WEC WORLD ENGINEERS CONVENTION AUSTRALIA 2019
20-22 NOVEMBER MELBOURNE CONVENTION EXHIBITION CENTRE
ENGINEERS AUSTRALIA
WFEO / FMOI

ISBN number 978-1-925627-25-1

Flood forecast technological platforms: an adaptive response to extreme events

Vieira*, J.M.P; Pinho*, J.L.S.; Vieira*, B.F.V.; Vieira*, L.M.V.

* Centre for Territory, Environment and Construction, Department of Civil Engineering, University of Minho, Gualtar Campus, 4710-057 Braga, Portugal

jvieira@civil.uminho.pt

ABSTRACT

Floods are among the most catastrophic natural disasters with great destructive impact that happen suddenly and sometimes unexpectedly. Although advanced technological tools are available for extreme events prediction, a significant number of floods and inundations still occur every year around the world, causing thousands of deaths and heavy economic losses. Climate change adds uncertainty and severity to intense precipitation phenomena, making it increasingly important to forecast their potential effects in a timely manner in order to minimize their impacts. Recently, the great progress in computational resources and modelling advances, as well as the increase of satellite remote sensing data provided new opportunities to create powerful hydroinformatic tools to be used in the implementation of flood forecasting and warning systems. These developments also benefit from the availability of real-time meteorological information, especially from satellite-based weather radar and meteorological radar and from a diverse range of atmospheric models forecasts that allow their use to force hydrological and hydrodynamic models. This study describes the incorporation of meteorological and hydrological data and models for a flood forecasting and early warning system implementation based on the Delft FEWS platform. The Portuguese river Ave basin was taken as study area. This platform, besides early warnings emissions, will help decision makers and planners to identify areas of potentially significant flood risk, and then the preparation of flood risk management plans, and to set out emergency preparedness plans for these areas.

Keywords: *Climate change, flood forecasting, warning systems, FEWS-AVE, engineering for response*

INTRODUCTION

Floods are natural phenomena with great destructive power that happen suddenly and sometimes unexpectedly. Although advanced technological tools are available for extreme events prediction, a significant number of floods and inundations still occur every year, causing thousands of deaths and heavy economic losses. Climate change (Pachauri *et al.* 2015) adds severity to intense precipitation phenomena, making it increasingly important to forecast their potential effects in a timely manner in order to minimize their impacts.

Entities responsible for minimizing the impacts of floods have been implementing and using hydroinformatic platforms worldwide for flood risk management (Werner *et al.* 2013, Schwanenberg *et al.* 2013, Gibertoni *et al.* 2014). These platforms are responsible for the automatic incorporation of all meteorological and hydrological data, for their validation and for the respective processing required in the modelling tasks and consequent warning emissions.

Such automatic tasks include importing of relevant historical and forecast precipitation data, processing of these data including its spatial interpolation to the sub-basins for hydrological modelling. Hydrometric data are also imported and includes measured water levels and discharges at gauge stations or dams within the river basin. These data are relevant to correctly represent a realistic hydrodynamic state of the river system at the initial time of the forecast. Proper tools to complete time series and to validate them should also be available since missing or bad sensors data are common in monitoring hydrological networks (Sun *et al.* 2011).

Flood warnings must be issued based on a robust models base that in this case must count on a realistic capacity to simulate the hydrology and the rivers hydrodynamics within the basin, and particularly for the flood prone areas. Application of lumped hydrological models are common when it is necessary to predict surface runoff from precipitations (Beven, 2001). Besides this models constitute a simplified approximation to the complex hydrological processes that take place in a catchment, their implementation requires the calibration of many parameters (Gibertoni *et al.* 2014). This calibration should preferably be carried out recurring to an automatic procedure based on an optimization algorithm.

Capacity of integrated modelling of hydrodynamics and hydrology it is also an important aspect for the success of any flood warning system implementation. Sobek software (Deltares, 2019) consists of a set of integrated modules, that allows the simulation of hydrologic rainfall-runoff models in watersheds and performs the simulation of hydrodynamics in fluvial systems (rivers and reservoirs), including urban areas. It is also possible to extend the one-dimensional hydrodynamic approach to a two-dimensional one for areas of complex geometry. Finally, this modelling software solution, integrates a real time control module that it is crucial to simulate hydrodynamics in river stretches dominated by hydraulic structures discharges.

A third essential component of a flood warning system is the capacity to allow automatic running of the involved models. Thus, although every computational operating system presents tools to customize automatic runs of specific applications, the synchronization and management of all the required data in the case of flood forecasting can be complex and a dedicated applications server is justified. All these services are assured in the Delft-FEWS platform (Werner *et al.* 2013).

This work presents the application of the platform FEWS-AVE in the construction of an early warning system for two sub-basins (Selho and Este) of river Ave basin, NW Portugal (Figure 1). Hydrological and hydrodynamic models were implemented, forced by prediction results from atmospheric models in order to forecast river discharge flows. The results of models calibration and illustrative forecasts are presented for different rain events.

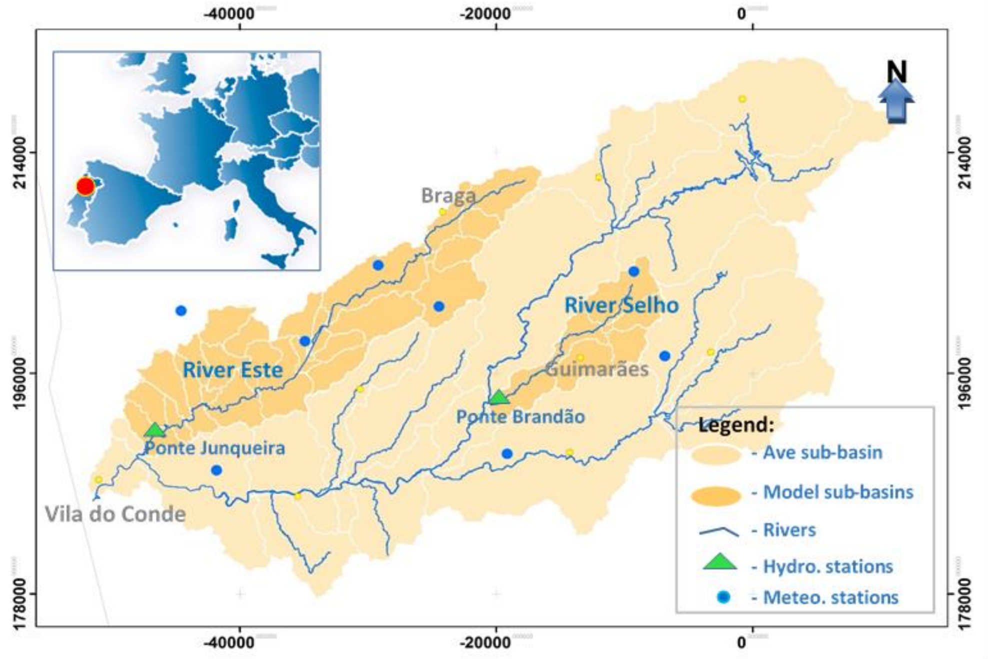

Figure 1. Study area: Location of river Ave basin and rivers Este and Selho sub-basins.

MATERIALS AND METHODS

River Ave basin has an area of 1470 km^2 and present two main flood prone areas: the downstream section of river Selho near Guimarães city and different locations along the river Este, including a location near an important industrial area downstream Braga city.

River Este basin has an area of 247 km^2. Its source is located at Serra do Carvalho, presents one main tributary (Macieira River, with an extension of about 11 km) and its mouth is located at the right bank of river Ave, 4 km upstream Vila do Conde city. This river has recently undergone a rehabilitation work to improve the flow conditions and prevent the floods occurring in urban areas of Braga, as well as improving water quality in the same area. However, besides these efforts, flood vulnerability maintains high and this platform constitutes an important tool for early warning in case of occurrence of floods resulting from extreme precipitation events.

River Selho basin with an area of 68 km^2 has its source at 580 m altitude at Senhora do Monte, in the municipality of Guimarães. It has a length of approximately 20 km and its mouth is located at the left bank of River Ave. Several inundations during floods take place along its main course, depending on various physical and climatic factors as the orographic characteristics of the basin, the geological constitution of the soil and its impermeability. Ponte Brandão hydrometric gauge station is located upstream of its mouth. It has a small tributary (Couros stream) that crosses the center of the city of Guimarães and, in situations of high precipitation, is also vulnerable in terms of floods,

especially at its downstream stretches that suffer from backwater effects during flood events at river Selho.

Several data sources were used for the implementation of FEWS-AVE. Hydro-meteorological data series from the Portuguese national water resources information system (SNIRH) were used in hydrological and hydrodynamic models calibration for the two sub-basins (Figure 2a)). Precipitation (Figure 2b)) and evaporation data at eight meteorological stations, as well as river flows data from hydrometric stations for a period of five years (1995 to 2000) were used in the automatic calibration procedure recurring to the Rainfall Runoff Library (CRC, 2004). Radar data from MeteoGalicia, the regional meteorological agency for Galicia (Spain) were used in the model state update step before the forecasts simulations. This includes reflectivity radar data with a time resolution of five minutes, a spatial resolution of 0,01º lonx0,01º lat, and covering the entire river Ave basin (Figure 2c)).

Precipitation forecasts were obtained from atmospheric model predictions that were properly configured for automatic download and processing as data-feeds of the system. Hydrological and hydrodynamic forecasts are performed based on deterministic and ensemble precipitation predictions of NOAA's GFS and GEFS, respectively (Figure 2d)) and MeteoGalicia's Weather Research and Forecasting WRF model (Figure 22)). The first presents precipitation forecasts for ten-days horizons with a spatial resolution of 0.1° lon x 0.1° lat at six-hour intervals. In the second, the forecast horizon is four days with a spatial resolution of 4 km x 4 km, with hourly resolution for a region that covers Galicia and Northern Portugal.

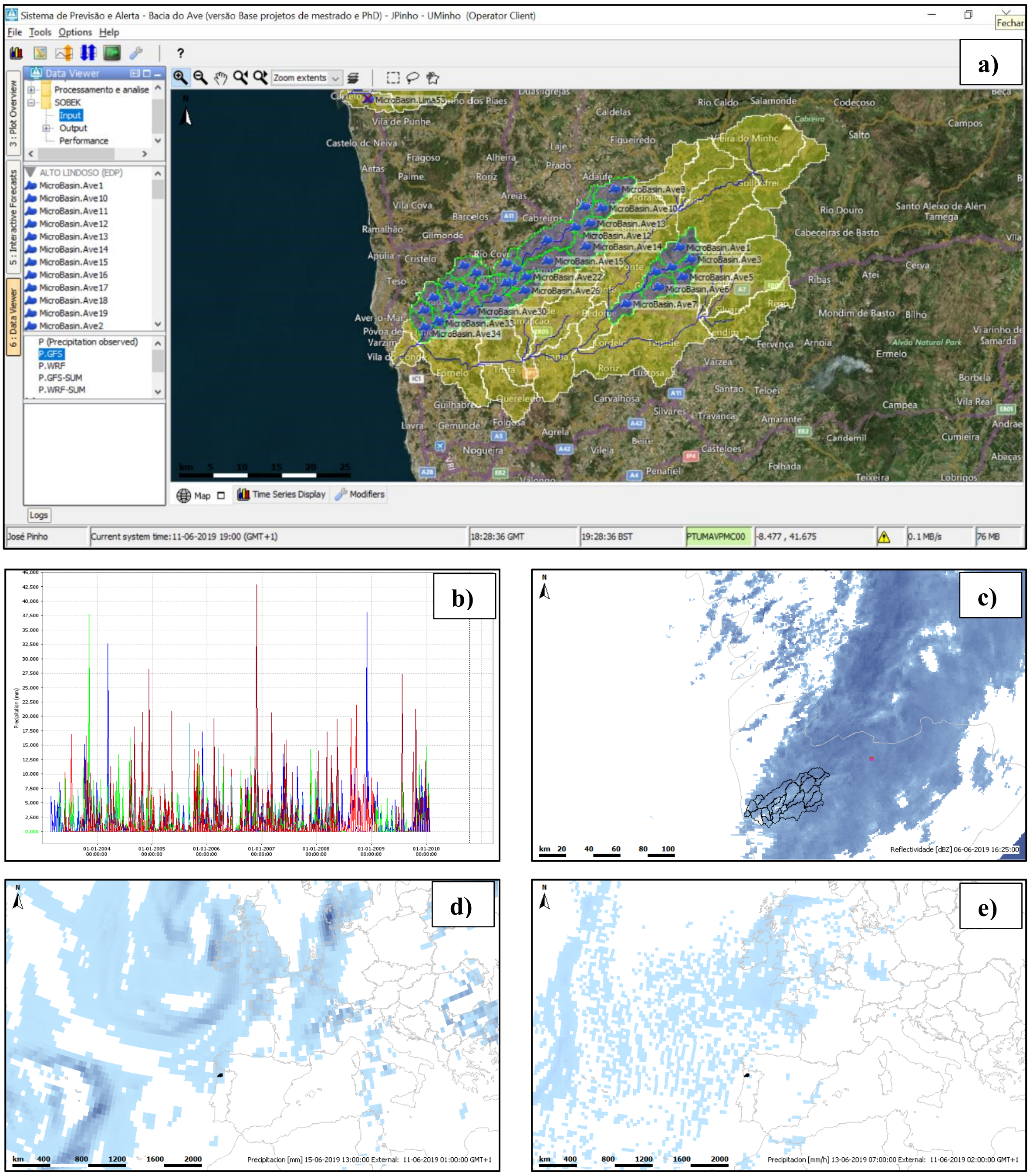

Figure 2. Data sources for FEWS-AVE flood warning system: a) sub-basins of rivers Selho and Este; b) historical precipitation data; c) short term historical radar data; d) GFS forecast precipitation; and e) WRF Meteogalicia forecast precipitation.

Sobek software was applied in models implementation. It consists of seven modules: hydrology, hydrodynamics in channels, hydrodynamics in rivers, urban drainage networks, real-time control, water quality and two-dimensional hydrodynamics. Its integrated environment allows the simulation of problems involving different modules simultaneously. It is based on a very robust numerical method that allows to obtain solutions even for the most complex simulations (Stelling and Verwey, 2005).

Hydrological models implemented with Sobek software are based on the Sacramento hydrological conceptual model (Lettenmaier and Gan, 1990). This model uses average precipitation and evaporation data to estimate flow rates in river basins.

For runoff flow estimation, a subdivision of the soil into two main layers, the top and bottom, are considered. At the top layer the fastest processes that occur along the surface (evaporation, seepage, runoff and subsurface flow) are represented and at the lower layer the slower processes associated with the unsaturated soil zone (infiltration, aquifer recharge and base runoff) are represented. In both layers, volumes where water is either under the effect of surface tension (capillarity) or hydrostatic pressure (free water) are considered; therefore it is possible to define at least four distinct storage soil reservoirs.

The basic mechanism of the model considers that if the maximum storage capacity of the upper tension water reservoir is exceeded, the water becomes available for storage in the upper free water reservoir. This represents a temporary storage of water that infiltrates (percolation) to the lower system and contributes to the flow in the reach by sub-surface flow. Similarly, the filling of the lower water reservoirs that will give rise to the base flow is considered. This model involves 16 parameters related to the soil and surface hydrological processes. Some of these parameters can be calibrated by analysing hydrographs, others may be derived from the physiographic characteristics of the basin and the others must be estimated based on a trial and error analysis. It is still possible to make use of algorithms for automatic calibration based on global optimization techniques, considering different error metrics as was the case in this work in which the Rainfall Runoff Library (RRL) for the calibration procedure was applied.

In the optimization approach for model calibration, initial values of model parameters were defined recurring to their usual range obtained from literature (Anderson *et al.* 2006) and also from soil characteristics (Koren *et al.* 2000). These initial values depend on the selected events and either on the analysed basin. In this way the final calibration was developed using the automatic features available at RRL, and the algorithms of global optimization that presented more satisfactory results was the Rosenbrock Single Start and the Pattern Search Single Start (Lewis *et al.* 2000) using as primary objective the Nash Sutcliffe Model Efficiency (NSE) and de secondary the Root Mean Squared Error (RMSE) as error functions to be minimized.

After RRL calibration, obtained parameter values were adopted in the Sobek models. Their performance was evaluated recurring to different metrics: NSE, a bias parameter computation based on the difference between the sum of simulated discharges and the sum of observed ones (BIAS), RMSE, and Mean Average Error (MAE), computed according equations 1 to 4, respectively,

$$NSE = 1 - \frac{\sum(\hat{Q} - Q)^2}{\sum(Q - \bar{Q})^2} \quad (1)$$

$$BIAS = \frac{1}{N}\left(\sum \hat{Q} - \sum Q\right) \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N}\sum(\hat{Q} - Q)^2} \quad (3)$$

$$MAE = \frac{1}{N}\sum|\hat{Q} - Q| \quad (4)$$

where $\hat{Q}$ is the measured value, Q is the simulated value and N the total number of values in the time series.

The implementation of FEWS-AVE requires the configuration of a relatively great number of files (XML files) according a predefined syntax, including: (i) the region configuration files that mainly considers the definition of all the locations and associated parameters; (ii) the automatic workflows definition and associated modules for importing and exporting data to the internal database and feeding and running external models; (iii) configuration of general adapters for external models; and (iv) several additional configurations related with displaying data, thresholds of data validity and warning rules. The system is configured on a local server and the final step to turn it into an operational server system imply the installation and configuration of different software services, including database, web and application servers and a java service.

RESULTS AND DISCUSSION

Sacramento parameters values obtained from automatic RRL calibration are presented in Table 1. Calibration simulation uses historical precipitations, evaporation and rivers discharges data for a period of five years. The same values were adopted in the hydrological Sobek model. Results for a validation simulation are depicted in Figure 3 and Figure 4 and the related metrics are presented in Table 2.

The performance of the model is acceptable since hydrological data available for the calibration was limited. Considering that more data will become available, the automatic calibration should be repeated and the calibration parameters values of Sobek model should be updated. It is expected that on future flood events the performance of the model will be improved since radar data will characterize better the precipitation distribution within the basin. The planned installation of additional monitoring stations at rivers Selho and Este will increase accuracy in assessing levels and inundations in vulnerable river stretches and will allow also improving the results of the state update before the simulations forecast.

Parameter/Basin	Range	Este	Selho
ADIMP	0 – 0,2	0,02	0,02
LZFPM	0 – 1000	712	565
LZFSM	15 – 300	186	50
LZPK	0,001 – 0,015	0,007	0,023
LZSK	0,03 – 0,2	0,08	0,00
LZTWM	0 – 500	61	139
PCTIM	0 – 0,5	0,04	0,09
PFREE	0 - 0,4	0,50	0,02
REXP	1 - 3	3,00	2,45
RSEWMRV	0 – 0,4	0,07	0,09
SARVA	0 – 0,5	0,12	0,20
SIDE	0 – 5	0,00	0,00
SSOUT	0 – 1	0,00	0,00
UZFWM	10 – 100	80	25
UZK	0 – 0,5	0,00	0,44
UZTWM	0 – 125	26	130
ZPERC	20 – 300	24	36

Table 1. RRL estimated Sacramento model parameters values used in Sobek hydrological models of rivers Este and Selho.

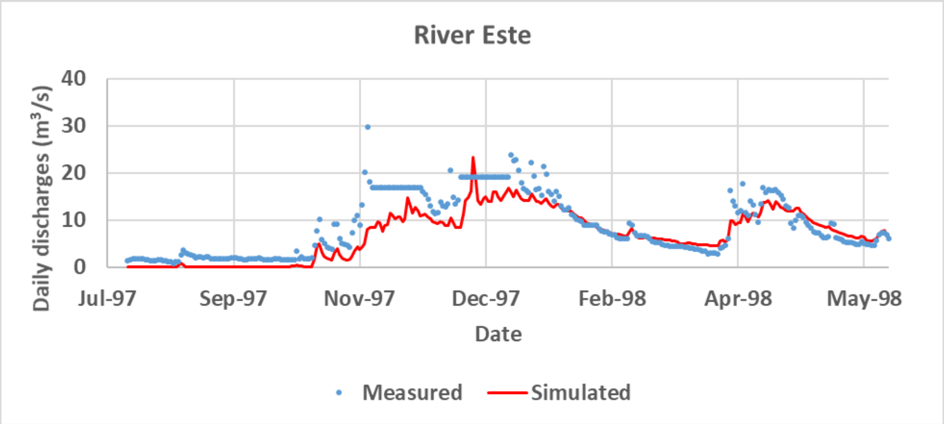

Figure 3. Observed and simulated daily discharges for river Este.

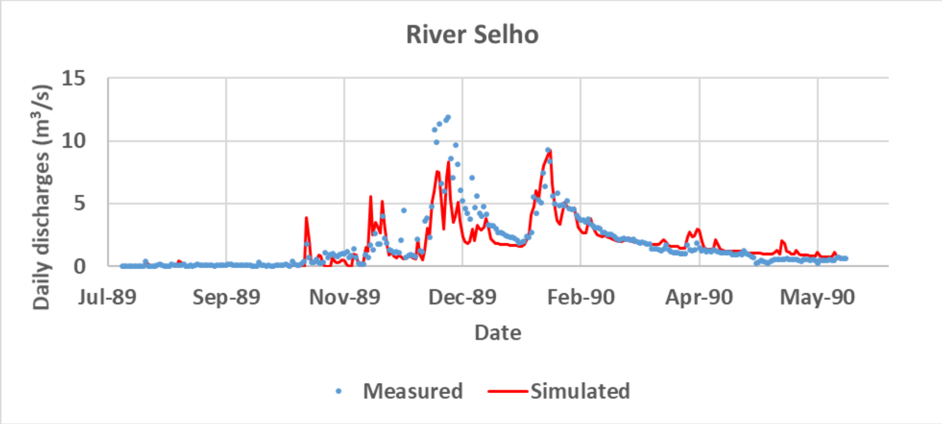

Figure 4. Observed and simulated daily discharges for river Selho.

Sub-basin (–)	NSE (–)	BIAS (m^3/s)	RMSE (m^3/s)	MAE (m^3/s)	R^2 (–)	Average (sim.) (m^3/s)	Average (obs.) (m^3/s)
Este	0,68	1,9	3,6	2,6	0,78	6,9	8,8
Selho	0,77	0,2	1,1	0,6	0,78	1,6	1,8

Table 2. Observed and simulated daily flow rates in rivers Este and Selho.

The flood warning platform FEWS-AVE is now operational and running simulations twice a day. Figure 4 depicts results of flow forecasts at Ponte Junqueira (river Este) and Ponte Brandão (river Selho) on October 31, 2017, for GFS and WRF predicted precipitations. In this simulations a precipitation event is expected to begin on 1 November and will achieve a cumulative precipitation value of about 24 mm according GFS and WRF predictions during the forecast horizons. Differences in time and spatial resolutions of these two precipitations forecasts explain the differences on the obtained flow hydrographs at the monitoring stations.

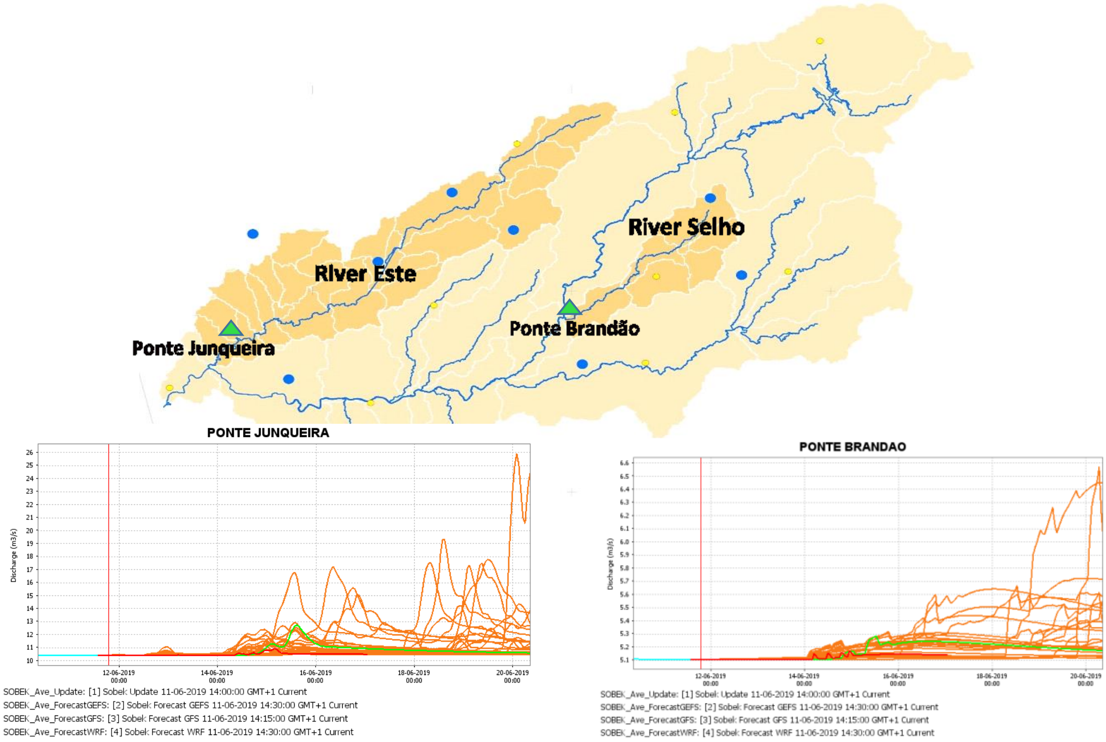

Figure 3. Flow forecasts results at monitoring stations in river Este (Ponte Junqueira) and river Este (Ponte Brandão).

CONCLUSIONS

A flood forecast platform involving advanced tools for flood simulation based on a Sobek hydrological and hydrodynamic model was presented. The calibration of the Sacramento hydrological model involves the quantification of sixteen parameters for each sub-basin. Results of automatic calibration using the RRL software were presented. These adopted values allows to obtain a reasonable performance of the Sobek model according different model performance metrics assessment.

The assessment of the skill of each individual precipitation forecasts source is under development using measured precipitation data at different precipitation gauge stations that were recently installed. Moreover, installation of pressure sensors at flood prone river stretches are planned which will allow analysing the performance of the hydrodynamic model in simulating river water levels which are key factors to produce reliable flood warnings.

REFERENCES

Anderson, R.M., Koren, V.I., and Reed, S.M., "Using SSURGO data to improve Sacramento model a priori parameter estimates", *Journal of Hydrology* 320(1), 103–116, 2006.

Beven, J.K., *Rainfall-Runoff Modelling – The Primer*, John Wiley & Sons Ltd., Chichester, 319, 2001.

CRC for Catchment Hydrology, "Rainfall Runoff Library – User Guide, 2004", avaliable in: https://www.tolkit.net.au/rrl, accessed in December 2016.

Deltares, "Sobek software", available in: https://www.deltares.nl/en/software/sobek/, accessed in June 2019.

Gibertoni, R. F. C., Pinho, J. L., Muhlenhoff, A. P., Kan, A., Schwanenberg, D., and Reis, A.A., "Sacramento model calibration using different methodologies: application to the Itabapoana-MG river basin", *6th International Conference on Flood Management-ICFM6,* Brazilian Water Resources Association, 2014.

Koren, V.I., Smith, M., Wan, D., and Zhang, Z., "Use of Soil Property Data in the Derivation of Conceptual Rainfall-Runoff Model Parameters", *American Meteorological Society 15th Conference on Hydrology*, Long Beach, CA, 2000.

Lettenmaier, D.P., Gan, T.Y., "Hydrologic sensitivities of the Sacramento–San Joaquin river basin, California, to global warming", *Water Resources Res.* 26, 69–86, 1990.

Lewis, R. M., Torczon, V., and Trosset, M.W., "Direct search methods: then and now", *J. Comput. Appl. Math.*, 124, pp. 191–207, 2000.

Pachauri, R.K., Meyer, L., Plattner, G.K., and Stocker, T., "IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change", 2015.

Schwanenberg, D., Talsma, J., Pinho, J.L., Assis dos Reis, A., Rodrigues Bessa, M., and Kuwajima, J., "Short-term reservoir optimization for mitigation downstream flood risks", *8th International Conference of EWRA Water Resources Management in an Interdisciplinary and Changing Context*, Porto, Portugal, 2013.

Stelling, G.S., Verwey, A., "Numerical Flood Simulation", *In: Encyclopedia of Hydrological Sciences*, John Wiley & Sons Ltd, Vol. 1, pp.257–270, 2005.

Sun, S., Bertrand-krajewski, J., Lynggaard-Jensen, A., Van den Broeke, J., Edthofe, F., Almeida, M.C., Ribeiro, A.S., Menaia, J., "Literature review for data validation methods", *SciTechnol*, vol. 47, no. 2, pp. 95–102, 2001.

Werner, M., Schellekens, J., Gijsbers, P., Van Dijk, M., Van den Akker, O., Heynert, K., "The Delft-FEWS flow forecasting system", *Environmental Modelling & Software*, pp. 1-13, 2013.

BIOGRAPHY

José M.P. Vieira: PhD in Civil Engineering. Full Professor and Hydraulics Division Head at the Civil Eng Department of University of Minho (Portugal). He has participated as coordinator of a large number of research and development projects in water resources planning, drinking water safety planning, and hydrodynamics in estuaries and coastal zones. José M.P. Vieira has been Vice-Rector and Pro-Rector of the University of Minho and Vice-President of the Portuguese Association of Engineers. He is currently member of the Executive Council of the World Federation of Engineering Organisations (WFEO) and President of the European Federation of National Engineering Associations (FEANI).

José L.S. Pinho: PhD in Civil Engineering. Associate Professor at the Civil Eng Department of University of Minho (Portugal). He has participated in a large number of national and international research projects in hydroinformatics and hydrodynamics in rivers, estuaries and coastal zones.

Bárbara F.V. Vieira: MSc in Civil Engineering. PhD student in the Centre for Territory, Environment and Construction of the University of Minho (Portugal). She is currently developing a thesis on "Engineering with Nature: An innovative solution for coastal erosion protection".

Luis M.V. Vieira: MSc in Civil Engineering. Researcher in the Centre for Territory, Environment and Construction of the University of Minho (Portugal). He is currently working in an international research project on "Adaptation measures to climate change and prevention and management of climate-related risks".