A QUALITY ANALYSIS IN HYDROLOGICAL FORECASTING. LESSONS LEARNT FROM THE BASQUE COUNTRY FLOOD EARLY WARNING SYSTEM (SPAIN).

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ABSTRACT: Flood early warning systems are increasingly becoming a common tool to reduce flood risks in wide parts of a certain region or country. Their low investment needs, short implementation times and significant effectiveness make them a desirable protection measure in comparison with other structural solutions. Nevertheless, in order to fully exploit their potential there are certain requisites that must be fulfilled, such as the availability of accurate real-time hydro-meteorological data, the development of well-calibrated hydrological models, the existence of detailed meteorological forecasts, the use of data assimilation algorithms and the implementation of a reliable integration software that ensures a proper automation of tasks. Advanced systems are now including weather ensembles and radar nowcasting as a way to improve hydrological forecasts and take into account the related uncertainty. However, before getting into more complex calculations, a special attention should be paid to the current quality of the system in an effort to identify the elements that mainly contribute to its performance. Such an exercise has been made in the Basque Country Flood Early Warning System, which is operational since September 2012. The hydrology of the region has torrential features, both due the occurrence of very intense and persistent convective storms and due to the fact that rivers are short and with steeply slopes, which means they have small concentration times. Therefore, a correct rainfall observation, a reliable short-term rainfall forecast, the availability of adequate antecedent moisture conditions, a valid model response and a consistent data assimilation procedure are key factors that need to be analysed and cross validated. Here we present the results of this analysis and the alternatives proposed to overcome the detected pitfalls, which in overall will contribute to build a better simulation core before other developments area implemented. In addition, this new developments are also outlined and their potential effect on the system discussed.

Key Words: Flood Early Warning System, Quality analysis, Uncertainty quantification.

1. INSIGHT INTO THE AREA

The Basque Country is located in northern Spain, nearby the ending western Pyrenees and divided from East to West by the Cantabrian Cordillera, with elevations over 1,000 m.a.s.l. and laying no more than 40 km from the seashore. To the North, narrow and steep valleys run towards the sea with torrential features, whereas a plateau with an altitude around 600 m.a.s.l is found to the South. The northern façade is temperate and humid. It benefits from warm sea temperatures due to the presence of a branch of the Gulf Stream reaching the area. The weather is also dominated by westerly winds that carry humid air from the ocean. As a result, mean average rainfall ranges from 1200 to 2000 mm per year decreasing only slightly in summer. Within this typical pattern, very intense, stationary and persistent storms can take placed caused by a combination of a warm sea, an unstable surface atmosphere and cold air at higher altitudes. Those situations are the major threat in terms of floods in the region. As an example, in August 1983, 500 mm in 24 hour were recorded in some locations of Biscay leading to a major flood that was thought to exceed a 1,000-yr return period causing a devastating impact on population and properties. There were 39 casualties, mostly in the area around Bilbao, and 800 M€ of economic losses. This particular rainfall pattern is accompanied by a territorial model highly focused on the bottom of the valleys. Floodplains, which are quite narrow, are packed with built-up areas. In the second half of the 20th century when there was an economic boom in the region, the lack of flat terrain forced people to build near the rivers, unaware of the risk this could imply for them. As a result, the Basque Country experiences recurrent and sometimes catastrophic floods.

In order to fulfill the requirements of safety against floods with a state of the art warning and decision support system, a kind of non-structural measure, the Basque Water Agency (URA) in collaboration with the Civil Protection Services started a project in 2011 for its completion, as the telemetry is being compiled and made available through the EuskalMet internet service since 1999, and the southern area shares hydrological data with the Ebro Basin Agency.

The present Real Time Flood Forecasting and Monitoring system covers a total surface of 8451 km^2, divided into 22 basins with a network of 2252 km of main rivers and tributaries, monitored with a total number of 108 rainfall gauges (approximately one every 80 km^2) and 51 discharge-level measurement stations (approximately one every 160 km^2, or one every two rainfall gauges). The maximum height of the terrain is at Aitxuri Mountain, 1551 meters above sea level, and 50 km away from the north seaside. The maximum storage capacity of man-made reservoirs in the region reaches 385 Mm^3 for a total population of 2.2 million.

The latest extreme event took place during November 2011, with precipitations over 200 millimeters in 24 hours for some of the catchments, leading to maximum discharge values of around 1000 m^3/s; undoubtedly a good representative case of a flash flood event.

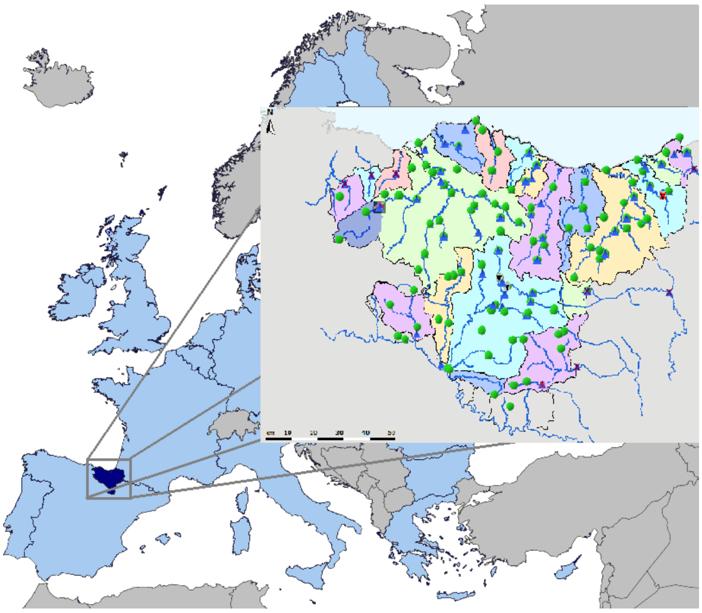

Figure 1: Location of the Basque Country inside the European Union, with the distribution of monitoring stations for rainfall, discharge, stage and snow.

2. DESCRIPTION OF THE SYSTEM

Since Rizzoli and Young, 1997, there have been many platforms dedicated to the monitoring of environmental resources and the forecasting of their key variables. Nowadays these frameworks are mature enough to be used with common desktops and software, but with the essential requirements of accessing to as much electronic file formats as possible, executing periodical tasks of data processing in an ordered and synchronized way, coupling a wide range of numerical engines to scheduled real time data (telemetry, prediction of meteorological external forces and boundary conditions like tides), satisfying an increasing demand on the number of stations, and other needs of scalability, the selected exploitation tool in this case was the Delft-FEWS architecture developed by Deltares. A complete description of this decision support shell can be found in internet, as well as many practical examples around the world (Weerts *et al.,* 2010) In addition the implemented shell is managed mostly by Free Software applications, such as JBoss, MySQL, Apache Tomcat and cygwin tools, which eases the maintenance tasks by IT administrators. The core of the application is made in JAVA, which guarantees a standard use over many platforms.

The entire hardware infrastructure is hosted and maintained by the Basque IT Service (EJIE).

A central data-base is accessed by the Master Controller Server, and delivers the information to the group of clients, including all the real time gauge measures, a rainfall RADAR and Numerical Weather Predictions (NWP). For general descriptions of flood warning systems with a whole technical description of the assembling techniques, Hydrological and Hydraulic approximations and schemes, risk dissemination, etc., the reader is referred to Knight and Shamseldin, 2006, and Werner *et al.,* 2005, for particular Mediterranean flash floods with less resources to Villanueva, 2007, and for continental areas with a large density of reservoirs to Villanueva, 2010, concerning NWP, see Tomkins-Warner, 2010, and related to rainfall RADAR, Reichel *et al.,* 2009. The authors summarize the key components below.

2.1 Summary of periodic tasks and numerical models

Without entering into a detailed description of the selected runoff schemes, two were chosen at the beginning: the classical lumped Mike11-NAM by DHI and the conceptual distributed TETIS (Francés *et al.,* 2007) for a 500x500 m grid. Both of them with over a dozen of parameters to optimize, for every hydrological unit or set of tanks: a catchment in case of the lumped model, and every grid cell in case of the distributed model.

The following Table 1 summarizes all the information that the system is able to cope with, including their frequency, spatial and temporal resolution, and horizon.

Table 1: Scheme of all the periodic tasks with their characteristic properties. Note that not all the information is exploited at the moment, particularly the Rainfall RADAR.

Input	Frequency of Exec	Horizon	Spatial Resolution	Time-Step	Operational/Exploited
Meteo Deterministic_9	12 h	72 h	9x9 km	1 h	Yes/Yes
Meteo Deterministic_27	12 h	72 h	27x27 km	1 h	Yes/Yes
Telemetry	10-15 min	Real Time	One St. per 80 km^2	10-15 min	Yes/Yes
Rainfall RADAR	1 h	-6 h	250x250m	1 h	Yes/No

The selected numerical schemes for the continuous simulations and forecasting are shown in Table 2.

Table 2: Scheme of all the codes exploited for simulation and forecasting.

Hydrological Model	Running frequency	Spatial Res	Time-Step
Lumped RunOff (NAM-DHI)	Historical=4h, Forecast= 12h and on demand	50-150 km^2	1h
Distributed RunOff (TETIS)	Historical=4h, Forecast= 12h and on demand	500x500 m	1h

3. REMARKABLE PAST EVENTS

After approximately 18 months from the set-up, the whole architecture continue running without interruption, and managed to monitor, store and launch forecasts with trial and error optimization in several episodes. Tables 3 and 4 show a selection of representative values corresponding to two flood events occurred during the first testing phase of operation (data retrieved from interim reports).

Table 3: Summary table for January 2013 Event (15^{th}-28^{th}).

Catchment	2 weeks Max (mm)	Daily Max (mm)	Hourly Max (mm)	Peak of Q (m^3/s) or H(m)
Erenozu	384.2	81	13.1	111
Sarria	328.1	82.6	7.7	1.4 (m)
Balmaseda	315.9	66	7.6	116

Table 4: Summary table for February 2013 Event (2^{nd}-13^{th}). In this event there was snow falling and melting at the top mountains, resulting in flatter discharge peaks.

Catchment	2 weeks Max (mm)	Daily Max (mm)	Hourly Max (mm)	Peak of Q (m^3/s) or H(m)
Erenozu	230.9	36.9	8.7	86.07
Sarria	386	106.3	7.2	0.79 (m)
Balmaseda	317.4	76.	10.7	77

The last recent event of November 2013 was weaker than the previous ones, but could be used as a first complete performance test for the rainfall prediction and discharge forecasting. It is remarkable that the observed precipitations and discharges in this last event were in the lower range of the calibration interval. Therefore, no serious damages occurred, but the overall performance of the hydro-meteorological models was not optimal, due to the key influence of the initial humidity condition of the hydrological tanks.

In order to understand the performance of the simulations in a deterministic approach, the Nash coefficient was used to compare the observed discharge time series versus the predicted with the NWP and the simulated in historic mode, i.e. when runoff models are fed with the rainfall detected by gauges. The results lead to the following conclusions:

- The forecasted rainfall with the Meteo-deterministic model is within a range of +/- 29 % of the measured by the gauges, in the first 24 hours horizon, and this error increases to +/- 34 % from 24 to 48 hours, ending with poorer and always lower results from 48 to 72 hours. Note that all the calculations were done with mean values across the sub-basins.

- The distributed model TETIS is acceptable while running in historic mode for 72 hours (Nash indexes between [0.49 – 0.88]) To be improved, it only needs slight adjustments on the Evapotranspiration parameter as first order action, and secondly through the imposition of initial hot-starts selected as percentile distributions of the internal humidity tanks, which are five in total for each cell of the grid. However, in predictive mode the results were less efficient (maximums of Nash down to 0.5), due to the first commented uncertainties in the initial humidity conditions, the discrepancy between the NWP rainfall and the gauge values, and the sharp variation of discharges while executing consecutive NWPs, see figure below.

- The lumped model is in general less accurate, but it still maintains good Nash coefficients in the historic mode reaching maximums of 0.78 (in 24h interval), which are reduced to 0.4 in predictive mode. In general, it tends to over-estimate the observed results.

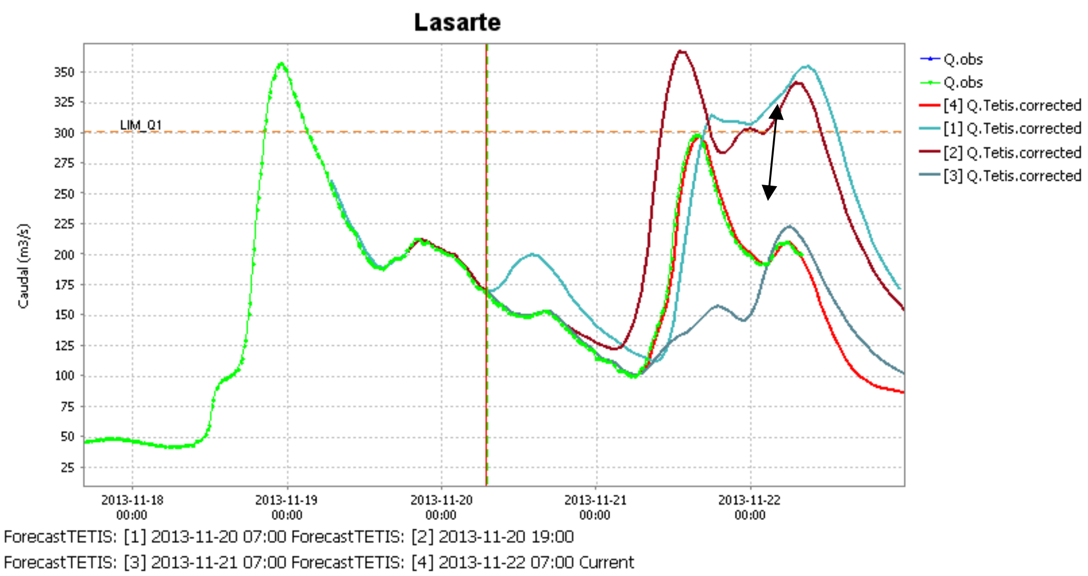

Figure 2: While a sequence of deterministic rainfall predictions is followed (as in this figure second peak, or right hand side), it can happen that a significant gap in discharge appears suddenly between consecutive predictions, within a 6-12 hours' time lapse. Green for observed discharge, garnet for 24h in advance prediction, light blue for 12h in advance, dark blue for 0h in advance, and red after 24 hours.

3.1 Reservoir management

One of the bottle necks of this basin is the management of a system of two reservoirs, Urrunaga (maximum capacity of 72 Mm^3) and Ullibarri (maximum capacity of 147 Mm^3), with a gallery exchange among them, that is accurately modeled with a mass conservation scheme, knowing the depths of the reservoir in real time, the free surface or volume-depth curve, the inflow forecasts, and the fixed rules for exchange and downstream release, in the current case with a delicate maximum of 75 m^3/s for Ullibarri, upstream the city of Vitoria-Gasteiz. The simulations carried out were successful enough to manage releases within a 24 hours horizon in a sense of developing preventive operations to make room for potential input volumes without compromising the downstream flooding thresholds, Figure 3. This is achieved by means of a trial and error technique, but it will be optimized in the future, as explained in Villanueva, 2010.

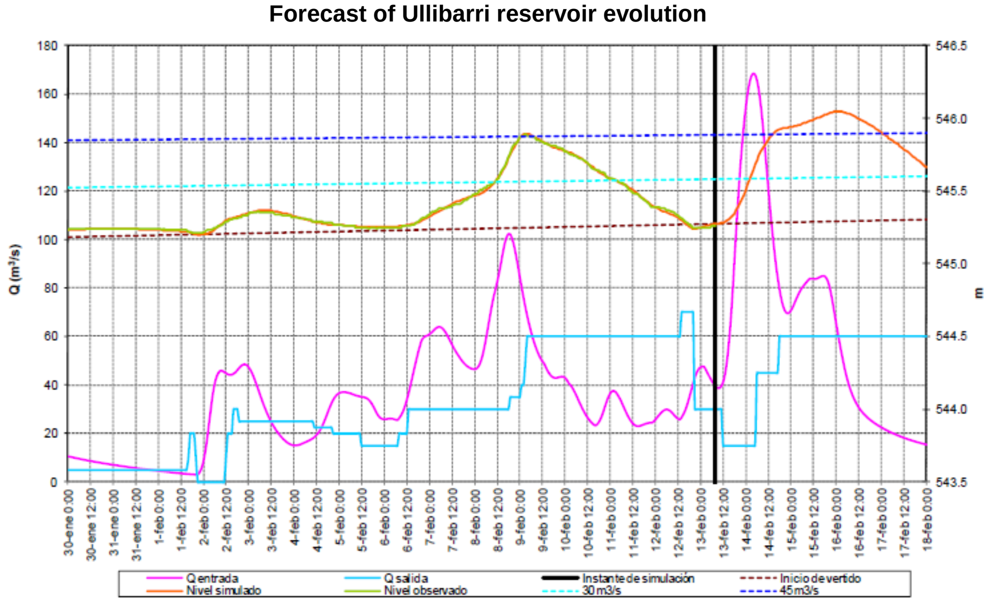

Figure 3: One of the main concerns during flooding crisis in this basin is the reservoir release at Ullibarri dam, where a restriction of a maximum of 75 m^3/s is fixed. This can be achieved by a correct planning and forecasting of extreme cases, where the simulation of the inflows depending on the rainfall is a key factor, that rainfall is analysed and varied in time and space, starting from the Meteo deterministic model, according to the experience of the team during the last events. A forecast of flows and levels is delivered to keep the safety margins; for instance in this case pink is the forecasted inflow, blue the scheduled release, green the monitored stage and orange the forecast of stage.

4. LESSONS LEARNT

Apart from the application of data-assimilation techniques in order to improve the hydrological parameters and the internal humidity or saturation states of the run-off models, with an expected frequency of four hours, another concern is how to solve the quantitative gap between the NWP and the detected rainfall. While having used only meteorological deterministic models, the answer clearly leads to the inclusion of ensemble simulations, but there is a time in between where the authors wish to address some related problems, these are:

- The weight or influence of downscaling techniques, which are not available during the set-up of the project, due to the lack of historical data, and ideally help to filter some peaks in values derived from the NWPs.

- The consideration and sensitivity of other uncertain states, that by limitations in time or budget, are included or defined as "ensembles of the poor", or in more respectful words "ensembles for the beginner", these would be the:

    - Variation of the internal humidity tanks with different Evapo-Transpiration values, in a continuous way, which was shown quite relevant in this study.

    - Variation of the internal humidity tanks following statistical distributions, as initial hot-starts.

- o Temporal and spatial translation of the deterministic Meteo grids, with a few hours backward and forward and a few dozens of kilometers in displacement.

5. REMAINING TASKS:

Directly related to the previous section, other tasks still to face are:

- Include a model of variation of the daily or hourly Evapo-Transpiration according to the wind forecasting.

- Use of a Grid to Grid Run-Off model, or a direct coupling between the rainfall grid and the terrain or digital model, and subsequently a complete hydrodynamic flood model.

- Use of an already settled rainfall RADAR as input of the hydrological models as soon as adequate data for calibration is available.

- Use of recalibration techniques or data-assimilation for the hydrological models.

And finally, the use of hydrodynamic models for the downstream bays, including tidal effects and pressure variation.

6. OTHER CONSIDERATIONS:

Between the context of the present congress it is important to remark that during the development, exploitation, and evolution, of such a complex decision support system, there are many specialized people involved, from bottom to top; Telemetry maintenance staff, IT experts, scientists from Meteorological bodies, practitioners in Hydrology and Hydraulic, Civil Servants from water agencies, Civil Protection Units, City or Council Mayors, local Politicians, etc., resulting in a complex web of interests and relations, with many different languages. The present team has detected the following challenges for years to come:

- A closer communication and sharing of models and assumptions between Meteorological and Hydrological forecasters is desirable. This is reinforced by the fact that the majority of run-off codes are black-boxes, whereas in atmospheric modeling the majority of codes are open, a gap that would require important efforts to be solved, and was warned more than a decade ago by Harvey and Han, 2002.

- To transmit that numerical models within flood forecast shells in real time are useful tools, not for an accurate wave tracking in the order of centimeters neither determining exact water extents, but for threshold evaluation and identification of control points with major downstream impact. In addition it is important not to hide the sequential set of predictions showing the evolution of the forecasts during dozen of hours, as it makes easier to understand the whole evolution of a dynamic forecast. This is considered a key task, especially if ensembles are going to be developed in the future.

As a result of these considerations, the group experience in the last years remarks the priority of using forecast horizons as large as possible with deterministic models at least (run with a minimum frequency of 12 hours), and of course the use of ensembles when available, although a clear picture of the event is only apparently clear below the 24 hours horizon in the described particular catchments, but a wider horizon helps to address resources for vigilance, to warm the connections up between the experts, know the limits of each modeling technique, correct a few of them if possible, and increase the general awareness for potential emergencies.

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