability of technical problems/emergency situations that violate the structural integrity of the nuclear power plant buildings:

2.1. Caused by:

deformation/damage to the plant buildings due to local subsidence ($R^{l}_{2.1}$), the development of uneven settlement of the foundation and unacceptable tilting of buildings and structures ($R^h_{2.1}$);

2.2. Caused by the destruction of plant buildings due to emergency collapses ($R^a_{2.2}$).

It should be emphasized that such differentiation reflects the external influence of the natural geodynamic exogenous process of karst formation on the safe functioning of the station. The level of influence of the external natural factor of seismicity and its impact on karst danger were not taken into account. Based on the conclusions of work [20] and report [17], it follows that the seismicity of the NPP site meets the requirements of the IAEA No. SSG-9 [21], and the value of PGA at MPS (peak ground acceleration at the design earthquake magnitude) is taken at a level of 0.1 g.

Sufficient research has been devoted to the internal factors of radiation safety of nuclear power plants, for example [22, 23]. In this context, the authors intentionally did not consider internal factors that determine the probability and scenarios of the development of a technogenic accident at an object of increased danger, such as an NPP.

To determine the quantitative assessment of various risk categories, we assume that the most significant impact on the territory of the NPP observation zone is made by the karst area with a territorial indicator of karst formation danger Rt_3 = 9,6 10^{-3}. We adopt an integral risk assessment [24] based on the relationship:

$$R_j^i = \sum_{k=1}^{n} R_k \times \beta_k,$$

where R_j^i – represents the risks $R_{1.1}$, $R_{1.2}$, $R_{1.3}$, $R^l_{2.1}$, $R^h_{2.1}$, $R^t_{2.1}$, $R^a_{2.2}$.

β_k – the weight coefficient β_k for a specific type of risk is determined by expert assessment based on the weight of the influence of the corresponding factor on the overall level of hazard, taking into account the dependence $\sum\beta_k$ = 1.

If we assume the weight coefficients are equally balanced, then β_k= 1/7= 0,143, and the average value of each type of risk is $R_{aver} = 0.143 \cdot 9.6^{-3} = 1.4 \cdot 10^{-3}$. However, based on the studies [4–6, 15, 19] on the impact of the above factors on $R_k$the authors of the article propose the following distribution of weight coefficients and corresponding risks (Table).

Calculation of Weighting Coefficients
and Corresponding Karst Risks

R_j^i	$R_{1.1}$	$R_{1.2}$	$R_{1.3}$	$R^l_{2.1}$	$R^h_{2.1}$	$R^t_{2.1}$	$R^a_{2.2}$
β_k	0.12	0.20	0.20	0.12	0.12	0.12	0.12
$R_j^i \cdot 10^{-3}$	1.15	1.92	1.92	1.15	1.15	1.15	1.15
R_{aver}	$1.4 \cdot 10^{-3}$						

Weight of factors 1.2 and 1.3 has been increased due to the increased probability of impacts on the geological environment from the station itself, as well as from infiltration, surface and groundwater. The hydrological regime of the territory of the Rivne nuclear power plant, built on karst rocks, leads to the emergence of risks of karst deformations. This is primarily justified by the large number (approximately 150) of small and medium-sized rivers, the watersheds of which cover almost the entire region, including the 30-km observation zone of the Rivne NPP. The hydrology of karst is very sensitive to both water withdrawal and inflow due to floods and spills that are typical for the location of the RNPP [17]. Thus, water inflows from extreme atmospheric downfall cause risks of karst sinkhole formation, while regular seasonal floods contribute to the erosion of karst rocks with cavity formation. Intensive water withdrawal and dehydration of surface soil layers, taking into account the direct connection between the surface and the lower aquifer, cause rapid downward percolation [25]. Such liquid infiltration through an immobile layer of solid matter reduces the mechanical strength of karst rocks and promotes subsidence or suffusion processes. Thus, risks $R_{1.2}$ and $R_{1.3}$ are interrelated and interdependent.

Additionally, we have taken into account that the water regime is the most vulnerable to urban load on the territory, and this will be discussed in the next section. The balance of factors 1.1, 2.1, 2.2 is derived from the data of regular monitoring of the RAES [14, 16, 17] and is determined by the landscape characteristics of the region, which is a undulating plain that slopes from south to north.

The distribution of differential types of territorial karst risk is presented in Fig. 3. It should be noted that such preliminary assessments of individual types of karst hazards must be supplemented and compared with the application of methods for assessing deterministic and probabilistic regularities of karst manifestations [4, 19]. Such data may include a time-spatial assessment of the dynamics of sinkholes development, correlations between sinkholes diameters and various natural and man-made factors, taking into account the mechanisms of funnel formation.

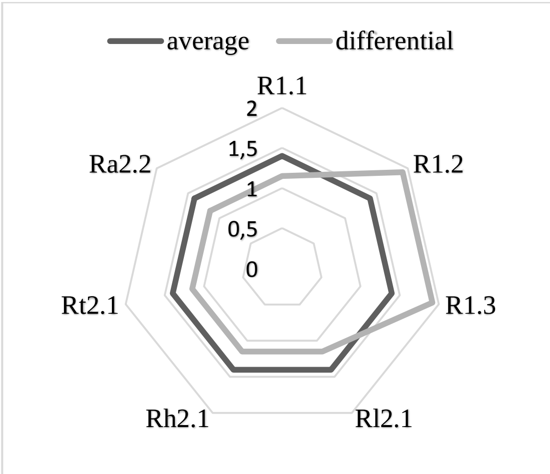

Fig. 3. Diagram of differential territorial risks of karst formation: R_{aver} – average risk value under the conditions of averaging the influence factor values; R_j^i – differential risk values

Based on the previous assessments of karst risk from external impact on the safety of the area of RNPP, it is rational to take them into account in emergency scenarios that can occur at the station, as well as their potential consequences. A risk-oriented approach enhances the effectiveness of current risk management measures.

When planning risk management strategies and making decisions in early warning systems and emergency response plans, it is important to consider the results of geoenvironmental monitoring. This monitoring includes the study of factors impacting urbanized areas.

Consideration of such factors requires a multidisciplinary approach and an understanding of various factors and parameters that affect the risk of adverse events and hazards for the nuclear power plant and surrounding urban areas.

2.2. THE IMPACT OF FACTORS FROM URBANIZED AREAS ON THE DANGER OF KARST MANIFESTATIONS IN THE AREA WHERE THE RIVNE NUCLEAR POWER PLANT IS LOCATED

The nature of impacts on the industrial site and the 30-km observation zone of the Rivne NPP is determined by both the station's impact on the geological foundation and the consequences of urban changes in the surrounding areas. This is also in line with the requirements of the IAEA (Requirement 24 [1]) for taking into account the destructive human activities.

Vegetation degradation, accidents of underground communications resulting in significant water and heat losses, changes in relief with the formation of deep sinkholes and depressions, lead to the activation of a complex of phenomena such as water and wind erosion, groundwater level rise, karst, landslides, and other hazardous exogenous geological processes. The consequences of military actions for the natural and landscape systems of Ukraine are not yet fully studied, but it is possible to predict the disastrous effects of armed conflicts on karst environments.

Urban impacts cause profound changes to the lithospheric foundation of both urban and natural landscapes. These changes include alterations to land use patterns, the presence of water and heat supply networks, highways, changes to vegetation cover, and urban-induced modifications to the terrain.

The Rivne NPP, like other power plants in Ukraine, is located in sufficiently urbanized regions. Previously, the authors of the current article already investigated changes in the potential instability of the karst relief due to urbanization [18]. An assessment of the dynamics of changes in karst-hazardous areas in regions of Ukraine from 2001 to 2020 was made, and the coefficient of expansion of karst territories was calculated. The impact of urbanized areas was evaluated through an index of ecological urbanization for Ukrainian regions, which takes into account the distribution of urban population and the relative area of cities [13]. The evaluation revealed the impact of urban systems on the contamination of karstic aquifers, increased underground drainage in karst environments, climate change, disturbance of natural vegetation cover, and technogenic changes to landscapes. Factors such as the diversion of surface runoff, the capacity of water supply networks, the purification capacity, and the proper technical condition of sewage facilities are important factors that control the water supply and hydrological regime of karstic rocks.

In the 30-km zone of the nuclear power plant (see Fig. 2), using data visualization obtained from an open resource [12], the total area of urban territories was determined to be 58.49 km^2 which includes the city and its suburban areas. The cities located within the potential impact zone of the nuclear power plant include:

Volodymyrets, with an area of 12.26 km^2 and a distance of 16.3 km from the lower boundary to the hypothetical center of the nuclear power plant;

Rafalivka, with an area of up to 5 km^2, located 5.8 km^2 from the nuclear power plant;

Varash, with an area of 11.31 km^{2}and a population of over 40,000, including the nuclear power plant personnel, as it is a satellite city of the station.

Thus, the dense infrastructure network, including the laying of highways, water pipes, and canals that provide the livelihood of the urban population, as well as the presence of industrial enterprises, create an urban-technogenic load in the area of close proximity to the nuclear power plant. The impact of urban areas is directly related to the vulnerability of karst aquifers, changes in water level, thickness and degree of groundwater pollution, as well as the permeability of rocks that make up the aquifers. In turn, the level of groundwater depth affects the stability of thick karst rocks, increases their active porosity, and causes a decrease in soil density.

Modernization of the mechanism for managing environmental safety based on risk-oriented approaches and decision-making in the conditions of post-war recovery of the country requires a shift of the main focus from elimination measures to ensuring a preventive stage and organizing a system for reducing and managing hazardous conditions.

The main tool for mitigating the consequences of emergencies at NPP, reducing the vulnerability of the station to external natural disasters, in our opinion, is the organization of effective geoecological monitoring. However, as noted above, starting from 2015, measurements at observation points for karsts located within a 30-km zone of the station have not been conducted.

Therefore, it is necessary to restore observations at network points studying exogenous geological processes primarily.

Overall, the relocation of monitoring stations in the urban environment requires a comprehensive understanding of the potential impact of urban infrastructure on local karst hazards, and the placement of observation points based on geotechnical research results should be adjusted to account for urban influence. Monitoring stations should be placed nearer to potential groundwater pollution sources like industrial or municipal treatment plants. They should also be located in areas where they can detect changes in the landscape (subsidence or settlement) caused by urban infrastructure, energy, and industrial facilities.. Groundwater monitoring is particularly important for determining changes in water levels, which may be an indicator of karst activity, especially if deep drainage systems or permanent drainage systems have been established.

The placement scheme for geoecological monitoring observation points should ensure maximum coverage of the area surrounding the Rivne NPP. We believe that the monitoring network cannot be limited to a 30-km zone around the plant and should be justified by the logic of landscape-geochemical zoning and the identification of homogeneous areas with similar characteristics for observation organization [26].

Therefore, it is appropriate to combine geoenvironmental monitoring observation points with a radiation monitoring system within the observation zone of the nuclear power plant to improve the overall effectiveness of the monitoring system. Another option is to merge these observation points with seismological monitoring points for comprehensive research on dynamic changes in rock seismic stress conditions, suffosion karst formation, and other manifestations of fluids in the lithosphere.

In order to develop a model that can assess the impact of karst activity on the safety of RNPP locations and predict potential consequences of different scenarios, it is necessary to create a centralized database. This database should include information on monitoring geological processes, soil and water conditions in urban areas, as well as data from a comprehensive system of geoenvironmental, radioecological, and seismic monitoring.

Additionally, an unresolved issue is the outdated equipment used in the observation process. For efficient operational monitoring, modern automated monitoring devices, such as water level sensors, piezometers, water meters, and others, should be installed. Such sensors can provide continuous data on the flow of groundwater and water levels, which are essential for detecting changes in local hydrology and evaluating potential risks of sinkholes, subsidence, and other karst manifestations.

CONCLUSIONS

Although nuclear power plants are designed to withstand significant impacts from hazardous external factors, the magnitude of such loads may vary over time due to technological and urbanization activities. The analysis of karst features in the observation area of the nuclear power plant suggests the need for regular assessment of karst risks, taking into account dynamic changes in the hydrogeological characteristics of the territory.

Based on the differentiation of karst threats by their significance for nuclear power plant safety, the most significant types of risks associated with changes in the hydrological regime of soils under the influence of urbanized territories have been proposed.

The effectiveness of risk management measures, as well as plans and procedures for responding to emergencies, depends on the efficiency of monitoring systems and early warning of karst hazards. Regular monitoring of the state of urban soils and groundwater, in combination with the organization of a comprehensive system of geoecological, radioecological, and seismic monitoring, is recommended.

Thus, the problem of preventing and reducing potential hazards of karst processes in the area of the Rivne Nuclear Power Plant, as well as other nuclear power plants, is solved by regulating the risks of urbanized environment impacts, limiting urban growth in vulnerable areas, and organizing an effective system of comprehensive geoecological monitoring.

Overall, the combination of effective monitoring and risk management strategies can help increase the safety of nuclear power plants in karst-prone regions such as the Rivne Nuclear Power Plant.

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ВПЛИВ УРБАНІЗОВАНИХ ТЕРИТОРІЙ НА РИЗИКИ КАРСТОВИХ ПРОЦЕСІВ У РАЙОНІ РОЗТАШУВАННЯ АЕС (НА ПРИКЛАДІ РІВНЕНСЬКОЇ АЕС)

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Метою статті є оцінка впливу урбанізованих територій на ризик розвитку карстових процесів у районі розташування АЕС і на безпеку АЕС (на прикладі Рівненської АЕС). Візуалізовані карстові особливості в зоні розташування Рівненської АЕС із застосуванням ГІС-методів. Проведено систематизацію карстових небезпек щодо впливів на конструктивну цілісність та безпеку тривалого функціонування Рівненської АЕС. Оцінено впливи урбогенних територій на геологічне середовище, та встановлена кореляція чинників урбанізації та активізації карстово-суфозійних процесів. Показано, що урбанізація може впливати на ініціювання карстопроявів і, як наслідок, поставити під загрозу безпеку АЕС. Запропоновано підходи, які спрямовані на покращення оцінки карстових небезпек, моніторингу основних чинників їх активізації, а також на практику управління урбанізованими територіями для підвищення безпеки атомних електростанцій.