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Hydrometeorological Phenomena and Multi-Hazards: Mathematical Modelling, Decision Support Systems, Geoinformation Systems (Review)

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Abstract
Purpose. The article represents the analysis of current state of research and achievements in the field of natural hazards (including hydrometeorological ones), and their ensembles (multi-hazards) based on the papers published in the specialized international and Russian scientific journals and monographs.
Methods and Results. Considered are the modern methods for mathematical modeling of hydrometeorological multi-hazards, the methods for assessing the relations between the hazards and multi-hazards, the existing decision support systems, and the methods for assessing the risks of occurrence of hazards and multi-hazards. The ensemble models and the possibilities of cloud computing were reviewed; the experience of integrating the geoinformation systems and the results of the Earth remote sensing in models was studied. Examples of the modeling platforms and the decision support systems (developed in different countries) intended for application in case of the natural hazards, are represented.
Conclusions. It is shown that solution of the problems including forecasting, monitoring and minimizing the consequences of natural hazards and their combinations requires interdisciplinary solutions, on the one hand, and interaction between all the stakeholders – society, government, science and business, on the other. It is important to develop and implement an integrated management in the regions that are particularly at risk. Field observations are of primary importance. Within the framework of the country, an integrated modeling system taking into account complex processes such as hazards, should be necessarily developed. Special attention should be paid to the peculiarities of natural disasters occurring in the northern regions of our country, since they are often characterized by extreme background weather conditions, inaccessibility and remoteness, lack of the infrastructure required for saving people and eliminating the consequences.

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

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Introduction

According to the World Bank report on the main sources of natural disasters [1], about 3.8 million km^2 of land and 790 million people in the world are subject to the potential threat of at least two hazards, about 0.5 million km^2 and 105 million people – to three and more dangerous phenomena [2]. The United Nations report [1] considered the potential multi-hazard threats for urban residents (with a population of 300,000 or more): for example, in 2014, 100 million people lived in areas that were at high risk of multi-hazard natural events, and 752 million (34% of the total urban population) were at medium or low risk [3].

According to a special report *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* of the Intergovernmental Panel on Climate Change (IPCC), since about 1950 there has been an increase in the frequency of natural hazards.

There are several types of extreme climate events that, according to the IPCC [4], will become more frequent, widespread or more intense in most parts of the world during the 21st century. These include heat waves, droughts and heavy rains. An increased risk of hazards can also be observed due to anthropogenic impact [2], for example, land use change has increased the risk of forest fires in the Mediterranean [5].

Integrated coastal zone management is based on comprehensive and carefully designed actions proposed by the parties concerned and active dissemination of information at the local level. This requires monitoring, regulation and responsible management. At the present stage of science development, reliable forecast of hydrometeorological phenomena is possible only with a lead time of 72 hours. This value is primarily due to the justification of mathematical models, the speed of calculations and the amount of data for model verification.

In order to effectively predict hazards and prevent their adverse effects, it is necessary to focus on their nature, risks and consequences on a spatial scale, both at the regional and national levels.

Despite the development of various systems using learning and forecasting technologies for disaster mitigation, effective disaster forecasting and risk management is still an issue worldwide.

In the present paper, based on the analysis of domestic and foreign scientific literature since 2005, the following aspects in the study of dangerous and multi-hazard phenomena are considered:

1) mathematical modeling of hydrometeorological multi-hazards;

2) use of cloud services for modeling natural hazards, early warning of the population and risk management;

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[1] Gu, D., Gerland, P., Pelletier, F. and Cohen, B., eds., 2015. *Risks of Exposure and Vulnerability to Natural Disasters at the City Level: A Global Overview*. New York: UN, 40 p.

[2] 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].

3) development of a decision support system and risk assessment of multi-hazards.

1. Materials and methods

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

The bulk of the information was obtained from such journals, as Oceanology, Water Resources, Meteorology and Hydrology, Progress in Oceanography, Mathematical Modeling, Oceanologia, Ocean Modelling, 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 articles was found on risk assessment and risk management, warning and forecasting systems for natural hazards (NHs), floods and storm surges. The literature review included 224 scientific papers in English and 32 in Russian.

2. Mathematical modeling of hydrometeorological multi-hazards

A wide range of models has been built to predict and effectively manage natural disasters. These include Swift flood propagation models [6], Rapid Flood Spreading Model (RFSM) [7], LHASA landslide prediction model [8], cyclone models (HWRF hurricane research and forecasting model) [3] and many others [9]. Some software systems take into account up to three types of hazards, but as independently occurring ones (HAZUS-MH [10], InaSAFE [11] and RiskScape [12, 13]).

For the analysis of natural hazards, climate variables can be obtained from observation series or from global and regional climate reanalyses, as shown in our previous work [4]. These are categories of primary variables (such as temperature, precipitation, wind speed), complex variables (such as evaporation or moisture) and proxy variables (such as soil moisture, river flow or flow velocity) [5]. The selected

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[3] Gopalakrishnan, S., Liu, Q., Marchok, T., Sheinin, D., Surgi, N., Tong, M., Tallapragada, V., Tuleya, R., Yablonsky, R. and Zhang, X., 2011. *Hurricane Weather Research and Forecasting (HWRF) Model: 2011 Scientific Documentation*. Boulder, CO: University of Colorado, 96 p.

[4] Yaitskaya, N.A. and Magaeva, A.A., 2022. Ensembles of Hazardous Hydrometeorological Phenomena: Legal and Regulatory Aspects, Terminology and Classification (Review). *Physical Oceanography*, 29(3), pp. 237-256. doi:10.22449/1573-160X-2022-3-237-256

[5] Willows, R., Reynard, N., Meadowcroft, I. and Connell, R.K., 2003. *Climate Adaptation: Risk, Uncertainty and Decision-Making:* UKCIP Technical Report. Oxford: UKCIP, Part 2, pp. 41-87.

variables should be representative and reflect not only spatiotemporal dynamics, but also anomalous and extreme values.

A more difficult task is to quantify the relationships between hazards and calculate multi-hazards. For this purpose, several types of probabilistic methodologies (e.g. Bayesian networks, event tree analysis, Monte Carlo simulations) which are commonly used for natural hazard assessment, can be applied.

However, uncertainties related to future climate changes and contribution of these changes to NHs performance remain a major concern. It is possible to solve this problem using ensembles of global and regional models. Multi-model ensembles are created based on the results of various modeling experiments [6], are characterized by greater reliability and consistency than single-model simulations, and provide a higher level of confidence in climate forecasts for a particular region [14]. The most widely used for creating climate scenarios are general circulation models (see the work [7] and [15–18]). To obtain correct data on global climate change, several different scenarios are used, the calculation results for which are published in special reports at intervals of about five years [19].

3. Cloud computing and ensemble modeling

Widespread introduction of geospatial models and models of natural hazards, the need to process an increasing amount of heterogeneous information caused the development and dissemination of cloud computing methods. The extremely complex nature of models, computational resource intensity, special time requirements for forecasting, the need for scalability for model ensembles and the resource-intensive nature of geospatial models all make the implementation of such models a complex process [20].

Cloud computing developed on the principles of distributed computing can be combined, shared, and the latest computing technologies and physically distributed computer resources can be integrated into them [21]. Cloud computing provides on-demand access to virtually unlimited storage, networking and computing resources. These features allow to solve problems associated with the amount of initial and received data, the volume of calculations and simultaneous access to calculations and results of an unlimited number of users.

C. Yong et al. [8] used GIS in combination with web technologies to develop a decision support tool to determine effective strategies for responding to large earthquakes and assess expected damage and losses. F. Wex et al. [22] proposed a decision support model based on the Monte Carlo heuristic using geographic information for NDM (Natural Disaster Management). This model minimized the sum of incident completion times weighted by the severity of incidents.

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[6] IPCC, 2022. *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Working Group II Contribution to the IPCC Sixth Assessment Report. Cambridge University Press. In Press. Available at: https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/ [Accessed: 20 July 2021].

[7] Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M., eds., 2013. *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press, 1535 p.

[8] Yong, C. and Chen, Q.F., 2001. Web Based Decision Support Tool in Order to Response to Strong Earthquakes. *Proceedings of TIEMS2001, Oslo, Norway*.

C. van Westen [23] demonstrated how GIS can be combined with satellite monitoring to develop effective disaster risk management tools for disaster risk prevention and preparedness to NHs, disaster relief and infrastructure recovery at various stages of disasters. M. Laituri and K. Kodrich [24] combined GIS and Internet capabilities to improve the effectiveness of response to natural disasters of great magnitude and management of the consequences of their occurrence. A. Jeyaseelan [25] confirmed the effectiveness of using GIS integrated with Earth remote sensing data for early warning of floods and droughts, real-time monitoring and assessment of subsequent damage. L. Manfré et al. [26] and L. Montoya [27] demonstrated the effectiveness of using GIS together with remote sensing and related technologies to more effectively manage the risks of natural disasters and urban risks, including in large cities. S. Cutter [28] explained the extent to which geoinformation science can be used by the community for post-disaster management.

Web technologies are used to post information from various services related to natural disasters, to facilitate access to observational data, reanalysis results and disaster forecasts. Various types of sensors can gather as much data as possible to get a better understanding of disasters. In [29] the use of satellite data and efficient image analysis techniques for rapid map generation during natural disasters to improve risk management are described.

Some geospatial and hazard models require running a large number of simulations to obtain a series of statistical measures rather than a single deterministic result. This approach is often used when model inputs are subject to sources of uncertainty and can only be expressed as probability distributions rather than fixed values. The cloud environment is well-suited to support resource-intensive model ensembles requiring hundreds to thousands of simulations to run. S. Garg et al. [30] explored the possibility of using cloud computing for ensemble running of geospatial science models by developing the SparkCloud service for the Spark Forest Fire Prediction software. Q. Huang et al. [21] developed a prototype platform for hybrid cloud computing (Hybrid Cloud Computing, abbr. HCC), which allows using the cloud infrastructure to run a complex model ensemble, such as a dust storm model, by deploying the parallel mode of the model based on Amazon EC2 at a lower cost compared to local resource computing. Z. Li et al. [31] developed the MaaS (Model as a Service) service, which runs an ensemble of models in parallel with individual requests from users. All the necessary data to run the ensemble is uploaded by users through the web interface. B. Behzad et al. [32] developed a geoinformation system based on CyberGIS Gateway cyber infrastructure and used it to present an ensemble modeling of a groundwater system in a cloud environment based on the Microsoft Windows Azure platform.

4. Warning systems

Many early warning systems have been developed to alert the public about NHs [33–37]. D. Puthal and a group of researchers [34] presented a development that supports dangerous phenomena detection and formation of alerts by analyzing the big data flow in real time. C. Rossi et al. [36] presented a service-oriented cloud architecture for mobile application servers, which makes it possible to send field observation data in real time. These data can be used for early warning during natural disasters. The Virtual Fire web platform [33] provides vital weather data needed to prevent fires and provide early warning to the public in the event of a fire. A cloud computing platform based on local communities, proposed by J. Li et al. [37], will contribute to early warning of natural disasters, the development of an emergency management strategy and help to minimize the consequences of a natural disaster. A study by A. Jeyaseelan [25] considers remote sensing and GIS application for timely warning of the population in case of any events associated with drought and floods.

The RiskMed (Weather Risk Reduction in the Mediterranean) project [9] brought together various partners from four regions of Mediterranean Europe (Southern Italy, Malta, Northwest Greece and Cyprus) to create and set up a weather early warning system that will continue to operate after the project completion.

Armagedom is a seismic risk analysis tool implemented in various urban seismic settings (Bouzareah (Algeria), four provinces in Iran, French departments along the French-Spanish border and overseas departments in the French Antilles) [38].

Central American Probabilistic Risk Assessment is a platform that includes tools for modeling and analyzing various NH types, vulnerabilities, risk assessment, etc. It has been used to implement various projects in Central and South America. The platform includes modules for the analysis of earthquakes, hurricanes, precipitation, volcanic hazards, landslides and floods. The risk assessment module includes CAPRA-GIS and software applications for probabilistic risk assessment based on NH, exposure and physical vulnerability data [10].

In Russia, for mathematical modeling of natural hazards, author’s models, both domestic and foreign, are used. In [39], based on the climatic version of the non-hydrostatic model COSMO (Consortium for Small-scale Modeling), for the first time in Russia, the numerical integration of the model for 30 years (1985–2014) was carried out. The hydrometeorological data arrays were obtained for three nested areas of the Sea of Okhotsk with different scale, a synoptic analysis of extreme situations was carried out. The predictive version of the COSMO-Ru model is used by the Hydrometeorological Center of Russia.

An example of the development of the Russian operational system for nowcasting and marine forecasting of the World Ocean, the Arctic and the Azov-Black Sea basins is the system implemented at the N.N. Zubov State Oceanographic Institute (SOI) [40, 41]. The set of numerical models consists of the Weather Research and Forecasting (WRF) Model [11] – a regional non-hydrostatic atmospheric circulation model; the Institute of Numerical Mathematics Ocean Model (INMOM) – a three-dimensional σ-model of marine circulation and sea ice dynamics in the version for the Barents, White, Pechora and Kara seas; and the Russian Atmospheric Wave Model (RAWM). The WRF non-hydrostatic atmospheric

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[9] Laboratory of Meteorology, Physics Department, University of Ioannina. *Riskmed - Weather Risk Reduction for the Mediterannean*. 2022. [online] Available at: http://www.riskmed.net [Accessed: 15 February 2021].

[10] Uniandes. *CAPRA (Probabilistic Risk Assessment) Platform*. 2022. [online] Available at: https://ecapra.org/topics/risk-assessment [Accessed: 05 March 2021].

[11] Skamarock, W.C., Klemp, B., Dudhia, J., Gill, O., Barker, D., Duda, G., Huang, X., Wang, W. and Powers, G., 2008. *A Description of the Advanced Research WRF Version 3.* Boulder, Colorado: National Centre for Atmospheric Research USA, 125 p. doi:10.5065/D68S4MVH

circulation model with a spatial resolution of 15 km is capable of reproducing mesoscale atmospheric processes [12]. All atmospheric parameters from the WRF model are used in the INMOM marine circulation model to calculate heat, fresh water and momentum fluxes at the sea surface.

5. Decision support systems and risk assessment of dangerous and natural multi-hazard phenomena. Methods for assessing the risks of natural multi-hazard phenomena

The concept of multi-hazards is concerned with the analysis of various relevant hazards, triggers and cascades that threaten the same exposed components of the environment, with or without temporal overlap. Methodologies for assessing the risk of multi-hazard events include aggregation of hazards, vulnerability assessment [42], assignment of scores and weights to identified classes [43]. The results allow a qualitative classification of the multiple hazard risk level (e.g., low, medium and high).

The term "vulnerability" first appeared in the 1970s [44], when vulnerability was identified as the true cause of disasters along with natural causes of NHs. However, there is no set of specific vulnerabilities for various objects [13]. As already mentioned in our previous work [4], vulnerability to NHs is partly determined by social vulnerability of population. Thus, poor or developing communities suffer more damage from natural disasters due to economic and political restrictions and environmental degradation [45].

Based on the modern scientific literature analysis, two main approaches to hazard assessment can be distinguished: risk assessment of multiple hazards and multiple risk assessment. These approaches consider both hazard and vulnerability. The first approach involves analysis of various hazards (and combining them to calculate the multiple hazard index) and assessment of the overall territorial vulnerability, which allows the assessment of risks of multiple hazards. The assessment procedure can be summarized as follows: hazard assessment; assessment of multiple hazards; hazard exposure assessment of vulnerable elements; vulnerability assessment; risk assessment of multiple hazards.

The second approach, multiple risk assessment, is more complex and includes the concepts of multiple hazards and multiple vulnerabilities, taking into account possible hazards and vulnerability interactions [46]. In this approach, the risks are analyzed separately for each hazard, and then aggregation allows multiple risk index assessment. In general, the approach is described by the following sequence: hazard assessment; risk exposure assessment of vulnerable elements; vulnerability assessment; unified risk assessment; assessment of multiple risks.

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[12] Diansky, N.A., Panasenkova, I.I. and Fomin, V.V., 2019. Investigation of the Barents Sea Upper Layer Response to the Polar Low in 1975. *Physical Oceanography*, 26(6), pp. 467-483. doi:10.22449/1573-160X-2019-6-467-483

[13] Kohler, A., Julich, S. and Bloemertz, L., 2004. *Guidelines: Risk Analysis – a Basis for Disaster Risk Management*. Eschborn: Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, 31 p.

The H2020 ESPREssO (Enhancing Synergies for Disaster Prevention in the European Union) project aims to identify existing research gaps and key priorities for scientific work in areas prone to NHs, to reduce disaster risk, to manage risk and to adapt to climate change. Key research priorities have been formulated in the Sendai Framework for Disaster Risk Reduction 2015–2030 and in the corresponding EU Action Plan. The innovation introduced by the Sendai Framework is a new understanding of risk based not only on records of past events, but also on more accurate forecasts that reflect evolving trends and dynamics over time and space [47].

The MATRIX [14] project proposes three different methods for describing and quantifying hazard interactions: event tree, Bayesian networks and stepwise time step Monte Carlo simulation. Moreover, individual risks within the framework of multiple risk assessment are calculated using a common unit of measure (life loss, economic loss) (e.g. [4, 48]). This allows direct comparison and aggregation of different types of risk. Both approaches result in areas subject to different general risk classes (e.g. [45, 49]. Spatially oriented maps can be used by different end users to provide specific information on risk quantification.

The Multi-Hazard Risk Assessment (MHRA) method is used to assess the risk of natural multi-hazards. Its main advantage is that it combines different types of hazards into a single system [15] for joint assessment (see the work [16] and [46]), takes into account the parameters of each natural hazard (probability, frequency and magnitude), their interaction and interrelationships (for example, one hazard may be repeated all the time; different hazards may occur independently of each other or sequentially in the same place) [5].

Nature-based solutions for risk mitigation have only recently been conceptualized [17], but have shown promising results in mitigating threats and

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[14] Garcia-Aristizabal, A. and Marzocchi, W., 2012. *Dictionary of the Terminology Adopted. Deliverable 3.2. MATRIX Project (Contract n 265138).* Available at: https://www.researchgate.net/profile/Alexander-Garcia-10/publication/255989333_Assessing_cascading_effects_in_multi-hazard_and_multi-risk_analyses_Examples_from_Naples_Italy/links/5a152ed0aca27273c9eb20c4/Assessing-cascading-effects-in-multi-hazard-and-multi-risk-analyses-Examples-from-Naples-Italy.pdf [Accessed: 12 July 2022].

[15] *Armonia – Applied Multi-Risk Mapping of Natural Hazards for Impact Assessment*. Available at: http://www.armoniaproject.net/ [Accessed: 12.12.2020]; Delmonaco G., Margottini C. and Spizzichino D., 2006. *Report on New Methodology for Multi-Risk Assessment and the Harmonisation of Different Natural Risk Maps. (Del. 3.1).* Rome, 85 p. Available at: https://www.researchgate.net/publication/317957266_New_methodology_for_multi-risk_assessment_and_the_harmonisation_of_different_natural_risk_maps [Accessed: 12 July 2022].

[16] Marzocchi, W., Mastellone, M.L., Di Ruocco, A., Novelli, P., Romeo, E. and Gasparini, P., 2009. *Principles of Multi-Risk Assessment: Interactions amongst Natural and Man-Induced Risks*. Luxembourg: Office for Official Publications of the European Communities, 72 p.

[17] World Bank, 2008. *Biodiversity, Climate Change, and Adaptation: Nature-Based Solutions from the World Bank Portfolio.* Washington, DC: The World Bank, 112 p. Available at: https://openknowledge.worldbank.org/handle/10986/6216 [Accessed: 14 July 2022]; Rizvi, A.R., 2014. *Nature Based Solutions for Human Resilience: A Mapping Analysis of IUCN's Ecosystem Based Adaptation Projects.* Gland, Switzerland: IUCN, 50 p.

conserving biodiversity [18]. However, such approaches need to be approved as recommended risk mitigation measures.

Nature-based solutions are considered as an umbrella concept that includes different ecosystem approaches [16], such as ecosystem-based adaptation (EbA), ecosystem-based disaster risk reduction (Eco-DRR), green infrastructure development used to address environmental degradation, risk reduction of natural disasters and adaptation to climate change [50].

The general principles of nature-based solutions are to strike a balance between ecosystem conservation and socio-economic benefits on a fair and equitable basis with a broad participation of society. NHs, risks from their occurrence and climate change adaptation are central to such ecosystem-based approaches as Ecosystem based Disaster Risk Reduction (Eco-DRR), Ecosystem-based Adaptation (EbA), Green Infrastructure and Nature Infrastructure [50]. Specific results of the implementation of individual elements of these concept nature-based solutions to reduce vulnerability of social and environmental systems to natural disasters have not yet been recorded.

Simultaneously with the development of principles of nature-based solutions by the International Union for Conservation of Nature (IUCN), the World Bank proposed comprehensive guidelines for the implementation of these solutions to reduce the risk of floods [51]. This guide proposes, as one of the five overarching principles, before making a final decision on risk mitigation approaches, to assess flood risks and the benefits of a full range of solutions not limited to green solutions. Finally, in 2019, the Convention on Biological Diversity (CBD) was published, providing voluntary guidelines for ecosystem-based approaches to climate change adaptation and disaster risk reduction. All of these overlapping, and sometimes complementary, sets of principles and guidelines are relevant to sustainable decision-making on a global scale as they bridge knowledge gaps and provide clear guidance to decision makers in planning and implementing green technologies in the climate change context, as well as reducing the risk of NHs [50].

Model-based decision support systems (DSS) are widely used to support environmental, social and economic management of the environment. For example, DSS have been developed for sustainable fisheries management [51]; agriculture and other agricultural systems [52]; habitat and ecosystem management [53, 54]; land development [52, 55]; community activity planning [14, 56, 57]; water resource management, taking into account rivers, lakes, wetlands, reservoirs and their watersheds [58, 59] and pollution management [12, 60].

The advantage of using DSS for solving problems is that they can be used to:

1) focus on long-term and strategic issues [61];

2) take into account group interaction [62];

3) facilitate effective decision-making in complex, poorly structured tasks that have many actors, factors and relationships and are characterized by high uncertainty and conflicting interests of participants [63];

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[18] Cohen-Shacham, E., Janzen, C., Maginnis, S. and Walters, G., 2016. *Nature-Based Solutions to Address Global Societal Challenges.* Gland, Switzerland: IUCN, 97 p. doi:10.2305/IUCN.CH.2016.13.en

4) enable intuitive interfaces enabling interaction between end users and software [64];

5) integrate interdisciplinary data and process knowledge [52];

6) operate on different time and space scales [52, 64];

7) adequately assess dynamics within the system, including feedback [52];

8) build flexible and modular programs that can be efficiently maintained, extended and adapted to similar case studies [65].

Conclusion

When solving the problems of predicting dangerous hydrometeorological phenomena and preventing their occurrence, it is necessary to rely on the experience of events that have already occurred such as analysis of databases, publication of documents from state organizations, insurance companies and private archives (pre-revolutionary observations). Field observations are of paramount importance, as well as development of a network of wide spatial coverage stations, further development of ship-based observations and regular remote monitoring of key variables or indicators of natural hazards. These will make it possible to obtain operational information, carry out fundamental studies of physical mechanisms of natural disasters and use this data for verification and assimilation of numerical models.

At the country level, the integrated modeling system development is needed to account for complex interaction processes, such as atmosphere and ocean, waves and currents, hydrodynamic and morphodynamic interactions, as well as the use of nested modeling techniques for large-scale studies of process dynamics.

Separately, it is necessary to take into account the peculiarities of natural disasters occurring in the northern regions of our country, which are often characterized by extreme background weather conditions, inaccessibility and remoteness, lack of necessary infrastructure to save people and eliminate consequences. The methods applied in disaster risk management are not universal, so the knowledge and experience gained as a result of NHs occurrence in warmer areas cannot be blindly transferred to natural disasters that occurred in cold conditions.

We believe that in the next 50 years, with the active development of synergy in science, the introduction of quantum computing and the reduction in the cost of space observations, the reliability of forecast of NHs and their ensembles will improve, and the timing of predictions will increase.

At the same time, the importance of research on fundamental climatic processes and phenomena cannot be underestimated. This requires training of qualified specialists in relevant specialties with classical fundamental knowledge of meteorology, hydrology, oceanology, biology, physics and mathematics.

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