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Water Flow Forecasting and River Simulation for Flood Risk Analysis

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***Abstract* – The paper presents the state-of-the-art in flood forecasting and simulation applied to a river flood analysis and risk prediction. Different water flow forecasting and river simulation models are analysed. An advanced river flood forecasting and modelling approach developed within the ongoing project INFROM is described. It provides an integrated procedure for river flow forecasting and simulation advanced by integration of different models for improving predictions of the river flood risk outputs. A case study on river flow modelling and simulation for river flood risk analysis is given**

***Keywords* – Flood risk output analysis, integrated forecasting and simulation, river simulation, water flow forecasting**

I. Introduction

Floods are the most common natural disasters that often cause significant economic losses, and human and social tragedies. Therefore, flood forecasting and its effective control is always a huge challenge for governments and local authorities [1]. Forecasts of river flow may be developed in the short term, over periods of a few hours or a few days, and in the long term, up to nine months [2]. An efficient flood alarm system based on a short-term flow forecasting may significantly improve public safety, mitigate social damages and reduce economic losses associated with floods.

Flooding may be caused by several reasons such as snow and ice melting in rivers in the spring causing freshet; heavy raining in the neighbouring areas, and wind-generated waves in the areas along the coast and river estuaries. In Latvia, springtime ice drifting and congestion can cause a rapid rise in water levels of the Daugava, Gauja, Venta, Dubna, Lielupe, Ogre and Barta rivers. The risk of flooding along the Daugava River is relatively high, and in most flood sensitive areas (e.g., in Daugavpils district) it may occur even twice a year. Floods in Riga and Jurmala districts located in the deltas of Daugava and Lielupe rivers and on the Gulf of Riga coast may be caused by the west wind during 2–3 days at a speed greater than 20 m/s following by winds in the north-west direction. As a result, the reverse water flow from the Gulf of Riga into the Daugava and Lielupe rivers may significantly rise to flood levels in these areas.

Flood forecasting and modelling is undoubtedly a challenging field of an operational hydrology, and a considerable amount literature has been written in that area in recent years. A flow forecast is an asset for flood risk management to reduce damage and protect an environment [3]. Reliable flow forecasting may present an important basis for efficient real-time flood management, including flood monitoring, control and warning. The integration of monitoring, modelling and management becomes important in the construction of alert systems. Nowadays, the application of remote sensing and GIS software that integrates data management with forecast modelling tools becomes a good practice [4]-[6]. Additionally, different flooding scenarios may be simulated based on the results of forecasting models to allow analysing dynamics of the river floods and evaluating their potential effects in the near future.

This paper provides the state-of-the-art in the area of river flood forecasting and modelling, as well as describing advanced river flood forecasting and simulation models developed within the ongoing research project INFROM “Integrated Intelligent Platform for Monitoring the Cross-border Natural-Technological Systems” [7], [8]. Different water flow and flood forecasting techniques have been used and compared – traditional regression-based forecasting techniques, symbolic regression [9], and cluster analysis of dynamic water flow data and identification of typical dynamic patterns. Among flood monitoring models, hydrodynamic and hydrological models have been reviewed and compared. A procedure for integrated river flow forecasting and simulation has been developed and advanced by integrating different models and metamodels for improving flood risk output analysis.

The project itself addresses the problem of integrated monitoring and control of natural-technological systems based on the analysis of heterogeneous data from space and ground-based facilities and integration of different types of models (i.e., analytical, algorithmic, mixed) to model behaviour of these systems.

II. The State-of-the-Art

There are several models and systems that allow predicting flood risk outputs by the remote sensing technology, GIS, hydraulic and hydrology modelling. In this paper, flood forecasting and simulation models and techniques that are used for river flow predictions and flood risk output generation are reviewed.

River flood monitoring and control require measurement and notification of the water level, velocity, and precipitation. Input data for precipitation forecast are meteorological data and weather forecasts as the most important components of a flood forecasting and early warning system [10]-[11]. In practice, river flood forecasting is based on mining historical data and specific domain knowledge to deliver more accurate flood forecasts. Effective flood monitoring and control use space and ground-observed data received from satellites and terrestrial (meteorological, automatic rain gauge, and climatological) stations. These data may be represented as images, terrain information, and environmental information, i.e., soil type, drainage network, catchment area, rainfall, hydrology data, etc. Data representation and processing proven technologies and expertise are offered in [11].

Besides, expert knowledge may be integrated into the flood risk assessment procedure, producing river flood scenarios to be simulated, and measures for flood damage prevention or reduction. When risk outputs are calculated, decisions for preventive actions can be made based on flood risk maps, flood forecast maps, flood emergency response maps, and based on detection and monitoring for early warning mitigation and relief.

Hydrodynamic river flow processes might be represented by a variety of different models based on geological surroundings, for example, the conceptual HBR model [13], ANN-based runoff predictors with a fuzzy classifier of the basin states [14], hydrodynamic deterministic models improved by uncertainty coping to produce the probabilistic hydrological forecast [15].

A conceptual model of the river may be described in different ways due to a different scope of the model [1], [10], [16]. One of common simplifications of the hydrodynamic river flow processes is achieved by lumping of the processes in space and limiting the study area to the region affected by the flood control. The lumping of the processes in space is done by the simulation of the water levels only at the relevant locations. These locations are required to be selected in upstream and downstream points of each hydraulic regulation structure and places along the river [1].

Flood monitoring models may be classified as hydrodynamic and hydrological models. *Hydrodynamic models* describe and represent the motion of water flow using the so-called Navier-Stokes equations, which describe the motion of fluid substances in physics.

Hydrological models are simplified conceptual representations of part of the hydrologic cycle. Hence, they are considered to be more suitable for water flow modelling in flood monitoring. Hydrological models used in the forecasts can be grouped as follows [16]: 1) *stochastic hydrological black-box models* that define input-output relations based on stochastic data and use mathematical and statistical concepts to link a certain input to the model output; and 2) *conceptual or process-based models* that represent the physical processes observed in the real world. While black-box models are empirical models and use mathematical equations without regard to system physics, conceptual models apply hydrological concepts to simulate the basin or river behaviour.

Stochastic hydrological models are more popular in literature due to their simplicity. Among them, linear perturbation models, HEC models and neural network-based flood forecast systems are considered to be the most efficient tools in practice [16]. In particular, linear perturbation models assume that the perturbation from the smoothened seasonal input rainfall and that of discharge are linearly related. However, the rainfall-runoff relationship was recognized to be nonlinear, and coupling fuzzy modelling and neural networks for flood forecasting that do not assume input-output model relationship to be linear was suggested in [14]. In the Hydrologic Engineering Centre (HEC), models are numerical models for simulation of hydrologic and hydraulic processes. HEC models solve the Saint-Venant equations using the finite-element method. The primary surface water hydrology model is HEC-1 Flood Hydrograph Package, which can simulate precipitation-runoff process in a wide variety of river basins. The predictive power of HEC models is also discussed in [1], [17].

Conceptual models usually have two components [3], i.e., a rainfall-runoff module, which transfers rainfall into runoff through water balance in the river hydrological components, and a routing module, which simulates the river flow. Conceptual models, such as Soil Moisture Accounting and Routing (SMAAR) model, NAM and Xinanjiang models, which have a number of parameters 5, 13, 15, respectively, were applied to seven river basins in Sri Lanka [16]. Data requirements for modelling were formulated, and the calibration and validation of models were performed. The results obtained demonstrated the applicability of all models, but NAM and Xinanjiang models were found more appropriate as flood peaks were represented by separate parameters in these models.

There are several major river modelling software tools, such as HEC-RAS, LISFLOOD-FP and TELEMAC-2D. HEC River Analysis System (HEC-RAS) allows performing one-dimensional steady flow, unsteady flow, and water temperature modelling. The HEC-RAS model solves the full 1D Saint-Venant equations for an unsteady open channel flow. LISFLOOD-FP is a raster-based inundation model specifically developed to take advantage of high resolution topographic data sets [18] and adopted to a 2D approach. TELEMAC-2D is a powerful and open environment used to simulate free-surface flows in two dimensions of a horizontal space [19]. At each point of the mesh, the program calculates the depth of water and the two velocity components. The model solved 2D shallow water (also known as Saint-Venant equations or depth average) equations for free surface flow using the finite-element or finite-volume method and a computation mesh of triangular elements (see http://www.opentelemac.org).

The predictive performance of three models is analysed in [17]. The different predictive performances of the models stem from their different responses to changes in friction parameterisation. Also, the performance of the LISFLOOD-FP model is dependent on the calibration data used. Nevertheless, performance of 1D HEC-RAS model gives good results, which are comparable with ones received from more sophisticated 2D approaches adopted by LISFLOOD-FP and TELEMAC-2D. In addition, HEC-RAS models allow building long-term flood forecasts, but require large input datasets. Finally, these models reflect moving in recent years from a 1D approach (represented by the US Army Corps of Engineers HEC-RAS model) towards 2D finite element (TELEMAC-2D developed by Electricite´ de France) and raster-based (LISFLOOD-FP) models.

III. Advanced Approach

River flow forecasting and simulation are advanced by integrating different models for improving flood risk output prediction, including input data clustering, digital maps of the relief, data crowd sourcing technology, symbolic regression-based short-term forecasting models, different hydrological models for modelling water flows in short-, mid- and long-term forecasts, computer simulation models for simulating behaviour of the river and its visualisation, techniques for flooding scenario generation and comparison. Real-time flood forecasting and monitoring are based on processing the data received from both space and ground-based information sources.

Clustering of dynamic historical data is introduced, which allows identifying typical dynamic flooding patterns in the real-life situations.

A symbolic regression-based forecasting model is integrated for river flow short-term forecasting and monitoring in a specific real-life situation. Here, main challenges are a small number of input factors and a small set of flow measurements. For developing a symbolic regression-based forecasting model, genetic programming within HeuristicLab [21] is used. A symbolic regression-based forecasting model is described in [9].

Hydrological models are advanced by realistic physical models that are derived from topological maps and represent geo information of the river and neighbouring areas. Additionally, different regression-based metamodels using river simulation results are introduced, which allow performing the sensitivity analysis of input factors influencing river water levels and flooding risk as well as improving output results received from the forecasting models. In the future, this approach will be extended by automatic generation and analysis of flooding scenarios for mid- and long-term flood management operations.

IV. Case Study

A case study was developed for water flow modelling and flood area modelling and simulation in the region of the Dubna River in Livani district (Latvia) in order to show the applicability of the proposed approach.

A. Description of Software

The above-mentioned Hydrologic Engineering Centre River Analysis System (HEC-RAS) is used for river water flow modelling.

HEC River Analysis System (HEC-RAS) allows performing one-dimensional steady flow, unsteady flow, sediment transport/mobile bed computations, and water temperature modelling. The HEC-RAS model solves the full 1D Saint-Venant equations for an unsteady open channel flow:

$$\frac{\partial A}{\partial t}+\frac{\partial \phi Q}{\partial x_c}+\frac{\partial (1-\phi) Q}{\partial x_f}=0, \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x_c}\left(\frac{\phi^2 Q^2}{A_c}\right)+\frac{\partial}{\partial x_f}\left(\frac{(1-\phi)^2 Q^2}{A_t}\right)+ \\ +gA_c\left(\frac{\partial z}{\partial x_c}+S_c\right)+gA_f\left(\frac{\partial z}{\partial x_f}+S_f\right)=0 \tag{2}$$

$$\phi=\frac{K_c}{K_c+K_f}, \text{ where } K=\frac{A^{5/3}}{nP^{2/3}}, \tag{3}$$

$$S_c=\frac{\phi^2 Q^2 n_c^2}{R_c^{4/3} A_c^2},\ S_f=\frac{(1-\phi)^2 Q^2 n_f^2}{R_f^{4/3} A_f^2} \tag{4}$$

Q is the total flow down the reach, A is the cross-sectional area of the flow (A_c in channel, A_f floodplain), x_c are distances along the channel and x_f are distances along the floodplain, P is a wetted perimeter, R is a hydraulic radius (A/P), n is the Manning's roughness value and S – the friction slope.

These equations are discretized using the finite difference method and solved using a four-point implicit (box) method. HEC-RAS executable code and documentation have been developed with the US Federal Government resources and are, therefore, available in the public domain.

B. Input Data

Two types of input data are used for river modelling, i.e., water quality and quantity monitoring data for water flow simulation and topographic data for developing a river physical model.

The Latvian Environment, Geology and Meteorology Centre ensures water quality and quantity monitoring, quality control of data and their availability for public, maintenance of the database on the use of water resources, river basin management, as well as preparation of various statistical reports for national and international institutions and calculation of flood territories.

Hydrology observations are performed using 71 observation stations, and the Centre website (http://www.meteo.lv/hidrologija-datu-meklesana/?nid=466) provides multiple parameter observation data.

At least 19 observation stations are located on the Daugava River and, thus, can provide the information required. Most of these stations provide information on water levels, heights of waves, a state of water, a flow direction, etc.

In the case study, hydrological data from three hydrologic stations on the water levels and flow directions are used as inputs to water flow simulation. The water level is measured as water height from the bottom of the river in millimetres, and a flow direction is measured in degrees, considering the north direction as a zero degree.

Geographic information is used in order to develop a realistic model of the river basin using information on the depth of the river and specifying a sufficient number of the river cross-sections. This geographic information is received from the topographic maps that contain information about the geodetic control points, topography, hydrographs, vegetation, soil, economic and cultural facilities, roads, communications, border areas and other facilities.

Topographic maps present an effective information source because of the contour lines. These lines drawn on the map connect points with an equal elevation. It means that if you physically follow a contour line, elevation will remain constant. Contour lines show elevation and illustrate the shape of the terrain or the shapes of the land surface. Using these shapes, information required from river-cross sections is obtained. The topographic map of the Dubna River is presented in Fig. 1.

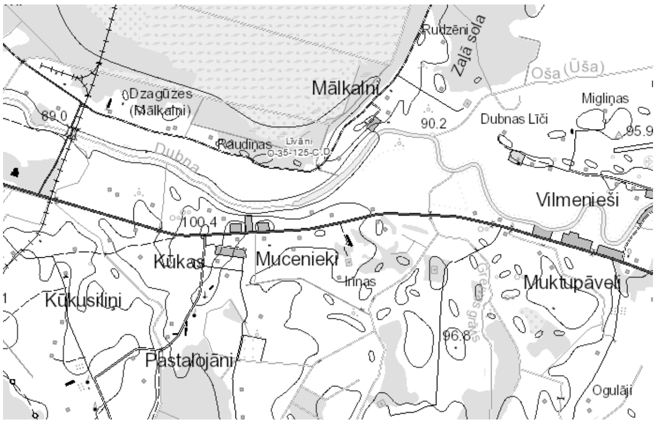

Fig. 1. Topographic map of the Dubna River

C. Model

A simulation model prototype for water flow forecasting and river simulation using HEC-RAS river modelling system software was built that models geometry of the Dubna River and simulates its flows.

Information from 3 observation stations was used for modelling: one station near the point where the Dubna flows into the Daugava River and one station at each of two Dubna tributaries.

Fig. 2. HEC-RAS based model of the Dubna River

The graphical model of the river is shown in Fig. 2 and contains information about 8 cross-sections that define all information required for calculations. The model is capable of performing simulation experiments with both steady and unsteady flows. Here, the flow is assumed to be unsteady as it is typical of areas with a flooding chance.

Numerical results of modelling are observed as a data set (see Fig. 3). Simulation output is also visualised by means of perspective plots (see Fig. 4).

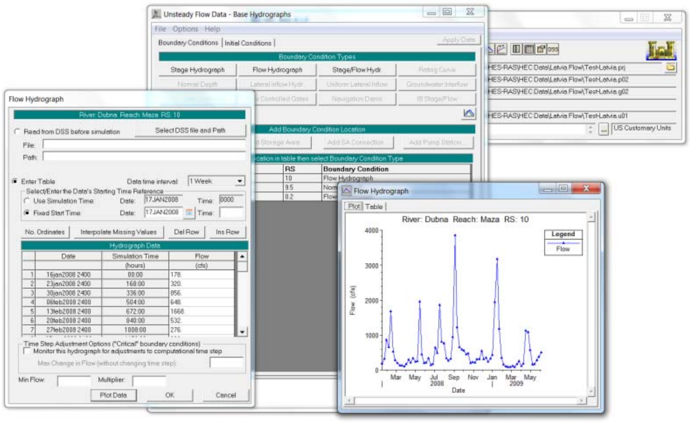

Fig. 3. River simulation model output visualisation

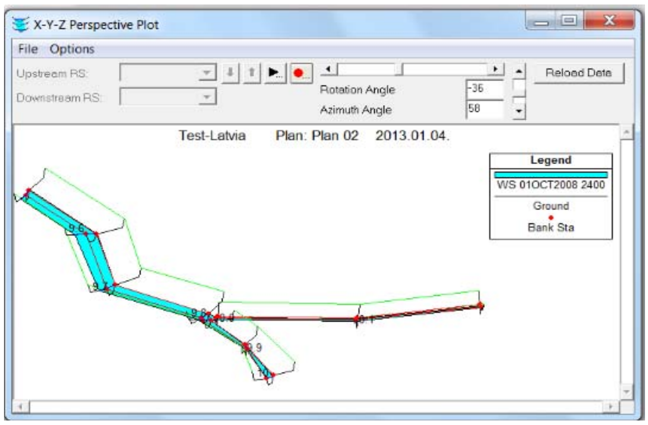

Fig. 4. River simulation model output visualisation

The results of modelling show possibilities of intense river flows in late autumn and winter; however, the level of water does not rise higher than river banks at the observed section of the river, and does not present a high flooding risk in this district.

V. Conclusions

The review of the state-of-the-art in river flood flow forecasting and simulation allows defining the most efficient models and tools for water flow forecasting and river simulation. The river flood forecasting and simulation procedure proposed in the paper allows integrating capabilities of both forecasting and simulation techniques for advancing risk analysis of river floods.

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REFERENCES

[1] P.-K. Chiang, P. Willems, J. Berlamont, "A conceptual river model to support real-time flood control," in *Demer,’ River Flow 2010 - Dittrich, Koll, Aberle & Geisenhainer,* 2010, pp. 1407-1414.

[2] K.P. Georgakakos, R. Krzysztofowicz, "Probabilistic and Ensemble Forecasting (Editorial)," *Journal of Hydrology*, 249(1), 2001, pp.1-4.

[3] C. Tucci, W. Collischonn, "Flood forecasting," WMO Bulletin 55 (3), 2006, pp. 179-184.

[4] B. Pradhan, "Effective Flood Monitoring System Using GIT Tools and Remote Sensing Data," *Applied Geoinformatics for Society and Environment,* Stuttgart University of Applied Sciences, 2009, pp. 63-71.

[5] A. Irimescu, V. Craciunescu, S. Gheorghe, A. Nertan, "Remote Sensing and GIS Techniques for Flood Monitoring and Damage Assessment. Study Case in Romania," in *Proceedings of BALWOIS 2010*, Ohrid, Republic of Macedonia, May 25-29, 2010, pp.1-10.

[6] C. Skotner, A. Klinting, H.C. Ammentorp, F. Hansen, J. Høst-Madsen, Q.M. Lu, H. Junshan, "A tailored GIS-based forecasting system of Songhua river basin, China," in *Proceedings of Esri International user conference*, San Diego, 2013, 6 p.

[7] Y.A. Merkuryev, B.V. Sokolov, G.V. Merkuryeva, "Integrated Intelligent Platform for Monitoring the Cross-Border Natural-Technological Systems," in *Proceedings of HMS 2012,* September 19-21, 2012, Vienna, Austria, 2012, pp. 7-10.

[8] G.V. Merkuryeva, Y. A. Merkuryev, "Advanced River Flood Forecasting and Simulation", *in Proceedings of the 25th European Modelling and Simulation Symposium, EMSS2013.* September 25-27 2013, Athens, Greece. Ed. by Agostino G. Bruzzone, Emilio Jimenez, Francesco Longo, Yuri Merkuryev, pp. 525-529.

[9] V. Bolshakov, "Regression-based Daugava River Flood Forecasting and Monitoring," in Scientific Journal of RTU, Series 5, Computer Science, 2013.

[10] Roy A. Badilla, "Flood Modelling in Pasig-Marikina River Basin," Master Thesis, International Institute for Geo-information science and Earth Observation Enschede, Netherlands, 2008, 73 p.

[11] S. M. Crooks, "Flood Studies at the River Basin Scale: Case Study of the Thames at Kingston (UK)," Centre for Ecology and Hydrology / Technical Report No. 53, 2011.

[12] "Astrium web site." [Online]. Available: www.astrium-geo.com/sg/3271-data-processing [Accessed: July 31, 2013].

[13] L. Iritz, "Conceptual Modelling of Flood Flow in Central Vietnam," Department of Water Resources Engineering, School of Engineers, Lund University, Sweden, P. 10.

[14] G. Corani, G. Guariso, "Coupling fuzzy modelling and neural networks for river flood prediction," in *IEEE Transactions on Men, Systems and Cybernetics*, 3 (35), 2005, pp. 382-391.

[15] ICPDR Report, Assessment of Flood Monitoring and Forecasting in the Danube River Basin, International commission for protection of the Danube River, Flood Protection Expert Group, 2010, P.19.

[16] G.T. Dharmasena, "Application of mathematical models for flood," in *Proc. Of the conference on Destructive Water: Water-Caused Natural Disasters, their Abatement and Control,* IAHS Publ., No 239, 1997, pp. 225-235.

[17] M. Horritt, P. Bates, "Evaluation of 1D and 2D numerical models for predicting river flood inundation," *Journal of Hydrology,* no. 268, 2002, pp. 87–99.

[18] P.D. Bates, A.P.J. De Roo, "A simple raster-based model for flood inundation simulation," *Journal of Hydrology*, 236, 2000, pp. 54-77.

[19] J. Galland, N. Goutal, J.-M. Hervouet, "TELEMAC—a new numerical-model for solving shallow-water equations," *Advances in Water Resources,* 3 (14), 1991, pp. 138-148.

[20] B. Gouweleeuwa, C. Ticehurst, P. Dycea, J. Guerschmana, A. Van Dijk, P. Thew, "An experimental satellite-based flood monitoring system for Sourthen Queensland, Australia," presented at IRSE 2011 Symposium, Sydney, 10-15 April 2011.

[21] M. Affenzeller, S. Winkler, S. Wagner, A. Beham, *Genetic Algorithms and Genetic Programming: Modern Concepts and Practical Applications*. Chapman & Hall/CRC, 2009.

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Gaļina Merkurjeva, Maksims Korņevs. Ūdens plūsmas prognozēšana un upes plūdu simulācija risku analīzei
Rakstā tiek izanalizēta prognozēšanas un modelēšanas labā prakse upju pārplūšanas analīzes un blakus teritorijās plūdu risku prognozēšana pielietojumos. Rakstā tiek aplūkotas pazīstamas literatūrā dažādas metodes un programmatūras sistēmas ūdens plūsmu modelēšanai un upju simulācijai. Tajā tiek apskatītas ūdens plūdu prognozēšanas un modelēšanas pieejas galvenās iezīmes, ko izstrādājusi pašreizējā projekta INFROM ietvaros. Šāda pieeja nodrošina plūdu modelēšanas integrētu procedūru, integrējot tajā dažādu veidu modeļus un metodes ieejas datu apstrādei, ūdens līmeņa prognozēšanai un plūsmu modelēšanai, kā arī upju pārplūšanas analīzei un tas seku grafiskai attēlošanai. Raksts arī sniedz gadījuma izpēti noplūdes un plūdu Dubnas upēs modelēšanai Latvijas teritorijā. Lai modelētu ūdens plūsmas upē, tiek izmantots hidroloģiskais modelis HEC-RAS modelēšanas programmatūrā, kas tiek definēts ar Sen Venāna diferenciālvienādojumiem nestabiliem upēs ūdens kustībām. Lai modelētu ūdens plūsmu upē, kā ieejas datus izmanto hidroloģiskos datus no trim hidroloģiskajām stacijām, tajā skaitā datus par ūdens līmeņiem Dubnas upē un ūdens plūsmu virzieniem tajā. Ģeogrāfiskā informācija, kas iegūta no Dubnas upes topogrāfiskajām kartēm, tiek izmantota lai izstrādātu reālu modeli upes baseinam, ņemot vērā informāciju par upes dziļumiemiem un pietiekamu skaitu sekciju tajā. Simulācijas gaitā iegūtie rezultāti tiek prezentēti ar modeļa izejas datu kopām un izanalizēti skaitliski, kā arī tiek paradīti lietotājam grafiskajā veidā.

Галина Меркурьева, Максим Корнев. Прогнозирование водных потоков и моделирование рек для анализа рисков наводнения
В статье анализируется состояние разработок в области прогнозирования и моделирования наводнений применительно к анализу разливов рек и прогнозированию рисков наводнений на прилегающих территориях. Дается обзор различных методов и программных систем для прогнозирования и моделирования наводнений, известных в литературе. Описываются основные особенности подхода к прогнозированию и моделированию разливов рек, разрабатываемого в рамках текущего проекта INFROM. Этот подход обеспечивает интегрированную процедуру прогнозирования и моделирования разливов рек, улучшенную путем интеграции различных типов моделей для обработки данных, прогнозирования уровня воды и моделирования потоков воды, а также визуализации разливов рек и их последствий. В статье приводится также тематическое исследование по моделированию потенциальных разливов и наводнений в районе реки Дубна на территории Латвии. Для моделирования потоков воды в реке используется гидрологическая модель в системе HEC-RAS, представленная системой дифференциальных уравнений Сен-Венана для нестационарных движений в реках. Для моделирования потоков воды в реке в качестве исходных используются гидрологические данные трех гидрологических станций об уровнях воды в реке и направлениях потоков. Географическая информация, полученная из топографических карт, используется для разработки реалистичной модели речного бассейна с учетом информации о глубине реки и указанием достаточного количества сечений реки. Анализируются численные результаты моделирования, представленные наборами данных и отображенные в графическом виде.