ECOLOGY

The object of the study is the territory that became the object of the influence of hostilities. The study is dedicated to finding ways to assess the state of ecosystems and ensure their stability in the conditions of military conflicts.

The impact of military conflict on the environment is highlighted through the analysis of risks and losses in ecosystems.

It has been studied that the intensity of armed conflicts determines the scale and degree of damage to ecosystems, and the use of destructive weapons leads to the direct destruction of natural environments and their components.

It has been determined by an expert survey that the most significant changes in natural ecosystems are the biodiversity losses, deforestation, territorial changes and the destruction of natural objects (scores ≥9.0). Factors of low impact (score <6.75) are air pollution, erosion due to air pollution, biodiversity losses due to water pollution.

The interrelationships between military actions and environmental pollution are studied for the importance of understanding these processes for effective management of environmental security during military conflicts.

A mathematical and graphic model of material flows has been developed, which allows taking into account resource flows, pollution and losses in the ecosystem during armed conflicts.

The model, tested in the Kyiv region, made it possible to determine the priorities of conservation and risk management. Analysis of 9,000 km^2 revealed contaminated areas, in particular, in the southwestern and western directions.

The practical use of the research results is in the development of strategies for minimizing and restoring the ecological consequences of armed conflicts. This can help improve the management of natural resources in the context of military operations and increase the resilience of ecosystems

Keywords: military conflict, risks, sustainability, ecosystem, mathematical model, material flows, geoinformation systems

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IDENTIFYING THE RISKS OF ARMED CONFLICT IMPACT ON THE ECOSYSTEM

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1. Introduction

The aggravation of geopolitical conflicts in different parts of the world, a large number of tension zones, as well as the use of heavy weapons cause a serious impact on natural ecosystems [1, 2].

Therefore, in the context of armed conflicts, there is a need for a systematic scientific study of risks to ecosystems and their effective management.

Research in this area becomes especially relevant due to several significant circumstances. First, the growth of geopolitical tensions and the intensification of conflicts on

different continents lead not only to a threat to people's safety, but also to serious consequences for the environment. Air pollution, biodiversity losses and deforestation are just some of the negative consequences of warfare that affect ecosystems.

Secondly, through the global vector to sustainable development and preservation of natural resources [3]. Biodiversity losses, water and land pollution, destruction of natural reserves are becoming acute problems that require solutions. The results of scientific research in this field can become the basis for the development of prevention strategies and minimization of the negative environmental consequences of military conflicts.

Thirdly, taking into account the impact of armed conflicts on ecosystems becomes relevant in the context of climate change. Increased erosion, loss of forest areas and deterioration of water resources can increase the effect of greenhouse gases and exacerbate environmental problems [4].

Therefore, the identification and assessment of risks to ecosystems caused by armed conflicts are of strategic importance for countries with conflict red spots. Research like this will help understand key risk factors by identifying areas of highest vulnerability in ecosystems during war.

This determines the research problem – finding ways and opportunities to manage natural resources and ensure their sustainability in the conditions of military conflicts.

The relevance of impact risk identification is confirmed by the fact that the results of such studies can provide a strategic scientific foundation for the creation of effective tools and approaches to minimizing and restoring the environmental consequences of armed conflicts.

Solving this problem is of great importance for scientists, practitioners and managers. The information obtained as a result of such studies will provide the basis for the development of the necessary tools and methodologies for the prediction, minimization and restoration of environmental risks in wartime.

Such studies solve not only the problem of knowing the risks for ecosystems, but also determine ways to overcome them and preserve them for the long term. Therefore, they can be relevant from the point of view of the systemic approach to ensuring sustainability of ecosystems and natural resources during military conflicts, which is critical for overcoming environmental challenges.

2 Literature review and problem statement

Although conflicts in societies have existed throughout the entire existence of mankind, their negative impact on the natural environment has become an object of study for scientists and politicians only in recent times. Armed conflicts not only cause physical and psychological trauma to people, but also damage the natural environment through the use of chemicals, metals and other polluting emissions.

The Institute for Economics and Peace indicates that almost one hundred and ninety countries face various internal or external conflicts, which emphasizes the size and prevalence of this phenomenon. Therefore, work [5] emphasizes the importance of taking into account not only the social and economic aspects of conflicts, but also their impact on the environment in order to develop effective strategies to reduce environmental damage due to such events. The impact of armed conflicts on the territory is described using various indices: both natural and social. The work [5] analyzed the impact of armed conflicts on the territory using various criteria. The assessment included consideration of the priority of preserving the natural environment, determining the level of risk for the territory as a result of the military conflict, and assessing ecosystem services. The aim is to determine what benefits, goods and services people can obtain, both directly and indirectly, as a result of the state of ecosystems. However, the environmental criteria of the study are based exclusively on the criteria of loss of resource potential: for example, the destruction of oil fields, bypassing the level of pollution of natural objects. The issue of assessing the importance of the criteria is also insufficiently covered: in the study, the criteria all have the same effect on the degradation of the soil cover, which is hardly possible.

The results [6] are aimed at assessing the integrity of the soil cover that fell into the combat zone. The study examines the impact of land cover changes caused by armed conflict on the prevalence of soil erosion in the North Al-Kabir River Basin in Syria from 2009/2010 to 2018/2019. Using the RUSLE model, the authors found that the zone with an acceptable rate of soil erosion is only 10.1 %, while 79.9 % of the territory showed signs of erosion at various levels. Land cover change, especially due to forest fires during the conflicts, led to increased soil erosion until 2013/2014, but after 2016, after the ceasefire, there was a decrease in pressure on the soil. However, the study has several significant shortcomings. First, its geographical area is limited only to the specified basin, which can make it difficult to generalize the results obtained to other regions. The study traces the ambiguity of the reasons for the change in the level of soil erosion. Although the findings link this process to forest fires, it is important to take a closer look at the relationships between conflicts, fires and the subsequent conversion of forest areas. The time frame of the study also raises questions: the analysis was conducted in different periods: before and after the introduction of the ceasefire, which can affect the interpretation of the results. Also, the definition of zones of increased erosion based on the conversion of forest zones after fires needs to be clearly defined.

The work [7] examines the impact of armed conflicts on the deterioration of the environment in the countries of South Asia in the period from 1984 to 2019. A feature of the work is that it examines the issues of long-term and short-term consequences of internal and external militarized conflicts, evaluating the following factors: GDP per capita, military spending, population density and energy consumption.

However, the research methodology has some potential drawbacks. One of the main limitations is that the study relies on secondary data sources, which may not cover all relevant factors or variables that may have a significant impact on the evaluation results. Furthermore, the study does not provide a detailed explanation of how environmental impact was calculated or the criteria for environmental degradation affected by armed conflict.

Another potential limitation of the model developed in this study is that it assumes linearity and may not demonstrate nonlinear relationships between variables. In addition, the study has a territorial focus and only considers the environmental impact of militarization in South Asia. This may limit the generalizability of the research results to other regions or countries.

The study of the combination of technologies of geographic information systems (GIS) and machine learning [8]

deserves attention. Scientists are using machine learning and satellite image processing techniques to map and analyze land surface changes in the conflict zone of Rakhine, Myanmar. As field visits were not possible due to conflict and travel restrictions, satellite data were used to create the training set and map.

The disadvantages of the method are the lack of field data, which can affect the accuracy and objectivity of the results. Using machine learning interpretation to build the training set can lead to subjectivity and limit the objectivity of the analysis. The limited number of land cover definition categories may affect the detail and accuracy of the classification. The inconsistency of the justification for choosing specific time points for comparison can make the analysis of the dynamics of changes less objective. The ambiguity of the causes of the conflict and their connections with changes in the surface relief can complicate the interpretation of the results. The technique of using machine learning and satellite data has prospects for studying changes in the conditions of an active conflict, but it is necessary to take into account the above-mentioned limitations to ensure accurate and objective results.

Research [9] is aimed at finding ways to assess the impact of war on agricultural land in Ukraine, using remote sensing and geoinformation systems technologies. The authors developed a combination of "random forest" machine learning methods, the Savitsky-Goley gap filling and filtering method, the FANTA algorithm, and the nuclear density method to analyze the spatio-temporal distribution of "abandoned" fields in the period from 2018 to 2022. The essence of the study is to quickly assess the impact of military conflicts on agricultural land and food security. The use of remote sensing and geoinformation systems is key to regular monitoring of the state of agricultural management. However, the dependence of information on cloud processing, such as Google Earth Engine, is a significant disadvantage of the study in terms of access and reliability.

The most similar is the study [10], which used Landsat images and GIS to monitor changes in land cover in Syria from 2010 to 2018. The study found that the conflict in Syria had a significant impact on changes in the structure of land cover: by increasing the destruction of agricultural areas and vegetation cover .The study also revealed the importance of considering socio-ecological impacts in land management strategies.

The innovation of the methods used in this study is the use of GIS systems to monitor land cover changes in Syria. This approach made it possible to carry out a comprehensive analysis of changes over time, which is important for understanding the impact of socio-ecological impact on the environment.

Limitations and weaknesses of the study include the lack of ground truth data to assess accuracy. Landsat images have a relatively coarse spatial resolution and cannot capture small-scale surface changes. The use of cloud images makes it impossible to recognize the exact cause of soil structure changes: natural or man-made anthropogenic changes. In addition, the study did not consider the impact of other factors, such as climate change.

It is possible to summarize that there are no studies that would comprehensively assess the degradation of ecosystems after active hostilities. Many studies are devoted to the process of soil erosion, loss of resource potential of natural objects. However, these works do not take into account the interrelationships between elements of ecosystems. This allows to state that it is appropriate to conduct a risk assessment study for ecosystems that have fallen into the war zone.

Therefore, the study proposes to search and identify risks for ecosystems that arise as a result of armed conflicts. For this, it is advisable to use geoinformation modeling tools.

3. The aim and objectives of the study

The aim of the study is to identify and assess the risks to ecosystems that arise as a result of armed conflicts. The construction of a mathematical and graphic model of material flows will allow to identify the key factors that determine the risks to nature and to determine the zones of the highest vulnerability in the ecosystem during the war. The research is aimed at creating an analytical tool that will help predict the consequences of military conflicts for nature and develop strategies for the protection and restoration of ecosystems in conditions of military operations.

To achieve the aim, the following objectives are set:

– to determine the environmental risk factors associated with the course of hostilities;

– to develop a mathematical and graphic model of material flows to assess risk and losses in ecosystems during armed conflicts.

4. Materials and methods of research

The object of research is the territory on which there was an active course of hostilities.

The research hypothesis is that the impact of armed conflicts can cause significant changes in ecosystems due to the degradation of natural objects. This impact will largely depend on the intensity of the conflict, the types of weapons used and the geographical features of the area.

In order to solve the task, the main factors of natural ecosystems, which are most affected during hostilities, have been evaluated and modeling has been carried out to assess their risk.

The research has been carried out in three stages, described below (Fig. 1).

The first step is to assess the problem of the impact of armed conflicts on the ecosystem according to the hierarchy, that is, to determine the important criteria. At this stage, the development of spatial layers of pollution maps of the territory according to each criterion is envisaged. The data for the construction of the maps is based on Zo Environment Network reports. The territory for analysis is divided into squares of 1,000 km^2.

At the second stage, industry experts were interviewed to assess the degree of importance of the criteria. Intuitive-logical analysis by experts was applied because it is difficult to formalize the impact of armed conflicts on the ecosystem due to the lack of accurate and complete information. The involvement of specialists made it possible to take into account various aspects of the problem, thus providing a more complete picture of the situation. The resulting estimates help avoid ambiguity and allow for consideration of multiple impact scenarios, which can be particularly important in the context of uncertainty typical of armed conflict. The experts' task was to evaluate the selected criteria for the element at the top level of the hierarchy. According to experts' evaluations, criteria weights are determined and summed up to determine local ratings for each group of factors.

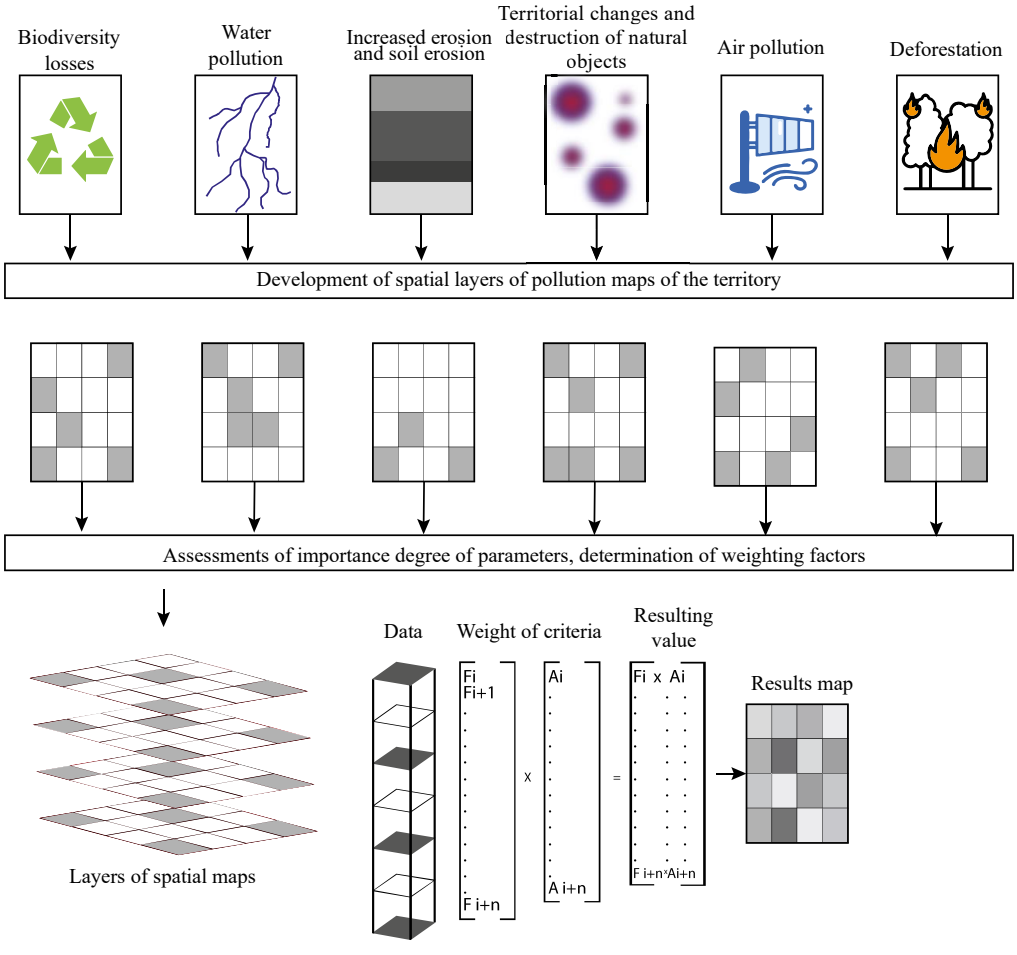

Fig. 1. Stages of research

The last stage is obtaining a consolidated map of the contamination of the territory, which demonstrates suitability or limited suitability. The map layers constructed in step 1 were used as input maps of the ascending level. GIS graphical visualization was performed using QGIS.

5. The results of the study of identification and assess the risks to ecosystems that arise as a result of armed conflicts

5. 1. Determination of environmental risk factors associated with the course of hostilities

Armed conflicts, regardless of their scale and duration, negatively affect natural ecosystems, which can lead to serious consequences for biodiversity, water resources, soils and other aspects of ecology. That is why it is so important to identify the key ecological risk factors associated with wars and to identify the factors that lead to the deterioration of the natural environment during conflicts.

One of the determinants of risk is the intensity of the armed conflict. At a high intensity of the conflict, there is a massive use of destructive weapons, such as heavy artillery weapons or air missiles, which leads to the direct destruction of ecosystems and their components. Other key factors include weapons, which may include chemical and biological agents that have the potential for extensive long-term environmental damage.

It should be noted that the ecosystems of different regions react to armed conflicts in different ways, depending on their natural characteristics. For example, the steppe ecosystem is more vulnerable to the negative impact of military actions due to the limited potential of natural resource recovery compared to the potential of forest-steppe and forest ecosystems.

That is why it is so important to understand what factors can pose risks to ecosystems.

The selection and justification of risk factors associated with military actions on the environment was guided by the principle of identifying and studying those aspects that have the greatest potential for impact on ecosystems and natural resources. This approach is based on strategically identifying the key elements that can cause the most significant changes and damage.

The study of biodiversity loss became a priority, as this aspect determines the threat of mass extinction of species and degradation of ecosystems, which can have far-reaching consequences for the sustainability of natural environments.

The second criterion of choice was air pollution, since emissions during military operations can significantly affect air quality and human health, making it an important object of research.

Water pollution has been identified as a third important risk factor, as toxic emissions can threaten aquatic ecosystems and pose a serious threat to ensuring access to clean water.

The study also factors in the dynamics of deforestation, erosion and soil erosion, territorial changes and destruction, as factors of serious consequences for biodiversity and climate change.

This strategic selection of risk factors is based on their importance and the possibility of causing significant changes in the environment during military conflicts.

Below is a full description of the selected risk factors.

1. Biodiversity losses:

– impact of military conflicts on ecosystems and biodiversity losses. Military actions can affect biodiversity through the destruction of natural environments, the destruction of habitats and the mass extinction of species. Population declines and ecosystem shifts caused by military conflicts can put some species at risk of extinction. Disruption of natural reproduction and migration processes can lead to irreversible changes in biodiversity, with far-reaching consequences for ecosystems and their sustainability;

– consideration of the risks of the emergence of new species and the spread of invasive species due to military actions. Military conflicts can interact with species distributions, promoting the spread of invasive species that normally harm local biodiversity. The absence of natural regulators of invasive species can be the result of a stressful state of the ecosystem caused by wartime conditions.

2. Air pollution:

– smoke and nitrogen emissions. Military conflicts can cause significant emissions of smoke and toxic nitrogen compounds, which affects air quality and can lead to negative effects on human health and ecosystems;

– pollution by solid particles and aerosols. Infrastructure destruction releases particulate matter and aerosols into the air, which can disrupt air quality and affect plants and animals.

3. Water pollution: chemical pollution. Hostilities can cause the release of toxic chemicals into water sources, which can lead to water pollution and threats to aquatic ecosystems.

4. Deforestation as a result of military actions:

– biodiversity losses due to fires. Large explosions and shelling can cause fires that spread to forests and other vegetation areas;

– destruction of natural barriers. Military operations can destroy natural barriers, such as different types of vegetation, which contribute to the spread of fire;

– impact on the global climate. Loss of forest cover affects the carbon cycle and can contribute to climate change.

5. Territorial changes and destruction:

– destruction of natural objects. Military actions can lead to the destruction of natural objects, such as rivers and landscapes, leading to changes in the natural environment;

– soil and water pollution. The destruction of infrastructure can cause soil and water pollution, which can affect plants and animals.

6. Increased erosion and soil erosion:

– reduction of vegetation. Military action can cause large-scale reduction of vegetation, increasing the risk of erosion and soil erosion;

– soil cover damage. Explosions and other military actions can damage topsoil, increasing its susceptibility to erosion.

These factors interact to determine the complex effects of warfare on the natural environment, disrupting ecological balance and having long-term consequences for biodiversity and ecosystem resilience.

5. 2. Construction of a mathematical and graphic model of material flows for assessing risk and losses in ecosystems during armed conflicts

A mathematical model was built that reflects resource flows, pollution between the atmosphere, water, soil and various elements of the biosphere, and losses in the ecosystem during armed conflicts. Material flows in the model determine how different components interact with each other as a result of military conflicts.

The parameters of the model are:

1. Biodiversity losses – $B(t)$.

2. Dynamics of air pollution – $A(t)$.

3. Dynamics of water pollution – $W(t)$.

4. Dynamics of deforestation – $D(t)$.

5. Dynamics of territorial changes and destruction of natural objects – $T(t)$.

6. Dynamics of erosion and soil washing – $E(t)$.

The process of pollution and loss in the ecosystem during armed conflicts can be described by a system of differential equations according to formula (1):

$$\begin{cases} \frac{dB}{dt} = k_{B1}\cdot B(t) + k_{B2}\cdot A(t) + k_{B3}\cdot D(t), B(t) \geq 0; \\ \frac{dA}{dt} = k_{A1}\cdot A(t) + k_{A2}\cdot T(t) - k_{A3}\cdot B(t), A(t) \geq 0; \\ \frac{dW}{dt} = k_{W1}\cdot W(t) + k_{W2}\cdot T(t) - k_{W3}\cdot B(t), W(t) \geq 0; \\ \frac{dD}{dt} = k_{D1}\cdot D(t) + k_{D2}\cdot T(t) k_{D3}\cdot B(t), D(t) \geq 0; \\ \frac{dT}{dt} = k_{T1}\cdot T(t) + k_{T2}\cdot E(t), T(t) \geq 0; \\ \frac{dE}{dt} = k_{E1}\cdot E(t) + k_{E2}\cdot D(t), E(t) \geq 0, \end{cases} \quad (1)$$

where k_{B1} – biodiversity loss due to direct military actions; k_{B2} – biodiversity loss coefficient due to the introduction of new species or the spread of invasive species; k_{B3} – biodiversity loss coefficient due to deforestation; k_{A1} – coefficient of emissions of harmful substances due to military operations; k_{A2} – air pollution impact coefficient on erosion; k_{A3} – air pollution impact factor on biodiversity loss; k_{W1} – water pollution risk coefficient as a result of military operations; k_{W2} – water pollution impact coefficient on soil erosion; k_{W3} – water pollution impact coefficient on biodiversity losses; k_{D1} – forest cover loss coefficient due to fires and military operations; k_{D2} – deforestation impact coefficient on soil destruction and erosion; k_{D3} – global climate impact coefficient due to the loss of forest cover; k_{T1} – destruction impact coefficient on soil and water; k_{T2} – air pollution impact coefficient on destruction and erosion; k_{E1} – vegetation loss impact coefficient on erosion processes; k_{E2} – coefficient factor taking into account the weather conditions impact on the erosion dynamics.

The described system of equations (1) makes it possible to take into account the complex structure of relationships between parameters. For example, that biodiversity loss due to direct military action and the introduction of new species or the spread of invasive species is caused by deforestation and destruction. Air pollution is increased by military emissions, while destruction and erosion can also increase pollution levels. Chemical water pollution follows military action and can increase through destruction and erosion, interactions with biodiversity loss and soil erosion and erosion. Deforestation occurs due to fires caused by military actions, and destruction contributes to the process of biodiversity loss. Territorial changes and destruction affect soil and water pollution, which in turn interacts with erosion and soil erosion. Loss of vegetation leads to erosion, and weather conditions affect these processes.

The gradation of parameters in terms of importance may vary depending on specific circumstances, the nature of the conflict, and features of the ecosystem in the study area. However, there is an urgent need to rank the parameters in order of overall importance for modeling the impact of military conflicts on the ecosystem.

The multi-criteria problem was solved by obtaining the hierarchy coefficients, which are weighting coefficients. These coefficients act as integral characteristics of the impact of factors on the level of risk. In other words, they reflect the importance and contribution of each factor to the overall analysis, allowing systematization and comparison of their impact on the level of risk to the ecosystems of the area.

To solve the problem of modeling resource flows, pollution and losses in the ecosystem during armed conflicts, expert evaluation methods were used to determine weighting factors in the model.

To determine the weighting coefficients of the model, individual personal evaluations of 8 environmental experts were collected. The results of the collected evaluation data are presented in the Table 1.

The adequacy of the obtained results is confirmed by the calculated value of the consistency indicator, which reflects reliability. Greater reliability of the results is indicated by an indicator below 0.25, which is a low discrepancy and, accordingly, good reliability of the result.

The result of GIS modeling of the generalized level of risk for the ecosystems of territories for the Kyiv region is shown in Fig. 2. The calculation of the average level of risk for the ecosystems of the territory is obtained by solving the system of equations (1), where the average rank of expert evaluations is the impact factor. The initial conditions are set to zero to facilitate the calculation. The Runge-Kutta method of the 4^{th} order was used for the numerical solution of systems of differential equations.

For conducting GIS modeling, the territory within the Kyiv region with a conditionally inactive course of military operations and an active course during February-March 2022 was selected. The movement of heavy military wheeled and tracked vehicles, anthropogenic changes to the ground cover through the construction of defensive military fortifications, and the destruction of natural objects caused by missile weapons were observed on the territory.

The aforementioned military activities had a significant impact on natural ecosystems and the ecological balance of the territory. The movement of heavy military equipment has caused compression of the soil, which leads to changes in its structure and hydrological characteristics. This has caused water retention, changes in drainage channels and contamination of groundwater with toxic substances, which affects plant and animal life.

Table 1

Results of expert evaluations when using the ranking method

Parameter	Expert evaluation								AR*	WC**
	1	2	3	4	5	6	7	8		
Biodiversity losses as a result of military operations	10	10	10	10	9	10	8	9	9.50	0.100
Biodiversity losses due to the introduction of new species or the spread of invasive species	6	7	7	7	8	8	9	6	7.25	0.056
Biodiversity losses due to deforestation	10	10	10	10	9	9	10	10	9.75	0.104
Harmful substances emissions impact as a result of military operations	8	8	9	8	7	9	8	7	8.00	0.083
Air pollution impact on erosion	7	6	5	6	8	7	6	7	6.50	0.067
Air pollution impact on the biodiversity losses	5	7	6	4	7	6	7	7	6.13	0.063
Risk of water pollution as a result of military operations	7	8	9	7	8	7	8	9	7.88	0.081
Water pollution impact on soil erosion	8	9	7	8	9	8	7	8	8.00	0.083
Water pollution impact on the biodiversity losses	6	7	7	6	7	8	6	7	6.75	0.070
Forest cover losses due to fires and military operations	10	8	7	8	10	9	10	8	8.75	0.090
Deforestation impact on soil destruction and erosion	7	8	6	7	8	6	7	8	7.13	0.073
Global climate impact due to forest cover losses	6	7	8	6	7	8	6	7	6.88	0.071
Impact of destruction of natural objects on soil and water	8	9	10	7	8	7	8	8	8.13	0.084
Air pollution impact on destruction and erosion	8	6	8	7	7	6	7	7	7.00	0.072
Vegetation loss impact on erosion processes	10	9	9	8	9	9	9	9	9.00	0.093
Taking into account the weather conditions impact on the erosion dynamics	7	6	7	8	7	7	7	9	7.25	0.075

*Note: *AR – average rank; **WF – weighting cooefficient*

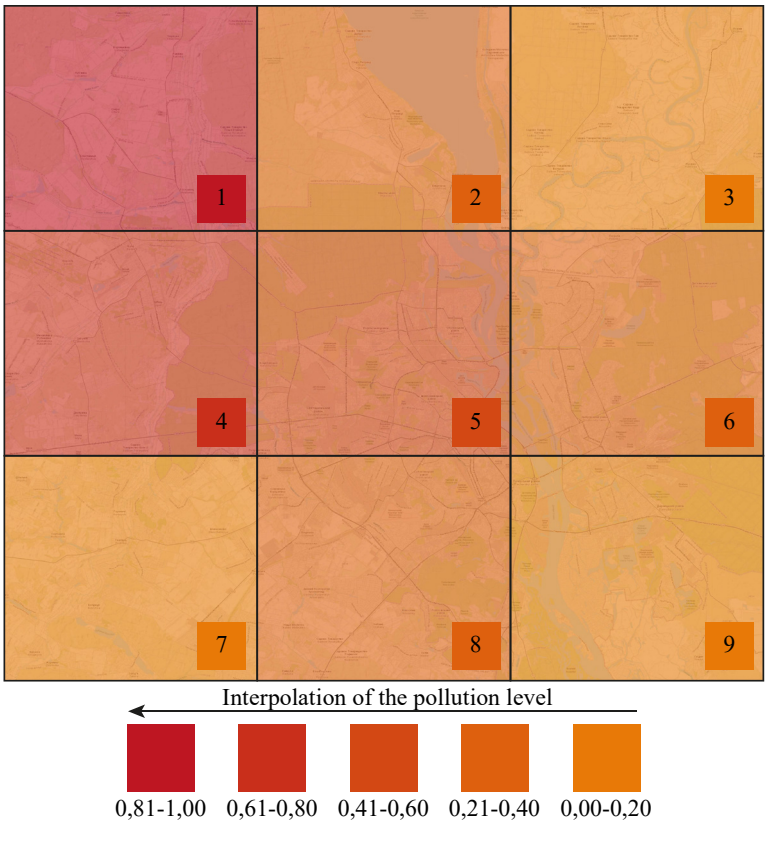

Fig. 2. Modeling of the generalized level of risk for the ecosystems of the territory

The construction of defensive military fortifications led to serious anthropogenic changes in the landscape. Cutting of soil cover, clearing of vegetation and changes in hydrological processes have created favorable conditions for erosion and soil loss.

The destruction of natural objects due to missile weapons, in turn, led to a serious disturbance of the balance of natural processes. Large explosions and shelling caused fires, destroying forests and other natural habitats. This has led to the biodiversity losses and the destruction of the habitat of numerous species of plants and animals.

Considering these factors in a GIS model, it is possible to gain a deep understanding of the impact of military actions on natural resources and to determine strategies for restoring and protecting the environment in a given area. This is an important step in ensuring sustainable development and preservation of natural heritage after military conflicts.

6. Discussion of the results of identification and assessment of risks to ecosystems that arise as a result of armed conflicts

The study identified biodiversity losses, air pollution, water pollution, deforestation, territorial changes and destruction of natural objects, erosion and soil erosion as the main risk factors for the ecosystem affected by armed conflicts, which were assessed by expert evaluation.

The evaluation by industry experts made it possible to identify the key parameters that must be taken into account when modeling the impact of armed conflicts on the ecosystem, as well as to determine their relative importance. Intuitive-logical analysis made it possible to take into account different aspects of the problem and provided an opportunity to avoid ambiguity.

The parameters were evaluated using the ranking method to determine the importance of one parameter in relation to others (Table 1). For each parameter, an average rank and weighting factor is determined, which reflects its importance in the general context of modeling.

Through a survey of experts, it was determined that the most significant impact on the change in ecosystem stability is caused by the biodiversity losses as a result of direct military actions, biodiversity losses due to deforestation, and loss of vegetation due to erosion processes. The impact of these factors was determined by the experts to be the highest, assigning a score of more than 9.0.

Biodiversity losses due to air pollution, erosion due to air pollution and biodiversity losses due to water pollution have the least significant correlation, the impact of which is estimated to be less than 6.75 points. In general, all factors have strong mutual influences.

The overall adequacy of the results is confirmed by a low consistency indicator, which indicates the reliability of the obtained results. This confirms the compliance of the obtained data with the requirements of scientific accuracy and reliability.

The obtained result of the interaction of various factors helped to develop a mathematical and graphic model for analyzing and forecasting the impact of military conflicts on ecosystems. The described parameters of the model and the system of differential equations (1) made it possible to take into account the complex interaction of various factors affecting the ecosystem.

The proposed mathematical and graphic model provides for the construction of spatial layers of pollution maps of the territory according to each criterion (Fig. 1). The resulting maps should be used as input maps of the ascending level, which, according to the weight criterion, should be combined into a composite map in GIS to demonstrate the suitability of the territory.

The model was tested on the example of the territory of the Kyiv region. With the help of the model, it is advisable to determine priorities for the preservation of ecosystems and the development of risk management strategies.

The practical application (Fig. 2) of the developed mathematical and graphic model for the district with an area of 9,000 km^2 made it possible to identify the most polluted areas of the territory in the Kyiv region.

Square 1 is the most polluted, since the military actions had a strong impact on all biotic and abiotic components of the ecosystem. At the same time, the square of plot 2, in which the Kyiv Sea is located, which has repeatedly become the object of war crimes, is not an area of heavy pollution. This is due to the fact that, in addition to water pollution factors, there was no significant destruction of other ecosystems in the studied area. Unlike square 2, square 4 had damage not only to water bodies, but also degradation of forest and soil cover. This indicates the need for comprehensive measures to restore various ecosystems in this area.

The obtained result indicates that military actions have a complex impact on various components of ecosystems, and it is important to take this fact into account when developing strategies for restoration and management of the natural environment.

In summary, the priority areas for restoring ecosystems and developing risk management strategies are the northwestern and western territories of Kyiv region. On the basis of this analysis, it is possible to develop effective measures for the restoration and protection of natural resources, as well as to determine the areas where the most urgent environmental measures are needed.

Comparing the proposed approach with existing research in the field, several key features and advantages can be identified.

Compared to the method [5], where the analysis was based mainly on the criteria of loss of resource potential, the methodology of the conducted research takes into account the hierarchical structure of the problem, providing a more detailed approach. The use of expert evaluation and a hierarchical approach to the weighting of criteria can increase the objectivity and accuracy of the results, taking into account the variety of influencing factors.

Unlike the study [6], where the geographical area was limited only to the river basin, the study takes into account more aspects of ecosystems. Using an expert approach also allows to take into account different aspects of the problem and improve the objectivity of the results.

In contrast to the study [9], which used a random forest classifier and gap-filling methods, the present study uses hierarchical analysis and expert evaluations to determine the importance of factors.

Unlike the results of works [7, 8], which focus exclusively on the destruction of natural objects or are limited by geographical boundaries, the methodology takes into account various aspects of the impact of armed conflicts and does not place a territorial emphasis on the assessment territory.

The use of hierarchical analysis and expert evaluations provides an opportunity to more precisely determine the importance of each criterion and avoid the ambiguity that can arise in the study of military conflicts.

The limitations of the conducted research are the possibility of its application only with known confirmed and recorded data of violations. The results of the study cannot be applied when combat operations are in an active phase in conditions of uncertainty and in the absence of data.

The disadvantages of using the developed model are that it requires accurate data to build the model, which can be a difficult task in a conflict zone. The model requires the processing of confirmed data, which are collected using the same methodology, as information from different sources may be incomplete or heterogeneous for different regions, which can complicate its understanding and interpretation. The disadvantage of the study is the possibility of a rather large error due to the inaccuracy of the data in the territory where hostilities are taking place or in the territory under occupation.

The developed mathematical and graphic model is distinguished by a more detailed and systematic approach to the analysis of the impact of armed conflicts on the natural environment, which makes it an effective tool for studying this issue.

The material flow method used in the study to analyze the impact of military conflicts on the ecosystem has several significant advantages. This approach allows considering the ecosystem as an interconnected complex, taking into account the transition of resources and pollution between different components. The model allows taking into account various types of pollution, resource loss and the effects of destruction, which contributes to a more complete understanding of the processes that occur in the natural environment during conflicts.

An important advantage is also the ability to predict the possible consequences of military actions and identify key factors causing changes in the ecosystem. The model allows to test different scenarios of conflicts, which makes it an effective tool for planning and decision-making in the field of nature protection. This allows effective planning and decision-making in the field of nature protection, as well as adapting strategies to reduce the negative impact on the ecosystem.

Taking into account the importance and interaction of various parameters, such as biodiversity loss, air and water pollution, deforestation, and others, allows to determine priorities and implement steps to preserve ecosystems. Developing strategies to prevent and manage the environmental consequences of war can include measures to limit the use of destructive weapons, implement effective emission control systems, and support initiatives to restore natural resources.

The obtained data are a valuable resource for making informed decisions in the field of nature protection and sustainable development.

7. Conclusions

1. It has been determined that the intensity of armed conflicts determines the scale and degree of ecosystem damage. The use of destructive weapons, such as heavy artillery and air-launched missiles, leads to the direct destruction of natural environments and their components. Also, important risk factors are the types of weapons used, including chemical and biological agents capable of large-scale, long-term environmental damage.

In the selection and study of environmental risk factors associated with military actions, the focus is on determining the factors that have the greatest potential for impact on ecosystems and natural resources. At the same time, the main emphasis is on biodiversity loss, air and water pollution, deforestation, territorial changes and destruction of natural objects, increased erosion and soil erosion.

Biodiversity loss, air and water pollution, deforestation and other factors have been found to have a significant impact on the ecosystem. Expert evaluation and ranking method revealed the importance of each factor. For example, the average rank of the parameters is determined from 1 to 10, taking into account the weighting factors. The greatest impact is seen in biodiversity loss due to direct military action and deforestation, with scores greater than 9.0, while losses due to air and water pollution are scored less than 6.75.

2. A mathematical and graphic model of material flows has been developed to assess risk and losses in ecosystems during armed conflicts. The important interrelationships of various components arising as a result of military conflicts have been analyzed. The developed model allows taking into account resource flows, pollution and losses in the ecosystem.

The parameters of the model determine the biodiversity losses, the dynamics of air pollution, water, deforestation, territorial changes and the destruction of natural objects, as well as the dynamics of erosion and soil washing. These parameters are determined by coefficients that represent the impact of various factors on the ecosystem during hostilities.

The model is based on the combination of the result of the solution of the system of differential equations, hierarchical analysis to determine the weighting factors and the application of GIS modeling.

The developed model is detailed and systematic, which makes it an effective tool for analyzing and studying the impact of armed conflicts on the natural environment. The application of methods of expert evaluation and hierarchical analysis allows obtaining objective results and detailed information about the impact of various factors.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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