ADVANCED RIVER FLOOD FORECASTING AND SIMULATION

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ABSTRACT
The paper presents the state-of-the-art in flood forecasting and simulation applied to 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 presented. It provides an integrated procedure for river flow forecasting and simulation advanced by integrating different models for improving flood risk outputs prediction. Demonstration cases in river flow forecasting and floods modelling are given.

Keywords: water flow forecasting, river simulation, integrated forecasting and simulation, flood risk outputs analysis

1. INTRODUCTION

Flooding is one of the natural disasters which often cause significant economic losses, human and social tragedies. Due to this, flood forecasting and its effective control is always a huge challenge for governments and local authorities (Chiang et al. 2010). Forecasts of river flow may be developed in a short-term, over periods of few hours or a few days, and in a long-term, up to nine months (Georgakakos and Krzysztofowicz 2001). An efficient flood alarm system based on a short-term flow forecasting may significantly improve public safety, mitigate social damages and reduce floods economical loss.

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 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 with 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 Daugava and Lielupe rivers may significantly rise to floods levels in these areas.

Flood forecasting and modelling is undoubtedly a challenging field of operational hydrology, and a huge literature has been written in that area in recent years. A flow forecast is an asset for flood risk management, reducing damage and protecting environment (Tucci and Collischonn 2010). Reliable flow forecasting may present an important basis for efficient real-time flood management including floods monitoring, control and warning. The integration of monitoring, modelling and management becomes important in construction of alert systems. Nowadays, application of remote sensing and GIS software that integrates data management with forecast modelling tools becomes a good practice (Pradhan 2009, Irimescu et al. 2010, Skotner et al. 2013). Additionally, different flooding scenario may be simulated based on the results of forecasting models to allow analysing river flood dynamics and evaluating their potential effects in the near future.

This paper provides the state-of-the-art in river flood forecasting and modelling as well as describes 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". Different water flow and flood forecasting techniques have been used and compared - traditional regression-based forecasting techniques, symbolic regression, cluster analysis of dynamic data, and identification of typical dynamic patterns. Among flood monitoring models, hydrodynamic and hydrological models were 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 outputs analysis.

The project itself addresses (Merkuryev at al. 2012) the problem of integrated monitoring and control of natural-technological systems based on analysis of heterogeneous data both from space and ground-based facilities and integration of different types of models (i.e., analytical, algorithmic, mixed) used to model behaviour of these systems.

2. STATE-OF-THE-ART

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

River flood monitoring and control requires 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 (Badila 2008, Crooks 2011). In practice, river flood forecasting is based on mining historical data and specific domain knowledge to deliver more accurate floods forecasts. Effective flood monitoring and control use space and ground-observed data received from satellites and terrestrial (meteorological, automatic raingauge, 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 (Astrium web site).

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 (Irits 2005), ANN-based runoff predictors with a fuzzy classifier of the basin states (Corani and Guariso 2005), hydrodynamic deterministic models improved by uncertainty coping to produce the probabilistic hydrological forecast (ICPDR 2010), etc.

A conceptual model of the river may be described in different ways due to different scope of the model (Dharmasena 1997, Badilla 2009, Chiang et al. 2010). 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. Lumping of the processes in space is done by 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 (Chiang et al. 2010).

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

Hydrological models are simplified conceptual representations of a part of the hydrologic cycle. Hence, they are considered as more suitable for water flow modelling in flood monitoring. Hydrological models used in the forecasts can be grouped as follows (Dharmasena 1996): 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 with no regards to the 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 networks-based flood forecasts systems are considered to be the most efficient tools in practice (Dharmasena 1997). 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 has been 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 (Corani and Guariso 2005). In The Hydrologic Engineering Center (HEC) models are numerical models for simulation of hydrologic and hydraulic process. 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 (Horritt and Bates 2002; Chiang 2010)**.**

Conceptual models usually have two components (Tucci 2006), i.e. a rainfall-runoff module which transfer 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, correspondingly, were applied to seven river basins in Sri Lanka (Dharmasena 1997). Data requirements for modelling were formulated, and calibration and validation of models was done. The results obtained demonstrated 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 unsteady open channel flow. LISFLOOD-FP is a raster-based inundation model specifically developed to take advantage of high resolution topographic data sets (Bates and De Roo 2000) and adopted to 2D approach. TELEMAC-2D is a powerful and open environment used to simulate free-surface flows in two dimensions of a horizontal space. 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 (Horritt and Bates 2002). 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. Also, 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.

3. ADVANCED APPROACH

River flow forecasting and simulation is advanced by integrating different models for improving flood risk outputs 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-term, mid-term 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 food forecasting and monitoring is based on processing 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 (Affenzeller et al. 2009, Wagner 2009) is used.

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 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 medium and long-term flood management operations.

4. DEMONSTRATION CASES

Two cases below were developed for river flood monitoring and forecasting in two Latvian districts and demonstrate applicability of the proposed approach.

The first demonstration case is developed for the Dubna River water flow modelling and flood areas modelling and simulation. Hydrological data from three hydrologic stations (water levels and flow direction) and topographic data from topographic maps are used as inputs to water flow simulation and developing a river physical model. The water level is measured as water height from the bottom of the river in millimetres, and flow direction in degrees, considering north direction as a zero degree. Geographic information is used to develop a realistic model of the river basin using information on depth of the river and specifying a sufficient amount of the river cross sections.

A simulation model prototype using HEC-RAS River modelling system software was built that models geometry of the Dubna River and simulates its flows. The graphical model of the river is shown in Figure 1 and contains information about 8 cross sections that defines all information required for calculations. The model is capable to simulate both steady and unsteady flows. Here, the flow is assumed to be unsteady as typically for areas with flooding chance.

Figure 1: HEC-RAS based model of Dubna river

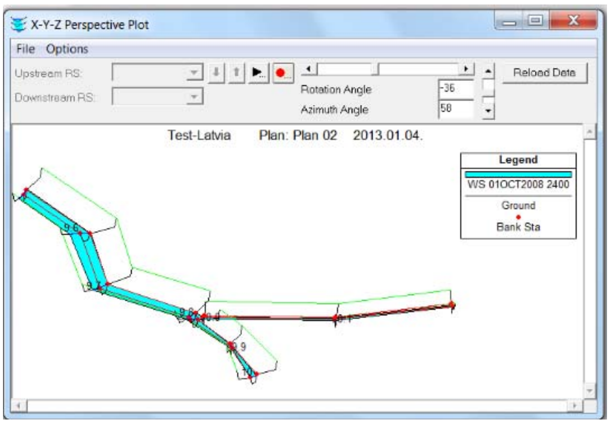

Figure 2: River simulation model output visualisation

Numerical results of modelling are observed as a data set or visualised means (see Figure 2).

The results of modelling demonstrate possibilities of an intense river flow in late Autumn and Winter, however the level of water does not rise higher than river banks at the observed section of the river.

The second case (see Potryasaev et al. 2013) was developed for a short-term flood forecast using space-ground monitoring data of the Daugava River near Daugavpils city in Spring 2013. The forecast horizon was defined by a period of up to 12 hours. A digital map of the relief of the specified area and hydrological river characteristics were received and integrated into the models. To train the forecasting model, historical data from the Daugava River monitoring station near Daugavpils city were used. Several forecasting scenarios – by using linear and nonlinear regression models, and symbolic regression - were tested. For operational forecasting in a time step of an hour and predicting related flood territory, real-time data received from the hydrological station were integrated into the input dataset. Figure 3 illustrates applicability of the developed symbolic regression-based models for predicting the Daugava River flow and flood forecast. The forecasting accuracy of the river water flow was within 95 %.

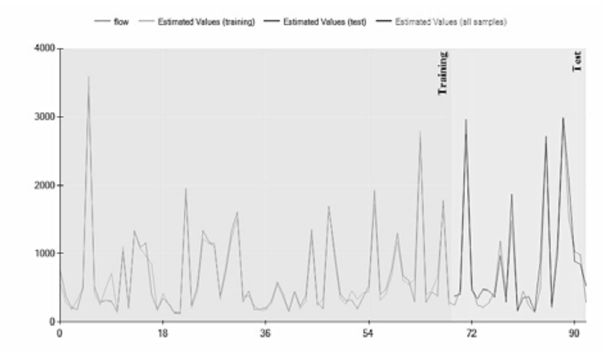

Figure 3: Empirical data versus model-based forecasting results

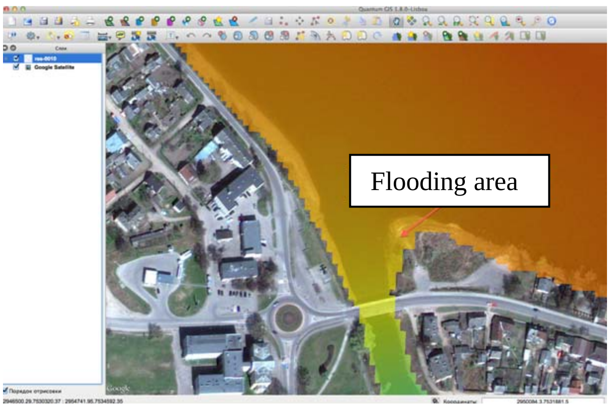

Figure 4: LISFLOOD model-based flooding area visualisation screen-short

A LISFLOOD model was developed to simulate water flows in the Daugava River and its floating routes. Calibration of the model has been performed based on satellite images and using data crowd sourcing through the geo-portal. As a result, the coincidence of flooding of significant objects (Fig. 4) has been received within 90%.

5. 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 flows 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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