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APPLICATION OF ADVANCED INFORMATION AND COMMUNICATION TECHNOLOGIES IN A LOCAL FLOOD WARNING SYSTEM

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Abstract. This paper deals with the practical application of a local flood warning system. The system is built on the mathematical model of a selected area. The rainfall-runoff processes are simulated in real-time. The warning system is designed as an on-line, real-time data inputs-processing system so that it can provide a timely warning. The warning system is based on a mathematical model and it uses modern information and communication technology tools. For the system to work properly, it is absolutely necessary to adhere to a real mathematical model, and therefore a calibration on real historical data and direct measurements is required. This article describes the tasks of data collection, of building the mathematical model of the rainfall-runoff process, and the monitoring system design. The composed algorithm is able, based on the measured input data and the modeled situation, send a notification message to the monitoring centre and warn respective civil protection authorities via SMS messages.

Keywords: Flood warning system, mathematical modeling, hydro-informatics, data mining, rainfall-runoff processes, MIKE 21, MIKE URBAN

Mathematics Subject Classification 2010: 65-C20

1 INTRODUCTION

Nowadays Information and Communication Technologies (ICT) permeate most domains of science, research and technology, from the hydraulic domain [17] (which is the target of this article), to meteorology [13], hydrology [16] and to the related field like crisis management [15], to such remote domains as psychology [14]. These technologies offer different approaches to computations, some based on the knowledge of physical principles resulting in traditional sets of differential equations [11], others based on statistical approaches [20]. All are enabled by advances in computer hardware power and affordability [12] and novel methods of its use and sharing [10, 21].

Modern hydraulic modeling extensively uses ICT tools for data acquisition, preparation, processing, presentation [18] and visualization [6]. The presented local flood warning system is built on a mathematical model of the target area, where it in real time simulates rainfall-runoff physical processes. Since rainfall-runoff modeling is a complex scientific field, using several sophisticated modeling tools, it was necessary to analyze, in cooperation with our academic partners [19], these tools not only from the point of view of their scientific merits, but also from the point of view of their usability in a warning system. Not-measured catchment areas are the basic surface building blocks of the warning system. Their extent does not allow to solve this task in a direct assignment to public authorities – SHMI[1] or SWME[2] – as they usually represent one small catchment area containing one small stream. The warning system has been designed as working on-line, that is on real-time data inputs, so that the warning can be issued immediately or as soon as possible. The warning system's core is a computer model. For it to work correctly, it is necessary that the model is as realistic as possible, so it must be calibrated on historical sets of

[1] Slovak Hydrometeorological Institute, `http://www.shmu.sk/en/?page=1`

[2] Slovak Water Management Enterprise, `https://www.svp.sk/en/uvodna-stranka-en/`

hydrological parameters coupled with direct measurements in the target catchment areas.

As the target an area south of Trenčín and north of Trenčianska Turná has been selected, shown in Figure 1. The area contains the shopping mall Laugaricio Trenčín and is in the catchment area of the *Lavičkový potok* stream.

Figure 1. The target area of our model is marked as a green polygon

The area is influenced by the sewer system of Trenčín since the stream is the recipient of a relieve drain of the sewer system (Figure 2), which significantly increases its flow during intense rainfall [1].

2 FLOOD MODELING IN EUROPEAN UNION

To put the work described in this article in the context of other work regarding flood management in the European Union, we will present several previous projects done by DHI or in cooperation with DHI. They were effected mainly as part of the effort envisaged by the so-called EU Flood Directive [23]. This directive, among other things, requires also flood-mapping which means creation of flood risk maps for several flow volume values for a mapped river or stream. These flood maps are key inputs to planning flood protection, flood risk management, urban planning as well as crisis management. In Slovakia, several flood mapping initiatives have already started, with various results depending on the requirements of their respective customers. We will summarise them below.

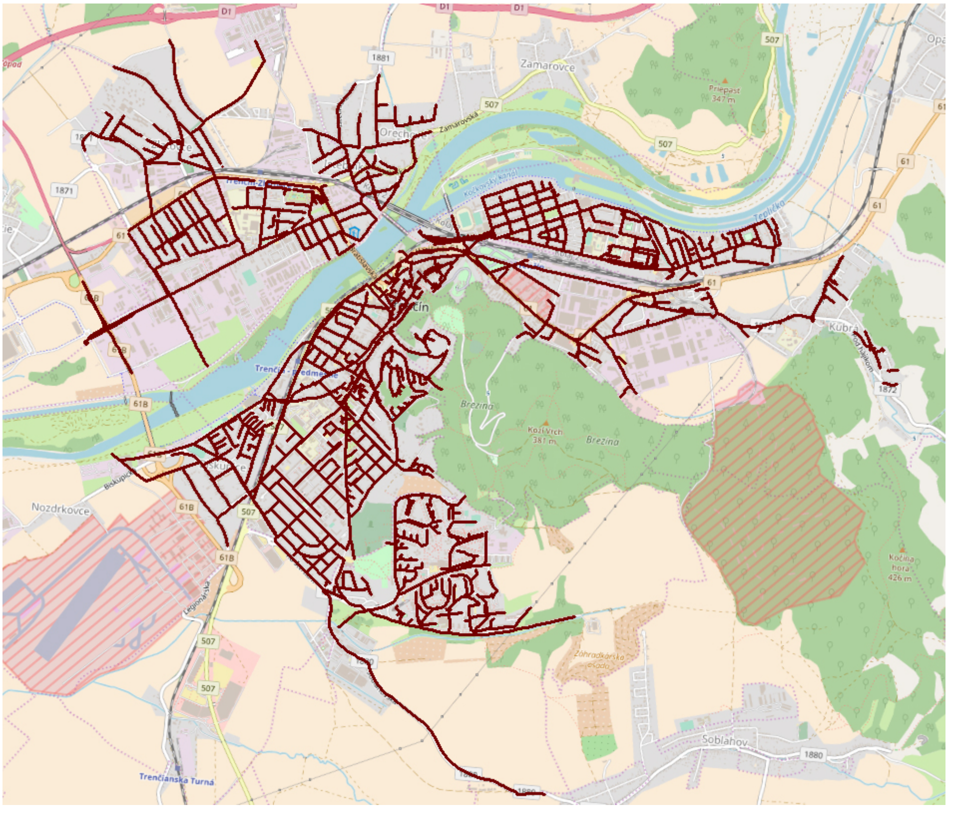

Figure 2. The extent of the model of sewer and drainage system of the city Trenčín

2.1 Banská Bystrica Flood Maps

- Modeled and mapped flow: Q5, Q10, Q20, Q50, Q100, Q1000
- Hydraulic modeling: 2D model with flexible computational mesh (MIKE 21 FM)
- Modeled detail: buildings and streets
- Outputs of hydrodynamical modeling: flood extents, water depth, flow velocity
- Map scale: 1:5 000
- Flood damage assessment: no

2.2 Levice Flood Maps

- Modeled and mapped flow: Q5, Q10, Q20, Q50, Q100, Q1000
- Hydraulic modeling: 2D model with flexible computational mesh (MIKE 21 FM)
- Modeled detail: buildings and streets

- Outputs of hydrodynamical modeling: flood extents, water depth, flow velocity
- Map scale: 1:7 500
- Flood damage assessment: no

2.3 Košice and Prešov Flood Maps

- Modeled and mapped flow: Q1, Q5, Q10, Q20, Q50, Q100
- Hydraulic modeling: 2D model with flexible computational mesh (MIKE 21 FM)
- Modeled detail: buildings and streets
- Outputs of hydrodynamical modeling: flood extents, water depth, flow velocity for grid 5×5 m
- Map scale: 1:10 000
- Flood damage assessment: no

2.4 Morava and Vlára Flood Maps

- Created in the international project CEFRAME [22]
- Modeled and mapped flow: Q50, Q100, Q500
- Hydraulic modeling: 2D model with flexible computational mesh (MIKE 21 FM)
- Modeled detail: less detailed, however important topological features are present: channels, dikes, road and railroad embankments
- Outputs of hydrodynamical modeling: flood extents, water depth, flow velocity for grid 5×5 m
- Map scale: Morava 1:50 000, Vlára 1:25 000
- Flood damage assessment: yes

3 DATA COLLECTION

A modern ICT system for transfer of measured data in water management uses a telemetry system, with a passive collection point receiving data from active measurement stations. The system of active measurement stations sends the measured data to a central server at certain intervals. Between those intervals the measurement station does not need to be connected to the telemetry system and may be in a standby mode, saving its stored power and extending its availability. The passive collection point is the database server. The data collected in the database from the measurement stations is subsequently processed and used in the modeling of the target area. Advances in measurement technology allow us to follow selected target attributes online and in offline mode, to store them and use them in the operation, maintenance, creation, reporting and also training of the mathematical prediction model. The data are processed by hydro-informatics systems.

The collection of data for our local flood warning system has been done on two automated rain gauges (telemetric probe HYDRO LOGGER H1 and a SR03 rain gauge), on one flow meter (M4016-G3 unit and a KDO probe) and on one water stage indicator (M4016 unit and the ultrasound probe US3200). Testing the data transfer has been executed using these modes:

- metallic symmetric mode,
- optical symmetric mode,
- wireless symmetric mode in a licenced frequency band 3.5 GHz,
- wireless symmetric mode in a free frequency band 5.8 GHz,
- GSM/GPRS/EDGE mode.

Testing proved GSM/GPRS/EDGE devices as the most successful because of their excellent signal coverage, high mobility of the measurement devices, independence on external power or on additional software and hardware.

	Metallic	**Optical**	**3.5 GHz**	**5.8 GHz**	**GSM**
External power	Yes	Yes	Yes	Yes	No
Additional sw	Yes	Yes	Yes	Yes	No
Additional hw	Yes	Yes	Yes	Yes	No
Connectivity	Needs conn. line		Needs direct visibility		Yes
Mobility	No	No	No	No	Yes
Mass deployment	Unsuitable				**Suitable**

Table 1. Comparison of different connection types of sensors

4 DEPLOYED INFORMATION INFRASTRUCTURE

A cloud composed of capable servers has been used for the data connection and evaluation tasks. This infrastructure hosts also the server which receives data from the deployed measurement stations. The data are first preprocessed and then stored in a database for later processing and archiving.

Based on the demands of the local flood warning system following servers were instantiated in the cloud:

- control and monitoring interface – used to monitor the cloud infrastructure, deployed measurement stations and component services of the warning system,
- data server for data collection and preprocessing,
- web server for measured data presentation in the form of graphs and tables,
- user interface server including an artificial intelligence component evaluating the probability of flood based on the measured data and underlying mathematical model of the target area.

A basic schema of the infrastructure used in the presented flood prediction system is shown in Figure 3.

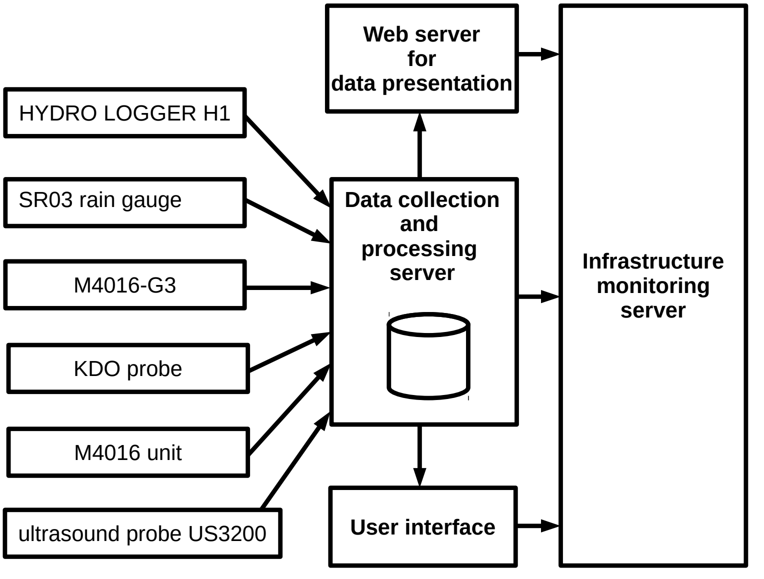

Figure 3. Schema of the deployed information infrastructure used to capture data, store them, present them and use them for flood modeling and prediction

5 MATHEMATICAL MODEL

To facilitate the creation of a mathematical model of the target area it was necessary to acquire and verify the set of input data. It contains a relatively large amount of information and their processing and verification is especially time-consuming [7].

The hydraulic mathematical model had to be then calibrated using the data from the measurement campaign, which had to be executed in advance. Missing data points, not acquired during the campaign (for example certain precipitation amounts) had to be added to the set by data mining.

Data mining is the process of non-trivial extraction of implicit, not known in advance, and potentially useful information from large data sets. It is therefore a process of discovery of hidden relations among the data and of patterns which can be then used for modeling and prediction.

There are also data mining applications in hydrology and meteorology, for example experiments realised during the FP7 project ADMIRE [2, 3], which for us simplify the data mining process.

6 CREATION OF THE HYDROLOGICAL SIMULATION MODEL

The hydrological model to simulate the rainfall-runoff process in the target watershed area has been created using the MIKE URBAN (MOUSE) level A module [9]. We have posited that there is 30 % of balast water in the sewage from Trenčín. The sewage flow has been computed using data on water consumption in the city. The balast water has been added to the computation for a total of 160 litres per person a day, including the added balast water.

The hydrodynamic model has been created using the simulation tool MOUSE, used to compute slow-changing, continuous flow in sewer systems and drainage canals.

As the basis of the creation of the sewer system model, the following data were used:

- sewer topology,
- geometrical data of the sewer pipes and other objects,
- pipe connections information,
- other data.

While creating the model a partial internal schematization was made, meaning the model of the sewer system contains all drains, objects and sewer segments, but smaller-dimension pipes do not include all drains.

For the composition of a two-dimensional hydrodynamical model and of the simulation itself the tool MIKE 21 FM has been used. MIKE 21 FM is a 2D mathematical model of continuous flow with a flexible computation mesh created by DHI. It is a complex simulation environment for 2D modeling of flow with a free surface. It is based on the solution of two-dimensional governing RANS (Reynolds averaged Navier-Stokes) equations integrated along the depth dimension [8]. The numerical solution is based in a discretization by division into non-overlapping components (triangles or quadrangles). The dependent variables of the system are represented as constant for the whole component and are tied to its center.

During the actualization and refinement of the model a computation mesh composed of triangles and quadrangles has been created, covering the complete target area. The mesh has been designed so as to sufficiently approximate the terrain details of the area. Mesh density is variable and chosen to allow for both sufficient model accuracy and numerical stability of the simulation. The mesh is composed of 211017 vertices and 309465 components. Part of it is shown for illustration in Figure 4.

Each vertex of the mesh in the 2D model has been described by the corresponding terrain height from a DTM model of the area. Based on geodetic measurements the model topography has been updated. This has lead to a model topography which we call *bathymetry* as it represents the bed of the potentially flooded area. It is partially shown in Figure 5.

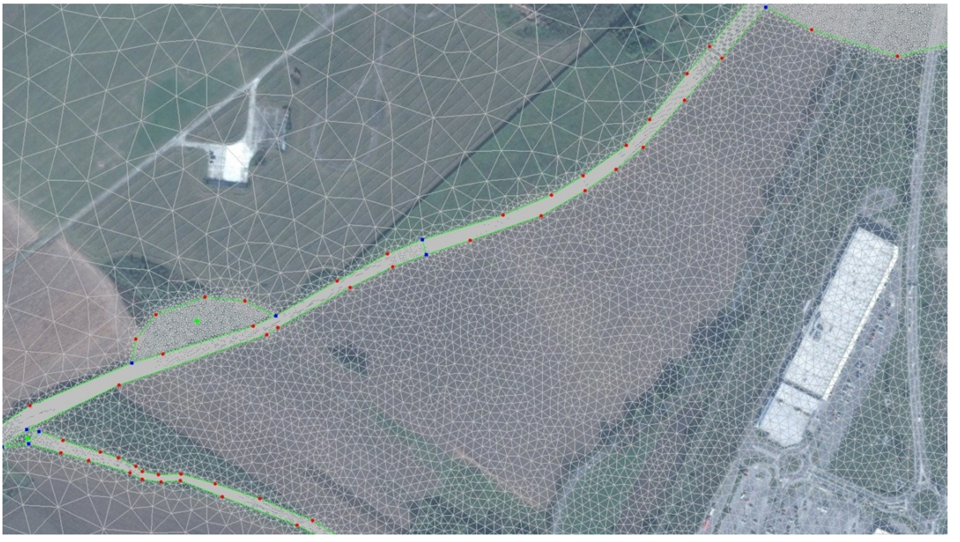

Figure 4. Partial computation mesh of the created two-dimensional mathematical model

Each component of the computation mesh of the model has a defined value of friction resistance in the form of Manning's roughness coefficient based on the type of terrain. The values have been selected based on the study of the ortophotomap, fotodocumentation and on an on-site inspection.

7 CALIBRATION OF THE HYDRODYNAMIC MODEL

The composition and following calibration of simulation models are highly specialized tasks with the goal to prepare a simulation environment for the following experiments with a variety of states of the model. Most of the tools for solving the surface flow tasks are based on a more or less exact description of the physical-chemical-biological processes in the rainfall-runoff action. This description is also determined by selection of the initial and boundary conditions of the simulation – the selection of parameters describing the initial state of the system (description of the watershed area, abundance of impermeable surfaces, infiltration capacity of the permeable surfaces and similar physical parameters). Some of these parameters are very difficult to measure. To obtain the correct values of these various coeficients and parameters of the governing equations or empirical equations a *model calibration* is used.

To calibrate a model, it is necessary to obtain a set of input and output parameters for known initial conditions (for example measured rainfall and the matching flow in the sewer system). Calibration assumes not only detailed knowledge of the mathematical model and its governing equations, but also the correct selection of a monitoring strategy, which will allow us to acquire sufficient empirical knowledge

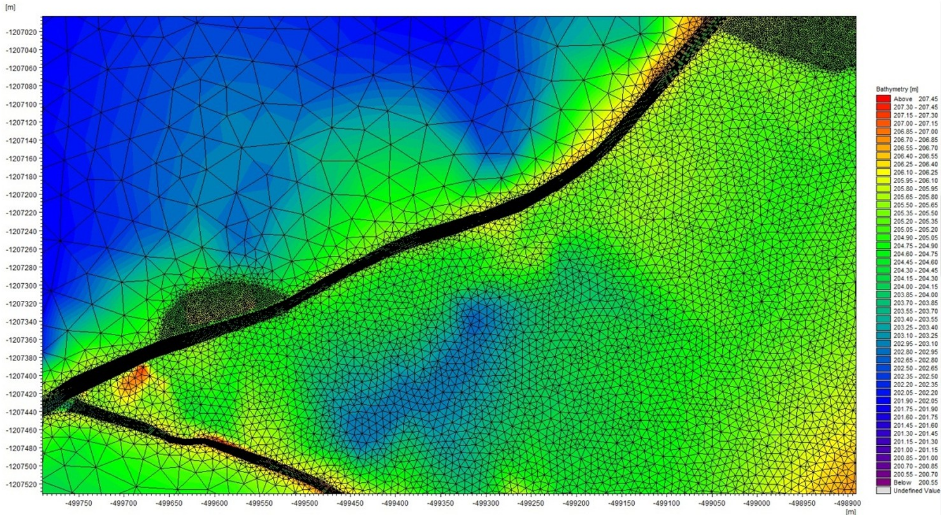

Figure 5. Partial bathymetry of the target area

of the parameters of the system in various meteorological conditions. It is the comparison of real, measured input parameters (causes) of the modeled system in various representative conditions and real, measured output parameters of the system (effects), which allow us to evaluate and tune the initial and boundary conditions of the model and the coefficients of the governing equations in situations when these cannot be reliably measured. Verification of the model is comparable to the process of calibration. The goal of verification is to evaluate the quality of the model on an independent series of input and output parameters. The process of calibration and verification of the simulation model is schematically shown in Figure 6 and in more detail described in [5].

It is obvious that the calibration process, additionally to the mentioned inputs, requires also extensive effort and resources from the user of the warning system. Selection of optimal parameters, which will provide the model with sufficient inputs for its calibration, while at the time will save as much time and resources as possible is one of the most important steps while solving the problem of urban drainage using modern simulation tools.

Despite being time-consuming and often costly, the process of calibration is an unavoidable part of the application of simulation models to most physical phenomena.

In order to simplify the calibration and subsequent verification of the mathematical model, a sensitivity analysis of the model may be an advantage. A sensitivity analysis of the input parameters (the influence of fraction of impermeable soil in the modeled area on the maximum flow, for example) can significantly speed up the calibration and verification process, even without considering simplification of the

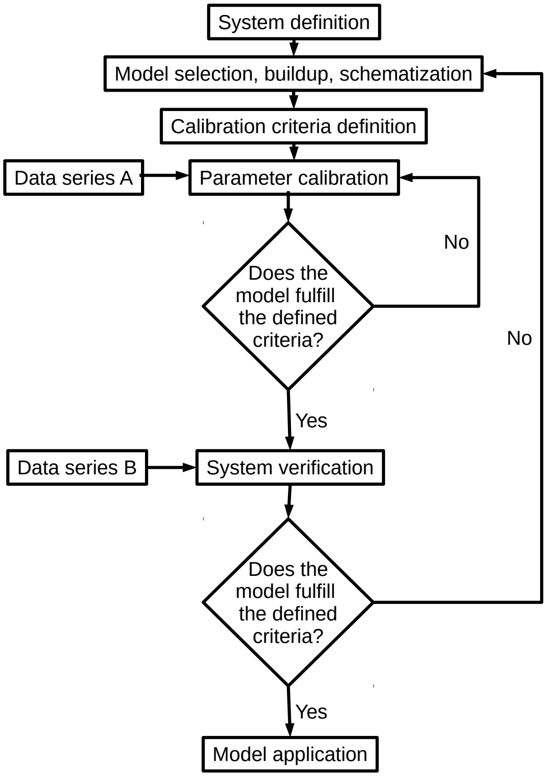

Figure 6. Schematic representation of the steps taken during the calibration and verification of the model

decision making on the monitoring strategy for the purpose of the calibration and verification of the model.

The schematization of the model is the initial step of the whole process, it defines the simplification of the whole system so that it is solvable, while not omitting any important element and allowing to achieve the stated goals for which the system is being created. After schematization, two tasks are being executed in parallel – physical measurements of the watershed and the composition and calibration of the simulation tools, based on the chosen technology.

Regarding schematization it is important to mention that some watershed areas have their parameters altered because of industrial drainage systems connecting into them. These are not included in the model, but are considered as point inflows (the Naza and Uni-Mier compounds in Trenčín, for example), or the drainage coeficient of the watershed may be increased.

8 MONITORING OF INFRASTRUCTURE AND SERVICES

Monitoring of the flood warning system can be divided into several groups:

- monitoring the availability of the measurement probes,
- monitoring the availability of network connectivity,
- monitoring the servers,
- monitoring the outputs being stored in the database,
- notification production and delivery.

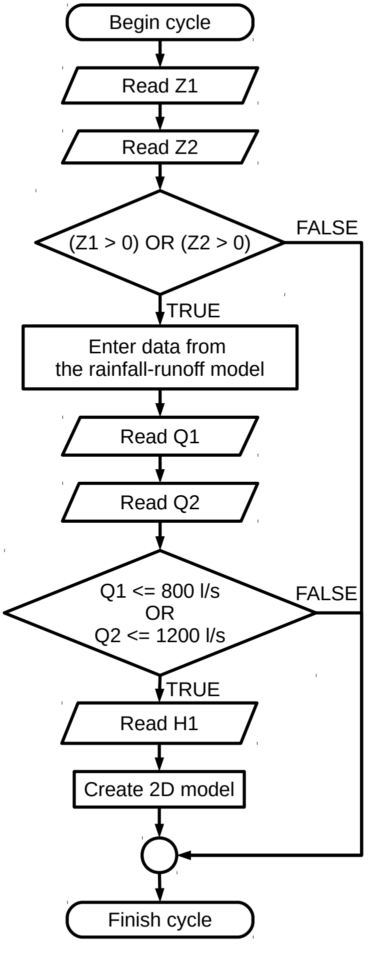

Figure 7. Algoritm for assessment of the flood possibility

For the purpose of the monitoring and control of services and hardware during the experimental work on the local flood warning system it was necessary to correctly configure the Nagios monitoring system [4]. Nagios' working principle is sufficiently uncomplicated. It performs checks of the services and hardware of the system using defined commands (plug-ins). If a check ends in a non-standard state, a predefined person will be notified about this problem.

Data which have been collected during the experimental setup were acquired in an actual stream, the *Lavičkový potok* in Trenčín. Data from the measurement probes were sent in selected time intervals to two data servers, called *sql1* and *sql2*, processed and stored in a database. The measured data on the state of the physical parameters of the stream were later used for monitoring measurement suites and processed using a neural net, which serves as the mathematical and hydraulic basis for the boundary conditions of the 2D model used to determine the flood extent, based on the rainfall-runoff model. For this purpose the data model shown in Figure 8 has been devised.

After receiving and processing data from the precipitation measurement suites (*TN_Z1* and *TN_Z2*), the flood possibility is determined using an algorithm based in the 2D rainfall-runoff model, shown in Figure 7.

The algorithm for sending notifications (Figure 9) to responsible persons is executed every time after a map of flooding is created and the extent of the flooded area is ascertained. This algorithm ensures that the respective persons are notified either by e-mail or an SMS message.

Display and presentation of outputs and results from the local flood warning system must be as simple as possible, so that the presentation is not time consuming or overly complicated. To fulfill this condition, a single-purpose web portal has been created (see Figure 10), which allows quick lookup of information about flooding by defining just three parameters. The parameters are:

- Total precipitation
  - less than 25 mm
  - from 25 to 50 mm
  - from 50 to 100 mm
  - more than 100 mm
- Rainfall duration
  - less than 2 hours
  - from 2 to 6 hours
  - more than 6 hours
- Watershed saturation
  - dry watershed
  - partially wet watershed
  - fully saturated watershed

After selecting the values of these three parameters, a flood extent map is shown, available in two different modes of quality (middle and high).

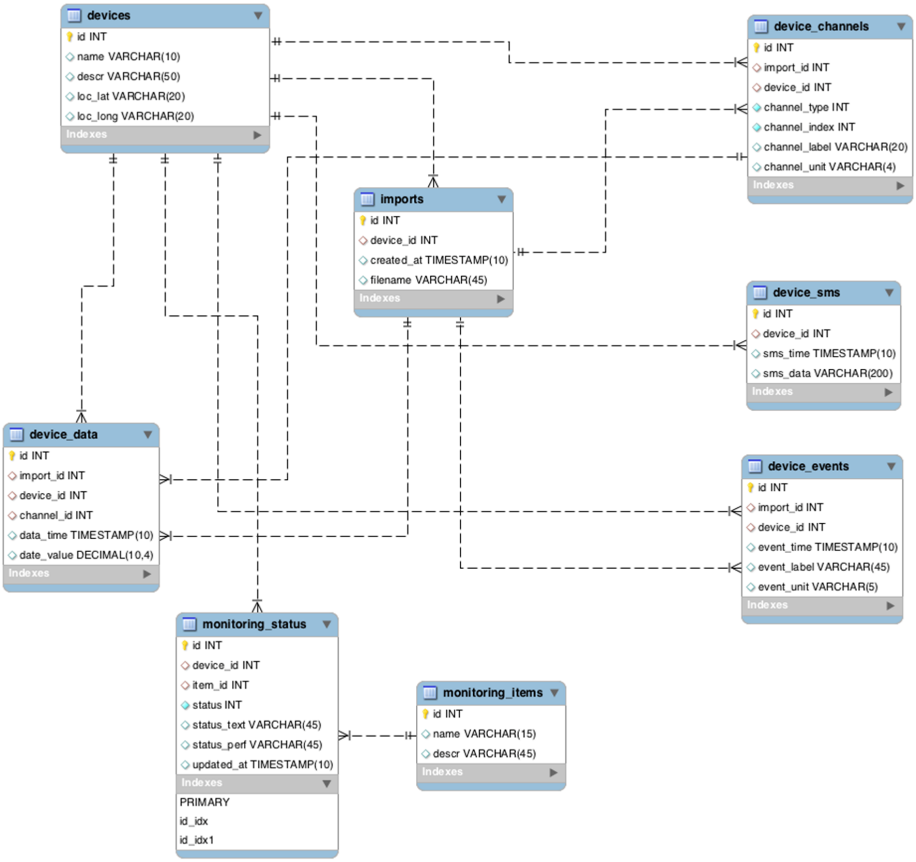

Figure 8. Data model of the database storing data of the experimental flood warning system

9 CONCLUSIONS

Results of our research show, that capabilities of current simulation models from the point of view of the underlying equations are sufficient to allow us to steer the effort to increase the effectivity and shorten the duration of the computation cycle – by way of parallelisation of the software implementation of the mathematical model, or by using modern high-performance ICT technologies in a combination with modeling tools.

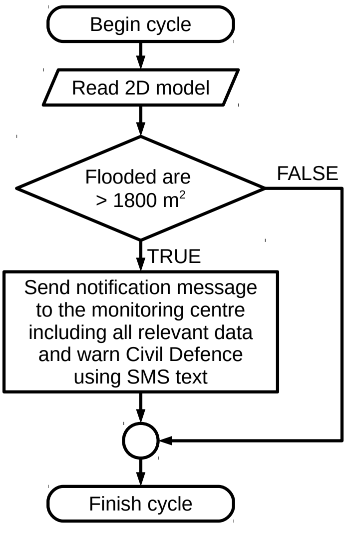

Figure 9. Notification decision algorithm of the local flood warning system

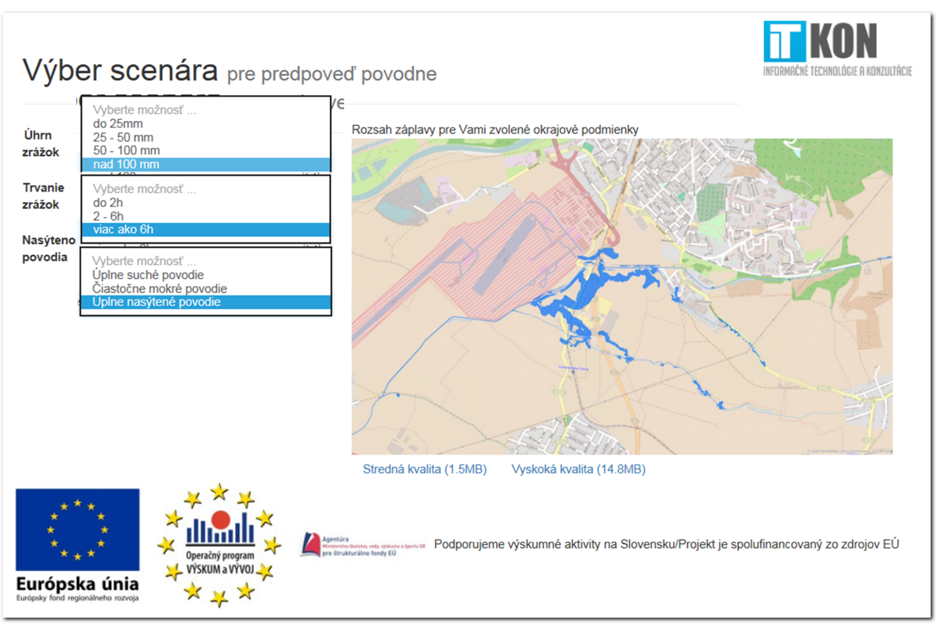

Figure 10. Portal for presentation of the flood extent, with the selection of parameters

The main result of our research is well tested and explored methodology to combine the state-of-the-art ICT technologies and mathematical models for hydraulics and create a viable local flood warning system which can be used not only in the target area selected for our experiment, but as well in any other locality with available terrain data.

Presenting the user with detailed results of the mathematical modeling is counterproductive, as that does not give a clear view of possible threats he/she is facing and thus unable to react quickly. It would diminish the effort put into creating a fast-reacting, on-line flood warning system. Research of viable user interfaces and their simplification show that it is important to present the results of the flood warning system as simply as possible, with the aim to streamline our decision making, and classify the results into several categories (for example various threat levels the modeled flood is presenting). Then the user can use the already prepared directly applicable response scenarios.

Results of the simulation of the rainfall-runoff process and its transformation in the target area for extreme rainfalls show, that the flood will be present in parts of the inundation area. We have prepared visualizations created by the 2D hydraulic model showing water depth map (Figure 11) as well as the inundation area without and with the flooded area (Figure 12). The results of the drainage system simulation show that it is able to perform its function even in the case of extreme rainfall transfering the runoff into the *Lavičkový potok* stream causing a downstream flooding.

Figure 11. Presentation of the flood extent, with the selection of parameters

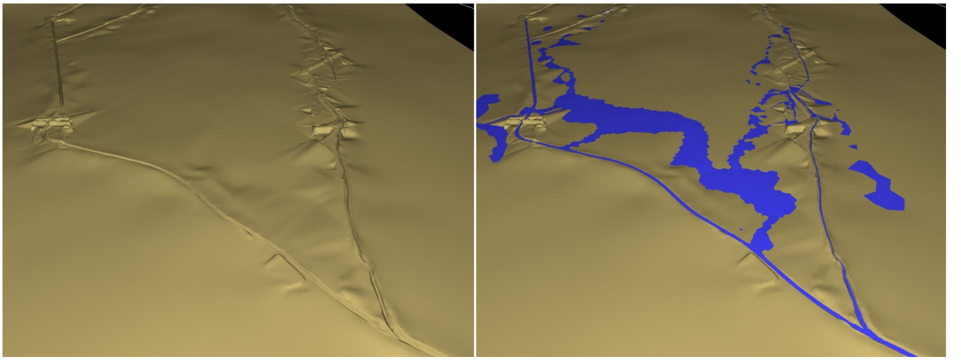

Figure 12. Presentation of the flood extent

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