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An Hybrid Methodology for Integrated Flood Forecasting from the Watershed to the Sea

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Abstract

Flood forecasting in small watersheds is a complex problem, given the stringent time scales to convey accurate alerts in due time and small spatial scales for both atmospheric and water basin domain prediction. The traditional forecast approach, based on a chain of numerical models for meteorological, hydrological and hydraulic processes is not sufficient, requiring the integration with tailored, real-time data to produce accurate inundation maps and provide timely warnings.
Herein, we present a new methodology for flash flood forecasting, based on a two-step procedure and on the use of WIFF, a generic forecast framework applied successfully in estuarine and coastal flood forecasting. In this methodology, WIFF executes two procedures in parallel. First, a large-scale approach, based on conventional numerical models, running continuously every day, to detect significant rain events. If a predicted rain event crosses a warning threshold, a second approach is triggered, involving a small-scale data-based model to predict flooding for the following hours, based on real time monitoring networks data and on the use of high performance computing for machine learning-based simulations. For the first step, we are updating the WIFF framework to integrate both hydrological and hydraulic models of the HEC model family (Brunner, 2021).
This methodology is being validated in the Ribeira das Vinhas basin, an area prone to torrential floods that inundate the urban area of the city of Cascais, located at the Tagus estuary mouth.

Keywords: Real time data; Flood forecast; Hydraulic modelling; Machine learning-based simulations; High performance computing

1. INTRODUCTION

Floods are the most frequent natural disasters, affecting millions of people worldwide every year. The capacity to anticipate these events through early warning systems is thus a fundamental part of the flood risk and emergency cycle. Flood forecasting systems have been developed in the last decades based on numerical models (Jain et al., 2018; Barthélémy, S. et al. 2018), data-based models (Lee and Kim, 2018, Okuno et al., 2021) and hybrid approaches using machine learning tools (Young et al., 2017). For riverine systems with a large retention time, numerical models that represent the entire basin are the adequate choice. Flood forecasting at a basin scale requires the availability of a chain of models including meteorological models for precipitation and wind products and hydrologic and hydrodynamic models, for runoff and inundation products. The Global Flood Forecasting Information System (GLOFFIS) is an example of such multi model operational river flood forecasting systems, based on Delft-FEWS (De Kleermaeker et al., 2017). To manage floods in small watersheds, where retention time is short and routing of flood waves is on the order of tens of minutes, the computational time and the resolution of basin wide models is not accurate for timely early warnings (Gaál et al., 2012). Furthermore, the resolution of the meteorological models is generally too coarse to properly simulate the small-scale atmospheric processes that govern the precipitation and wind features of these events (Zhang and Smith, 2003). The availability of a local, tailored meteorological and hydrologic/hydraulic near real time monitoring network is necessary to accurately quantify forcings and its consequences, and integrate them with the large-scale modelling.

In the scope of the INTERREG INUNDATIO project a novel methodology for flash floods was proposed, based on a two steps approach and the usage of the modular forecast framework already in operation for estuarine and coastal floods at LNEC (Water Information Forecast Framework - WIFF, Fortunato et al., 2017). A new hybrid forecast information is thus being developed to address floods from the head of the watershed to the sea, in a seamless way. It combines high resolution numerical models based forecasts for the large scale analysis with small scale data-based predictions, supported by a tailored monitoring network with a reliability layer for data confidence (Jesus et al., 2021).

The new forecast system is being applied to the Ribeira das Vinhas basin, an area prone to torrential floods that lead to severe inundations in the urban area of the city of Cascais, located at the Tagus estuary mouth. In chapter 2, we present the hybrid forecast methodology, while chapter 3 is devoted to review the WIFF framework and pinpoint the new features. The application to Ribeira das Vinhas is presented next, followed by major conclusions and directions for further research.

1. METHODOLOGY

Flash flood predictions are required at very short time scales, making a hybrid process combining process-based models and near real time data-based models necessary to convey accurate alerts in due time. The methodology proposed herein is composed of two parallel procedures. First, a chain of conventional numerical models runs continuously every day, providing large scale predictions for atmosphere and hydrographic basins. A warning threshold procedure is checked continuously to assess the presence of significant rain events. If a predicted rain event exceeds the warning threshold, a second approach is triggered, involving a small-scale data-based model to predict flooding for the following hours. This data-based model is fed by data from a near real time monitoring network and uses machine learning tools. Through the use of high performance computing, machine learning-based predictions can then be provided in a very fast way, after a training period. The methodology is generic and can be applied to any set of numerical models and AI-based tools (Figure 1).

2. THE WATER INFORMATION FORECAST FRAMEWORK FOR THE INUNDATIO PROJECT

The Water Information Forecast Framework (WIFF, Fortunato et al., 2017, Oliveira et al., 2020) is a framework that contains all building blocks required to assemble forecast systems in a customized way. These blocks include the different components of a forecast system: the top block – Forecast – includes a “Simulation” block, divided into “Steps”. Each step is a sequence of tasks, selected depending on the specific prediction to be operationalized, to be executed following a specific order.

The modular conceptualization of WIFF allows for the possibility to reuse any of the steps depending on the requirements of each Simulation. Through this approach, moving from one model to another performing the same role in a forecast chain only requires replacing the Step of the model execution to the one for the new model (Oliveira et al., 2020). The same approach is used for forcings, initial conditions or model parametrizations. Through the application of this concept, WIFF can now be applied to 2D or 3D simulations, including wave-current interactions, baroclinic simulations or water quality processes, from rivers to the sea, including estuaries and coastal regions and the land flooding processes. It has been applied to a multitude of sites for urban, river, estuarine and coastal flood forecast (David et al., 2013, Gomes et al., 2017, Fortunato et al., 2017, Rodrigues et al., 2021), many of which built through the on-demand service OPENCoastS (Oliveira et al., 2021).

WIFF was extended in the INUNDATIO project to address flash flood forecasts by integrating computational models that simulate all relevant processes at the adequate time and spatial scales, based on numerical representations of these processes and on data-based models. Currently, it uses SCHISM, MOHIDLand and XBEACH models, implemented in high performance computing environments at several European Open Science Cloud providers. The framework now integrates both hydrological and hydraulic models of the HEC model family (Brunner, 2021), as illustrated in Figure 2. WIFF offers multiple choices of atmospheric forcings available from NOAA, METEOFrance, MeteoGalicia and IST, with outputs from models GFS, Arpege and WRF at several time and space scales. The integration of the data-based model will be one of the next improvements.

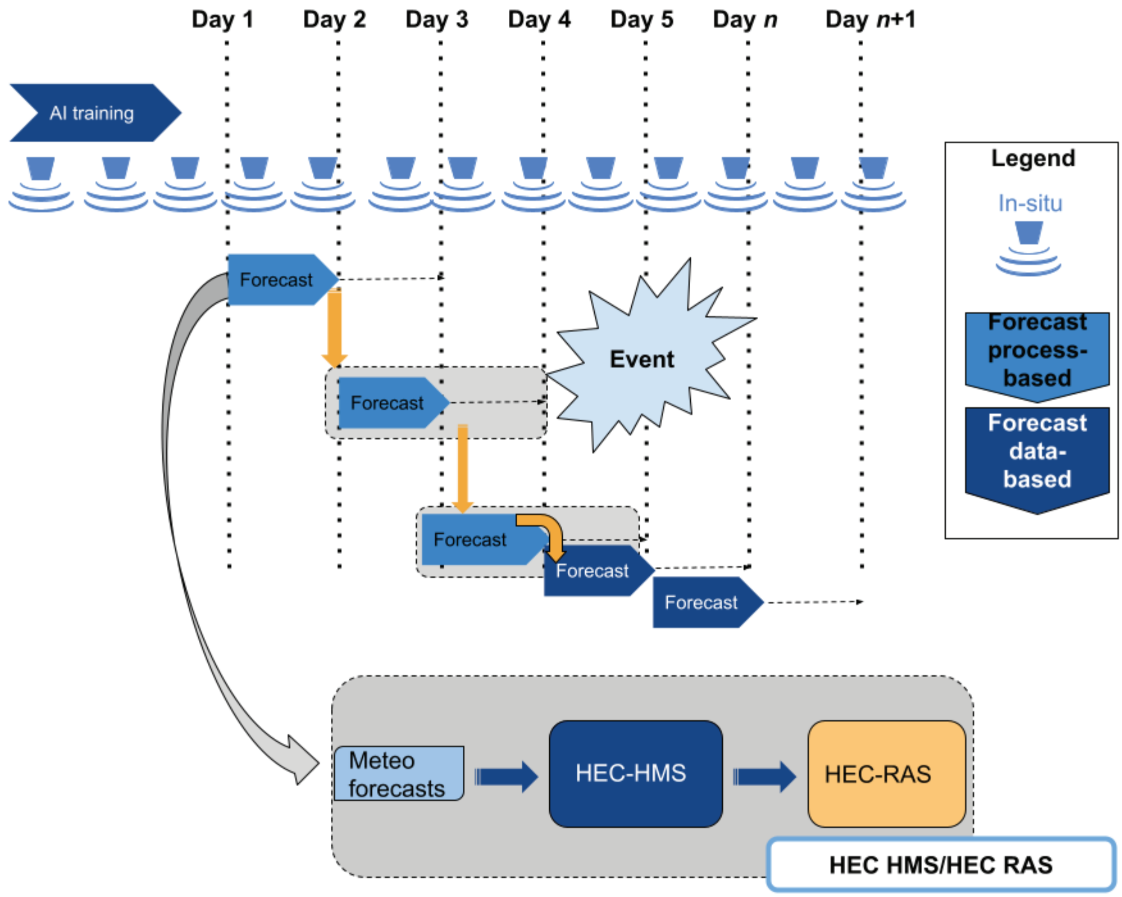

Figure 1. Workflow of flash floods methodology

3. USE CASE DESCRIPTION

Ribeira das Vinhas is a small basin located in Lisbon's west metropolitan area, with a large city (Cascais) occupying 10% of the drainage area located downstream. This area has a high exposure and vulnerability to inundations generated by torrential floods (Figure 2). The streams are dry in the vast majority of the year and are exposed to sporadic events of large floods. A major flood event occurred in 1983 but no monitoring stations were operating at the time. After that event, two monitoring stations were installed but were only in operation for 5 years, most of which were very dry (measured river floods under 5 m3/s).

Model applications are thus limited by the availability of data and model establishment is based on the consequences downstream (inundation levels).

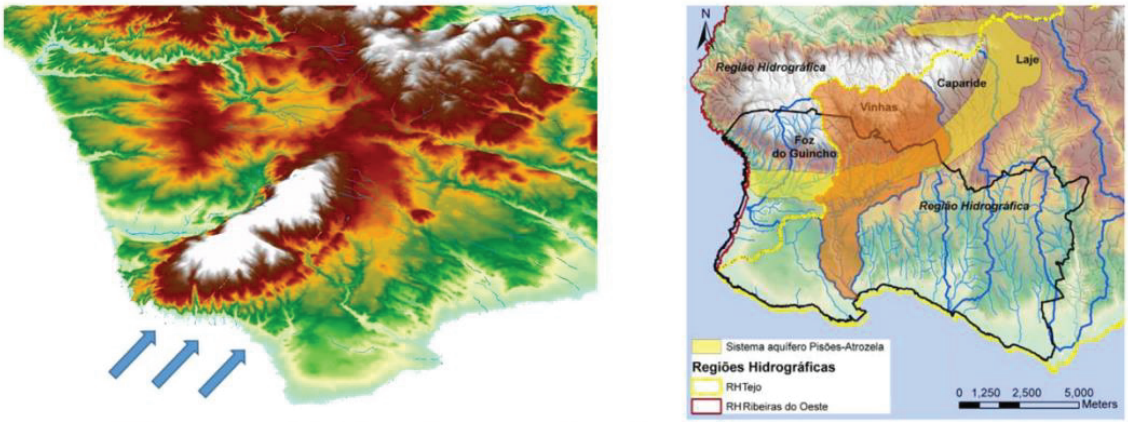

Figure 2. Ribeira das Vinhas: a) schematic representation of the atmospheric conditions that may lead to flooding events b) Watershed representation over the map.

4. MODEL APPLICATION AN IMPLEMENTATION IN WIFF

Given the characteristics of the watershed and the lack of field data for proper calibration and validation, model HEC-HMS (Hydrological Engineering Center- The Hydrologic Modeling System) was selected for the hydrologic modelling. This model allows for simulation of heterogeneous basins as a collection of sub-basins with different rainfall/runoff models that exchange river flows among themselves in a semi-distributed configuration. In this case, the Soil Conservation Service model was used for the estimation of the precipitation excess. This model uses the Curve Number that was estimated for the watershed taking into account the soil and land use characteristics. As the historical monitoring data is rather insufficient, the model was calibrated with the 1983 flood event that was studied due to its severity.

The hydraulic modelling was done using model River Analysis System (HEC-RAS version 6.0.1) developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers. This model uses the peak river flows to estimate inundation for several return periods. The domain was divided as 1D in the upper area and 2D in the downstream area with a 2m cell, where inundation takes place. Figure 4 illustrates the simulated inundation for a 100-year return period.

Both models are integrated in WIFF and are now being operationalized for forecast mode, using one of the several atmospheric forecast providers. The sensitivity of the results to different forcings will be explored next.

Figure 3. a) sub-basin distribution for the hydrologic modelling; b) sample inundation results of the hydraulic modelling of the 100 year return period flood.

5. CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

A new methodology to forecast floods in a small watershed is presented, integrating process-based numerical models and AI-based data models in a two-step procedure. The methodology is implemented in the generic forecast framework WIFF, applied successfully to floods in estuarine and coastal regions, and in urban cities. The numerical modelling is based on the application of the HEC family of models.

The first step in the methodology is demonstrated herein in the Ribeira das Vinhas basin, where the complexity of the atmospheric conditions under strong precipitation conditions leads to torrential floods that inundate downtown Cascais, a city located at the month of the Tagus estuary.

The several tasks to be performed include the settlement of the monitoring network and an improvement of the numerical models, based on that data and on a new lidar dataset for the lower basin and downtown area. The data-based model will be then developed, starting with the training of the AI algorithm and the definition of the precipitation threshold. Then, this model will be integrated in WIFF, closing the development component of the INUNDATIO project and providing the full operational forecast system.

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