A Web-Based Modelling and Monitoring System Based on Coupling Environmental Models and Hydrological-Related Data

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Abstract — The floods recognition on the net (Floreon+) is a system primary developed to provide flood monitoring and simulating capabilities that support flood management process within the Moravian-Silesian (MSK) region in the Czech Republic. The major aim of this paper is to introduce the basic design, structure, components and algorithm of the FLOREON+ system that integrates different types of environmental models and data sources. Part of the article, as a secondary goal, is inducted to the interconnection between the HPC infrastructure and the system. The FLOREON+ system with modular structure design continuously monitors the status of water behaviour within the region. The system improves public information about the past and present flood events by integrating hydrodynamic and rainfall runoff models. Overall, this system improves processing of disaster-related datasets as well as improves an ability of flood modelling and predictions and therefore it brings additional value for decision support in disaster management within the MSK region.

Index Terms—Modelling system; architecture; HPC; floods; dynamic data

I. Introduction

River floods are the most common and destructive natural hazard that cause high direct and indirect losses regarding economic activities or personal injuries [1], [2]. Hence, there is a need for detailed mapping of such phenomenon to decrease its impact on all human activity components. To acquire such mapping, numerical hydrological modelling (e.g. hydrodynamic or rainfall runoff) is essential because it provides crucial information about flood behaviour [3]. Nowadays, usage of numerical models for flood simulations has dramatically increased as a result of enhanced computational techniques and the operational availability of flood disaster digital data [4].

Recent developments in information technologies provide opportunities to make flood mapping by integrated multidisciplinary systems that may cover various types of modelling SW or hydrological and meteorological data. These systems require innovative technologies to improve data acquisition, analysis and presentation of a big amount of disaster-related information. Especially, storing and processing of real-time data are very challenging for almost every modelling oriented system. Current examples of such systems show that they have the ability to join to different phases of flood disaster management. The four phases of disaster management are well recognized in the current literature-mitigation, preparedness, response and recovery [5]. According to their functionality, these systems can be divided into three groups [6]: (1) Systems provide early warning and simulations in the early stage of flood disaster management [7] (e.g. the National Flood Forecasting System) (2) Systems concentrate on extraction of information after a disaster occurs (e.g. the Iowa Flood Information System) (3) Systems focus on sharing and managing information about disaster events (e.g. CyberFlood) [8].

This article introduces the basic design, components and algorithm of FLOREON+ system that integrates different types of environmental models and data sources (for more general information about the FLOREON+ please follow the link floreon.eu). The main goal is to focus on the part of the system related to hydrological models and simulations. The FLOREON+ system with modular structure design continuously monitors the status of water behaviour within the MSK region. The system improves public information about the past and present flood events by integrating hydrodynamic and rainfall runoff models.

In addition to the flood modelling and simulation area, the FLOREON+ system tackles other thematic areas - air and water pollution and environmental hazards and traffic situation. The results of these areas still focus on supporting the decision and planning disaster management processes. These thematic areas are also being integrated into the FLOREON+ system to cover a wider array of possible influences.

The article is organised into five main sections: (1) Section 1 briefly reviews state of the art (2) Section 2 describes the area of modelling interest that is covered by our system (3) Section 3 presents information about models and data used in the system (4) Section 4 and 5 presents system design and basic algorithm (5) Section 6 discusses the future work and the major conclusions.

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II. Details of Study Area

The Moravian-Silesian region (MSK) is located in the north-eastern part of the Czech Republic (see Fig. 1). The capital of the region is Ostrava, the third largest city by area and population within the Czech Republic. MSK in the east consists of the very hilly country with Jeseníky Mountains or Beskydy Mountains. The region belongs to a temperate climate zone characterized by four typical seasons with warm summers and cool winters. Hydrologically, the area may be divided into four catchments (according to the major rivers) – Odra catchment, Ostravice catchment, Olša catchment and Opava catchment.

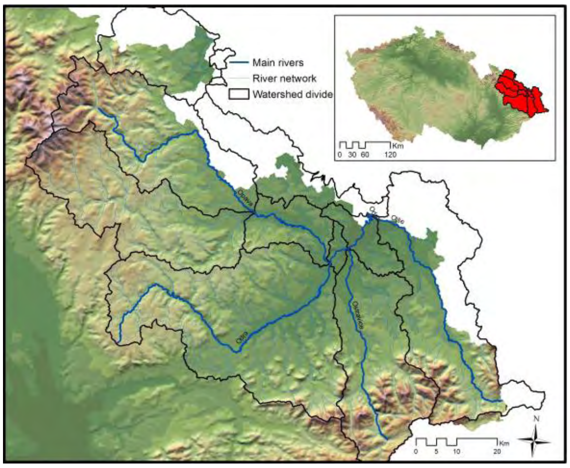

Fig. 1. Study area

The study area is densely covered by watercourses and therefore the area is exposed to a high risk of river flooding. Since 1990, many records of floods have been recorded within the MSK region and the floods in 1997 and 2010 belonged to the most severe observed events. To protect against such river floods hazard, flood modelling system (Floreon+) have been developed to mitigate their impact on public services and economic activities.

III. Data Availability and Models

A. Input Data

Input data as an important part of environmental modelling are divided into two categories within the system: (a) static data and (b) dynamic data. Static data include, among other, topographic data (LiDAR and Photogrammetry DEMs), channel geometry or data about friction coefficients and evapotranspiration. We know that mentioned data are not entirely static but in our case, we consider them like a static or quasi-static (data are updated every year – depends on data availability). The term dynamic data means that data are collected continually (hourly basis) from external parties and data networks (geo-servers). Appropriate examples of such data are precipitation, discharges, temperatures or data from numerical forecasting model MEDARD (precipitation, temperature, wind). Hourly rainfall is collected from the hydrological network of stations, which consists of more than 70 automatic and semi-automatic measuring devices within the MSK region (see Fig. 2). The Medard project service provides weather forecast data for the Floreon+ system that is based on the Weather Research & Forecasting model (every 6 hours - new forecast for the next 3 days).

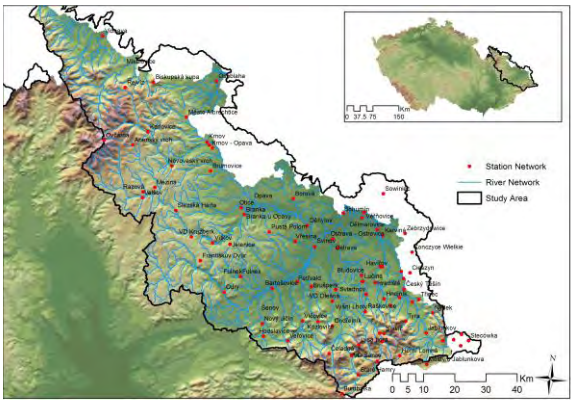

Fig. 2. Station network

Therefore, the Floreon+ system uses various types of static and dynamic data for operational purposes and thus suitable database structure must be applied to ensure optimal and fast access to them. The database has to be prepared not only for storing a big amount of continual data that are obtained from different geo-servers but also for extremely structurally and semantically heterogeneous data (detailed information about DB is out of the scope of this article).

B. Hydrodynamic Models

Hydrodynamic models are complex and efficient tools for representing coastal [9] and river water dynamics. These mathematical models simulate water movement by solving equations formulated by applying laws of physics [10]. Typical usage of such models covers various types of applications as a simulation of water levels and velocity, sediment transport [11] or water quality [12]. According to their spatial representation of the computational domain, the models can be divided into three specific groups – 1D (e.g. MIKE 11), 2D (e.g. HEC-RAS 2D, TELEMAC 2D) and 3D (e.g. DELFT3D) models.

The Floreon+ system integrates the 1D (HEC-RAS, MIKE 11) and 2D (HEC-RAS 2D) models to generate flood simulation information across the MSK region. The main focus is concentrated on flood alerts and data extraction associated to flood extent and water level. HEC-RAS and MIKE 11 as members of a group of 1D model are determined to compute mainly water levels at particular places (cross-sections) within the river channels [13], [14], whilst HEC-RAS 2D is mainly set to simulate flood extent over an entire computational area [15]. Both types of models are coupled with rainfall – runoff models to adopt boundary data about the relationship between discharge and time (hydrographs) (Fig. 3).

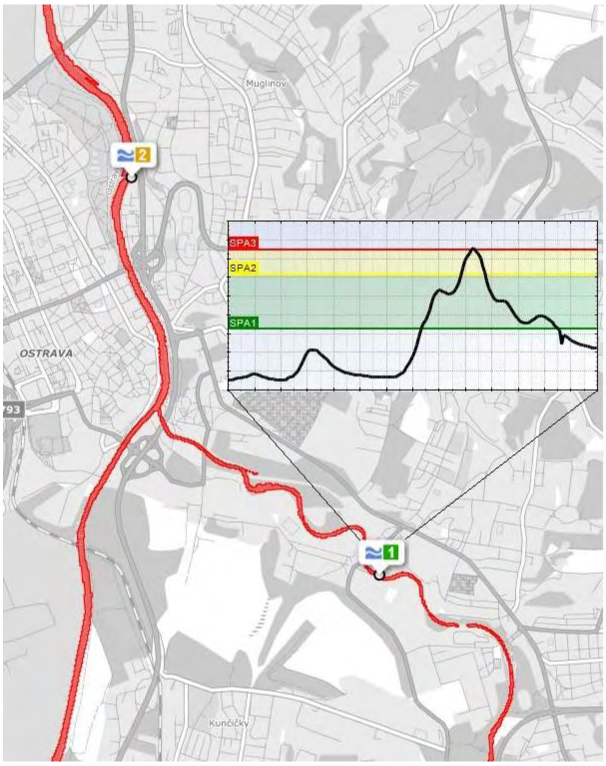

Fig. 3. Flood extent (red part) and associated hydrograph

In our system, each type of model is defined by its own workflow within the structure. This workflow includes parts that are typical for model processing such as pre-process, run simulation, post-process and visualisation (see Fig. 4). The workflow is designed to be very fast, flexible and modular in order to meet requirements of real- time monitoring and modelling. The system structure reflects model demands to input/output data at the attribute, temporal and spatial levels.

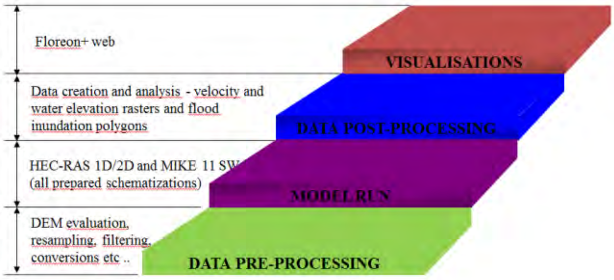

Fig. 4. Hydrodynamic model processing

C. *Rainfall–Runoff Models*

Rainfall–runoff models are commonly used to estimate the catchments response due to precipitation [16]. In other words, these types of models calculate transformation from rainfall to runoff. Rainfall–runoff (R-R) models are usually used in a wide range of practical tasks such as flood warning system planning, river restoration or as a flood prediction tool [17]. In the case of flood predictions, R-R models are very useful because they are applicable even in the areas with lack of hydrological input data. Two major groups of R-R models are semi-distributed and fully distributed. The principle of semi-distributed models is based on a uniform characteristic of each specific sub-basin unit. It means that every sub-basin unit has its own physical and hydrological parameters such as precipitation, evapotranspiration or infiltration. In the latter case, fully distributed models are able to compute the entire domain with the more detailed discretization of a grid (level of cells) and therefore we can obtain results for each defined grid cells.

The Floreon+ system uses models that are based on semi-distributed approach - HEC – HMS [18] and Math 1D (in-house model). Both models are applied to analyse flow status at the outlet of each defined sub-basin and typically, they provide data in the form of hydrographs (Q/t). Since they are a source of boundary data for a group of hydrodynamic models they have to be prioritised in the structure of the system and therefore must be computed preferably.

Simulations of the models are executed every hour with new observed data and each simulation consists of a 5-day long hydrological simulation with observed data and a 2-day long hydrological prediction (MEDARD) with forecast data with a time step of one hour [19].

IV. System Design and Basic Algorithm

Since the automatic run of particular procedures can reduce the time modelling process, the Floreon+ is developed to be fully automatic or in some parts semi-automatic because the manual interference is still necessary for the structure of the flood modelling process (e.g. DEM processing). There is a big effort not only to focus on an automatic run but also run all possible processes in parallel. According to our research, parallel approach significantly reduced cost, model execution/processing time and improved efficiency of our hydrological models.

The Floreon+ automatic process is triggered hourly on the HPC infrastructure and includes running of all defined rainfall-runoff and hydrodynamic simulations. In the first phase of the process (see Fig. 5), all required data are loaded from the database and pre-processed according to the needs of selected model. Subsequently, the simulation is run and all output data simulated by the models are processed and stored back to the database. The process continues with two parallel lines that consist of rainfall-runoff visualisations and statistical techniques and processing of hydrodynamic simulations. In “rainfall runoff” line all obtained data are evaluated by different methods (e.g. RMS error, Nash-Sutcliffe method) and visualised mainly in the form of hydrographs. Second “hydrodynamic” line is run parallel with the “rainfall runoff” line and covers complete hydrodynamic simulation process with data pre-processing, model run, post-processing and of course visualisations as a flood inundation area or water elevations. The process is finishing with uploading of all suitable results on the Floreon+ web.

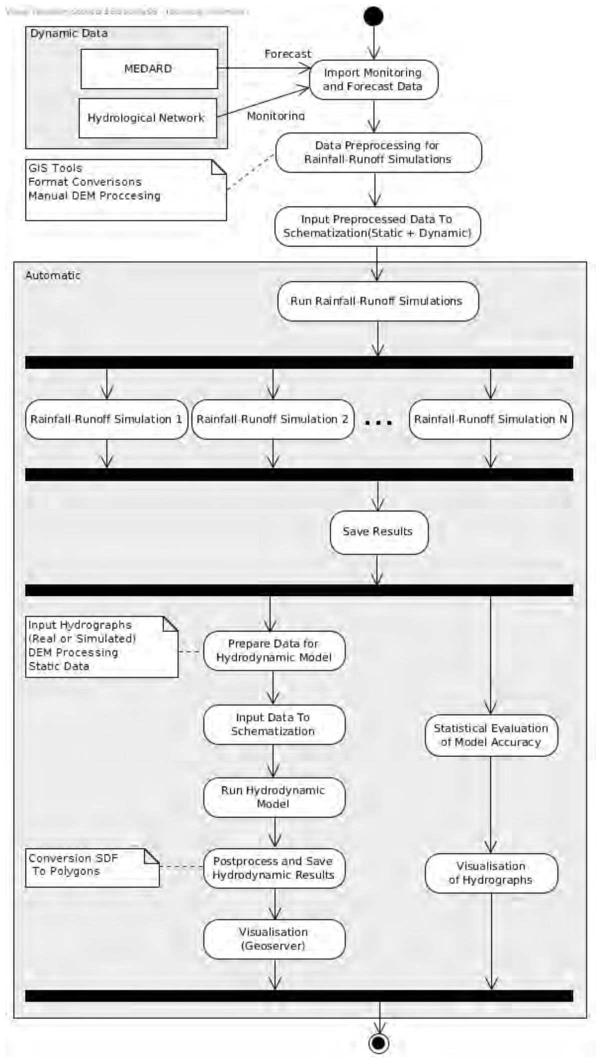

Fig. 5. Floreon+ system data process

V. Architecture

FLOREON’s architecture may be viewed from several angles, starting with its distribution among individual internet services and the level of communication within the system. Here we can see a set of basic models at the highest level of the hierarchy: a module for storing data (Warehouse), a module for mathematical calculations (FloodMathematic – implemented here mathematically, but also used as an existing application), a module for calculating model statistics (Postprocessing), a module for importing GIS data (Geograph), and/or a module for importing meteorological data (current version of the system uses many more modules – above mentioned are fundamental).

The Floreon+ system architecture uses the high-performance computing infrastructure at IT4Innovations National Supercomputing Center in Ostrava, Czech Republic. High-performance computing (HPC), in general, employs parallel processing to perform large computations in short time [20]. Therefore, HPC technologies mainly focus on developing parallel algorithms and systems. According to [21], parallel computing is the science discipline that deals with the system architecture and software issues related to the concurrent execution of applications. IT4Innovations operates 2 supercomputers: (1) Salomon (24192 cores, 129 TB RAM, 2 Pflop/s); it was put into operation in July 2015 (2) Anselm (3344 cores, 15 TB RAM); in May 2013, Anselm, a computing cluster with theoretical computing performance of 94 TFLOP/s, was put into operation. These two HPC clusters are currently available to use within the Floreon+ system to run all suitable simulations.

In terms of dynamic data processing the Floreon+ system enables to execute automatic simulation process or user initiated on-demand simulations. An automatic process, which includes running of rainfall-runoff simulations with hydrodynamics, is triggered on the HPC infrastructure every hour. The automatic flood prediction simulation is calculated for the next 48 hours with the last 5 days used as an input for the model. The framework for running on-demand What-If Analysis (WIA) with the user-defined input parameters is created to simulate crisis situations. Due to the user-defined parameters, the user initiated simulations can be more computationally demanding than automated simulations, therefore they are executed directly on the HPC cluster.

A. *HPC as a Service*

To provide the possibility to execute simulations on the HPC infrastructure for expert users using hydrologic applications, and for automatized flood monitoring and prediction systems, we have developed the HPC as a Service (HaaS) framework that enables integration of HPC computations to internal and external applications. Hydrologic model parallelization and remote execution on HPC also allows users to decrease computational time or increase the precision of the results by increasing the computing mesh resolution while maintaining usable run-time. This HaaS framework supports functions like job management, monitoring and reporting, user authentication and authorization, request and result file transfer and encryption, and various notification mechanisms [22].

Before performing the calculation of the task, the user must be authenticated. In the case of successful authentication, he can run the calculation. The system obtains the required data from the database at first step and prepares them for the calculation. Subsequently, these data are uploaded to the computing cluster through the HaaS framework. Here are the required computing resources allocated due to a priority of computational job and difficulty of this job. The task is divided into multiple smaller, less demanding tasks that can be processed in parallel. The framework is immediately informed of the completion of the calculation and ensures the download of the results from the computing cluster and then the results are provided to the system, which processes these results and saves them into the database. The system instantly informs the user about the completion of the calculation. The user is now able to visualize results through the system and then make appropriate decisions.

The above-mentioned principles of the HaaS as well as methods of the Floreon+ are very modular and adaptable, and therefore they can be used in a numerous of environmental impacts modelling issues. The HaaS is going to be used as an auxiliary tool within the TACR project PaReTran which as a main objective defines to improve the possibilities of a potential risk analysis of the environment contamination due to the long-term decay of radioactive species spread out from a deep radioactive waste repository. This aim will be made by integrating HPC infrastructure into the process of the reactive transport modeling (by means of the HaaS). The solution is complicated by a low accuracy of known rock medium parameters values in large depths and in far future. The sensitivity analysis using numerical simulation computations is then very computationally demanding. Also, the individual reaction-transport simulations themselves are computationally demanding and their parallelization and HPC (High-Performance Computing) use allow the execution of the simulations in real scale and affordable time.

The flexible-mesh groundwater flow and contaminants transport simulation software FEFLOW ver.7 and the geochemical reaction module PhreeqcRM designed specifically to perform equilibrium and kinetic reaction calculations for reactive transport simulators will play key roles within such proposed process. PEST method (FEPEST embedded in FEFLOW) will be used for calibration of the models, for uncertainty associated with parameters and predictions determination, and for other related task.

VI. Conclusions and Future Work

FLOREON+ (its hydrological part) is a system developed to provide complex support over the process of flood disaster management. It provides a modular architecture that is able coupling different environmental models from various scientific fields (e.g. flood modelling, groundwater modelling or air pollution modelling). New tools, extensions, algorithms or services can be easily incorporated into a system structure through modular interfaces. In this system, at the data level, all daily collected meteorological, hydrological and remote sensed data are stored in the MS SQL Server database whilst data derived from hydrodynamic simulations are stored in the PostgreSQL database. These databases are prepared for storing large amounts of information and provide a flexible environment for new types of data formats. Visualizations of simulations and monitoring data are done through the web-based interactive graphical user interface (see link floreon.eu). The system improves processing of disaster-related datasets as well as improves an ability of flood modelling and predictions and therefore it brings additional value for decision support in disaster management within the MSK region.

Overall, the system contribution can be summarized as: (1) **The integration of all the features into one tool** allows a detailed overview of the modelled situation and monitoring of the influence of the particular phenomenon on its evolution. (2) **The unified data management** ensures continuity in simulations of different models and availability of data across all system's features. Thanks to the archiving of all data it is also possible to run simulations of events from the past. (3) **The web interface with the map component** visualises summarised information from all the features in different time slots and from different places. Provided web based services simplify the usage of the outputs in other software products. (4) Timeliness of the results is ensured by **automatic run of simulations** of the Rainfall – Runoff models as well as the models of the river overflow. (5) Exploitation **of the HPC infrastructure** ensures much faster processing of large sets of data and their accuracy.

We have suggested two major directions of further development of the Floreon+ system: (1) There is a need to extend the system to other regions to validate our system and its modularity in different data and modelling environments (2) To make all parts of the system fully automated in order to obtain alarming information directly after the disaster event occur (reducing of processing time with no manual interferences during the modelling process).

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References

[1] J. Yin, Y. Dapeng, Z. Yin, M. Liu, and Q. He, "Evaluating the impact and risk of pluvial flash flood on intra-urban road network: A case study in the city center of Shanghai, China," *J. Hydrol.*, vol. 537, pp. 138-145, 2016.

[2] A. Thiboult, F. Anctil, and M. H. Ramos, "How does the quantification of uncertainties affects the quality and value of flood early warning systems?" *Journal of Hydrology*, May 2017

[3] A. Paquier, E. Mignot, and P. H. Bazin, "From hydraulic modelling to urban flood risk," *Procedia Engineering*, pp. 115, pp. 37-44, 2015.

[4] S. Elga, J. Bronders, and B. Okke, "Hydrological modelling of urbanized catchments: A review and future directions," *J. Hydrol.*, vol. 529, pp. 62-81, 2015.

[5] P. Kohler and J. Wachter, "Towards an open information infrastructure for disaster research and management: Data management and information system inside DFNK," *Nat. Hazards*, vol. 38, pp. 141-157, 2006.

[6] L. Qiu, Z. Du, Q. Zhu, and Y. Fan, "An integrated flood management system based on linking environmental models and disaster-related data," *Environ. Modell. Softw.*, vol. 91, pp. 111-126, 2017.

[7] E. Artinyan, B. Vincendon, K. Kroumova, *et al.*, "Flood forecasting and alert system for Arda River basin," *J. Hydrol.* vol. 541, pp. 457-470, 2016.
[8] Z. Wan, Y. Hong, S. Khan, J. Gourley, and Z. Flamig, D. Kirschbaum, and G. Tang, "A cloud-based global flood disaster community cyber-infrastructure: development and demonstration," *Environ. Model. Softw.*, vol. 58, pp. 86-94, 2014.
[9] G. M. J. Hasana, D. S. Marenb, and S. K. Ooid, "Hydrodynamic modeling of Singapore's coastal waters: Nesting and model accuracy," *Ocean Modelling*, vol. 97, pp. 141–15, January 2016.
[10] J. Teng, A. J. Jakeman, J. Vaze, B. F. W. Croke, D. Dutta, and S. Kim, "Flood inundation modelling: A review of methods, recent advances and uncertainty analysis." *Environ. Model. Softw.*, vol. 90, pp. 201-216, 2017.
[11] L. Boudet, F. Sabatier, and O. Radakovitch, "Modelling of sediment transport pattern in the mouth of the Rhone delta: Role of storm and flood events," *Estuarine, Coastal and Shelf Science*, pp. 1-15, 2016.
[12] C. Lindim, J. L. Pinho, and J. M. P. Vieira, "Analysis of spatial and temporal patterns in a large reservoir using water quality and hydrodynamic modeling," *Ecological Modelling*, vol. 222, pp. 2485–2494, 2011.
[13] P. Dimitriadis, A. Tegos, A. Oikonomou, V. Pagana, *et al.* "Comparative evaluation of 1D and quasi-2D hydraulic models based on benchmark and real-world applications for uncertainty assessment in flood mapping," *Journal of Hydrology*, vol. 534, pp. 478–492, 2016.
[14] M. Podhoranyi and D. Fedorcak, "Inaccuracy introduced by LiDAR-generated cross sections and its impact on 1D hydrodynamic simulations," *Environ Earth Sci.*, vol. 73, pp. 1-11, 2015.
[15] E. Bladé, M. Gómez-Valentín, J. Dolz, J. L. Aragón-Hernández, G. Corestein, and M. Sánchez-Juny, "Integration of 1D and 2D finite volume schemes for computations of water flow in natural channels," *Advances in Water Resources*, vol. 42, pp. 17–29, June 2012.
[16] D. Halwatura and M. M. M. Najim, "Application of the HEC-HMS model for runoff simulation in a tropical catchment," *Environ. Model. Softw.*, vol. 46, pp. 155-162, 2013.
[17] T. K. Chang, A. Talei, S. Alaghmand, and M. P. Ooi, "Choice of rainfall inputs for event-based rainfall-runoff modeling in a catchment with multiple rainfall stations using data-driven techniques," *Journal of Hydrology*, vol. 545, pp. 100–108, February 2017.
[18] C. C. Young, W. C. Liu, and M. C. Wu, "A physically based and machine learning hybrid approach for accurate rainfall-runoff modeling during extreme typhoon events," *Applied Soft Computing*, vol. 53, pp. 205-216, 2017.
[19] S. Kuchar, M. Golasowski, R. Vavrik, M. Podhoranyi, B. Sir, and J. Martinovic, "Using high performance computing for online flood monitoring and prediction," *Environmental and Ecological Engineering*, vol. 1, no. 5, 2014.
[20] R. Hassani, M. Aiatullah, and P. Luksch, "Improving HPC application performance in public cloud," *IERI Procedia*. vol. 10, pp. 169-176, 2014.
[21] A. R. Hernandez, A. M. G. Torres, and E. V. Gallegos, "HPC implementation in the time-dependent neutron diffusion code AZKIND," *Ann. Nucl. Energy*., vol. 99, pp. 174–182, 2017.
[22] J. Martinovic, S. Kuchar, V. Svaton, and V.Vondrak, "Hydrological model remote execution and HPC as a Service," *Supercomputing in Science and Engineering ed.1*, pp. 97-100, 2017.

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