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# ASSESSMENT OF THE EFFECTIVENESS OF THE CIVIL PROTECTION SYSTEM IN PREVENTING AND RESPONDING TO EMERGENCIES IN THE BORDER AREAS OF UKRAINE

*The article is devoted to the development of models for assessing the effectiveness of the civil protection system for preventing and eliminating emergencies in the border areas of Ukraine, taking into account military, natural and man-made risks, with the involvement of state structures, communities and international partners to strengthen cross-border security and cooperation*.

***Key words:*** *civil protection, border areas, emergencies*

## Problem statement

The relevance of the topic is determined by the rapid growth in the number, complexity and scale of emergencies in Ukraine, covering all spheres of life – from natural and man-made disasters to biological, social and military threats. The problem has become particularly urgent due to the latest challenges posed by climate change, deterioration of critical infrastructure, the global COVID-19 pandemic, and war. All of these factors create an extremely complex security environment in which the civil protection system is forced to operate in the face of a multidimensional threat.

The border regions of Ukraine, the territories located directly near the state border with other countries, are particularly vulnerable. It is here, at the intersection of external and internal risk factors, that numerous challenges accumulate, making it difficult to ensure an adequate level of public safety. These challenges include cross-border floods (on the Prut, Tysa, and Zakhidnyi Buh rivers), the movement of large numbers of people across the border in crisis situations, threats of environmental or radiation pollution, and the difficulty of operational coordination with foreign partners.

At the same time, the level of institutional preparedness to respond in the border areas remains limited: there is an insufficient number of SES forces and means, poor integration between services, lack of funding for preventive measures, and problems with public access to modern warning systems and shelters. The events of recent years – the catastrophic floods of 2020 in the western regions, large-scale forest fires in Polissia, explosions at ammunition depots, and the extraordinary humanitarian crisis caused by the full-scale war – once again confirm the need to develop effective, scientifically based approaches to disaster prevention and response in border regions, taking into account cross-border specifics and the international context.

## Analysis of recent studies and publications

The problem of preventing and eliminating emergencies in border areas is considered in the works of both domestic and foreign researchers. Particular attention is paid to the issues of cross-border security, integrated response and community resilience to crises.

Among Ukrainian studies, it is worth highlighting the works of Goncharenko Yu., Farahov O., Rashkevych N., Proshchyna I., Berezyuk V. and Tokarchuk M. [1-4]. Goncharenko Yu. and Farahov O. investigate the effectiveness of using mathematical models in ensuring the safety of critical infrastructure facilities. Rashkevych N. is researching technological schemes for the passage of persons, vehicles and cargo across the state border. Proshchyn I., based on the analysis of international experience in preventing and eliminating the consequences of natural emergencies, has developed a technology that can be adapted for the border regions of Ukraine. Berezyuk V. and Tokarchuk M. investigate the problems of interaction between integrated border management entities and offer recommendations for assessing and predicting threats at borders with EU countries.

In the international context, researchers from the EU, NATO, and the UN have made a significant contribution to the topic [5, 6]. In particular, they analyze models of cross-border cooperation, early warning systems, experience with refugees, and the use of GIS technologies, drones, and satellite monitoring in operational response.

At the same time, most existing works consider the problem either from the point of view of military security or certain types of disasters (e.g., man-made or natural), without paying due attention to a comprehensive approach to border areas as a specific risk zone.

Thus, there is a need to summarize the existing developments and formulate a quantitative assessment of the effectiveness of the civil protection system focused

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on the border areas of Ukraine, which was the purpose of this study.

## Statement of the purpose of the article

The purpose of the study is to develop scientifically based models for assessing the effectiveness of the civil protection system for preventing and eliminating emergencies in the border regions of Ukraine.

Therefore, the main objectives of the study will be:

- to analyze the theoretical foundations of emergency classification, as well as the legislative framework and specifics of border areas;
- to assess the current state of the emergency response system and the effectiveness of the authorities' actions, taking into account the vulnerability of border areas;
- to study international experience in emergency management and cross-border cooperation;
- to develop models for assessing the effectiveness of actions of public authorities, local communities and rescue services to prevent and respond to disasters.

## Outline of the main research material

The issue of preventing and responding to emergencies in the border regions of Ukraine is extremely relevant in the context of current security challenges [7-9]. The geographical location of border areas makes them highly vulnerable to external threats, including military operations, cross-border accidents, migration crises, illegal movement of hazardous substances, and natural disasters that do not recognize state borders. The complexity of rapid emergency response in such circumstances requires a systematic approach that includes legal regulation, threat classification, consideration of the specifics of the territories, and a thorough risk analysis.

As a result of studying the theoretical foundations, it has been established that emergencies are classified by the nature of their origin, scale, level of threat and social consequences [10, 11]. The border areas are characterized by a complex of risks that have both natural and man-made, social and military origin. The specifics of geographical location, socio-economic development, critical infrastructure and cross-border interaction significantly affect the probability of disasters.

The analysis of the current legal framework shows that there is a legal framework that regulates the activities of the authorities in preventing and responding to emergencies, but its effective implementation requires strengthening interagency coordination and adaptation to modern threats. The review shows that the emergency response system in Ukraine is a complex multi-level mechanism that covers the national, regional and local levels. This system is of particular importance in the border regions where there is an increased risk of disasters of both natural and man-made, social or military nature. Given the current challenges – the aggression of the Russian Federation, migration flows, dangers associated with the movement of explosive objects, smuggling, etc. - the civil protection system should be adapted to a flexible real-time response [12].

The system is organized on a unified basis within the state. The national level is represented by the State Emergency Service of Ukraine, which coordinates the work of regional units, including regional departments [13]. At the local level, in communities, there are operational rescue services, fire and rescue units, and voluntary fire brigades.

Table 1

Key levels of disaster response management

| Level | Structure | Responsibilities |
|---|---|---|
| National | State Emergency Service of Ukraine | Legislative coordination, strategic management |
| Regional | Main departments of the SES in the regions | Tactical management, coordination with regional military administrations |
| Local | Fire and rescue units, teams, and volunteer groups | On-site response, evacuation, first aid |

**The material and technical base and its problems.**

Despite the updated legislative framework (Code of Civil Protection of Ukraine, 2013), the system faces problems [14]. Much of the equipment, especially in rural border areas, is outdated, with the average age of fire trucks exceeding 20 years. This leads to a decrease in efficiency [6]. The mathematical model for estimating response time will be as follows:

$$T_r = \frac{D}{V} + t_n \quad (1)$$

where:

$T_r$ – response time; $D$ – average distance to the disaster site; $V$ – average movement speed of the unit; $t_n$ – preparation time for departure.

**Statistical analysis of the effectiveness of response in border regions.**

To assess the level of preparedness and quality of response in border regions, it is advisable to use the

Comprehensive Response Effectiveness Index ($I_{CRE}$), which includes the following variables [9, 12]:

$T_c$ – average time for the first rescue unit to arrive at the scene of an emergency (in minutes);

$C_p$ –resource availability ratio (as a percentage of the regulatory requirement);

$R_o$ – the level of organisational training of personnel (based on the training and exercises conducted, in points);

$A_c$ – average accident rate per capita (number of accidents per 100,000 people per year).

Dependence of the calculation of the index:

$$I_{CRE} = \frac{(100 - T_c) \cdot C_p \cdot R_o}{A_c \cdot 100} \quad (2)$$

To quantify the effectiveness of emergency response, a formalised mathematical model can be applied that takes into account various factors, such as response time [15], the amount of resources involved, the level of coordination between services and public awareness. According to the study, such a model allows predicting possible losses and assessing the system's readiness to respond to emergencies.

Defining model parameters

Let's define the main variables:

$T_r$ – response time (minutes) – the time from the moment the emergency is detected until the first responders arrive;

$R$ – the amount of resources involved (conventional units: equipment, personnel, finance);

$C$ – coordination coefficient between services (from 0 to 1), where 1 is perfect interaction;

$I$ – public awareness index (from 0 to 1), where 1 means full and timely awareness;

$D_p$ – losses avoided due to timely response (UAH);

$D_f$ – actual losses (UAH);

$E$ – an integral indicator of response effectiveness (from 0 to 1).

The mathematical model will look like this:

$$E = \left(\frac{D_p}{D_p + D_f}\right) \cdot \left(\frac{C + I}{2}\right) \cdot \left(\frac{R}{R + \alpha}\right) \cdot e^{-\beta T_r} \quad (3)$$

where:

$\alpha$ – resource factor (if resources are abundant, the impact increases more slowly);

$\beta$ – the coefficient of efficiency decline over time (depends on the type of disaster; for example, it is higher for a fire).

The developed model allows for the assessment of response scenarios, identification of bottlenecks (delays, lack of awareness, etc.), and optimisation of resource allocation to improve preparedness.

**Man-made accidents (large-scale fires, explosions).**

To quantify the effectiveness of the response, we will use a modified integral model:

$$E_{tech} = \left(\frac{N_e}{N_t}\right) \cdot \left(\frac{C + I}{2}\right) \cdot \left(\frac{R}{R + \alpha}\right) \cdot e^{-\beta T_r} \quad (4)$$

**де:**

$N_e$ – number of successfully evacuated people;

$N_t$ – total number of people in the affected area;

$C$ – coordination coefficient between services (0-1);

$I$ – level of public awareness (0-1);

$R$ – amount of resources attracted (units);

$T_r$ – response time (min);

$\alpha$, $\beta$ – saturation and delay coefficients (chosen empirically).

The suggested mathematical model allows to quantify the effectiveness of the response of authorities and civil protection services to man-made emergencies by integrating the main indicators – response time, public awareness, level of coordination and the amount of resources involved.

**Social crises: COVID-19 pandemic, mass migration (2020-2022).**

Social crises have become a real challenge for the civil protection system, particularly in the border regions of Ukraine. A striking example is the COVID-19 pandemic, which in 2020 revealed the need for rapid interagency coordination between the Ministry of Health, the State Emergency Service, the police, regional state administrations, and border guards. An emergency regime was introduced without the introduction of a state of emergency, which preserved civil liberties but also required effective public information, border control, and quarantine restrictions.

The main difficulties at the initial stage were: lack of personal protective equipment, insufficient equipment in hospitals (including AVLs), logistical difficulties at checkpoints, and restrictions on international traffic. A positive example is the widespread use of SMS messaging, the launch of mobile applications for self-diagnosis, and the introduction of testing points at the borders.

The migration crisis of 2022 also demonstrated the effectiveness of solidarity actions by communities and local authorities: hundreds of thousands of internally displaced persons (IDPs) were received by the border regions of Lviv, Zakarpattia, and Chernivtsi. Many processes showed signs of self-organization: schools were turned into shelters, volunteers provided food, psychological assistance and logistics.

A mathematical model for assessing the effectiveness of response in social crises.

The following formula can be used to estimate the effectiveness of the response E:

$$E = (I + C + R) \cdot e^{-\frac{T}{10}} \quad (5)$$

where:

$T$ – time until the response is fully deployed (in hours or days);

$I \in [0;1]$ – level of public awareness (e.g. via SMS, media);

$C \in [0;1]$ – level of coordination between agencies (SES, Ministry of Health, local authorities);

$R \in [0;1]$ – availability of necessary resources (medicines, transport, beds);

$e^{-\frac{T}{10}}$ – an exponential decrease in efficiency with an increase in response time.

The mathematical model for assessing the effectiveness of social crisis response allows quantifying the ability of the civil protection system to adapt to difficult conditions involving various factors: response time, level of information, availability of resources, organizational mobility and interagency cooperation.

**Military emergencies: response assessment and analysis model.**

The major challenge to the civil protection system was the events when Ukraine suffered massive missile attacks, especially in the border regions (Kharkiv, Chernihiv, Sumy, and Mykolaiv oblasts). In the fall of 2022, the enemy began to target the energy infrastructure – more than 40% of electricity generation and transmission facilities were damaged [8, 16]. In response, the state implemented operational innovative solutions – a network of "Points of Unbreakability" equipped with generators, heat, and communication facilities was created. By the end of the winter of 2022-2023, more than 5,000 such points were operating.

The efficiency of the air raid warning system plays a critical role in population protection – it operates at an average interval of 1-2 minutes after a threat is detected. But the problem of the state of protective shelters remained critical. As of 2022, only 11% of them were fully ready, but by the end of 2024, thanks to investments (over UAH 10 billion), their share had increased to about 50%.

A generalized mathematical model of response can be used to quantify the effectiveness of the authorities' actions:

$$E = \alpha R + \beta C + \gamma I - \delta D \quad (6)$$

where:

$E$ – response efficiency (integral indicator);

$R$ – level of resource availability (share of ready-made shelters, availability of generators, etc.);

$C$ – coordination speed (the average time between the attack and the opening of the Invincibility Zone);

$I$ – quality of public notification (access to sirens, mobile applications);

$D$ – delay in decision-making (e.g., delayed response to a threat);

$\alpha, \beta, \gamma, \delta$ – coefficients determined by experts based on statistics and analysis of actions.

In real-world conditions, the values of these parameters can be obtained from surveys, State Emergency Service and Cabinet of Ministers reports, which allows the model to be adapted to a particular region.

The suggested mathematical model is a universal tool for quantitative analysis of the effectiveness of response to military emergencies, in particular in border regions. It allows for the integration of resource provision, coordination speed, public awareness, and decision-making delays.

**Cross-border efficiency of emergency response: analysis and mathematical model.**

Ukraine traditionally adheres to the principles of openness and cooperation in cross-border emergency response. In cases where the possible consequences of an emergency go beyond the borders of the state, the competent authorities timely inform neighbors and international organizations [17]. For example, during the large-scale fire at the Vasylkiv oil depot in 2015, Ukraine received offers of assistance from European countries. Even though the situation was stabilized on its own, the openness to cooperation emphasizes the reliability of the system. Similarly, in 2016, when there was a threat of pollution of the Dnipro River due to an accident at a sewer in Kyiv, the possible consequences downstream as far as Kherson were promptly reported.

Coordination with the EU Civil Protection Mechanism has become especially important [10]. Since 2022, Ukraine has repeatedly applied to the Mechanism and, as a result, the country has received more than 154 thousand tons of aid (including equipment, generators, and CBRN protection). In 2023, Ukraine became a full member of this European system, which opened up opportunities for mutual support in the future.

To formalize cross-border response effectiveness, it is advisable to use a mathematical model for assessing integrated capabilities [18]:

$$E_t = \mu L + \nu M + \rho A - \sigma D \quad (7)$$

where:

$E_t$ – cross-border response efficiency index;

$L$ – level of local response (speed of action, availability of local resources);

$M$ – m degree of international assistance ( amount, quality and efficiency of resources provided);

$A$ – activity in international networks (for example, participation in EU mechanisms);

$D$ – delays or shortcomings in coordination (internal bureaucracy, inconsistency);

$\mu, \nu, \rho, \sigma$ – coefficients that may vary depending on the situation.

The model allows for an objective comparison of the cross-border capacities of regions and an assessment of the dynamics of international integration in the field of civil protection. It allows to quantify the level of Ukraine's cooperation with international partners in emergency situations and identify weaknesses that need to be strengthened.

**Conducting an experiment.**

In order to analyze the effectiveness of the emergency response system in the border regions of Ukraine, an experiment was conducted, the scenario of which modeled a man-made emergency. The experiment was based on a conditional event – a leak of a chemically hazardous substance at a railway junction located near the Ukrainian-Romanian border. This type of incident was chosen due to its high probability of occurrence in real life, the potential scale of the consequences, and the cross-border nature of the threats, which may require international coordination.

The scenario assumed that an ammonia tanker accident resulted in a depressurization release of a toxic substance spreading towards settlements on the Ukrainian side and potentially in the Romanian border area. Particular attention was paid to modeling the speed of the pollution cloud spreading, taking into account meteorological conditions, terrain and building density.

As part of the experiment, two scenarios were compared: the baseline scenario (without implemented measures) and the scenario with the criteria for assessing the effectiveness of the civil protection system. Below are the results of the comparison of key indicators.

Table 2

Experimental results

| Indicators | Basic scenario | Scenario based on the criteria for assessing the efficiency of the civil protection system |
|---|---|---|
| Response time of SES units | 45 minutes | 20 minutes |
| Evacuation time for the population | over 2 hours | up to 40 minutes |
| Conditional number of victims | 35 people | 8 people |
| Involvement of a cross-border partner | not available | coordinated |
| Access to monitoring data sources | limited | centralised via the platform |
| Coordination of services | low level of interaction | coordinated management by the headquarters |

The conducted experimental study confirmed the feasibility and effectiveness of the proposed mathematical models in the context of disaster management in border regions. The analysis of the scenarios demonstrated a significant reduction in response time, increased efficiency of evacuation measures, and a reduction in the number of conditional victims. Digital solutions, prior training of personnel and coordinated interagency cooperation played a significant role in this. Thus, the results of the experiment serve as a basis for improving existing approaches to risk management in border regions.

**Conclusions from the present study and perspectives for further research in this area.**

The study carried out a comprehensive analysis of the problems of preventing and eliminating emergencies in the border areas of Ukraine. The work covered all major types of emergencies – natural, man-made, socio-biological and military – and revealed the increased vulnerability of border areas due to geographical location, cross-border risks and infrastructural heterogeneity.

The scientific novelty of the study lies in the combination of strategic analysis of the current situation with specific practical and interdisciplinary solutions that take into account the experience of a full-scale war and European integration processes. The practical value of the work lies in its applied nature, which can be used to update civil protection policy, regional planning and international cooperation.

Ensuring the security of Ukraine’s border regions is a realistic and achievable task, provided that the efforts of government agencies, professional services, local communities and international partners are combined. Implementation of the proposed solutions will help reduce risks, preserve the lives and health of the population, and ensure the stability and development of border areas as an important component of national security.

Prospects for further research lie in the development of an information and analytical system of civil protection. Such a system will allow identifying the strengths and weaknesses of all participants of the civil protection system for disaster prevention and response in an automated format and will formulate appropriate proposals for them.

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## ОЦІНКА ЕФЕКТИВНОСТІ СИСТЕМИ ЦИВІЛЬНОГО ЗАХИСТУ З ПОПЕРЕДЖЕННЯ ТА ЛІКВІДАЦІЇ НАСЛІДКІВ НАДЗВИЧАЙНИХ СИТУАЦІЙ У ПРИКОРДОННИХ РАЙОНАХ УКРАЇНИ

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*У науковій статті розглядаються проблеми та можливості удосконалення системи цивільного захисту в контексті специфіки прикордонних регіонів України. Актуальність дослідження зумовлена загостренням безпекової ситуації через зростання кількості надзвичайних ситуацій (НС) природного, техногенного, соціального й воєнного характеру. Прикордонні райони особливо вразливі до таких загроз через географічне положення, наявність об'єктів критичної інфраструктури, транскордонну міграцію та складність координації з іноземними партнерами. У роботі висвітлено наявні недоліки в організації системи цивільного захисту: застаріла матеріально-технічна база, обмеженість людських ресурсів, слабка взаємодія між структурами, дефіцит фінансування та недостатня готовність до реагування на комплексні ризики.*

*Метою дослідження є розробка науково обґрунтованих моделей оцінки ефективності системи цивільного захисту з попередження і ліквідації наслідків надзвичайних ситуацій у прикордонних регіонах України. Запропоновано системний підхід до аналізу взаємозв'язаних чинників, що впливають на ефективність реагування на НС, з урахуванням нормативно-правової бази, міжнародного досвіду та локальних особливостей. Визначено, що для прикордонних територій характерні транскордонні повені, пожежі, вибухи, міграційні кризи, загрози екологічного забруднення, а також вплив воєнних дій.*

*У роботі представлено модель оцінки часу реагування та індекс комплексної ефективності реагування, який враховує час прибуття підрозділу, рівень ресурсного забезпечення, підготовку персоналу та аварійність. Наведено результати статистичного аналізу діяльності рятувальних служб у прикордонних районах та запропоновано рекомендації щодо удосконалення системи: підвищення міжвідомчої координації, модернізація техніки, впровадження інноваційних технологій, розширення транскордонного співробітництва.*

*Проведене експериментальне дослідження підтвердило доцільність та результативність запропонованих математичних моделей у контексті попередження і ліквідації НС у прикордонних регіонах. Аналіз змодельованих сценаріїв продемонстрував суттєве зменшення часу реагування, підвищення ефективності евакуаційних заходів, а також зниження кількості постраждалих. Значну роль у цьому зіграли цифрові рішення, попередня підготовка персоналу та скоординована міжвідомча взаємодія. Результати*

*дослідження підтверджують необхідність посилення міжвідомчої взаємодії, модернізації матеріально-технічної бази та впровадження сучасних технологій моніторингу й оповіщення.*

*Одержані результати мають як наукове, так і практичне значення. Вони можуть бути використані для розробки програм зміцнення системи цивільного захисту на місцевому та державному рівнях, а також для оцінювання ефективності заходів у сфері запобігання та ліквідації наслідків надзвичайних ситуацій у прикордонних районах України.*

***Ключові слова:*** *цивільний захист, прикордонні райони, надзвичайні ситуації*