Multiple Scenarios Computing in the Flood Prediction System FLOREON$^+$

Jan Martinovič, Štěpán Kuchař,
Ivo Vondrák, Vít Vondrák
VŠB - Technical University of Ostrava
FEECS, Department of Computer Science
17. listopadu 15
Ostrava - Poruba
Emails: jan.martinovic@vsb.cz, stepan.kuchar@vsb.cz,
ivo.vondrak@vsb.cz, vit.vondrak@vsb.cz

Boris Šír, Jan Unucka
VŠB - Technical University of Ostrava
Institute of geoinformatics
17. listopadu 15
Ostrava - Poruba
Emails: sir.boris@vsb.cz, jan.unucka@vsb.cz

KEYWORDS

Hydrologic forecasting, rainfall-runoff models, hydrodynamic models, scenarios making, FLOREON$^+$

ABSTRACT

Floods are the most frequent natural disasters affecting the Moravian-Silesian region. Therefore a system that could predict flood extents and help in the operative disaster management was requested. The FLOREON$^+$ system was created to fulfil these requests. This article describes utilization of HPC (high performance computing) in running multiple hydrometeorological simulations concurrently in the FLOREON$^+$ system that should predict upcoming floods and warn against them. These predictions are based on the data inputs from NWFS (numerical weather forecast systems) (e.g. ALADIN) that are then used to run the rainfall-runoff and hydrodynamic models. Preliminary results of these experiments are presented in this article.

INTRODUCTION

There are many types of natural disasters in the world. Many of which depend specifically upon geography. Floods are one of the worst and most recurrent types of natural disasters in our region (Wohl, 2000; Brázdil et al., 2005; Bedient et al., 2007).

Local governments require reliable models for flood simulations and predictions to save on ample funding that must be otherwise invested in post-flood repairs for impacted regions (Brázdil et al., 2005). Therefore, the issue of flood prediction and simulation has been selected as a case of choice for experimental development.

Modelling of the water component in the landscape together with consequent environmental aspects becomes a frequently discussed activity. Water is both element and irreplaceable resource in this context (Unucka et al., 2009).

The geographic information systems and hydrologic models became more frequently used with the development of informatics in the field of hydrology and environmental issues. These products represent the most efficient tools for the hydrologic analyses beyond any doubt. Numerous projects for the improvement of such tools were realized worldwide. Both particular hydrologic and environmental problems were solved together with design of more complex systems, in which communication of GIS and hydrologic models were solved in the system way. ArcHydro is amongst the most sophisticated projects in that way (Maidment, 2002; Bedient et al., 2007; Unucka et al., 2009).

Our project FLOREON$^+$ (FLOods REcognition on the Net) (Vondrák et al., 2008; Martinovič et al., 2008; Unucka et al., 2009) endeavours to achieve such a complex solution to environmental issues. The system is being developed as a tool for disaster management and decision support. It is a prototypal open modular system of environmental risks modelling and simulation, which is based on modern internet technologies and platform independency. Environmental problems are solved via automatic communication of environmental models and GIS, visualised and published via internet interface. The first milestone of the project was the development and operative running of complex decision support and prediction system for hydrologic problems as are the floods. The first aim was to achieve near real-time predictions of hydrographs and flood lakes, which were accomplished. The project is running in operative way nowadays and HPC capabilities are tested within the system. The final product of the project is going to be the system offering online communicational man-machine interface and providing a various types of products for decision support. The project results should help to simplify the process of crisis management and increase its operability and effectiveness.

HPC USE IN HYDROLOGY AND ENVIRONMENTAL MODELING

The speed of the computation is the main advantage of HPC. Solving the tasks occurring in the space and time (such as environmental modelling tasks), the capacity of HPC enables to accomplish the computations in the high resolution, both temporal and spatial (Kumar et al., 2008).

The combination of environmental modelling and HPC is not new. Distributed computers have the poten-

Proceedings 24th European Conference on Modelling and
Simulation ©ECMS Andrzej Bargiela, Sayed Azam Ali
David Crowley, Eugène J.H. Kerckhoffs (Editors)
ISBN: 978-0-9564944-0-5 / ISBN: 978-0-9564944-1-2 (CD)

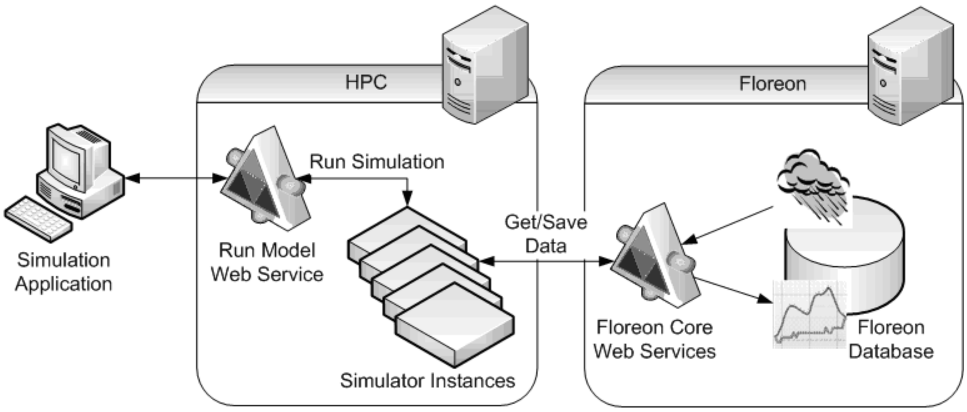

Figure 1: Running hydrological simulations on HPC in the FLOREON$^+$ system

tial to provide an enormous computational resource for solving complex environmental problems, and there is active research in this area to take better advantage of parallel computing resources (Vrugt et al., 2006). Environmental models of many kinds have been computed using HPC cluster. For example, coupled hydrogeological and biogeochemical models were computed by (Gwo et al., 2001) or surface-subsurface flow and reactive transport coupled models were computed by (Gwo and Yeh, 2004). In hydrology field, autocalibration computations were done using HPC (Cheng et al., 2005; Vrugt et al., 2006; Sharma et al., 2006; Tang et al., 2007; Liu et al., 2009), as well as multidimensional hydrodynamic or fluvial-geomorfological modelling and contaminant transport computations (Dortch and Gerald, 2001; Allen et al., 2008). In hydrogeological modelling, contaminant transport and water (including coastal ones as well) quality modelling, cluster computing was applied by (Thompson et al., 1997), (Espino et al., 1997), (Peters et al., 1997), (Wu et al., 2002) or (Hammond et al., 2005), for example. (Li et al., 2006) used HPC advantages to run fully distributed hydrological model, similarly (Lien et al., 2001, 2004) used the capabilities of (to HPC close) grid computing for the distributed solution of flood prediction. Typical area of HPC use is meteorological and climatologic modelling (Sathye et al., 1996; Bougeault, 2008). Another sphere of its use is, for example, a land surface modeling (Tian et al., 2008). Our FLOREON$^+$ system is an example of coupled rainfall-runoff and hydrodynamic models.

RUNNING HYDROLOGICAL SIMULATIONS ON HPC WITHIN THE FLOREON$^+$ SYSTEM

HPC as a parallel environment is able to run many hydrological simulations at the same time. This allows the users to use the environment effectively and it shortens waiting time for simulation results even during the high level of demand (e.g. during critical situations). Parallel computing is also very useful for model calibration, in which many simulations with different calibration parameters can be run simultaneously and their results can be compared gradually.

However, this comes with the implementation cost, because used simulation models are not ready for such simultaneous launching. We had to solve this problem by creating multiple simulation environments integrated with preparation and finalisation code. We named these functional environments *Simulators* and created one instance for each node and computation core that would be used to perform simulations.

Therefore, when a user needs to run a simulation, he uses FLOREON$^+$'s *Simulation Application* to create new simulation and fill it with desired attributes based on the model he wants to use. The Simulation Application then calls the *Run Model Web Service* deployed on the HPC server and sends all given parameters. This web service utilizes the HPC environment to find a suitable Simulator instance in the pool of available instances (see Figure 1). The chosen Simulator prepares the required model and asks *Floreon Core Web Services* for snow thickness, rainfall, temperature and other data, saved in the central *Floreon Database*. These are used as the input data to the model and the Simulator starts the simulation. Results of the simulation are sent to the Floreon Core Web Services to be saved in the Floreon Database for the future use. At the same time, the resulting hydrographs are displayed to the user in the Simulation Application and the Simulator instance is returned to the pool of available instances.

CASE STUDY

As it was mentioned, FLOREON$^+$ is a complex and modular system for hydrologic and environmental modelling. The FLOREON$^+$ system disposes partly of automated hydrometeorological data collecting, partly of automated computational cascade of event rainfall-runoff and hydrodynamic models. The hydrometeorological data are collected from network of gages run professionally by the Czech Hydrometeorological Institute (CHMI) and the Povodi Odry (the river Odra basin board) state enterprise and by methods of remote sensing (radar estimation of precipitation rates, provided by the CHMI). Together with the precipitations predicted by NWFS AL-

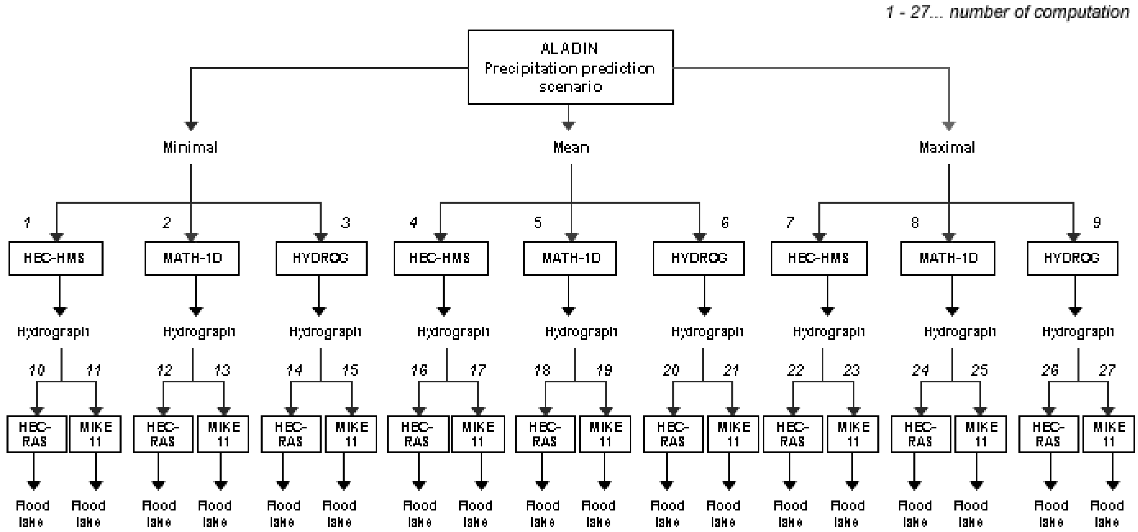

Figure 2: Computation tree for one modelled watershed/river network

ADIN model (Aire Limite, Adaptation Dynamique, Development International), which is meso-beta scale numerical meteorologic model co-developed and computed by CHMI (Zagar, 2000; Řezáčová et al., 2008), they are used as the inputs of the rainfall-runoff models.

Meteorological inputs include precipitation depth in particular, and furthermore the air temperature and the data about snow pack (thickness and water equivalent) during the winter time. The time step of the obtained precipitation depth and temperature data is 1 hour. Hydrological inputs cover data on hourly discharges and water levels from the hydrologic gages. This discussed data are used within the FLOREON$^+$ system as inputs of the runoff response calculation to causal rainfall (possibly runoff caused by snowmelt). The outputs of these models (hydrographs, also in the profiles over and above the professionally monitored gages and gages of professional hydrologic prediction) together with the observed discharges are then used as the boundary conditions inputs to the hydrodynamic models, which solve the water routing in riverbeds, possibly outside riverbeds during floods. One of their outputs is the spatial localization of potential flood lakes. The whole cascade including the input data collecting at the beginning, postprocessing of model outputs, and the web visualisation of the results at the end is constituent of fully automated server solution. The models are run every 6 hours and their prediction is set for 54 hours in advance. Nowadays, the outputs are used as a basis for the decision-making within the disaster management.

Hydrologic prediction is based on the meteorological prediction. In other words, the predicted values of some meteorological factors are used as input data for hydrologic prediction. Meteorological prediction itself is lumbered by uncertainty. This is one of the reasons why the temperature forecast is often published as four degrees wide intervals of temperatures, for example. Therefore, there is no reason why the results of hydrologic prediction should be taken at a face value, both in the aspect of timing or magnitude of predicted discharge. However, in common operational practice, approximately 20% difference of predicted and then observed discharges are taken as a satisfactory prediction. The issue of modelling uncertainties are generally widely discussed in the literature (Beven and Binley, 1992; Anderson and Bates, 2001; Aronica et al., 2002; Ajmi et al., 2007; Beven, 2008; Arnold et al., 2009; Geza et al., 2009; Mishra, 2009; Todini, 2009); and many others.

The important fact is that the predicted meteorological input data coming from the ALADIN NWFS model are not single numbers but intervals (ranges of possible values). Because of these input data uncertainties, it is appropriate to calculate the hydrological prediction via utilization of various precipitation forecast scenarios or ensemble model runs (e.g. combination of various rainfall-runoff models with various methods and parameters). These ensembles are minimal, maximal and mean scenarios of rainfall predictions computations in various types of rainfall-runoff models sense.

Our rainfall-runoff models are computed for 4 watersheds with an approximate area of 1000 km^2 and an average number of 49 subbasins. For each of these watersheds, 3 rainfall-runoff models are computed simultaneously, HEC-HMS (HEC-USACE, 2010), HYDROG (HySoft, 2010), and our own MATH-1D model (Kubíček and Kozubek, 2008), specifically. HEC-HMS (Hydrologic Engineering Center - Hydrologic Modelling System) is a product of HEC-USACE (Hydrologic Engineering Centre - U.S. Army Corps of Engineers). It is a semidistributed rainfall-runoff model working with various advanced methods for hydrologic and hydraulic transformation of rainfall-runoff process. HYDROG is a semidistributed rainfall-runoff model developed by HySoft company. It is currently operatively run by the CHMI. The model is designed for simulation, operative hydrologic forecast and operative management of watershed system. Besides the HEC-HMS model, it works with the Hortons method for overland flow. MATH-1D model is own product of the FLOREON$^+$ solutions team. It is a rainfall-runoff model accumulating contribution of interflow modeled by convolution integral and simplified differential equation and contribution of surface runoff using non-stationary linear and non-linear isochrones. Computation results of these rainfall-runoff models then serve as the boundary conditions inputs to hydrodynamic models.

For each watershed, the river network of the watershed respectively, two hydrodynamic models are computed, HEC-RAS (HEC-USACE, 2010) and MIKE 11 (DHI, 2010) specifically. As well as HEC-HMS, the model HEC-RAS (Hydrologic Engineering Center - River Analysis System) is a product of HEC-USACE. It is a one-dimensional hydrodynamic model applicable for both steady and unsteady flow computations and computations of subcritical and supercritical flow in the network of natural and constructed channels including technical objects as well. The basic mathematical apparatus are the Bernoulli's and Manning's equations. The computation of flood lakes is fully supported. HEC-RAS and HEC-HMS models are free software products downloadable from the HEC-USACE website. MIKE 11 is a commercial product of DHI (Danish Hydraulic Institute). It is a one-dimensional hydrodynamic model enabling simulation of both steady and unsteady flow computations and computations of subcritical and supercritical flow in both natural and constructed channel network including technical objects as well. In the inundation areas model is able to simulate quasi 2D flow. Its basic mathematical apparatus are the Bernoulli's and energy loss equations together with the Manning's and Chezy's equations. Both models, HEC-RAS and MIKE 11, are industry standards for hydrodynamic simulations. MIKE 11 model is, as well as MIKE SHE model (DHI, 2010) (see bellow), a part of the hydrologic and hydrodynamic models platform MIKE Zero (DHI, 2010).

Because of the ensemble hydrographs (Figure 3) resulting from the rainfall-runoff models computations, the ensemble computation of hydrodynamic models are desirable. It is exacerbated by the fact that the FLOREON+ system is intended for decision making support within operational disaster management.

Since there is quite a big number of computation operations needed in order to compute the whole cascade of models considering the rainfall inputs ensembles (see the Figure 2), HPC capabilities offer a significant increase of computation speed, which is very important in operational practice, especially during the critical events. There is a computation tree for one modelled watershed in the Figure 2. In fact, due to 4 modelled watersheds, the number of computations is 4-times bigger for the complete area covered by FLOREON$^+$ system, if we do not consider different hydrologic computation methods and parameters ensembles.

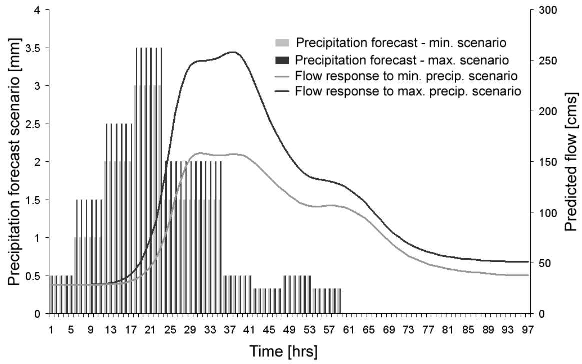

Figure 3: Rainfall-runoff prediction scenarios

Resulting flood lakes are processed by GIS tools and archived with other output data (hydrographs, water levels etc.). The minimal and maximal extents of possible flood lakes (see the Figure 4) and hydrographs scenarios are provided to authorities of crisis management as a support for decision-making and coordination of possible actions. Every other scenarios and ensemble computation outputs are stored and ready to be used in the case of need.

DISCUSSION

The use of the HPC cluster for the computations of FLOREON$^+$ system tasks seems to be necessary for the future. Only in terms of hydrologic modelling, the parallel scenarios computations based on the ensembles of meteorological forecasts will be more demanding on computer performance during a snowmelt episodes. Snowmelt runoff modelling takes into account next to the precipitation air temperatures and snow water equivalent as well. So, at least one more ensemble forecast of meteorological element - temperature - will need to be considered.

Further to the above mentioned, another field of hydrologic modelling that is going to be tested using HPC under the FLOREON$^+$ system is the automatic calibration of models. Since our models are event ones (not continuous for long-term simulations) running on the hourly inputs, the calibration runs automatically started before each model simulation/prediction run are going to be tested. We are aware of the fact that for successful operational deployment of automatically calibrated event models, such a calibration procedures have to be properly tested separately for every single modelled watershed. Parameterisation of the hydrologic model to fit best to actual conditions of the real watershed is difficult, especially in the case of larger and heterogeneous watersheds as well as in routine operation with automatically run event models and automatic continual input data download. Spatial and temporal distribution of rainfall input

Figure 4: Simulated flood extents for variuos precipitation forecast scenarios

is often quite unpredictable and leads to a large heterogeneity in catchment conditions (e.g. saturation of soils), both spatial and temporal. The values of optimized parameters have to fall within the interval of realistic conditions. The automatic optimization can results in a good fit of observed and simulated discharges at the expense of unrealistic parameter values. In operative it could lead to the useless results of the prediction, if the external conditions would suddenly change. Nowadays, we automatically optimise the value of initial abstraction using API (antecedent precipitation index).

Another step of FLOREON$^+$ system development is going to be a fully distributed hydrologic model MIKE SHE deployment. Some hydrologic issues such as runoff response to convective rainstorms or hydrologic balance computations in high resolution have to be solved by this kind of models. Despite of all the quick development in the field of IT, it is still very time-consuming to run distributed models for a larger watershed. HPC thus offers the way of operational running of these models.

In terms of another purpose and use of FLOREON$^+$ system it is good to mention that the system is based on client-server architecture. The three levels of users (divided according to their expertise) will be allowed to run the simulation with different rights of setting the models. So that all computing operations will be performed on HPC servers, by which users are made available only in the form of the award and subsequent results. Using high performance computing brings the possibility to satisfy a big amount of users in real and near-real time (Unucka et al., 2009).

ACKNOWLEDGEMENT

We acknowledge the support of projects SP/2010196 Machine Intelligence and SP/2010192 Possibilities of modelling of natural and environmental risks caused by extreme hydrometeorological situations.

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AUTHOR BIOGRAPHIES

JAN MARTINOVIČ studied computer science at the VŠB - Technical University of Ostrava, the Czech Republic and obtained M.S.E. degree in 2004 and Ph.D. degree in 2008. Nowadays, he works as an assistant professor at the same university. He is a researcher dealing with data mining and data processing, with emphasis to web search, data compression and social networks.

JAN UNUCKA studied physical geography and geoecology at the University of Ostrava and obtained M.Sc. degree in 2003 and Ph.D. degree in 2006. For a few years he worked for the Czech Hydrometeorological Institute as a worker of regional hydrological forecast office. Since 2003 he has been working as an assistant professor at the VŠB - Technical University of Ostrava. The main field of his professional interest is environmental modelling and linking GIS with environmental models.

BORIS ŠÍR studied physical geography and geoecology at the University of Ostrava, the Czech Republic and obtained MSc. degree in 2007. In 2008, he obtained M.S.E. degree in environmental engineering at VŠB - Technical University of Ostrava. Nowadays, he is a doctoral student of geoinformatics at VŠB - Technical University.

ŠTĚPÁN KUCHAŘ studied computer science at the VŠB - Technical University of Ostrava and obtained M.S.E. degree in 2007. Nowadays, he is a postgraduate student of computer science and applied mathematics at VŠB - Technical University of Ostrava.

IVO VONDRÁK studied computer science at the VŠB - Technical University of Ostrava and obtained M.S.E. degree in 1983 and Ph.D. degree in 1988. He has been working as assistant professor at the VŠB - Technical University of Ostrava since 1989, since 1991 as associated professor and since 1998 as a professor of engineering informatics. Between 1992 and 2002 he was visiting professor at the Montanuniversitat Leoben, Austria, and in the years 1996 and 1997 he worked as a researcher for Software Research Labs, Texas Instruments, Inc., Dallas, TX, USA. Nowadays, he is the president of the VŠB - Technical University of Ostrava.

VÍT VONDRÁK studied mathematics at the Palacký University in Olomouc, the Czech Republic and obtained M.Sc. degree in 1992 and Ph.D. degree in 2003. Since 1992 he has been working as an assistant professor and since 2007 as an associated professor at the VŠB - Technical University of Ostrava. For a couple of years, he was working for Institute of Thermomechanics of Academy of Sciences of the Czech Republic.