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Ensembles of Hazardous Hydrometeorological Phenomena: Legal and Regulatory Aspects, Terminology and Classification (Review)

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Abstract
Purpose. The paper is devoted to the analysis of the current state of research and achievements in the field of natural hazards and hydrometeorological phenomena and their ensembles (multi-hazards) from works published in specialized international and Russian scientific journals and monographs.
Methods and Results. Normative legal documents regulating the terminology in the field of hazardous and multi-hazardous natural and hydrometeorological phenomena, differences in the adopted terminology; existing classifications of multi-hazardous hydrometeorological phenomena, methods for performing such classifications, possible prospects for use, hazard threshold values and methods for their calculation; studies of multi-hazardous hydrometeorological phenomena based on the results of field observations and global reanalysis are considered in this article. Special attention is paid to the current stage of development of natural and exact sciences in Russia, contributing to the prevention and forecasting of dangerous hydrometeorological phenomena.
Conclusions. The increase in the recurrence of dangerous phenomena since the beginning of the XXI century, along with the development of information technologies, such as the creation of electronic databases, geoinformation systems, the use of satellite information and mathematical modeling made it possible to analyze, predict, evaluate and minimize (albeit to an incomplete extent) the consequences of manifestations of hazardous natural phenomena. It is shown that solving the problems of forecasting, monitoring, and minimizing the consequences of the occurrence of hazardous natural phenomena and their combinations requires interdisciplinary solutions and interaction with all stakeholders – society, government, science, and business. It is important to develop and implement plans for integrated management in regions that are particularly at risk. A big problem, in our opinion, is that in Russian and world science there is a large gap between fundamental research and decision-making bodies.

Keywords: natural hazards, storm, ice, floods, geographic information systems, mathematical modeling, reanalysis, decision support system, planning, risk management

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Introduction

According to the special report "Managing the Risks of Extreme Events and Disasters for Promoting Adaptation to Climate Change" of the Intergovernmental Panel on Climate Change (IPCC), an increase in the frequency of natural hazards caused by climate change in the world since about 1950 has been taking place. From 1998 to 2017, according to information from the Emergency Events Database, natural disasters caused economic losses of about $ 3 trillion and 1.3 million human casualties, more than 4.4 billion people were affected [1].

On the territory of Russia, an increase in the number of hazards that caused significant damage to the economy and population has been observed since the mid-1990s. Since the beginning of the 2000s, the number and scale of natural disasters have increased by about five times, and their danger by nine times [1]. At the same time, they have become more intense and destructive than before, and entail man-induced emergencies. The annual damage from the effects of dangerous and adverse hydrometeorological phenomena in our country is at least 30–60 billion rubles [2].

The consequences of an increase in the number of natural disasters associated with climate change [1] may be aggravated against the background of an increase in the frequency of dangerous phenomena in certain regions and their more extreme manifestations [2], as well as an increase in the already large proportion of the world population living in the zones of dangerous phenomena occurrence. It is predicted that by 2050 the world's population will reach 9.2 billion people [3], and the growing variability of the environment due to the higher frequency and severity of extreme events is likely to be an important consequence of climate change [4].

In this context, the urgency of developing and adopting a unified approach to assessing climate change at various spatial scales at the global level, taking into account multiple risks (multi-risks), is increasing (for example, [5, 6]). In a special report on extreme events and natural disasters, the IPCC [3] points out that taking into account multi-hazard phenomena will ensure that more effective measures are taken to reduce negative consequences and adapt people's lives to possible disasters.

At the global and European levels, an interest in the assessment of multiple risks, especially with regard to initiatives related to the assessment of risks of various natural and man-induced hazards [4], to the analysis of multi-hazard [5] henomena [7, 8] has increased in recent decades. The concept of multi-hazard phenomena was first

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[1] CRED. *EM-DAT: The International Disaster Database*. 2022. [online] Available at: www.emdat.be [Accessed: 15 April 2022].

[2] Kattsov, V.M. and Porfiriev, B.N., eds., 2020. [*Report on Scientific and Methodological Foundations for the Development of Strategies for Adaptation to Climate Change in the Russian Federation (in the Field of Roshydromet Competence)*]. Saint Petersburg, Saratov: Amirit, 120 p. (in Russian).

[3] Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K. [et al.], eds., 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, 582 p. Available at: https://www.ipcc.ch/report/managing-the-risks-of-extreme-events-and-disasters-to-advance-climate-change-adaptation/ [Accessed: 19 April 2022].

[4] ESPON. *ESPON Project 1.3.1: The Spatial Effects and Management of Natural and Technological Hazards in General and in Relation to Climate Change.* 2022. [online] Available at: https://www.espon.eu/programme/projects/espon-2006/thematic-projects/spatial-effects-natural-and-technological-hazards [Accessed: 05 May 2022]; Farrokh, N., Liu, Z., Vangelsten, B.V., Garcia Aristizabal, A., Woo, G., Aspinall, W., Fleming, K. and van Gelder, P., 2014. MATRIX Framework for Multi-Risk Assessment. In: W. Aspinall, M. Bengoubou-Valerius, N. Desramaut, A. Di Ruocco, K. Fleming, A. Garcia-Aristizabal, P. Gasparini, P. Gehl, B. Khazai [et al.], 2014. *New Multi-Hazard and Multi-Risk Assessment Methods for Europe: MATRIX Reference Reports*. Potsdam: Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, pp. 31-36. Available at: https://pure.iiasa.ac.at/id/eprint/11194/1/XO-14-026.pdf [Accessed: 12 May 2022]; United States government. *FEMA.gov: An official website of the U.S. Department of Homeland Security*. 2022. [online] Available at: http://www.fema.gov/ [Accessed: 05 May 2022].

[5] Garcia-Aristizabal, A. and Marzocchi, W., 2012. *Dictionary of the Terminology Adopted*. Deliverable 3.2. MATRIX Project (Contract n 265138).Garcia-Aristizabal, A. and Marzocchi, W., 2012. *Bayesian Multi-Risk Model: Demonstration for Test City Researchers*. Deliverable 2.13. CLUVA Project (Contract n265137).

proposed in 1992 at a conference in Rio de Janeiro [6]. Then, the Johannesburg Plan of Implementation of the World Summit on Sustainable Development in 2002 [7] considered an integrated approach to disaster risk management and risk reduction in multi-hazard events. Further, these phenomena were discussed at the meetings in Hyogo (2005) [8] and Sendai (2015) [9]. The consideration of multiple risks was identified as an important element of various documents at the European and global levels [9, 10].

In foreign scientific literature, we can find the term *multi-hazards* – multi-dangerous phenomena (ensembles of dangerous phenomena). The phenomena themselves and their consequences are studied, and more attention is paid to the development of evacuation plans, the interaction of authorities and local residents, as well as the assessment of the socio-economic consequences of such events. At the same time, many authors note the lack of universal terminology for the entire scientific community. Currently, there is no clear definition of "multi-risk" and "multi-hazard" terms either in the scientific literature or in practice; decision-making in multi-risk conditions is an emerging field of research [11].

However, since climate change is likely to change the hazard thresholds, frequency, recurrence, and spatial distribution of various climatic and natural variables [10], it is necessary to take into account the climate change contribution in future decisions. Very few methodologies for predicting future risks and decision-making rely on climate change scenarios that take into account future environmental risks and natural disasters. At the same time, the lack of a scientifically-based approach to assessing future climate changes, taking into account multi-hazardous natural phenomena and multiple risks, can lead to maladaptation (i.e., to an increase in vulnerability or exposure to other types of hazards) [6].

Despite the development of various systems that use the technologies of training and forecasting the mitigation of the consequences of natural disasters, effective forecasting of natural disasters and risk management of their occurrence remains a problem all over the world.

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[6] UN, 1993. *Report of the United Nations Conference on Environment and Development (Rio de Janeiro, 3-14 June 1992). Volume 1: Resolutions adopted at the Conference*. New York: UN, pp. 3-14. Available at: https://digitallibrary.un.org/record/160453 [Accessed: 01 May 2022].

[7] UN, 2002. *Report of the World Summit on Sustainable Development.* 2002. New York: UN, 212 p.

[8] UN, 2005. *Report of the World Conference on Disaster Risk Reduction Kobe, Hyogo, Japan, January 18-22,* 2005. UN, 64 p.

[9] UN, 2015. *Sendai Framework for Disaster Risk Reduction for 2015-2030.* UN, 40 p.

[10] Field, C.B., Barros, V.R., Mastrandrea, M.D., Mach, K.J., Abdrabo, M.A.-K., Adger, W.N., Anokhin, Y.A., Anisimov, O.A., Arent, D.J. [et al.], 2014. Summary for Policymakers. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O. [et al.], eds., 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, pp. 1-32. Available at: https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartA_FINAL.pdf [Accessed: 19 April 2022].

In this paper, based on the analysis of domestic and foreign scientific literature since 2005, the following are considered:

1) regulatory legal documents regulating terminology in the field of multi-hazardous natural and hydrometeorological phenomena;

2) existing classifications of multi-hazardous hydrometeorological phenomena, methods of classification, hazard thresholds, and methods of their calculation;

3) studies of multi-hazardous hydrometeorological phenomena based on the results of field observations.

1. Materials and methods

Scientific publications from the full-text collection of electronic journals published by Elsevier, Springer, and the scientific electronic library E-Library were selected for the work. The search was carried out on the platforms of these publishers and in the international scientific databases Scopus and Web of Science by keywords in English and Russian "natural hazards", "multi-hazardous phenomena", "storm", "surge", "flood", "ice", "reanalysis", "database", "decision support system", "mathematical modeling", "planning", "government", "risk management", "vulnerability". The search covered the time period from 2005 to 2021. 311 papers and monographs in English and 49 in Russian were selected.

The bulk of the information was obtained from the journals: *Okeanologiya*, *Vodnye Resursy*, *Meteorologiya i Gidrologiya*, *Progress in Oceanography*, *Mathematical Modeling*, *Oceanologia*, *Ocean Modeling*, *Journal of Marine Systems*, *Ocean and Coastal Management*, *Marine Policy*, *Coastal Engineering*, *Cold Region Science and Technology*, *International Journal of Disaster Risk Reduction*, *Quaternary Science Reviews*, *Environmental Impact Assessment Review*, *Weather and Climate Extremes*, *Journal of Environmental Management*, etc. The largest number of scientific papers has been found by risk assessment and risk management, warning and forecasting systems for natural hazards (NH), floods, storm surges. The literature review included 224 scientific papers in English and 32 in Russian.

2. Terminology in the field of multi-hazardous natural and hydrometeorological phenomena

The world's leading organizations – the IPCC, the World Meteorological Organization (WMO), and the United Nations (UN) – are concerned about the issues of both natural and man-induced hazards. Solving problems related to terminology disorder has become a priority task of the UN Office for Disaster Risk Reduction (UNDDR, formerly UNISDR) after the adoption of the Hyogo Framework for Action 2005–2015 [8] and the document "2009 UNISDR Terminology on Disaster Risk Reduction" [11]. Subsequently, the Sendai Framework Program of Action 2015–2030 [9] supplemented previous publications and covered issues related not only to the

[11] UNISDR, 2009. *2009 UNISDR Terminology on Disaster Risk Reduction*. Geneva, Switzerland: UN, 30 p. Available at: https://www.preventionweb.net/files/7817_UNISDRTerminologyEnglish.pdf [Accessed: 01 May 2022].

occurrence of small- and large-scale hazards with different frequency and velocity of propagation caused by natural factors or anthropogenic activities but also related environmental, man-induced and biological hazards and risks [12].

According to the international standard ISO 31000:2018, risk is defined as "the effect of uncertainty on an object" or "a combination of the probability that an event will occur and its outcome". The probability that an event will occur depends on the disaster source and its properties, and the result is associated with vulnerability, which affects the damage scale and the ability to reduce damage.

During the research and analysis of the literature, many different definitions for the same processes and phenomena were found (see Appendix). They do not contradict each other, but sometimes significant differences are obvious.

Within the Russian Federation, the basic concepts, terms, and definitions concerning dangerous natural processes or phenomena, as well as actions for their prevention, forecasting, and elimination are regulated by Federal Law No. 113-FZ of 19.07.1998 "On Hydrometeorological Service"; Federal Law No. 384-FZ of 30.12.2009 "Technical Regulations on Safety of Buildings and Structures"; GOST R 22.0.03-97 "Safety in Emergency Situations. Natural Emergencies. Terms and Definitions".

In each of the regulatory documents, the definition of a dangerous phenomenon differs from the others. Thus, Federal Law No. 384-FZ of 30.12.2009 (ed. of 02.07.2013) [12] defines **dangerous natural processes and phenomena** as "earthquakes, mudslides, landslides, avalanches, flooding of the territory, hurricanes, tornadoes, soil erosion and other similar processes and phenomena that have negative or destructive effects on buildings and structures". In accordance with Federal Law No. 21-FZ of 02.02.2006 "On Amendments to the Federal Law "On Hydrometeorological Service", a **dangerous natural phenomenon** is "a hydrometeorological or heliogeophysical phenomenon that, by the intensity of development, duration or moment of occurrence, may pose a threat to the life or health of citizens, and may also cause significant material damage". In accordance with GOST R 22.0.03-97, a **dangerous natural phenomenon** is "an event of natural origin or the result of the activity of natural processes that, by their intensity, distribution scale and duration, can cause a damaging effect on people, economic objects and the environment" [13]. GOST R 22.0.03-97 also defines a **natural disaster** as "a destructive natural and (or) natural-anthropogenic phenomenon or process of a significant scale, as a result of which a threat to human life and health (may) arise, as well as loss or destruction of material values and components of the environment may occur".

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[12] The Federal Law of the Russian Federation of 30.12.2009 No. 384-FZ *"Technical Regulations on the Safety of Buildings and Structures"* (in Russian).

[13] State Standart 22.0.03-97, R 22.0.03-95. *Safety in Emergency Situations. Natural Emergencies. Terms and Definitions.* Minsk: IPK Publishing House of Standards, 16 p. (in Russian).

In RD 52.04.563-2013, **hydrometeorological NH** include individual hydrometeorological phenomena or their combinations that may pose a threat to the life or health of citizens, as well as may cause material damage [14].

3. Classification of multi-hazardous hydrometeorological phenomena

In a broad sense, hazards are divided by origin, duration, scale, and consequences. The largest number of variants of typologies is by origin (Table). Hazards can be natural (earthquake, seismic impacts, floods, etc.), technological (dam collapse, chemical explosion, etc.), or caused by anthropogenic factors (vegetation removal, mining, drainage, etc.). Different hazards may threaten the same elements at risk. Some authors note that, in essence, all hazards are anthropogenic, since the level of danger is measured in the amount of damage to humans [12].

Hazards can be single, sequential (hazard caused by another phenomenon or domino effect), combined (multi-hazards) in consequences; can increase or decrease depending on the initial event; can be related in space or time; can increase the vulnerability of elements at risk. They can occur both sequentially and in parallel [13].

In addition, hazards can be divided into rapidly occurring intense events of limited duration (short, sharp shocks, such as landslides, sometimes called *acute hazards*) and slowly occurring, widespread phenomena that often affect large areas over longer periods of time (for example, drought, sometimes called *chronic hazards*).

Some authors consider the NH division on various grounds formal and note that they cannot be found in the world in a pure form [19]. Hazards of different types can affect each other, and they are better described as quasi-natural or mixed (hybrid) hazards. Social and technological hazards affecting the natural environment generate quasi-natural hazards. Hybrid hazards are the product of the relationship between social and technological phenomena, while environmental hazards are the result of the interaction between three elements (natural, social, and technological) [15].

Each hazard is characterized by geographical location, intensity, frequency, and probability. In each country, there are separate classifications depending on the prevailing hazards, hazards gradations (threshold values) have been developed according to the degree of their impact and methods for differentiating such phenomena. Methods of classification and risk assessment of various hazards are also being developed.

[14] Guidance Document RD 52.04.563-2013 “*Instructions for the Preparation and Transmission of Storm Messages by Observation Units*”. SPb., 52 p. (in Russian).

The classes of natural hazards by origin according to various sources

Classes	Source						
	Report [15]	Report [16]	[14]	[15]	[16]	[17]	Report [16], [16, 17]
Anthropogenic			x		x		
Biological	x		x			x	x
Extraterrestrial							x
Geophysical	x	x					x
Hybrid / Mixed				x	x		
Hydrological		x	x				x
Global						x	
Climatic	x	x	x				x
Meteorological	x	x					x
Natural				x	x	x	
Social				x		x	
Tectonic			x				
Technological				x		x	
Physiographic (anthropogenic and natural)			x				
Chemical			x				

Most of the methodologies for the NH classification are problem-oriented and are aimed at assessing the consequences at the national, regional, or local levels.

[15] Guha-Sapir, D. and Hoyois, P., 2012. Existing Databases on Disaster Impacts. In: Guha-Sapir, D. and Hoyois, P., 2012. *Measuring the Human and Economic Impact of Disasters: Report*. London: UK Government Office of Science. Chapter 2, pp. 6-13. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/286966/12-1295-measuring-human-economic-impact-disasters.pdf [Accessed: 24 May 2022].

[16] Integrated Research on Disaster Risk, 2014. *Peril Classification and Hazard Glossary (IRDR DATA Publication no. 1)*. Beijing: Integrated Research on Disaster Risk, 28 p. Available at: https://irdrinternational.org/uploads/files/2020/08/2h6G5J59fs7nFgoj2zt7hNAQgLCgL55evtT8jBNi/IRDR_DATA-Project-Report-No.-1.pdf [Accessed: 24 May 2022].

Their application requires the processing and analysis of huge amounts of data. Most methods use historical data (for example, the project ESPON [17], see [11]) and cartographic information reflecting potentially at-risk components of the environment and their characteristics (for example, [20, 21]). At the same time, scenarios of future climate changes are not considered [6].

4. Methods of NH classification

Within the framework of the European ARMONIA [18] project (Applied Multi Risk Mapping of Natural Hazards for Impact Assessment) (2004–2007), the purpose of which was to develop a unified methodology for creating maps of various types of hazards and risks, as well as decision support tools for risk management, a method for classifying hazard intensity (low, medium and high), which enables one to compare the "importance" of hazards and determine the consequences in spatial planning, was developed.

Switzerland uses a classification approach to hazard assessment. At the first stage, the type of hazards, their magnitude (high, medium, low), and probability (high, medium, low, and very low) for a particular area are determined. Then the results are classified according to the magnitude – probability diagram (hazard level diagram). The result is a hazard map indicating the level of danger [22]. The authors of [23] also use the classification method for assessing the hazard, but the hazard level in overlap zones is determined not by the maximum of overlapping classes, but by using a matrix.

Multiple-Criteria Decision Analysis (MCDA) is a widely used method of decision-making in the presence of several criteria. It is used for integrated land use planning in areas prone to landslides [24], for assessing the vulnerability of territories to drought [25], for constructing flood zones [26], and for assessing natural risks [27].

The Technique for Order of Preference by Similarity to an Ideal Solution (abbr. TOPSIS) is used to estimate the distance of indicators from the initially defined ideal and anti-ideal points separately, then these two indicators are converted into one overall assessment [28]. In [29], the TOPSIS method was applied to identify potential natural disasters in the city of Bandar Abbas, Iran. The method integration into GIS allowed the authors of the study [30] to create maps of the danger and risk of earthquakes in Istanbul, and the authors of the work [32] to assess the vulnerability to floods in South Korea, etc.

The Driving forces – Pressure – State – Impact – Response (DPSIR) concept was adopted by the European Environment Agency (EEA) in 1999. This method is designed to identify cause-effect relationships and systematize information for

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[17] ESPON, 2006. *ESPON Project 1.3.1: The Spatial Effects and Management of Natural and Technological Hazards in General and in Relation to Climate Change [ESPON-HAZARD PROJECT]*. Available at: https://www.espon.eu/programme/projects/espon-2006/thematic-projects/spatial-effects-natural-and-technological-hazardshttps://www.espon.eu/ [Accessed: 05 May 2022].

[18] ARMONIA, 2007. Assessing and Mapping Multiple Risk for Spatial Planning, Approaches, methodologies and Tools in Europe. [online] Available at: http://www.eurosfaire.prd.fr/7pc/doc/1271840032_armonia_fp6_multiple_risks.pdf [Accessed: 12 May 2022].

solving problems in the field of the environment and considers socio-economic and natural systems in a close relationship [19]. Using this method, the NH risk assessment in coastal areas was carried out [32], and erosion processes caused by storms and floods were analyzed [33].

The Coastal Hazard Wheel (CHW) is a classification system developed for the assessment and management of multi-hazard natural phenomena in coastal territories. The system is based on the most important bio-geophysical components that are accepted as common within a specific area of the coastal environment [34]. The method is used to assess erosion on the coast of Malta [35] and the Caribbean coast of Colombia [36], as well as the disturbance of Djibouti coastal ecosystems [34].

It should be noted that the classifications developed in Russia do not have special names, they can be identified only by the author's team and none of them has found wide application. In the scientific literature, when describing the hazards, the authors often do not rely on the all-Russian classification of Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) and the Ministry of Emergency Situations. Meanwhile, Roshydromet has defined a standard list of NH with specific quantitative hazard characteristics, compiled taking into account the WMO recommendations [14]. For each subject of the Russian Federation, the list and thresholds of hazards vary. On the basis of this list, territorial authorities develop regional lists and criteria of hazards, taking into account natural and climatic features and economic conditions.

5. Indices

For a comprehensive assessment of the NH consequences various indices are used:

– aridity index (the ratio of precipitation to potential evapotranspiration) – applied to assess climate change in certain areas;

– normalized vegetation difference index (NDVI) – to estimate the amount of photosynthetically active biomass;

– heat index (HI), which combines temperature and humidity;

– environmental performance index (EPI) – a method of quantitative assessment and comparative analysis of environmental policy indicators of the countries, etc.;

– the universal thermal climate index (UTCI), introduced in 1994, takes into account dry thermometer temperature, relative humidity, solar radiation and wind velocity and is considered as the reference ambient temperature [37];

– physiological equivalent temperature (PET) is one of the most commonly used indicators for measuring thermal stress in the open air [38];

– the wet bulb globe temperature (WBGT) – proposed by K. Jaglu and D. Minard (1957) as the most commonly used indicator of thermal stress [39]. Four parameters (dry thermometer temperature, relative humidity, wind velocity and

[19] UNECE, 2006. *Strategies for Monitoring and Assessment of Transboundary Rivers, Lakes and Groundwaters.* 2006. New York; Geneva: UN, 34 p. Available at: https://unece.org/DAM/env/water/publications/documents/StrategiesM&A.pdf [Accessed: 12 May 2022].

thermal radiation) are taken into account when calculating this index, which makes it more accurate compared to other simple thermal indices;

– the disaster risk index (DRI) tracks the evolution of risk [40]: correlations are identified by hazard types in accordance with the impact degree, relative vulnerability, and risk [20] for each zone. Within the DRI framework, vulnerability is considered a factor that describes why people who are in the same condition may be at greater or lesser risk [40].

6. Methods of risk assessment of multi-hazardous natural phenomena

The term "vulnerability" first appeared in the 1970s [20], when the vulnerability was indicated as the true cause of disasters [9]. The definition of vulnerability for NH can be applied to any system that interacts with society. There is no set of specific vulnerabilities – there is only a vulnerability that is affected by various factors (human deaths, financial losses, quality of life of the population, etc.). In part, vulnerability for hazards is determined by the social vulnerability of people. Poor or developing communities suffer more damage from natural disasters due to economic and political constraints, as well as environmental degradation [41].

Multi-hazard risk assessment methodologies perform hazard aggregation, vulnerability assessment [42], assignment of scores and weights to identified classes [21]. The results make it possible to qualitatively classify the risk of multiple hazards.

The MATRIX [21] project offers three different methods for describing and quantifying the interactions of dangerous phenomena: event tree, Bayesian networks, and Monte Carlo simulation. Individual risks within the framework of multiple risk assessment are calculated using a common unit of measurement (for example, loss of lives, economic losses) (see works [11, 20]). This allows for direct comparison and aggregation of different types of risks. As a result of the application of both approaches, the areas exposed to different general risk classes are identified (for example, [7, 21]).

To assess the risk of multi-hazardous natural phenomena, the method of Multi-Hazard Risk Assessment (abbr. MHRA) is applied accordingly. The main advantage of the MHRA is that it combines different types of hazards into a single system for joint assessment [20], takes into account the parameters of each natural hazard (probability, frequency, and magnitude), their interaction and interrelationships (for example, one hazard can be repeated all the time; different hazards can occur

[20] Pelling, M., ed., 2004. *Reducing Disaster Risk: A Challenge for Development: A Global Report*. New York: Bureau for Crisis Prevention and Recovery, 161 p. Available at: https://www.undp.org/publications/reducing-disaster-risk-challenge-development [Accessed: 05 May 2022].

[21] Farrokh, N., Liu, Z., Vangelsten, B.V., Garcia Aristizabal, A., Woo, G., Aspinall, W., Fleming, K. and van Gelder, P., 2014. MATRIX Framework for Multi-Risk Assessment. In: W. Aspinall, M. Bengoubou-Valerius, N. Desramaut, A. Di Ruocco, K. Fleming, A. Garcia-Aristizabal, P. Gasparini, P. Gehl, B. Khazai [et al.], 2014. *New Multi-Hazard and Multi-Risk Assessment Methods for Europe: MATRIX Reference Reports*. Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, pp. 31-36. Available at: https://pure.iiasa.ac.at/id/eprint/11194/1/XO-14-026.pdf [Accessed: 12 May 2022].

independently in the same place; different hazards may occur depending on the same location) [20].

7. Studies of multi-hazardous hydrometeorological phenomena based on the results of field observations

NH, their repeatability, patterns of occurrence and development, as well as emerging consequences are studied on the basis of various historical sources (personal archives, mass media, archives of insurance companies), results of field observations, Earth remote sensing data, and mathematical modeling results. The observational data on the NH are of particular interest as they contain unique information about the events that have occurred. At the same time, special attention is required to control the correctness of the values due to changes in measurement methods throughout the entire period of meteorological observations and repeated reproduction.

In their works, some authors give an extensive overview of existing methods of analyzing hazardous and multi-hazardous natural phenomena and approaches to them and highlight the following main problems: 1) the difference in the characteristics of processes, which makes it difficult to compare several hazards, and 2) the presence of relationships and interactions between hazards. WMO has created a Global Framework for Climate Services (abbr. GFCS), which coordinates worldwide actions on the application of climate service tools, improving their quality and quantity, as well as on the definition of various indices, for example, climate change indices from the CCL/WCRP/JCOMM expert group [22] [43].

Databases

At the global level, the World Bank [5] and the Munich Reinsurance Company *Munich Re Group* [23] perform a large-scale analysis of natural disasters, visualizing hot spots using simple risk indices of various hazards [6].

In the Russian Federation, monitoring of the environmental state and pollution is carried out by the Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet). The duties of Roshydromet also include the release of emergency information about the NH, actual and predicted sudden weather changes, environmental pollution, which may threaten the life and health of the population and cause damage to nature. Annually, information about the dangerous phenomena that have occurred is published in the print editions of Roshydromet. The results of the NH monitoring are transmitted to the automated database on hazards and adverse weather conditions "Information on dangerous and adverse hydrometeorological phenomena that caused material and social damage on the territory of Russia", which

[22] WSRP. *Expert Team on Climate Change Detection and Indices (ETCCDI)*. 2019. [online] Available at: https://www.wcrp-climate.org/etccdi [Accessed: 12 May 2022];

WMO. *Expert Team on Sector-Specific Climate Indices (ET-SCI)*. 2018. [online] Available at: https://public.wmo.int/en/events/meetings/expert-team-sector-specific-climate-indices-et-sci [Accessed: 12 May 2022].

[23] Munich Re Group. *Munich RE*. 2022. [online] Available at: www.munichre.com [Accessed: 12 May 2022].

has been maintained since 1997 (updated daily) by RIHMI – WDC and is official in the Roshydromet system. The database contains information about meteorological, hydrological, and agrometeorological hazards that have caused damage to the economy and the population.

The Unified State System of Information on the Situation in the World Ocean (ESIMO) provides data on the natural hazards in the form of an appendix “Natural Disasters”. The information is provided on the basis of the above-mentioned RIHMI–WDC database. There are also local databases, such as, for example, GIS “Dangerous Natural Phenomena of the Voronezh Region”, a database of dangerous weather phenomena of the Perm Region.

The International Disaster Database EM–DAT was created with the support of the World Health Organization (WHO) and the Government of Belgium and provides information on the impact of natural disasters on humans, for example, the number of dead, injured or affected, estimates of economic damage.

The European Severe Weather Database (ESWD) collects and verifies reports on dust, sand or steam, tornado sightings, wind gusts, heavy hail, heavy rain and snowfall, strong wind gusts, destructive lightning strikes, and avalanches throughout Europe and the Mediterranean. ESWD is the most comprehensive database of such events in Europe.

The National Centers for Environmental Information of the National Oceanic and Atmospheric Administration of the USA (NCEI NOAA) is responsible for environmental monitoring, preservation, and evaluation of national geophysical data and information, ensuring public access to them. One of the center tasks is the storage and assimilation of data on tsunamis, earthquakes, and volcanoes to support their research, planning actions in case of threats of hazards, rapid response to them and mitigation of consequences.

The mission of the United States Geological Survey (USGS) in relation to the NH is to develop and apply the science of the dangers of the surrounding world to ensure the security and economic well-being of the USA. The USGS scientific research helps to reduce the risks of natural disasters and to inform about possible future disasters, to obtain reliable information about the characteristics of hazards – their frequency, magnitude, degree, onset, consequences, etc.

In Italy, a database of historical information about landslides and floods in the country has been maintained since 1990 – the AVI project of the National Research Council, which provides regular information from 1917 to 2000 and irregular for the periods from 1900 to 1916 and from 2001 to 2002 and includes information on more than 32,000 landslides that occurred on more than 21,000 sites, and more than 29,000 floods occurred in more than 14,000 sites. Independently of the AVI project, Italy has also developed an Information System on Hydrological and Geomorphological Disasters SICI (Sistema Informativo sulle Catastrofi Idrogeologiche), which is currently the largest single repository of historical information about landslides and floods in Italy.

Remote observations

The use of satellite data is adapted for monitoring natural disasters and obtaining important information before, during, and after events. Currently, the use of satellite monitoring results in the struggle against the consequences of the NH occurrence is a common practice [44, 45]. This is the only tool that can provide large-scale spatially distributed sets of geographically linked data.

N. Kerle and K. Oppenheimer [46] studied the effectiveness of using optical and radar sensors as disaster management tools in Lahar. S. Voit in his study [44] applied effective methods of image analysis based on satellite data from several sources for the rapid creation of maps in the management of natural disasters and crises. The study also used satellite data to quickly assess the consequences of natural disasters that occurred in different parts of the world.

The work carried out by D. Tralli [47] demonstrated how satellite monitoring data can be effectively used in combination with mathematical modeling for forecasting and visualizing results, effective decision-making in the event of earthquakes, floods, landslides, and volcanic eruptions. The work [48] shows the effectiveness of disaster management when remote sensing results are combined with other technologies, such as GIS and the Global Navigation Satellite System (GNSS).

L. Montoya [49] has developed a cost-effective and fast method of data collection for inventory based on remote sensing, Global Positioning System (GPS), digital video (DV), and GIS for urban risk management. The works [11, 48] show effective methods for monitoring and preventing the consequences of earthquakes, volcanic eruptions, floods, landslides and coastal hazards based on a combination of the results of the Earth, GIS, and GNSS remote sensing.

Monitoring of natural disasters, provided by visualization of data collected from various sources, provides the public with important information about the spread of natural disasters and helps to prepare for their consequences. A web-based visualization service created by Australia and based on the *Sentinel* [24] satellite provides publicly available graphical information about forest fires occurring throughout Australia.

The monitoring system developed by K. Zou [50] contributes to the rapid extraction of information from satellite data of the Earth remote sensing to prepare for possible disaster scenarios. K. Bohm with co-authors/colleagues [51] proposed geo-visual analytical solutions in the public health sector to improve emergency planning and response. *Climate Engine*, developed by D. Huntington and colleagues [52] helps to visualize climate data in an interactive graphical user interface to prepare for any natural disasters. D. Trali and co-authors [47] focused on the use of satellite data of the Earth remote sensing in the construction of geospatial models for monitoring natural disasters in order to effectively prepare for them.

[24] Australian Government. *Geoscience Australia*. 2022. [online] Available at: https://www.ga.gov.au/ [Accessed: 02 May 2022].

Conclusion

The increase in the NH repeatability since the beginning of the 21st century, along with the development of information technologies, such as electronic databases, geoinformation systems, the use of satellite information and mathematical modeling has made it possible to analyze, predict, evaluate and minimize (albeit to an incomplete extent) the consequences of manifestations of natural hazards.

Solving the problems of forecasting, monitoring, and minimizing the consequences of the NH occurrence and their combinations requires an interdisciplinary approach and especially the need for interaction with all interested parties – society, government, science, and business. It is important to develop and implement integrated management plans in regions that are particularly exposed to risks. This is required for the sustainable management of natural and man-induced systems, especially in coastal areas, and concerns the elimination of the entire spectrum of hazards, including environmental pollution, for the protection of natural habitats of flora and fauna, infrastructure, residential areas, and tourist destinations.

It is important to develop an international network of observations of natural phenomena and processes around the world, including territories with extreme conditions (the Far North, high-altitude areas, deserts). This will enable one to track the origin, development and evolution of processes, their transformation and distribution.

In our opinion, the big problem is that in Russia and in the world as a whole there is a big discrepancy between the conclusions of fundamental research and the decisions taken by the authorities. The results of fundamental work become known only to narrow specialists, are not popularized/brought to the attention of the relevant authorities and services, and, accordingly, are not applied in practice.

Appendix

Terms and definitions in the field of hazardous and multi-hazardous phenomena according to various sources

Disaster / extreme meteorological or climatic phenomenon / dangerous phenomenon:

– a natural disaster or anthropogenic event that has caused widespread human, environmental, economic, or material losses. The adverse consequences of a natural disaster may exceed the ability of the affected community or society to cope with the situation using its own resources [A.1];

– a phenomenon that is rarely observed in a particular place and at a particular time of the year. A meteorological phenomenon is usually considered extreme if it is observed as rarely or even less frequently than the 10th or 90th percentile of the probability distribution function estimated from observational data [A.2];

– the occurrence of a natural or anthropogenic phenomenon in a certain place for a certain period of time due to the presence of a hazard (https://www.undrr.org/terminology);

– a hydrometeorological, geophysical or human-caused event that creates a danger of any level to life, property or the environment. These are necessarily severe and extreme meteorological and climatic phenomena (https://library.wmo.int/doc_num.php?explnum_id=7904).

Multi-hazards:

– several main dangerous phenomena that are observed in a particular country / dangerous phenomena that can occur simultaneously, cascadingly or cumulatively over a period of time and taking into account possible interrelated effects [A.1];

– various dangerous events threatening the same objects (coincidence in time) / dangerous events occurring simultaneously or soon following each other (cascade effects). Refers to the totality of the corresponding hazards in a certain administrative zone [A.2];

– several main dangerous phenomena that are observed in a particular country / dangerous phenomena that can occur simultaneously, cascadingly or cumulatively over a period of time and taking into account possible interrelated effects (https://www.undrr.org/terminology).

[A.1] Krausmann, E., Cruz, A. and Salzano, E., 2016. *Natech Risk Assessment and Management: Reducing the Risk of Natural Disasters on Hazardous Installations*. Elsevier, pp. 241-243.

[A.2] Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J. and Plattner, G.-K., eds., 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, 582 p.; UNISDR, 2009. *2009 UNISDR Terminology on Disaster Risk Reduction*. Geneva, Switzerland: UN, 30 p. Available at: https://www.preventionweb.net/files/7817_UNISDRTerminologyEnglish.pdf [Accessed: 01 May 2022].

Hazard:

– a combination of the frequency or probability of occurrence and consequences of a hazardous event. Thus, the risk includes the probability of converting the danger into actual bodily injury, damage or harm. Risk is always associated with uncertainty related to the event occurrence [A.1];

– hazard source. Hazard does not necessarily lead to harm, but provides only the possibility of harm [A.1];

– a physical phenomenon associated with climate change (for example, sea level rise, storm surge), which can cause damage and losses to property, infrastructure, sources of livelihood, provision of services, and environmental resources [A.2];

– a potentially dangerous physical event, phenomenon, or human activity that may lead to death or injury, property damage, social and economic disruption, or environmental degradation (https://www.undrr.org/terminology).

Risk:

– quantifies and classifies the potential consequences of dangerous events in the studied territories and impact objects (i.e. elements potentially at risk), combining danger, exposure and vulnerability. It can be expressed in probabilistic or relative/semi-quantitative terms [A.2].

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Natalia A. Yaitskaya – literature review in terms of the analysis of regulatory documents, methods for classifying the NH, studies of the NH based on databases, mathematical modeling, and satellite monitoring

Anastasia A. Magaeva – literature review in the field of mathematical modeling of multi-hazards, decision support systems, multi-hazards associated with ice

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