ABSTRACT

Doctor of Philosophy (PhD) dissertation
in the educational program
8D06101 – "Information Systems (by Branch)"

RUSLAN KAIRATOVICH CHETTYKBAYEV

INFORMATION AND ANALYTICAL SYSTEM FOR FORECASTING FLOODING DURING SEASONAL FLOODS

General characteristics of the work: This dissertation is devoted to the development of an intelligent information and analytical system for flood forecasting during seasonal floods. The paper proposes a scientifically sound architecture for integrating hydrological, meteorological, and satellite data into a unified digital environment, enabling automated collection, modeling, visualization, and forecasting of flood zones. The developed mathematical models and algorithms allow for the simulation of flood dynamics, improving the accuracy of identifying potential risk zones and the efficiency of emergency prevention. The system has been tested on the rivers of East Kazakhstan and demonstrated high convergence of calculations with actual flood zones.

Keywords: floods, flood forecasting, remote sensing, hydrodynamic models, MIKE, HEC-RAS, Saint-Venant equations, GIS modeling, digital elevation models, machine learning, emergency monitoring, hydrological data, flood zone visualization, information and analytical system.

Relevance of the Study.

Floods are among the most destructive natural phenomena, annually causing economic losses, infrastructure degradation, and threats to human life. East Kazakhstan is a high-risk hydrological region due to its complex topography, unstable snow and rainfall patterns, and dense river network. Existing forecasting systems are typically based on disparate data and do not provide sufficient decision-making timeliness.

The relevance of this study is determined by the need to create an integrated system capable of combining satellite, hydrometeorological, and terrain data, modeling flood processes, and producing highly accurate flood zone forecasts. The dissertation presents the first comprehensive approach to building an intelligent information and communication system adapted to the river systems of East Kazakhstan.

In addition, part of the dissertation research was completed as part of the research project BR21882022, "Research on Avalanche Activity in the East Kazakhstan Region for the Development of Monitoring Systems and Scientific Substantiation of Their Placement," for 2023–2025. This project explored a subject area including natural and climatic factors, snow mass formation mechanisms, slope process characteristics, and hazardous event forecasting methods.

The research focuses on flood processes in the river systems of East Kazakhstan.

The study focuses on methods for integrating heterogeneous hydrological, meteorological, and satellite data, mathematical modeling, and comprehensive analysis of their spatiotemporal characteristics, aimed at developing an intelligent system for high-precision flood forecasting.

The objective of the study is to improve flood monitoring and management in the East Kazakhstan region by developing a scientifically based intelligent information and analytical system that provides comprehensive monitoring, multivariate analysis, and highly accurate flood zone forecasting during emergency situations.

Research objectives:

1. To analyze the natural, geographical, and socioeconomic prerequisites for flood hazard in East Kazakhstan.
2. To study modern methods and software for hydrological and hydrodynamic modeling and determine their capabilities and limitations.
3. To develop a methodology for integrating remote sensing data, hydrological observations, and digital elevation models into a single information base.
4. To create a physical and mathematical model of river flow based on the Saint-Venant equations and numerical algorithms for calculating unsteady flow.
5. To develop the architecture and functional structure of an information and analytical system, including modules for data collection, modeling, forecasting, and visualization.
6. To test the system in pilot areas of East Kazakhstan and evaluate the effectiveness of forecasts compared to actual data.

Main research methods: the work used methods of hydrodynamic and hydrological modeling (Saint-Venant equations, laws of conservation of mass and momentum, Chezy and Manning formulas), numerical methods for solving systems of differential equations (finite difference method, Range-Kutta scheme, implicit methods), machine learning methods (Decision Tree, Random Forest, LSTM networks) for predicting water levels with incomplete observations, geoinformation technologies and tools for spatial data analysis (NextGIS, QGIS, Leaflet, Copernicus DEM), the MIKE 11 software package for modeling hydraulic regimes and constructing flood maps.

Scientific provisions submitted for defense:

1. A mathematical model of the flood process, based on the Saint-Venant equations and modern numerical algorithms for modeling unsteady flows, allowing for the reproduction of water flow dynamics and improved flood forecast accuracy.
2. Algorithms for a comprehensive assessment of the impact of key hydrometeorological factors—precipitation totals, average temperature, snow depth, temperature gradient, and soil freezing depth—on the quality of a flood forecast model, providing a quantitative determination of their contribution to forecast accuracy and stability.

3. The architecture and functional structure of an information and analytical flood forecasting system, providing automated collection, processing, analysis, and visualization of hydrological, meteorological, and satellite data.

The scientific novelty of this work lies in the fact that for the first time, an integrated flood forecasting architecture has been developed for the conditions of East Kazakhstan, including a data collection module, hydrodynamic modeling, forecasting, and GIS visualization. Algorithms for comprehensively assessing the impact of precipitation, temperature, snow cover, temperature gradient, and freezing on flood formation are proposed. The developed methodology enables the generation of highly detailed flood forecast maps and their use for operational decisions.

Publications. The results obtained in this dissertation have been published in five papers, including three articles in a peer-reviewed journal (with a CiteScore percentile score of over 60%) and two articles in journals recommended by the Committee for Supervision of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan.

The research results presented in the published articles:

1 Natalya Denissova, Ruslan Chettykbayev, Irina Dyomina, Olga Petrova, Nurbek Saparkhojayev. Integration of Space and Hydrological Data into System of Monitoring Natural Emergencies (Flood Hazards) // Appl. Sci. 2025, 15(14), 8050; DOI: https://doi.org/10.3390/app15148050. Impact factor 2.5. Citescore 5.5. Q2. Percentile: 69.

2 Yevgeniy Fedkin, Natalya Denissova, Gulzhan Daumova, Ruslan Chettykbayev, Saule Rakhmetullina. Avalanche Hazard Prediction in East Kazakhstan Using Ensemble Machine Learning Algorithms // Algorithms 2025, 18(8), 505; DOI: https://doi.org/10.3390/a18080505. Impact factor 2.1. Citescore 4.5. Q2. Percentile: 72.

3 Natalya Denissova, Nurakynov Serik, Petrova Olga, Daumova Gulzhan, Daniker Chepashev, Marua Alpysbay, Ruslan Chettykbayev. Dependence of Avalanche Risk on Slope Insolation Level and Albedo. // Atmosphere 2025, 16, no. 5: 556; DOI: https://doi.org/10.3390/atmos16050556. Impact factor 2.3. Citescore 4.9. Q2. Percentile: 60.

4 Chettykbayev R.K., Denissova N.F. Development of an information and analytical system for monitoring the flood situation on the rivers of the East Kazakhstan region. // Bulletin of the D. Serikbaev EKTU. - Vol. 4. - Ust-Kamenogorsk, 2020. - p. 54-59. https://www.ektu.kz/files/vestnik/Vestnik_4-2020.pdf.

5 R.K. Chettykbayev, N.F. Denissova. Information-analytical system for forecasting the flooding of territories during seasonal flood (статья) // Bulletin of the D. Serikbaev EKTU. – Vol.4. – Ust-Kamenogorsk, 2022. - p. 243-254. DOI: https://doi.org/10.51885/1561-4212_2022_4_243.

The main results of this dissertation were presented and discussed at international conferences:

- International Conference v.Int.Exchange, West Saxon University of Applied Sciences Zwickau, Germany, January 5, 2021.

- IX International Forum of Young Scientists (March 28 – April 4, 2019), Ust-Kamenogorsk, 2019.

- International Scientific and Practical Conference, Khabarovsk, Russia, December 2022.

Structure and scope of the dissertation.

This dissertation is presented on 123 computer-printed pages and consists of an introduction, four sections, a conclusion, a list of 122 references, and appendices. The text is illustrated with 30 tables, 36 figures, and 108 formulas.

The first chapter analyzes the natural, geographical, and socioeconomic factors of flood hazard, as well as modern approaches to flood forecasting and modeling. Existing monitoring systems and methods for integrating remote sensing data and hydrological observations are examined. The concept of an information and analytical system is formulated, and requirements for its architecture and functional modules are defined.

The second chapter presents the fundamentals of mathematical modeling of hydrological processes, providing a physical and mathematical formulation of the problem based on the Saint-Venant equations. Numerical solution methods, model implementation algorithms, and the adaptation of the HEC-RAS and MIKE 11 software packages are discussed. Flood modeling was performed using river systems in East Kazakhstan as an example, and the calculation accuracy was verified and analyzed.

Chapter three presents the structure and architecture of the system, including modules for data collection, modeling, forecasting, and visualization. The operating principles, module interactions, and the technologies used (Python, PostgreSQL/NextGIS, FastAPI, QGIS) are described. Information security, reliability, and user interface issues are addressed.

Chapter four presents the results of experimental calculations and system testing in pilot areas (the Kurchum, Bukhtarma, and Irtysh rivers). The calculated and actual flood zones are compared, and the accuracy and effectiveness of the system are assessed. The feasibility of integrating the developed solution into regional emergency monitoring systems and the prospects for scaling it up for other basins in Kazakhstan are demonstrated.

The conclusion summarizes the results of the study and formulates the main scientific and practical results confirming the achievement of the dissertation's objective. Directions for further research are identified, including the development of forecasting algorithms based on neural networks and the expansion of the system's application to other climatic and hydrological conditions.

The dissertation concludes with a list of references and appendices.