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Advanced river flood monitoring, modelling and forecasting

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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 and systems are analysed. An advanced river flood monitoring, modelling and forecasting approach is introduced. It extends the traditional approach based on modelling river physical processes by integration of different types of models and technologies such as input data clustering and filtering, digital maps of a relief and river terrain, data crowdsourcing, heterogeneous data processing, hydrological models for time scale modelling water flows and geo-simulation, inundation visualisation and duly warning on flooding. A case study on river flow forecasting and simulation for river flood risk analysis and management is given.

1. Introduction

Flooding is one of natural disasters that often cause significant economic losses, human and social tragedies. Therefore, flood forecasting and its effective control is always a huge challenge for governments and local authorities [4]. Forecasts of river flow may be developed in the short term, over periods of a few hours or a few days, in the medium term, for several weeks, and in the long term, up to nine months [9]. 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.

Floods may be caused by different 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 and Lielupe rivers [19]. 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 the 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 followed 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.

The EU Directive 2007/60/EC on the assessment and management of flood risks states that it is feasible and desirable to reduce the risk of adverse impacts of floods, especially for human health and life (http://ec.europa.eu/environment/water/flood_risk/). Flood risk management generally involves flood monitoring, risk assessment and forecasting of the flood inundation areas. Flood monitoring can be performed by using satellite images which allow detecting river overflows and provide data for flood damage modelling and assessment.

Flood forecasting is a challenging field of an operational hydrology, and a considerable amount literature has been written in that area in recent years. A water flow forecast presents an asset for flood risk management to reduce damage and protect an environment [25]. 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 forecasting becomes important in the construction of alert systems. Nowadays, the application of remote sensing and GIS software that integrates data management with forecast modelling

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tools becomes a good practice [10,14,21,23]. 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 field of river flood modelling and forecasting [19], as well as describes advanced river flood monitoring, modelling and forecasting techniques developed within the research project ESTLATRUS/2.1/ELRI-184/2011/14 INFROM "Integrated Intelligent Platform for Monitoring the Cross-border Natural-Technological Systems" [18]. Different water flow and flood forecasting models have been used and compared – traditional regression-based forecasting techniques, symbolic regression [3], 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 new approach to integrated river flow monitoring, modelling and forecasting has been developed and advanced by integrating different models and technologies for improving flood risk forecasting, based on analysis of heterogeneous data received from different information sources. The development of the flood monitoring and forecasting system is based on the recent progress in the sphere of spatial modelling and simulation, modern geoinformation systems (GIS) and earth remote sensing technologies.

2. 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 [6,22,26]. 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, and hydrology data. Data representation and processing proven technologies and expertise are offered in [27].

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.

A traditional approach to flood modelling is based on modelling of river physical processes which describe the water motion or the hydrological cycle. In this context, flood monitoring models may be classified as hydrodynamic and hydrological models.

Hydrodynamic models represent the motion of water flow using the so-called Navier–Stokes equations, which describe the motion of fluid substances in physics.

Hydrodynamic river flow processes might be also represented by a variety of different models based on geological surroundings, for example, the conceptual HBR model [15], ANN-based runoff predictors with a fuzzy classifier of the basin states [5], hydrodynamic deterministic models improved by uncertainty coping to produce the probabilistic hydrological forecast [13].

A conceptual model of the river may be described in different ways due to a different scope of the model [4,7,22]. 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 at upstream and downstream points of each hydraulic regulation structure and places along the river [4].

Hydrological models are simplified conceptual representations 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 [7]: (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 [7]. 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 recognised 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 [5]. In the Hydrologic Engineering Centre (HEC), numerical models for simulation of hydrologic and hydraulic processes are used. 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 [4,11].

Conceptual models usually have two components [25], that is, 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 the number of parameters 5, 13, 15, respectively, were applied to seven river basins in Sri Lanka [7]. 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.

The results of flood forecasting based on the traditional modelling approach heavily depend on the preciseness of weather forecast (precipitation, wind direction and strength, etc.).

There are several major river modelling software tools including HEC-RAS, LISFLOOD-FP and TELEMAC-2D. The HEC River Analysis System (HEC-RAS) allows performing one-dimensional steady flow, unsteady flow, and water temperature modelling and solves the full 1D Saint-Venant equations for an unsteady open channel flow. The implementation of HEC-RAS models requires large datasets. LISFLOOD-FP is a raster-based inundation model specifically developed to take advantage of high resolution topographic data sets [2] 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 [8]. At each point of the mesh, the programme calculates the depth of water and the two velocity components. The model solves 2D shallow water