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EARLY-WARNING SYSTEMS IN CROSS-BORDER REGIONS: TECHNOLOGIES, ACTORS, EFFICIENCY

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Abstract
In the context of increasing instability in cross-border regions, the study and improvement of early warning systems (Early Warning Systems, EWS) is becoming especially relevant. Modern threats, including cross-border conflicts, natural disasters, epidemics and migration crises, go beyond national borders, which requires collective efforts and a coordinated response. The purpose of this study is a comprehensive analysis of the architecture, technologies and actors of EWS in a cross-border context. The methodological base includes case analysis, comparative-historical and normative-analytical approaches, which made it possible to classify technologies (GIS, remote sensing, IoT, AI), identify key forms of institutional interaction (national bodies, international organizations, NGOs) and determine the performance indicators of systems. Particular attention is paid to the problems of institutional trust, data incompatibility and legal barriers that impede effective coordination. The practical significance of the study lies in the formulation of recommendations for the standardization of technological solutions, strengthening interstate cooperation and increasing the adaptability of early warning systems to multi-level cross-border risks. The results obtained contribute to a deeper understanding of the role of EWS as a key instrument for sustainable security and development.

Keywords: Early warning system (EWS); transboundary risks; coordination; geoinformation technologies; institutional actors; digitalization; efficiency; sustainable development; crisis management; international cooperation.

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Introduction

In recent decades, there has been an increase in the number and intensity of transboundary threats, which by their nature are not limited to national borders. This applies to both natural disasters (earthquakes, floods, landslides, climate change) and anthropogenic risks - transboundary conflicts, epidemics, technological accidents, migration waves and environmental disasters. A classic example is the COVID-19 pandemic, which, in the context of insufficient international coordination, has demonstrated the critical vulnerability of the global threat response system.

Transboundary regions are particularly susceptible to these risks due to their high degree of dependence on resources, infrastructure interconnections and political and administrative heterogeneity. Modern challenges require states not only to respond promptly, but also to proactively manage crises based on forecasts and monitoring. In this regard, the importance of early warning systems (Early Warning Systems, EWS) as a key element of the architecture of sustainable development and collective security is increasing. However, in a transboundary context, the implementation of effective EWS is complicated by a number of factors: differences in technical support between countries, lack of trust in information exchange, incompatibility of databases, and insufficient legal regulation of cross-border response procedures. In the context of interstate asymmetry and fragmentation of institutions, a comprehensive scientific approach to the analysis of EWS as a tool for multi-level risk management is needed. Modern scientific approaches emphasize the need for an interdisciplinary analysis - based on risk management models (UNDRR, OECD), geoinformation technologies, international law and institutional theory of cooperation. For example, the United Nations in the "Sendai Framework for Disaster Risk Reduction 2015-2030" emphasizes the importance of EWS for sustainable development and reducing the vulnerability of transboundary communities.[1]

The purpose of this article is a comprehensive scientific understanding and system analysis of early warning systems (Early Warning Systems, EWS) in

[1] United Nations Office for Disaster Risk Reduction (UNDRR). Sendai Framework for Disaster Risk Reduction 2015–2030. Geneva: UNDRR, 2015.

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transboundary regions with an emphasis on their architecture, applied technologies, key actors and coordination mechanisms. The study aims to identify the factors that determine the effectiveness of EWS in the context of transboundary risks, as well as to develop practical recommendations for strengthening interstate cooperation, standardization of technical solutions and increasing trust in the field of information exchange. The article pays special attention to the institutional sustainability, digital interoperability and predictive potential of EWS as an integral component of the collective security and sustainable development system.

An Early Warning System (EWS) is a set of institutional, technical and information mechanisms aimed at early detection of threats, timely notification of stakeholders and initiation of response measures to minimize damage to population, infrastructure and the environment. According to the definition adopted by the United Nations, an EWS includes four interrelated elements: (1) risk analysis; (2) monitoring and forecasting; (3) dissemination of warning information; (4) institutional preparedness for action.[2]

The key difference between an effective EWS is its proactive rather than reactive nature: the system's task is not simply to record the fact of an event, but to provide a warning with a sufficient time interval to develop a management decision. In transboundary contexts, the importance of EWS increases, since threats often affect several states at once, and a coordinated system of observation, forecasting and response is needed. The first forms of early warning can be traced back to ancient societies, where watchtowers, messengers and signaling systems were used to signal impending threats. The modern understanding of EWS began to take shape in the 20th century, especially in the context of counteracting natural disasters (tsunamis, hurricanes, volcanic eruptions). After the 1980s, under the influence of globalization and climate change, the concept began to expand, covering biological (epidemics), man-made and socio-political risks.[3]

A milestone was the adoption of the Hyogo Framework for Action (2005–2015) in 2005, which enshrined the need to create "people-centered, timely, and multi-

[2] UNDRR. Global Survey of Early Warning Systems. United Nations, 2006.
[3] Glantz, M. H. Climate Affairs: A Primer. Island Press, 2003.

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layered early warning systems." In 2015, it was replaced by the Sendai Framework for Disaster Risk Reduction (2015–2030), where EWS took center stage as a tool for preventing disasters and strengthening the resilience of states.[4]

In trans-border regions, early warning systems play an important role in strengthening joint security and reducing the risk of escalating crises. Such regions are usually characterized by a high degree of environmental and social interdependence (rivers, glaciers, migration flows, trade routes). The inability of one party to respond to a threat in a timely manner can cause cascading consequences in neighboring states.[5]

For example, in Central Asia, glacial disasters in one country can lead to flooding of settlements and destruction of infrastructure in other countries. Effective functioning of EWS helps reduce the level of mistrust between countries and create a platform for dialogue and cooperation in the context of limited sovereignty and competition for resources.

Several methodological approaches are used in the scientific and practical environment to analyze the effectiveness of EWS. One of them is the normative approach of the Organization for Economic Cooperation and Development (OECD), according to which the effectiveness of systems is assessed according to the following criteria: timeliness, accuracy, coverage, institutional readiness and sustainability.[6]

Another approach is proposed by the United Nations Office for Disaster Risk Reduction (UNDRR) and is based on the End-to-End Warning System model, which emphasizes the need for a full management cycle - from risk assessment to response measures. Significant attention is also paid to the participation of local communities, data transparency and adaptability of systems to new types of threats.[7]

It is impossible to imagine modern early warning systems (EWS) without a technological component, which is of key importance in the context of

[4] UNDRR. Sendai Framework for Disaster Risk Reduction 2015–2030. Geneva: United Nations, 2015.

[5] Dabelko, G. D., et al. Environmental Security: Approaches and Issues. Johns Hopkins University Press, 2003.
[6] OECD. Review of Risk Management Policies: Future Global Shocks. Paris: OECD Publishing, 2011.
[7] UNDRR. Words into Action Guidelines: National Disaster Risk Assessment. Geneva: United Nations, 2017.

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transboundary risks. The evolution of EWS is closely linked to the development of digital technologies, including satellite remote sensing, geographic information systems (GIS), Internet of Things (IoT) sensor networks, automatic monitoring systems, as well as artificial intelligence algorithms and Big Data processing. These tools allow not only to record current environmental parameters, but also to build predictive models that warn of possible catastrophic scenarios long before they occur. It is especially important that with proper architecture, the technological infrastructure can be adapted to the conditions of different regions, including transboundary watersheds, mountain glaciers, and border areas with high population density. The digitalization of EWS has ensured the transition from disparate and reactive systems to integrated platforms operating in real time. Central to this transformation are geographic information systems that enable risk visualization, spatial data management, and modeling of potential impact zones. In a transboundary context, such systems become a tool for collective analysis and a basis for negotiations between countries. Satellite monitoring, such as that used by the Copernicus (EU), SERVIR (NASA and USAID), or Sentinel programs, continuously collects information on weather anomalies, temperature fluctuations, glacial melting, and other risk indicators. These data, if openly accessible and interoperable, serve as the basis for joint decision-making and coordinated response. Artificial intelligence algorithms that are trained on historical data to predict recurring patterns of crisis events have significant potential to improve the accuracy and speed of EWS. For example, neural network models are used to predict floods, seismic activity, and the spread of forest fires. Big Data technologies make it possible to integrate diverse data streams – from climate models to water station readings, as well as signals from the population received via mobile platforms and crowdsourcing.[8]

However, despite technological advances, the cross-border nature of threats exacerbates the problem of interoperability of digital solutions. In some cases, different states use incompatible data transfer protocols, closed monitoring

[8] WMO. Big Data Guidelines for Disaster Early Warning Systems. Geneva: World Meteorological Organization, 2020.

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platforms, and restrict access to critical information. This reduces the effectiveness of joint responses and increases the risk of misunderstanding. In addition, the problem of cybersecurity remains, especially in conditions where sensor and satellite systems become the object of geopolitical rivalry.

An analysis of international practices allows us to highlight a number of successful examples of technological cooperation. For example, the Copernicus Emergency Management Service system within the European Union provides timely maps and analytical reports on risks for participating countries, including border regions. In Central Asia, there are initiatives supported by organizations such as the Almaty Disaster Prevention Center (ADPC), which are developing regional platforms for collecting and disseminating information on floods, mudflows, and glacial threats. However, unlike the EU, institutional and technological integration in this region is still fragmented. Overall, the analysis shows that the technical component of EWS in a cross-border environment requires not only innovative solutions, but also institutionalized digital diplomacy, which involves the creation of common standards, open data exchange protocols, and joint monitoring centers. Only with such mechanisms in place will technologies be able to realize their potential within the framework of a sustainable and collective early warning system.

The functioning of early warning systems in transboundary regions requires not only a technological base, but also a clearly structured architecture of institutional interaction. Unlike domestic EWS, where the main role is played by national ministries and agencies, transboundary warning mechanisms involve a wide range of actors: national authorities, regional organizations, international institutions, research centers and non-governmental organizations. It is their coordinated activities that form the basis for the efficiency, reliability and political legitimacy of the warning system. At the state level, the main role is played by civil protection structures (e.g. the Ministry of Emergency Situations), the ministries of defense, ecology, health and national hydrometeorological services, which ensure the collection and transmission of data, decision-making and warning of the population. However, in the context of transboundary threats, coordination between these bodies can be limited by differences in protocols, legal norms and the level of technical equipment. In addition, the lack of trust

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between countries often hinders the full exchange of information and joint response.[9]

Non-governmental organizations and scientific institutions are of particular importance in the EWS structure. They act as intermediaries between states and the population, conduct independent monitoring, ensure scientific verification of data, and implement innovative solutions. For example, institutions such as the International Institute for Applied Systems Analysis (IIASA) or the Red Cross Climate Centre are actively developing forecasting models and local warning methods in border areas.

Models of interaction between actors vary from formal interstate agreements to flexible network platforms. Mechanisms that ensure information compatibility, such as standardized data exchange protocols, interdepartmental training, and cross-border simulations of crisis scenarios, are considered the most effective. However, the actual implementation of such models often faces barriers: differences in legal systems, lack of trust, limited funding, and technical incompatibility of information platforms. One of the most pressing challenges remains the issue of sovereignty: states are often reluctant to disclose potentially sensitive information (e.g. on military infrastructure, water reserves, critical risks) even in the context of cross-border cooperation. This requires building trust at the institutional level, which is only possible with strong agreements that provide mutual guarantees and equal access to information.[10]

Assessing the effectiveness of early warning systems (EWS) in cross-border contexts requires a comprehensive approach combining technical, institutional and behavioural parameters. The key principle here is not only the timeliness of response, but also the quality of interstate coordination, the degree of trust between participants, openness of data and the adaptability of the system to changing risks.

[9] Boin, A., & Rhinard, M. (2008). "Managing transboundary crises: What role for the EU?" International Studies Review, 10(1), 1–26.
[10] Zwitter, A. (2012). "Big Data and International Law: The Good, the Bad and the Ugly." European Journal of International Law, 23(3), 707–736.

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According to UNDRR and OECD recommendations, the effectiveness of EWS is measured by four main criteria: (1) the system's response time from the moment a threat is identified to the start of action; (2) the ability for interstate interaction; (3) the availability, openness and interoperability of data; (4) the level of integration of predictive analytical algorithms into the system(1). These parameters are especially important in conditions of cross-border instability, where a delay in signal transmission or limited access to information can lead to cascading consequences in neighbouring countries.

The practical application of these criteria is demonstrated in a number of cases. In Central Asia, where a significant portion of water resources is formed in the mountains and moves through several countries, threats associated with glacier melting and glacial lake outbursts require early monitoring and coordination. For example, incidents on the Abrakhimov Glacier (Kyrgyzstan, 2021) and in the Ingichka region (Uzbekistan, 2022) showed that the consequences of disasters were significantly reduced with the presence of an automatic monitoring system and cross-border information exchange. However, despite improvements, the problem of disunity in sensor systems, differences in data transmission formats, and a lack of joint training between countries in the region remains.[11] Similarly, the experience of the Danube Basin in Europe demonstrates a high degree of integration of transboundary early warning. Coordination is achieved through the Danube Flood Risk Management Plan, which includes a common hydrological data exchange platform, transboundary areas of responsibility and regular joint exercises. A high degree of institutional coherence helped to minimise human and economic losses during the floods of 2010 and 2014.

To systematize the results of the assessment of the effectiveness of cross-border EWS, the SWOT analysis method is applied. Strengths (S) include the existence of international platforms, technical progress in the field of satellite monitoring and growing awareness of the importance of joint response. Weaknesses (W) include fragmented regulatory frameworks, lack of long-term funding, incompatibility of IT infrastructure and lack of trust. Opportunities (O) are related to digital transformation, development of AI, and increased cooperation through

[11] UNEP. Assessment of Glacier Monitoring Systems in Central Asia. Nairobi: UNEP, 2021.

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regional initiatives. Threats (T) include increased geopolitical tensions, cyber risks and increased isolationism during global crises.[12]

Based on the conducted analysis, it can be argued that the effectiveness of early warning systems (EWS) in cross-border regions is determined not so much by the level of technological development as by the degree of institutional compatibility, the presence of trust and mechanisms of interstate cooperation. Despite the availability of numerous technical solutions and international standards, the implementation of fully functioning cross-border systems remains difficult due to regulatory fragmentation, differences in the level of digitalization and limited political will.

Firstly, the most important task is the standardization of technological solutions in the field of monitoring and warning. This involves the development of uniform data transfer formats, response protocols and technical regulations, especially in parts related to sensor systems, satellite platforms and big data analysis algorithms. The EU experience shows that it is technical interoperability that can form the basis for sustainable cross-border cooperation.Secondly, it is necessary to strengthen the mechanisms of institutional trust between states. This is possible through the signing of bilateral and multilateral agreements on mandatory and timely data exchange, the creation of joint monitoring centers, and the inclusion of transparency elements (for example, the participation of scientific institutes and NGOs in independent data audits). Such measures help reduce geopolitical tensions and strengthen the culture of preventive interaction.

EWS in transboundary regions is not only a warning tool, but also a key element of the architecture of sustainable peace. Such systems perform not only a technical function, but also a socio-political one: they become platforms for dialogue, platforms for peaceful cooperation and indicators of the maturity of interstate relations. In this context, the concept of “prevention as diplomacy” is of particular importance, in which technical cooperation forms the basis for de-escalation and trust between countries.

[12] OECD. Strategic Crisis Management and International Cooperation. Paris: OECD Publishing, 2022.

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