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An operational flood warning system for poorly gauged basins. Demonstration in the Guadalhorce basin (Spain)

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Abstract

This paper deals with the presentation of a flood warning system (GFWS) developed for the specific characteristics of the Guadalhorce basin (3200 km², SE of Spain), which is poorly gauged and often affected by flash and plain floods. Its complementarity with the European Flood Alert System (EFAS) has also been studied. At a lower resolution, EFAS is able to provide a flood forecast several days in advance.

The GFWS is adapted to the use of distributed rainfall maps (such as radar rainfall estimates) and discharge forecasts are computed using a distributed rainfall-runoff model. Due to the lack of flow measurements, the model parameters calibrated on a small watershed have been transferred in most of the basin area. The system is oriented to provide distributed warnings and fulfils the requirements of ungauged basins.

This work reports on the performance of the system on two recent rainfall events which caused several inundations. These results show how the GFWS performed well and was able to forecast the location and timing of flooding. It demonstrates that despite its limitations, a simple rainfall-runoff model and a relatively simple calibration could be useful for event risk management. Moreover, with low resolution and long anticipation, EFAS appears as a good complement tool to improve flood forecasting and compensate for the short lead times of the GFWS.

34 **1. Introduction**

35 Floods represent the most serious natural hazard in Europe, and flood management is a
36 critical component of public safety (Hajat *et al.* 2003; Barredo, 2007). During the last 50
37 years significant efforts to improve flood warning systems (FWS) have been carried out by
38 the scientific, technical and administration sectors. Thus in the context of medium to large
39 river basins, with response times of the order of tens of hours, forecasts, warnings and
40 public preparedness for reducing casualties from extreme plain floods have clearly
41 improved (Meon 2006). However, the achievements for forecasting flash floods,
42 characterized by short-lasting storms affecting reduced areas of a watershed, have been less
43 impressive. As flood forecasting is in many countries limited to the main streams or to
44 specific watersheds with particular assets like hydropower dams, which are in most cases
45 well-gauged river sections, it leaves large parts of the territory not covered by flood
46 monitoring networks (see for instance: Borga *et al.* 2007; Costa and Jarett 2008; Gaume *et*
47 *al.* 2009).

48 A major concern in the context of FWS operating in basins prone to flash floods is to
49 monitor the variability of rainfall in space and time. In particular, the use of radar-based
50 quantitative precipitation estimates (QPE) and nowcasts has been demonstrated to be an
51 interesting tool for anticipating and quantifying the consequences of rainfall at the ground.
52 Radar products are particularly interesting in areas frequently affected by severe storms
53 with complex spatio-temporal patterns (of tens of km²) and response times of the order of
54 tens of minutes to few hours (see for instance: Sempere-Torres *et al.* 1999; Berenguer *et al.*
55 2005; Berne *et al.* 2005; Borga *et al.* 2006; Germann *et al.* 2009).

56 The use of distributed rainfall-runoff models represents a second key element in the
57 production of distributed flow forecasts. Distributed models in general do not seem to
58 perform significantly better than classic simple lumped models when they are used to
59 forecast the discharges at a few specific points of gauged watersheds, although this topic is
60 still a matter of discussion (e.g. Carpenter and Georgakakos 2006; Reed *et al.* 2004).
61 However they provide much richer information than lumped models as they are able to
62 consider the spatial distribution of model inputs (in particular, rainfall) and/or parameters,
63 and produce distributed runoff simulations. In the case of ungauged watersheds,

64 regionalization techniques (see for example Blöschl and Sivapalan 1995) are frequently
65 used to extrapolate model parameters estimated from closest gauged catchment.

66 In this context, two types of warnings can be delivered in the framework of FWS: (i)
67 warnings based on rainfall measurements, and (ii) warnings based on simulated discharges.
68 Both have advantages and limitations.

69 Basically, warnings based on rainfall can be delivered by comparing precipitation
70 accumulations (on different time) to a corresponding reference associated to a probability
71 of occurrence and a return period. As soil moisture condition is not taken into account, the
72 results can sometimes be very different to those based on hydrological simulations (see
73 Alfieri *et al.* 2011). A another well-known approach to issuing warnings based on rainfall is
74 the Flash Flood Guidance, FFG (Georgakakos 2006). The FFG computes the amount of
75 rainfall of a given duration required to cause flooding in a certain basin. If the
76 corresponding observed or forecasted rainfall amounts (integrated for the same duration
77 within the basin) exceeds the pre-computed threshold, a flood warning is issued. The FFG
78 represents a first attempt to evaluate the potential flooding and can be employed at different
79 time and scale resolutions (Norbiato *et al.* 2008). It requires information on the antecedent
80 soil moisture conditions, but does not explicitly compute the discharge responsible for
81 flooding.

82 Alternatively, FWSs may use rainfall-runoff model to issue warnings based on explicit
83 discharge simulations and forecasts. They run at different resolutions depending on the
84 characteristics of the floods that are to be forecasted. Covering whole Europe with a spatial
85 resolution of 5 km, the European Flood Alert System (EFAS, Thielen *et al.* 2009) aims at
86 alerting for floods in trans-national European river basins up to 10 days in advance using
87 model inputs generated with an ensemble weather prediction system. At regional scale,
88 there are several operational FWSs based on discharge simulations. Some examples can be
89 cited: AIGA run by Meteo France¹ in the south-east of France (Lavabre and Gregoris
90 2006), EHIMI run by ACA² in Catalonia (Corral *et al.* 2009) and PREVAH, run by WSL³

1 French Meteorological Agency

2 Catalan Water Agency

91 in Switzerland (Viviroli *et al.* 2009). Further work is still under development and not yet
92 operational (Reed *et al.* 2007; Javelle *et al.* 2010 for example). Note these regional models
93 can be aggregated at the national scale as the UK National Flood Forecasting System
94 (NFFS) or VIGICRUES run by SCHAPI⁴ in France (Tanguy *et al.* 2005). Although they
95 are devoted to a limited area, these regional systems are run at higher resolutions and,
96 consequently, they are more adapted to forecast flash floods. These FWSs are generally
97 based on a similar scheme: the distributed rainfall-runoff model is run to simulate the
98 discharges in several locations of the basin, and these are compared to a database of pre-
99 established flow thresholds to quantify the hazard at each location. A warning is issued
100 when the simulated discharges exceed certain thresholds. The advantage of this method is
101 the use of a discharge value to assess flood hazard. The main weakness generally related to
102 discharge simulation is that model calibration requires stream gauges distributed over the
103 watershed and available historical time series for its calibration.

104 Based on these considerations, a real-time FWS was implemented in 2009 in the
105 Guadalhorce basin (Andalusia, Spain) in collaboration with regional stakeholders interested
106 in flood warning. The main objective was to operationally deliver spatially-distributed early
107 flood warnings, as a tool to raise the awareness of rescue services and increase their
108 preparedness. To suit the short response time and high space resolution required for
109 operational management of this basin, a specific and local FWS (referred to as GFWS
110 hereafter) has been developed. The main challenge the GFWS had to face was the scarcity
111 of stream gauges and the lack of historical hydrometeorological data. In part to overcome
112 this situation, we chose to explore the two approaches presented above: flood warnings in
113 the implemented system are based on both (i) distributed rainfall measurements, and (ii) the
114 discharge simulations obtained with a distributed rain-runoff model.

115 This paper describes the GFWS implemented in the Guadalhorce basin and the
116 methodology chosen to workaroud the lack of data. Results obtained during two recent
117 flood events that affected the basin have been analysed. Flood warnings issued with the

3 Swiss Federal Research Institute

4 French Hydro-meteorological Nacional Center in charge of Flood Forecasting

118 GFWS have been compared to effective flooding records collected by the emergency
119 services. In addition, the complementarity between EFAS' low-resolution and long-
120 anticipation warnings and high-resolution and short-anticipation warnings of the GFWS has
121 been analysed from an operational point of view. The lead-times provided by both systems,
122 and the time separating the warning issuance and the inundation occurrence, have been
123 particularly discussed.

124 The paper is organized as follows. Section 2 presents the framework of study: the
125 Guadalhorce basin and the compilation of historical and real-time hydro-meteorological
126 data. Section 3 describes the distributed hydrological model and the calibration procedure.
127 Section 4 presents the two configurations of the GFWS (based on rainfall and discharge).
128 Two rainfall events that occurred at the beginning of 2010 and caused significant floods are
129 presented in Section 5 as case studies. Section 6 briefly presents EFAS warning system and
130 analyses the warnings delivered for both events. Finally, Section 7 summarizes the main
131 results and concludes on future improvements.

132

133 **2. Case study:**

134 **2.1. The Guadalhorce basin**

135 The Guadalhorce basin (3200 km²) is located in Andalusia, South of Spain. The river
136 passes through the city of Málaga (500,000 inhabitants) near the outlet of the
137 Mediterranean Sea. The basin is bordered on the West by moderately high mountains (1900
138 m amsl) and by a low plateau (500 m amsl) on the North. The dominant climate is warm-
139 temperate Mediterranean, characterized by a marked dry season, with hot summers and
140 generally mild winters. The warmest months are July and August with an average
141 temperature of 23°C, and the coldest season covers the period between December and
142 February with an average of 13°C. Annual precipitation is comprised between 500 and 600
143 mm. Rainfall is concentrated during the period October to April (90% of the total amount).
144 Historically, the Guadalhorce river represents a major risk for the city of Málaga and
145 periodically causes floods along its course. Although the region is mainly rural with
146 dominant bare land cover, stakes are numerous, with the population concentrated close to

147 Málaga and many activities related to tourism. For this reason, the regional government of
148 Andalusia has decided to implement an operational FWS with the aim of minimizing risk to
149 people and economic activity.

150 **2.2. Hydrometeorological data**

151 The studied watershed is covered by a quite scarce measuring instrumentation network. A
152 total of 25 automatic hourly rain gauges are located within or near the basin (see Fig. 1),
153 representing an average density of about one rain gauge per 180 km². Such a density can
154 appear insufficient to enable accurate high resolution rainfall estimates through spatial
155 interpolations on small watersheds. Here, time and space scales suited to flash flood
156 dynamics are small: sub-hourly time step and kilometric scale (e.g. Collier 2007; Creutin
157 and Borga 2003; Moulin *et al.* 2009). Nevertheless, this rain gauge network should be
158 enough for larger basins characterized by a response time at least higher than the rain gauge
159 time step. The region of Málaga is also covered by a C-Band Doppler radar operated by the
160 Meteorological Spanish Agency (AEMET). The radar is located at 1173 m amsl and fully
161 covers the basin. The GFWS has been developed to operationally consider radar products
162 characterized by a higher spatio-temporal resolution (1 km² and 10 minutes).

163 Four reservoirs and three hourly automatic gauge stations are also located in the upstream
164 part of the Guadalhorce basin: Bobadilla (761 km²), Ardales (211 km²), and Teba (202
165 km²) as illustrated in Fig. 1. They cover a third of the total basin area, leaving the remaining
166 area ungauged (where Málaga is located). Measured discharges are also available in real
167 time for operational purpose. Available historical discharge data have been compiled since
168 2008 to calibrate the rainfall-runoff model.

169 Statistical climate data on historical precipitation are also available (MOPU 1990) as maps
170 of maximum daily rainfall amounts (MOPU 1999), and Intensity-Duration-Frequency
171 curves (IDF), as well as regionalised parameters for the application of the rational Method
172 are described in MOPU (1990).

173 3. Rainfall-runoff model

174 A grid-based distributed rainfall-runoff model has been implemented and adjusted with the
175 aim of computing warnings based on simulated discharges at every pixel of the grid inside
176 the area of study. Such a distributed structure allows to take into account the spatial
177 variability of precipitation. Due to the lack of historical hydrological data, and in order to
178 simplify the calibration procedure, the model was chosen to be simple, robust, and
179 depending on a reduced number of adjustable parameters.

180 3.1. Presentation of the distributed rainfall-runoff model

181 The Guadalhorce basin has been split into hydrological cells of 1 km² that are connected to
182 the outlet of the basin following a simplified drainage network based on the analysis of the
183 topography. To take into account the effect of the three dams, it was considered that the
184 drained area located upstream of each dam does not contribute to cells located downstream.
185 Each 1-km² cell is treated as a hydrological unit, where a lumped model is applied. The
186 lumped model employed here is based on the common Soil Conservation Service (SCS)
187 Curve Number (CN) method (Mockus 1957) for computing excess rainfall, combined with
188 the linear diffusive wave unit hydrograph for flow routing (Szymkiewicz 2002).

189 The SCS-CN method assumes that flood flows are essentially composed of surface runoff
190 water or at least fast responding runoff processes. Because of its simplicity and minimal
191 data requirements, the SCS-CN method is widely used in flash flood simulation (see for
192 examples Borga *et al.* 2007; Rozalis *et al.* 2010; Versini *et al.* 2010, 2013). It is based on
193 the water balance equation and a proportionality stating that the ratio of the amount of
194 cumulative infiltration ($F[i]$, in mm) to the amount of potential maximum retention
195 capacity (S , in mm) is equal to the ratio of the amount of total runoff volume ($V[i]$, in mm)
196 to the maximum potential runoff volume. The latter being represented by the total rainfall
197 amount from the beginning of the event $P_{tot}[i]$, to which the initial abstraction I_a (both in
198 mm) is subtracted. Assuming $F[i]=P_{tot}[i] - I_a - V[i]$, the total runoff volume generated at the
199 cell scale is computed as:

$$200 \quad V[i] = \frac{(P_{tot}[i] - I_a)^2}{P_{tot}[i] - I_a + S} \quad (1)$$

201 From this formula, the instantaneous runoff coefficient for time step i , $C[i]$, can be
 202 deduced. This coefficient has then to be multiplied by the rainfall intensity $P[i]$ to estimate
 203 the direct runoff, $Q_f[i]$:

$$204 \quad C[i] = \frac{\partial V[i]}{\partial P_{tot}[i]} = 1 - \frac{S^2}{(P_{tot}[i] - I_a + S)^2} \quad (2)$$

205 Retention capacity S is related to the CN coefficient which is usually estimated from the
 206 soil properties and taking a value between 0 and 100. The original SCS equation was
 207 adjusted for events with large amounts of precipitation accumulated during long periods
 208 (several days). Thus, when the total amount of precipitation increases during an event, the
 209 soil drainage process is not explicitly represented and there is no possibility for the system
 210 to recover the basin's water retention capacity. The instantaneous runoff coefficient
 211 increases simultaneously and the simulated direct runoff has a strong tendency to be
 212 overestimated. In this study, an attempt was made to take into account the process
 213 accumulating rainfall on an adapted time period. After several tests, a period of 24 hours
 214 has been arbitrarily chosen to accumulate rainfall:

$$215 \quad Q_f[i] = P[i] \cdot \left[1 - \frac{S^2}{(P_{24h}[i] + S)^2} \right] \quad \text{when } P_{tot}[i] > I_a \quad (3)$$

$$216 \quad Q_f[i] = 0 \quad \text{otherwise}$$

217 Where $P_{24h}[i]$ is the amount of precipitation in a 24-moving window which ends at time
 218 step i , and from which the initial abstraction I_a is deduced.

219 Additionally, the conceptual function proposed by Weeks and Boughton (1987) has been
 220 chosen to model the slow flow $Q_s[i]$:

$$221 \quad Q_s[i] = \Delta t \cdot \alpha \cdot Q_f[i] + Q_s[i-1] \quad \text{if } Q_f[i] > 0 \quad (4)$$

$$222 \quad Q_s[i] = Q_{ini} + [Q_s[i-1] - Q_{ini}] \cdot (1 - \Delta t \cdot \alpha) \quad \text{if } Q_f[i] = 0 \quad (5)$$

223 Where α (with units of time^{-1}) is a parameter to calibrate, Δt is the time step, and Q_{ini} is the
224 initial flow computed with the observed runoff at the beginning of the event.

225 It assumes that there is a constant ratio between the runoff component $Q_f[i]$ and the
226 variation of the slow component between two time steps. Base flow is also recursively
227 estimated from the previous value. It is initialized with the initial flow Q_{ini} measured in
228 gauged cells at the beginning of the event, and extrapolated to the rest of the basin
229 proportionally to the drainage area of each cell. When there is no direct runoff, the
230 recession curve $Q_s[i]$ becomes exponential. We have verified that the base flow assumption
231 made does not affect the mass balance, and it is beneficial to improve the representation of
232 the simulated discharge.

233 The total runoff $Q_{tot}[i]=Q_f[i]+Q_s[i]$ generated at each cell is then routed downstream
234 following the drainage network. A single unit hydrograph based on the linear diffusive
235 wave function and Muskingum parameters (Szymkiewicz 2002) has been used:

$$236 \quad HU[i] = \frac{1}{\sqrt{2\pi \cdot (1 - 2X)}} \cdot \frac{N}{K} \cdot \left(\frac{K}{i \cdot \Delta t} \right)^{\frac{5}{2}} \cdot \exp \left[- \frac{(i \cdot \Delta t - N \cdot K)^2}{2 \cdot (1 - 2X) \cdot K \cdot i \cdot \Delta t} \right] \quad (6)$$

237 Where $HU[i]$ is the unit hydrograph at time step i , X is the weighting factor (dispersion
238 parameter) that varies between 0 and 0.5, K is the storage time for one path, and N the
239 number of paths of the course.

240 A specific unit hydrograph (HU) is defined for both kind of cell. One first HU is applied in
241 each cell to represent the hillslope flow propagation. Then a second is applied on the river
242 course connecting the hillslope cell to the downstream point of interest to represent the
243 propagation of the stream flow. The linear diffusive wave function can represent both
244 processes changing its parameters. For each cell, both hillslope and river routing parameters
245 (N, X, K) need also to be adjusted.

246

247 **3.2. Reduction of the number of parameters to calibrate**

248 As described above, the number of parameters to adjust is rather large. It has to be reduced
249 to make the model robust and to limit uncertainty due to over-parameterisation (see Perrin
250 *et al.*, 2001): (i) spatially distributed CN [used in Eq. (3)], the base flow parameter α [see
251 Eq. (4) and (5)] for the loss function and, (ii) spatially distributed routing parameters for
252 both hillslope (N_h, X_h, K_h) and river (N_r, X_r, K_r) routing functions.

253 An *a priori* method has been used to estimate distributed CN values over the entire
254 watershed. Geomorphological data (slope, geology and land cover) at cell scale have been
255 used to compute the CN distribution within the basin with a 1-km resolution according to
256 the recommendations of the Spanish Ministry of Public Works (MOPU 1990). Previous
257 studies based on this method (Corral *et al.* 2000; 2002) have shown significant differences
258 between effective field capacities and those obtained with this *a priori* method: simulated
259 discharges have a clear tendency to be overestimated. For this reason, an average curve
260 number correction factor (FCN) has been calibrated to scale the map of CN values. Note
261 that this kind of correction was already used in Borga *et al.* (2007) for example.

262 In many applications of the SCS method, the initial abstraction I_a does not take into account
263 antecedent moisture condition and is deduced from the potential maximum retention S . In
264 this study, I_a is not considered as a parameter and is assumed to be independent of S . It is
265 firstly approximated as the difference between the total amounts of antecedent
266 evapotranspiration and rainfall over the previous 15 days. Then, I_a is updated in real time
267 from stream gauge measurements identifying by means of the hydrograph initial rising time
268 (see more details in Corral *et al.* 2002). I_a represents the total amount of precipitation from
269 the beginning of the event to the first initial hydrograph rising time (deducing the response
270 time of the watershed).

271 The three parameters that govern both hillslope and river routing functions have also been
272 simplified. Concerning the hillslope function, N_h is fixed to one path, and X_h to 0
273 representing a maximum attenuation in peak discharge. Concerning the river function,
274 applied on the river course to the outlet, N_r is assumed to represent the number of cells until
275 the outlet; the remaining weighting factor X_r needs to be calibrated and is assumed to be

276 uniform over the basin. Both storage times K_h and K_r are computed as the ratio between
277 hillslope or river course lengths (derived from the DTM) and flow velocities. These
278 velocities v_l and v_r are also considered uniform over the basin and represent the last
279 parameters to be calibrated.

280 Summarizing, the adjustment of the model required the calibration of 5 parameters: the
281 curve number correction factor (FCN), the base flow parameter (α), and three routing
282 parameters [hillslope velocity (v_h), river velocity (v_r), river weighting factor (X_r)].

283

284 **3.3. Adjustment of the parameters**

285 The rainfall-runoff model described above has been calibrated using observed discharges
286 available at the gauged watersheds (see Section 2). Eight rainfall events for 2008 have been
287 selected for the adjustment of the model parameters. Radar data were not available for this
288 period, so spatially interpolated rain gauge data have been used. The total rainfall amounts
289 of these events were not very large (between 20 and 100 mm). The calibration of the model
290 has been carried out with the observations measured at the Bobadilla stream gauge (no
291 significant discharges were measured at the two other stations and/or the data were not
292 available). Because the number of interesting rainfall events was rather small, we chose to
293 calibrate the model manually, and to reproduce the most intense events. The results have
294 been evaluated with the Nash criterion (Nash and Sutcliffe 1970) and are summarized in
295 Table 1.

296 The performance of the model in term of Nash efficiency varies from one rainfall event to
297 another. The simulations accuracy is acceptable in the light of the results obtained in
298 comparable case studies (ungauged basins or poor instrumented framework), for which the
299 model calibration was made with a longer historical database (for example: Borga 2008;
300 Versini *et al.* 2010). The performance of the model is generally better for the largest rainfall
301 events, where the effort of calibration was made (the more significant events are
302 represented on Fig. 2). The hydrological response to smallest events appears a little more
303 erratic and is probably linked to the non-linearity of the rainfall—runoff transformation. In
304 this case, initial abstraction plays a major role and can strongly affect the simulated

305 discharges. Note that to achieve reasonable simulations, a curve number correction factor
306 FCN of 0.5 has been chosen, implying that the map of CN calculated a priori, strongly
307 overestimate discharges. This value may seem rather large, but tends to be common in
308 flood simulation in Mediterranean basins (see Corral *et al.* 2002; Francés and Benito 1995).

309 Rainfall estimates based on spatial interpolation of rain gauge measurements could also
310 represent a source of uncertainty. The coverage of the current rain gauge network may be
311 insufficient to estimate reliable distributed rainfall in the gauged watershed used for
312 calibration (Bobadilla), where no rain gauge is available inside (see Fig. 1). This may
313 partially explain the differences between simulated and observed discharges.

314 The calibration of the rainfall-runoff model has been carried out under a number of
315 limitations (given the scarcity of data, number of rain gauges, model structure...) that may
316 have a significant impact on the performance of the model. This needs to be considered
317 when analysing the results of the GFWS. Post-flood field investigation and new time series,
318 as they become available, may be used to improve the rainfall-runoff model (specially its
319 calibration).

320 Finally, the values of the parameters calibrated in the Bobadilla stream gauge (i.e. FCN , α ,
321 v_h , v_r and X_r -) have been transferred to the remaining (ungauged) part of the basin,
322 implicitly assuming a similar hydrological behaviour.

323 **4. The GFWS**

324 The purpose of the GFWS, presented here, is to provide distributed warnings based on
325 rainfall accumulations and runoff simulations (at the same resolution of 1 km^2). In the
326 current configuration, the warnings are computed at each time step from all the
327 precipitation data available up to the present. Three different types of warnings related to
328 hazard probability expressed in terms of return periods are delivered. Two of these are
329 based on rainfall estimates and one on simulated discharges. Note that because of data
330 collection and fast response of small basins, lead times provided by the GFWS are quite
331 short (usually of the order of 1 hour).

332 **4.1. Warnings based on rainfall estimates**

333 Without taking into account any hydrological process, the distributed rainfall data can bring
334 a first interesting attempt related to the expected consequences of the rainfall event and to
335 localize the potential inundations. Two different types of warnings can be computed for
336 every cell of the studied area and using these precipitation fields: (i) based on estimated
337 rainfall at point locations (cells of 1 km²), (ii) based on spatially aggregated rainfall at each
338 point (i.e. accumulated within the area upstream of each point). These warnings have the
339 advantage to be computed quickly and effectively, without any information other than
340 rainfall.

341 **4.1.1. Use of IDF curves**

342 IDF curves are used as a benchmark for estimating the return period associated with a given
343 rainfall. IDF curves are widely used, and different techniques exist to compute them [see
344 Ben-Zvi, (2009) for an exhaustive review]. In Spain a common methodology is that
345 recommended by the Spanish Ministry of Public Works for drainage design studies (MOPU
346 1990). It has been chosen in this study and has the following synthetic expression:

$$347 \quad P_D(T) = \frac{P_{24h}(T)}{24} \cdot FR^{\frac{28^{0.1} - D^{0.1}}{28^{0.1} - 1}} \quad (7)$$

348 Where $P_D(T)$ is the rainfall (in mm) associated with a duration D (hours) and a return
349 period T , $P_{24h}(T)$ is the daily accumulated rainfall (mm) for a return period T , and FR is a
350 regional factor equal to 8.5 for the area of study.

351 The extension of IDF to radar rainfall estimates is not straightforward (as illustrated in
352 Norbiato *et al.* 2007 and Wright *et al.* 2013). IDF curves are usually developed from rain
353 gauge networks that are often characterized by low spatial density and short observation
354 periods. Moreover, point-to-area transformation is achieved through area reduction factors
355 ignoring local rainfall climatology or storm type (see section 4.1.3). Despite these
356 limitations, the Spanish methodology has been applied here. Finally, IDF maps have been
357 calculated with a resolution of 1 km², for different return periods (2, 5, 10, 25, 50, 100, 200
358 and 500 years) and different durations (1, 2, 3, 4, 6, 12 and 24 hours) for both point and
359 spatial aggregated rainfall.

360 **4.1.2. Warning based on point rainfall**

361 This type of warning is calculated from the point rainfall measurements accumulated during
362 one hour. It is assumed that this accumulation time is relevant to deliver information about
363 the most critical situations at cell scale. It could be of interest for issuing warning in urban
364 environment or for very sensitive points such as roads (e.g. Versini *et al.* 2010). The
365 warning computation is based on a direct comparison, cell to cell, between estimated
366 rainfall, and the IDF threshold values computed for $D=1$ hour and different return periods
367 T . The value assigned to the warning in a particular cell is the maximum of the return
368 period values that has been exceeded by accumulated rainfall estimates.

369 **4.1.3. Warnings based on aggregated rainfall**

370 In this case, the warning is computed to represent as well as possible the consequences of
371 rainfall at watershed scale (every cell draining an area larger than 4 km^2). With this aim,
372 rainfall is accumulated for a duration D equal to the estimated concentration time of the
373 basin. This concentration time is obtained from both river length and average slope data
374 according to MOPU 1990). These same recommendations propose a correction factor to
375 diminish the thresholds for areal rainfall amount which depends on the drained area S :

$$376 \quad k = 1 - \log\left(\frac{S}{15}\right) \quad \text{when } S > 15 \text{ km}^2 \quad (8)$$

$$377 \quad k = 1 \quad \text{otherwise}$$

378

379 **4.2. Warnings based on simulated discharges**

380 Warnings based on simulated discharges are computed with the distributed rainfall-runoff
381 model for every cell where the drained area exceeds 10 km^2 . At these locations, the
382 simulated discharges are compared with peak flow thresholds estimated for return periods
383 $T=\{2, 5, 10, 25, 50, 100, 200, 500 \text{ years}\}$. They are based on the Rational Method, as
384 described in MOPU (1990).

385

386 **5. Test case studies**

387 The GFWS started operating in May 2009. Little after, two serious rainfall events occurred
388 (in January and February 2010), both resulting in significant flooding in the region of
389 Málaga. These two events were not used in the calibration of the rainfall-runoff model (see
390 Section 3.3), and resulted the largest accumulations since the GFWS has started. As
391 weather radar observations were not available for these events, the rainfall field was
392 estimated by spatial interpolation of rain gauge measurements with a resolution of 1 hour.
393 A third event has been selected. It corresponds to a minor event for which the C-band radar
394 of the Spanish Meteorological Agency (AEMET) located near Málaga was operating.
395 Although no inundation occurred during this event, it illustrates the use of radar QPE. The
396 events and the associated performance of the GFWS are presented herein, also considering
397 the information on the inundations in the Guadalhorce basin reported by the emergency
398 services.

399

400 **5.1. Event of 6-7 January 2010**

401 **5.1.1. Description of the rainfall event**

402 The maximum observed accumulations reached up to 70 mm on the southern portion of the
403 Guadalhorce basin (see Fig. 3-a). The event started at about 23:00 UTC on 6 January 2010
404 and lasted for 12 hours. However, most of the precipitation was registered between 08:00
405 and 10:00 UTC (during this period rain gauges around Málaga registered accumulations of
406 40 mm) as a consequence of a mesoscale convective system sweeping the basin.

407 The intense precipitation registered in the morning of 7 January caused flooding of houses,
408 basements, garages and streets, mainly in the suburbs of Málaga and in Alhaurín de la
409 Torre (Fig. 4): emergency services registered a hundred flooding incidences between 9:00
410 and 10:00 UTC in these two cities. These areas are frequently affected by inundations and
411 this event illustrates a typical case of urban flash flood due to an intense storm that is not
412 rare in southern Andalusia.

413 During this event, two of the three stream gauges of the basin (Bobadilla, Teba) operated
414 normally. These gauges (see Fig. 1) are located far upstream from the area mostly affected
415 by precipitation (around the city of Málaga), and the total precipitation amounts in the sub-
416 catchments drained at these points were relatively minor (around 30 mm). Consequently,
417 the resulting observed discharges were not significant (see Table 2).

418 **5.1.2. Performance of the GFWS**

419 The comparison between stream gauge observations and the simulations obtained with the
420 rainfall-runoff model at these locations show some agreement, as quantified in terms of the
421 Nash efficiency (presented in Table 2). It is worth noting the performance of the model at
422 the stream gauge in Teba, whose measurements were not used in the calibration of the
423 rainfall-runoff model (stated in Section 3.3).

424 The GFWS was able to issue warnings in the areas where flooding actually occurred. Fig. 4
425 shows the maximum warnings based on point rainfall (issued at 9:00 UTC), and based on
426 aggregated rainfall and simulated discharges (both at 10:00 UTC). Concerning the former
427 (Fig. 4a), a warning was issued around the city of Málaga and matching the area where the
428 most intense convective cell affected the basin. The core of the warning (in green)
429 corresponded to an hourly intensity over 35 mm/h, which correspond to a return period of
430 around 5 years. Around this core, the 2-year return period warning level was reached in the
431 blue area (which corresponds to an average hourly intensity over 25 mm/h). These patterns
432 had some correspondence with the flooding that occurred in this area between 9:00 and
433 10:00 UTC. These warnings were confirmed by those based on aggregated rainfall and
434 simulated discharge in the area. Because these two use information on the spatial structure
435 of the basin, they have advantage to localize more precisely the location of potential
436 flooding. Both predicted the maximum threat of flooding at 10:00 UTC West of Málaga
437 (Fig. 4-b and 4-c), where a small tributary stream crosses the suburbial industrial area, and
438 at Alhaurín de la Torre (respectively, draining basins of 30 and 73 km²). Both criteria were
439 consistent with each other and only differed on the assigned return periods: 2 years when
440 assessed based on aggregated rainfall and 5 years when the computations are based on
441 simulated discharges. This difference is due to the estimated initial abstractions almost

442 equal to 0. In any case, these warnings coincided very well with the reaches where flooding
443 was reported within the basin.

444

445 **5.2. Event of 15-16 February 2010**

446 **5.2.1. Description of the rainfall event**

447 There are clear differences between this rainfall event and that presented in Section 5.1:
448 Rainfall intensities were much lighter, maximum hourly intensities hardly exceeded 20
449 mm/h, but it lasted significantly longer (it did not stop raining for about 24 hours), which
450 resulted in progressive saturation of the soils of the basin. The area located near the coast
451 was particularly affected, with substantial amounts of rainfall registered in Alhaurín de la
452 Torre (totals reached up to 215 mm -nearly a third of the mean annual precipitation), and
453 over 100 mm around Málaga (see Fig. 3-b). In terms of daily rainfall, and according to
454 MOPU (1990), the 50 years return period (180 mm) was exceeded in Alhaurín de la Torre,
455 and it was between 5 and 10 years (90 and 115 mm, respectively) in Málaga. Along the
456 event, the accumulated precipitation caused several floodings in the morning of 16
457 February 2010 (after 24 hours of precipitation). The rescue services did more than 40
458 actions related to flooding (essentially homes and garages) in several municipalities in the
459 province of Málaga: Alhaurín de la Torre, Coín, Campanillas and Cártama (see Fig. 5).
460 These actions included the use of helicopters to evacuate people trapped at home or in
461 flooded roads.

462 As in the previous event, the largest rainfall amounts occurred downstream the gauged
463 watersheds (50 and 20 mm in the sub-basins of Ardales and Bobadilla, respectively). As a
464 result, observed discharges were not significantly high, and the observed peaks were
465 comparable to those of 6-7 January 2010 (see Table 2).

466 **5.2.2. Performance of the GFWS**

467 The hydrographs simulated with the rainfall-runoff model can be considered acceptable in
468 terms of the Nash efficiency (see Table 2). Despite of the rough calibration, the model
469 seems to reproduce correctly the hydrological response at the location of stream gauges.

470 The GFWS was able to issue consistent warnings in the flooded areas depending on the
471 type of warning used (based on rainfall or simulated discharge). As explained above, the
472 large rainfall accumulations recorded during this event were the result of the long duration
473 of the event, rather than very intense precipitation. As a result, observed precipitation
474 intensities did not exceed the thresholds to issue warnings based on hourly point rainfall at
475 any time: The highest observed intensity in the basin was around 20 mm/h, lighter than the
476 average value for the 2-year return period around 25 mm/h.

477 The highest warning levels issued based on aggregated rainfall and simulated discharges
478 are presented in Fig. 5 (at 6:00 and 7:00 UTC, respectively). Aggregated rainfall exceeded
479 the 2-year return period for the first time at 03:00 UTC in the main stream between Coín to
480 Málaga. The levels progressively increased and at 6:00 UTC the 5-year return period was
481 exceeded. At the same time, small tributaries to this main stream were also marked as
482 potentially flooded. It is clear how the areas where the warnings were issued match the
483 points where the main floods actually occurred (Alhaurín de la Torre, Coín, Cártama, and
484 Málaga, circled with solid red ellipses), being the only exceptions Campanillas and the
485 suburbs of Málaga where no warning was issued. After 3:00 UTC, warning levels
486 decreased and remained only for the main stream. At 12:00, 4 hours after the rainfall had
487 ceased, only the Guadalhorce stream located between Cártama and Málaga was identified
488 as a risky area and remained so until the end of the day.

489 Warnings computed from simulated discharges were more intense and more numerous than
490 those already calculated with the aggregated rainfall (the estimated initial abstractions were
491 null). Indeed, the first warning appeared at 23:00 UTC, and at 3:00 UTC exceeded the
492 return period of 5 years (i.e. higher than the 2-year one issued for aggregated rainfall). At
493 7:00 UTC, the simulated discharges passing through Cártama and Alhaurín de la Torre
494 were exceeding the 25-year return period, and in Coín, Campanillas and Málaga, the 10-
495 year return period. The simulated peak discharge in Málaga outlet occurred at 10:00 and
496 reached a value of 817 m³/s, although rescue services, based on ground observation,
497 estimated the discharge to temporarily exceeded 2000 m³/s. The fact that drained area
498 located upstream of each dam were not considered can explain this large difference.
499 Warnings based on simulated flows, thus, corresponded very well with the floods that

500 occurred in this area. Unlike for the warnings based on aggregated rainfall, the flooding in
501 Campanillas and the suburbs of Málaga at 7:00 UTC (see Fig. 5-b) were not missed:
502 warnings of 10- and 5-year return period were issued at these points, respectively.

503 A flood warning (5-year return period) was also issued for the Ardales stream, downstream
504 of one of the dams of the basin (Conde Guadalhorce dam, surrounded in Fig. 5-b), where
505 no problem actually occurred. This area is not anthropized and for this reason was not
506 affected. As the simulated discharge was not propagated downstream the dam, no warning
507 was issued further.

508 **5.3. Event of 21 April 2011**

509 **5.3.1. Rainfall inputs: processing of radar data**

510 The very-high resolution of radar QPE products both in space and time (for the case of the
511 Málaga radar, 1km and 10 minutes) fits very well the requirements of flood monitoring in
512 fast response basins such as the Guadalhorce basin, as it allows an accurate representation
513 of the variability of the rainfall field and capture local intensities that could be missed by
514 rain gauge networks. However, radar measurements require a thorough processing to
515 convert them into Quantitative Precipitation Estimates.

516 In our case, we have implemented the chain of algorithms of the EHIMI package (Corral *et*
517 *al.* 2009), which includes: (i) reduction of the effects of beam blockage by the orography
518 using the approach of Delrieu *et al.* (1995), (ii) clutter elimination with the technique of
519 Sánchez-Diezma *et al.* (2001), (iii) identification of the type of precipitation and
520 extrapolation of elevated reflectivity measurements to the surface according to a double
521 Vertical Profile of Reflectivity as described by Franco *et al.* (2006, 2008), and (iv)
522 conversion of reflectivity into rain rate using a double Z-R relationship for stratiform and
523 convective rain. Hourly accumulations were generated from instantaneous rainfall maps
524 with an algorithm similar to that of Fabry *et al.* (1995).

525 **5.3.2. Description of the rainfall event**

526 The river rise of 21 April 2011 is the result of a widespread system that crossed Andalusia
527 from west to east. Over the basin, 10 mm of rainfall were accumulated in 10 hours
528 (approximately from 14:00 UTC to 24:00 UTC), with totals locally reaching up to 25 mm
529 near Málaga and on the southern portion of the Guadalhorce basin (see Figure 6-a). The
530 most intense precipitation was concentrated at about 17:00 UTC with local hourly
531 intensities around 20 mm/h.

532 The event accumulation based on radar measurements does not show the artefacts that
533 frequently affect radar rainfall products (due to e.g. sub-estimation “corridors” due to beam
534 blockage or systematic holes from ground clutter filters). It is also noticeable that radar-
535 based QPE values at gauge locations reasonably matches rain gauge records inside the
536 basin (the differences can be attributed to remaining errors in radar QPE, errors in rain
537 gauge measurements and representativeness errors, since the two systems measure rainfall
538 at different scales).

539 **5.3.3. Performance of the GFWS**

540 During 21 April 2011, the GFWS did not deliver any warnings whatever the type (based on
541 point rainfall, spatially aggregated rainfall or simulated flows). Despite some intense
542 precipitation, no significant increase in discharge was noticed and no alert thresholds were
543 exceeded. The propagation of rainfall through the drainage network reduced the magnitude
544 of the hazard, which was already low in terms of point rainfall.

545 However, the benefit of using radar-based QPE is illustrated by the location of intense
546 precipitation (about 20 mm/h) around Málaga and in the central part of the basin at 17:00
547 UTC. As shown in Figure 6, there is no rain gauge at the location where the most intense
548 precipitation occurred, and the field interpolated from rain gauges did not reproduce these
549 local rainfall intensities (or any warning, see Fig. 6-c). Despite some possible
550 overestimation of the radar-based QPE, this proves the use of weather radar may provide a
551 better understanding of intense rainfall away from the rain gauge network. These
552 differences could have been even more significant for more convective situations
553 characterized by very intense local rainfall.

554 It has to be noticed that no flooding occurred during this event. This is also a satisfactory
555 result for the GFWS, which can be interpreted as follows: First, spatial distribution of
556 precipitation represented by radar-based QPE indicate the location and timing of the highest
557 intensities, which can identify the possible consequences caused by direct rainfall as it may
558 be the case of local floodings in urban areas. Second, the absence of warning in the river
559 network shows there was no significant consequence in terms of discharges, showing that,
560 for this particular case, the rainfall-runoff model did not overestimate the discharges
561 produced by moderate rainfall.

562 **5.4. General comments**

563 Regarding the two examples for which flooding occurred, warnings based on point rainfall
564 seem to be well adapted to prevent from the consequences on the ground of intense
565 precipitation. They are particularly useful to alert of urban flood where the rainfall is
566 directly responsible for flooding. As the current GFWS does not take into account urban
567 drainage (which requires a cadastral resolution), these warnings could be sufficient to
568 localize the areas prone to flooding during intense precipitation event.

569 Although the model was calibrated for only one gauged basin and for few rainfall events,
570 the results computed with the rainfall-runoff model for these two recent events are rather
571 satisfactory: the simulated discharges calculated at the other stream gauges locations are
572 quite similar to the observed ones. The fact that only warnings based on simulated
573 discharge have pointed out every effective flooding for both events, illustrates the interest
574 of working with a distributed rainfall-runoff model. This rather positive result could, at
575 least in part, be attributed to the significant magnitude of the events, especially given the
576 limitations of the model calibration.

577 Moreover, return period characterizing warnings based on simulated discharges appear to
578 be higher than those based on aggregated rainfall for both studied rainfall events. Regarding
579 the consequences at the ground and the frequency of the total amount of precipitation
580 locally measured, discharge return periods seem to be the more representative. In these
581 cases, the underestimation of aggregated rainfall-based warning may be due to different
582 reasons. First, this method has intrinsic limitations due to the non-consideration of rainfall-

583 runoff transformation. Second, the antecedent soil moisture conditions, which have a
584 significant role in the catchment response (see e.g. Merz and Blöschl 2009), is not
585 considered. Despite the basic function used to estimate initial losses, the rainfall-runoff
586 model is able to take into account soil moisture *via* the parameter I_a in Eq. 3. For both
587 studied events, the estimated initial abstractions were almost equal to 0, which result to
588 increase the amount of water producing runoff.

589 These provisional remarks have to be taken with caution because based on the analysis of
590 only two events. They have to be confirmed in the future by studying the performances of
591 the GFWS for new rainfall events.

592

593 **6. Combined use of EFAS with the GFWS for flood forecasting**

594 **6.1. The European Flood Alert System (EFAS)**

595 The European Flood Alert System (Thielen *et al.* 2009) issues flood warnings based on
596 probabilistic flood forecasts with lead times up to 10 days at European scale. It is based on
597 the hydrological model LISFLOOD (Van Der Knijff *et al.* 2010) and rainfall inputs come
598 from a medium-range ensemble weather predictions (NWP-EPS), consisting of a first set of
599 51 members generated at the European Centre for Medium-range Weather Forecasts
600 (ECMWF) over a 80-km grid, and a second set of 16-member ensemble from the COSMO
601 Consortium (COSMO-LEPS), run at 10-km grid resolution. Both sets of weather forecasts
602 are included in the hydrological model to produce two ensembles of 51 and 16 members of
603 flow forecasts. The hydrographs generated in such a way are then analysed to issue early
604 warnings on the basis of a threshold exceedance analysis.

605 LISFLOOD was not adjusted for the Guadalhorce basin using discharge measurements (as
606 it is for other European catchments). However, the discharge thresholds associated to flood
607 warnings are directly defined based on a statistical analysis of simulated discharges over a
608 historical 30-year period. The highest discharge obtained from these long-term simulations
609 is used to set the “severe” situation (that is, when the model outputs exceed the 30-year
610 maximum flow situation, a “severe” warning is issued). Similarly, the discharge value

611 corresponding to the 99% percentile of historical flow simulations is chosen as the
612 threshold for which a “high” warning is issued. When comparing “high” discharges with
613 records from level gauges in Europe where the model was calibrated, Thielen et al. (2009)
614 reported that the value obtained for “high” warnings usually corresponds to return periods
615 around 1 to 2 years.

616 **6.2. EFAS forecasts for the studied events**

617 EFAS did not issue any warning in advance for the case of 6-7 January 2010 (neither for 21
618 April 2011), since rainfall accumulations were due to a local and intense rainfall core that
619 NWP-EPS had missed.

620 Alternatively, for the second event (15-16 February 2010) the NWP-EPS did depict the
621 main space and time features of the rainfall field. Consequently, EFAS delivered flood
622 warnings with an anticipation of four days: probabilistic forecasts issued a significant flood
623 warning on the main stream of the Guadalhorce River between the 3 dams and Málaga,
624 leaving the secondary streams (where most of the inundations occurred) safe. From the 51
625 ECMWF members, 80% forecasted floods, whereas the simulations of 2 of the 16 COSMO
626 members exceed the threshold of “high” level 4 days in advance (8 out of 16 members 2
627 days in advance). For this second event, the outlet peak flow simulated with LISFLOOD
628 was around 160 m³/s. Although this is enough to exceed the “high” level warning in the
629 Guadalhorce basin (around 142 m³/s, and, as discussed above, corresponding to a 1-2 years
630 return period), it is far from the maximum discharges simulated with the GFWS (817 m³/s
631 in Málaga) and the 25-year return period obtained for the GFWS simulations (see section
632 5.2). We believe that the latter may be more accurate as it matches better the reports of
633 local rescue services, which had not faced similar flooding for 20 years (reports based on
634 eye witness estimated the peak flows in about 2000 m³/s, higher than the 100-year return
635 period). It is worth insisting on that the version of EFAS currently running in the
636 Guadalhorce basin is uncalibrated, and, therefore, flow simulations cannot be interpreted in
637 absolute terms. Also, it is necessary to remark that no intermediate threshold is established
638 between the “high” and “severe” warnings, which in cases such as the one analysed here
639 could have helped. Note that a more general discussion on the matching between simulated
640 discharges and reference thresholds is conducted in the last section.

641 **6.3. Use of EFAS warnings to extend lead-time**

642 In the case studies, most of the watersheds responsible for flooding are small (less than 100
643 km²) and, consequently, characterized by short response times (less than 1 hours). In the
644 operational framework, GFWS warnings based on weather radar and/or rain gauges
645 measurements require the collection of rainfall measurements (which, currently, takes up to
646 20 minutes). This means that it takes very short time after the warnings are issued for the
647 inundations to occur in the smallest watersheds (or even equal to 0). This is often
648 insufficient to prevent the concerned population from the flooding. Recent works (e.g.
649 Creutin *et al.* 2009; Siccardi *et al.* 2005) have shown that when the social response time is
650 longer than the catchment response time, the planning of management measures requires
651 the use of forecast rainfall fields such as NWP-EPSs. That is why mid-term rainfall
652 forecasts and EFAS warnings represent a good complementary tool for the GFWS.
653 Delivering these forecasts some days in advance, despite the rough spatial accuracy, can be
654 useful from a practical point of view. They can be used as pre-alarms to inform decision-
655 makers about a possible flooding and advise the population, for example, to reduce their
656 trips and to protect vulnerable items. Similarly, emergency services can prepare their teams
657 and anticipate their future actions around the areas of possible flooding to intervene more
658 rapidly the day in question. According to this configuration, the warnings issued by EFAS
659 on the main stream of the Guadalhorce for the 15 and 16 February 2010 could help to limit
660 damages. Warnings issued by the GFWS could have then been used to act more precisely
661 on the affected tributaries.

662 **7. Discussion and Conclusion**

663 A local Flood Warning System has been implemented in the Guadalhorce basin, frequently
664 affected by plain floods and flash floods. The system delivers distributed warnings over the
665 entire basin based on the available sources of information: rainfall estimates and runoff
666 simulations are compared to pre-computed values of hazard probability (separately for
667 rainfall and runoff) to determine the warning level expressed in terms of return period.

668 The performance of the GFWS has been demonstrated on two major events that occurred in
669 the basin at the beginning of 2010 (the most intense since the system is operating). In
670 general, the warnings issued by the system matched the timing and location where actual

671 inundations occurred. The performance of the system during the presented cases has shown
672 how the different warnings (based on rainfall estimates or on flow simulations) are well
673 adapted to the types of hazard that affect the Guadalhorce basin. Indeed, results obtained
674 for 7 January 2010 confirm that warnings based on point rainfall are well adapted to alert of
675 urban or flash floods, as they are driven by very intense precipitation. As urban drainage is
676 not considered in the system, the precise location of intense rainfall could be enough from
677 the end-user point of view. On the other hand, results obtained on 16 February 2010
678 illustrate the effectiveness of warnings based on aggregated rainfall and discharge
679 simulations to forecast the inundations caused by stream overflows.

680 Moreover, on the analysed events, a significant difference has also been noticed between
681 the return period characterizing warnings based on aggregated rainfall and simulated
682 discharges. Those calculated with the rainfall-runoff model, usually higher, have also
683 pointed out every effective flooding. This underlines the importance of taking into account
684 rainfall-runoff transformation and antecedent soil moisture conditions.

685 In parallel, the European Flood Alert System (EFAS) has proved to be a valuable
686 complementary tool for flood warning. It forecasted the consequences of the larger-scale
687 and long-lasting event of 15-16 February 2010 four days in advance. Although it did not
688 forecast the exact location of flooding and underestimated the magnitude of the event, it
689 provided useful information to prepare the emergency services to operate. However, EFAS
690 did not anticipate the event of 7 January 2010, for which GFWS showed a good
691 performance. We attribute this miss mainly to the inability of the NWP-EPS model to
692 depict the intense but very local precipitation system that produced the event. This kind of
693 events show the interest of rapid-updating and high-resolution FWSs to issue warnings at
694 resolutions that are closer to the scales at which flooding occurs in this basin (for the
695 analysed events most of the inundations occurred in secondary streams for which EFAS
696 does not produce flow forecasts).

697 The presented results illustrate the interest of using the GFWS for flood warning in the
698 Guadalhorce basin, but it has to be recalled that this analysis is based on the study of only
699 two rainfall events. These conclusions need to be confirmed in the future regarding the

700 performance of the GFWS on new events. In addition, there are a number of implicit
701 hypotheses and limitations that are worth discussing:

702 (1) The selection of thresholds for issuing warnings with GWFS is arbitrary according to
703 the usual practices in Spain (i.e. according to the MOPU 1990 and 1999 for runoff and
704 rainfall respectively). This is so because long series of observations are inexistent in the
705 basin. In particular, the method used for setting flow warning thresholds uses historical
706 daily rainfall accumulations (implicitly assuming a very simple rainfall-runoff model to
707 estimate design peak flows). This results in some sort of inconsistency when the discharges
708 simulated with the rainfall-runoff model presented in section 3 are compared to the
709 thresholds established with an obviously different model. The availability of longer series
710 of hydrological records would allow establishing better thresholds (e.g. as suggested by
711 IACOW 1982 and Reed *et al.* 2007). In any case, the used thresholds can still be considered
712 as indicators of the relative degree of severity of the events, despite the fact that the
713 associated return periods cannot be taken in absolute sense. For example the results
714 presented above show a clear correspondence between the issued warnings and the reported
715 inundations, and indicate relative significance of the events, but cannot be considered
716 extreme (the 100-years return period was certainly not exceeded).

717 (2) The number of hydrometeorological sensors (both rain and stream gauges) in the basin
718 poses an important challenge for the performance of the GFWS. The density of rain gauges
719 (in average, 1 every 180 km²) and its time resolution (1 hour) limit the ability of the system
720 to monitor the variability of the rainfall field at smaller scales, thus reducing the skill of the
721 system to forecast flooding due to very local precipitation, especially in convective
722 situations. However, this factor did not seem to be critical for the case of January 2010
723 presented above: although intense rainfall was mainly localized in the southern part of the
724 catchment and gauges recorded maximum accumulations of 40 mm in 2 hours (see section
725 5.1), the system was able to diagnose the magnitude of the event and useful warnings were
726 issued. On the other hand, the number of stream gauges and their location (around 40 km
727 from the outlet of the basin) implies that the calibration of the rainfall-runoff model is
728 mostly valid for the upper part of the basin. Consequently, the simulations obtained
729 downstream (for instance in the area near Málaga, more urbanized than the upper part) are

730 based on an extrapolation of the calibrated parameters, which are assumed to be valid for
731 the entire basin. The lack of flow measurements downstream does not allow any
732 quantitative validation of the simulations.

733 (3) As it has been implemented here, the GFWS has been run with rainfall observations,
734 and, consequently, the results presented above assess the ability of the GFWS to emulate
735 the response of the catchment for two case studies. However, from the operational point of
736 view, it is also fundamental to analyse the ability of the system to forecast the hydrological
737 response of the basin (and resulting warnings) upon all the knowledge available up to the
738 present (see Todini 1988). By only using rainfall observations, the flow forecasting skill is
739 limited to the response time of the considered basin (Berenguer *et al.* 2005; Vivoni *et al.*
740 2006). On top of that, the time resolution of rainfall records (1 hour for rain gauge records)
741 and the data collection time (about 20 minutes) are factors that reduce the time between the
742 forecasts/warnings are issued and the inundations occur. That means the current
743 configuration of the GFWS (using only rain gauge data) may provide valuable flood
744 warnings only for basins larger than 200 km², with response times over 1 hour. In other
745 words, the system evaluates what is happening in the smallest basins and has some
746 predictive skill for the largest ones thanks to the response time of the basin.

747 In part, (2) can be addressed with the use of radar-based QPE maps (as illustrated for a
748 minor event in Section 5.3): these allow monitoring the space and time variability of the
749 rainfall field at resolutions fulfilling the requirements of rainfall-runoff model for small- to
750 medium-sized basins (see, among many others, Sempere-Torres *et al.* 1999; Rossa *et al.*
751 2005; Cole and Moore 2008; Corral *et al.* 2009; Delrieu *et al.* 2009). However, it has been
752 classically recognized that there are a number of errors (listed, e.g. by Zawadzki 1984;
753 Austin 1987; Joss and Waldvogel 1990) that affect radar-based QPE and that require the
754 implementation of sophisticated algorithms to mitigate their effect (also, the blending of
755 radar QPE maps with rain gauge measurements has shown significant improvements –see,
756 e.g. Velasco-Forero *et al.* 2009 ; Schiemann *et al.* 2010 and references therein-).

757 Radar rainfall products also allow generating very short-term rainfall forecasts (nowcasts)
758 that can be used to extend the time series of rainfall inputs to the rainfall-runoff model
759 [critical in point (3) above]. Previous works on this subject show significant improvements

760 in the quality of forecasted hydrographs (see Berenguer *et al.* 2005; Versini 2012; Vivoni *et*
761 *al.* 2006; Zappa *et al.* 2011): The anticipation of flow peaks could be extended for up to a
762 few hours in small to medium basins and, when included in the GFWS, should enable
763 improving the skill of the system for flood forecasting. Beyond these time horizons (critical
764 for flood management and rescue services to prepare and plan their actions), rainfall
765 forecasts based on the combination of radar-based products with numerical weather
766 prediction (NWP) precipitation outputs (as suggested by Li and Lai 2004; Lin *et al.* 2005;
767 Atencia *et al.* 2010) should be used. Also, other works (see Jasper *et al.* 2002; Zappa *et al.*
768 2010 and references therein) have shown the interest of coupling NWP precipitation
769 outputs for flood forecasting in small and medium catchments. In our case, it represents an
770 opportunity to fulfil the gap between the lead-times provided by EFAS (several days in
771 advance) and those provided by the GFWS (few hours in the best case). The 2 or 3 hours
772 gained by this combination are critical in crisis management. They should be useful to
773 anticipate the direct consequences of the current event and to optimize emergency services
774 resources. It should also allow to better anticipate small-scale event and to deliver warning
775 on smaller watersheds.

776 In this sense, it should be noted that the GFWS is ready to use any gridded rainfall product.
777 In particular, the GFWS is currently using the radar-based QPE and QPF products
778 generated with the EHIMI packages using observations from the Málaga radar (not
779 available for the analysed events). As discussed above, with the inclusion of these high-
780 resolution precipitation products we expect a better performance of the system, especially
781 for issuing warnings at local scales.

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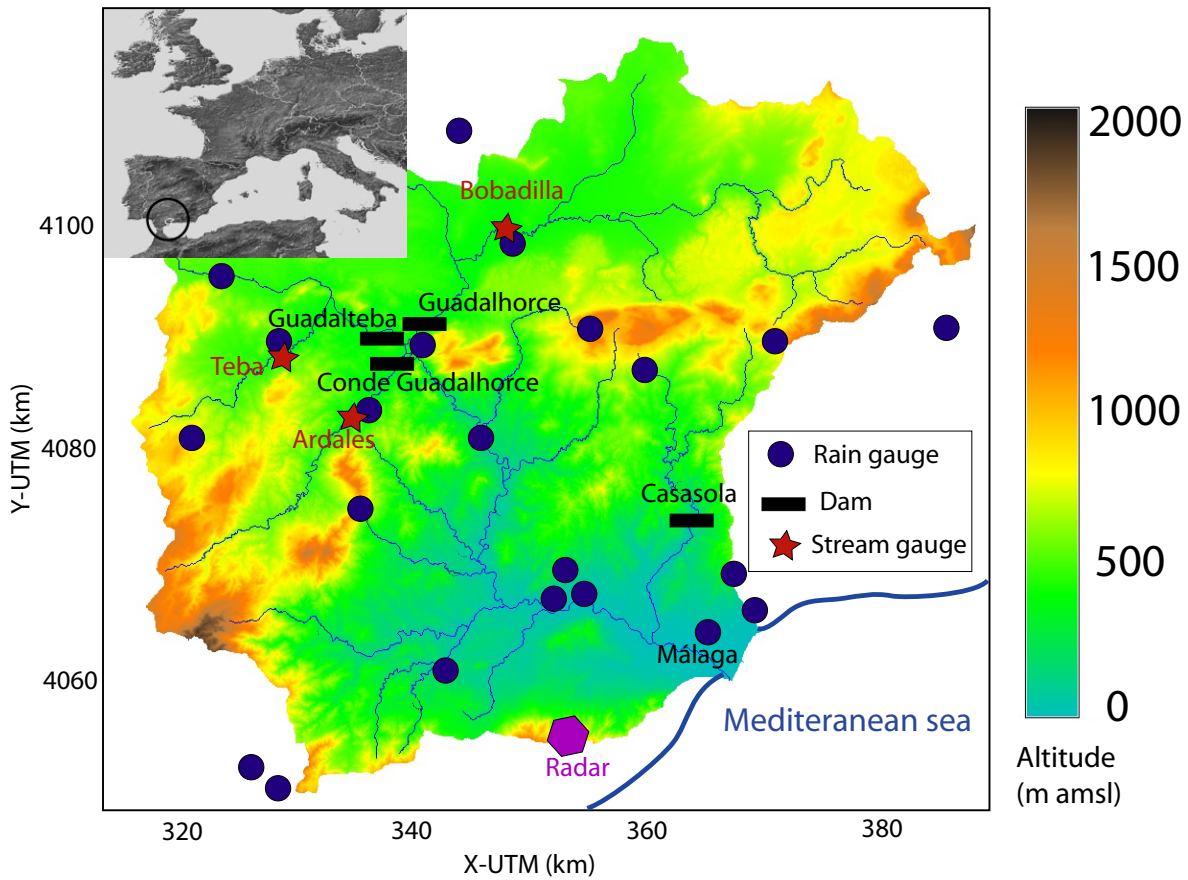
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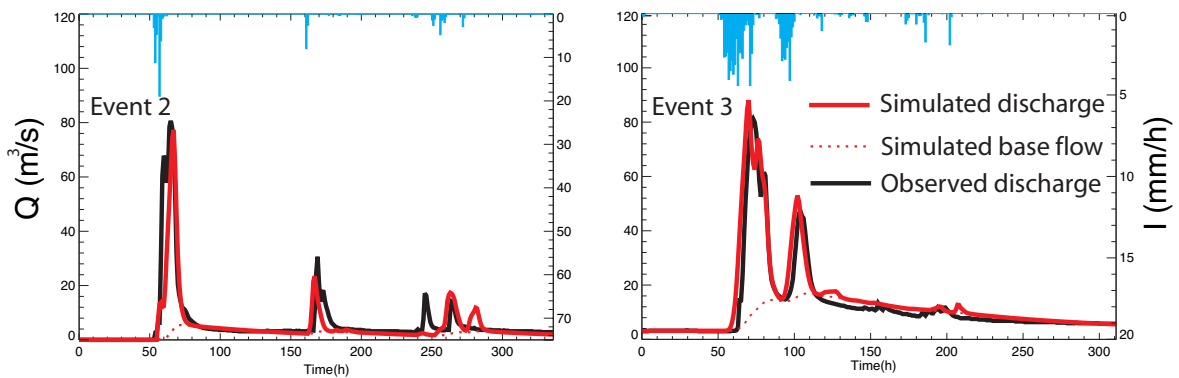
1007 **Figure captions**



1008

1009 Figure 1. The Guadalhorce basin and its hydro-meteorological sensors

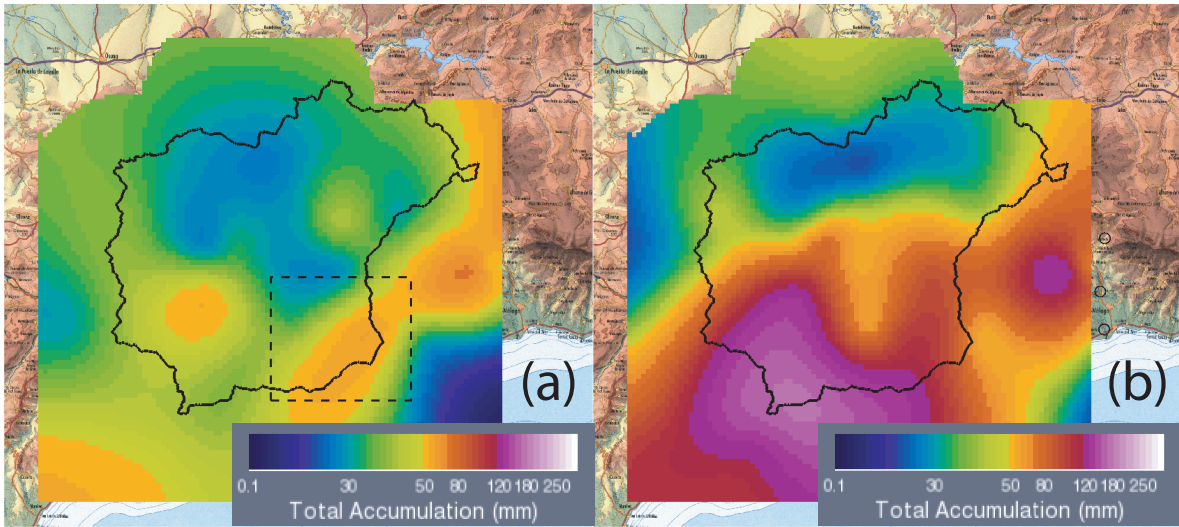
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1011

1012 Figure 2. Comparison between observed (black line) and simulated (red line) discharges on
1013 Bobadilla basin. The left vertical axis represents the discharge (in m³/s). The right vertical
1014 axis represents the rainfall intensity (in mm/h).

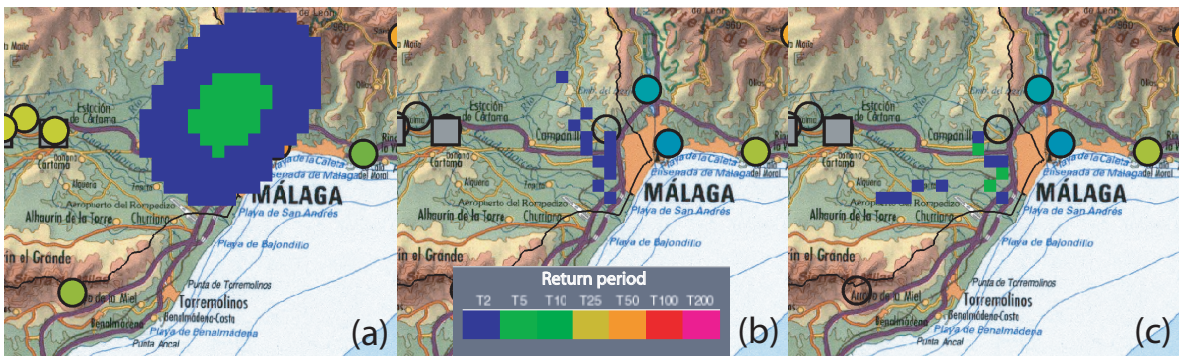
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1016

1017 Figure 3. Total estimated precipitation accumulation estimated from rain gauges for (a) 6-7
 1018 January 2010, and (b) 15-16 February 2010.

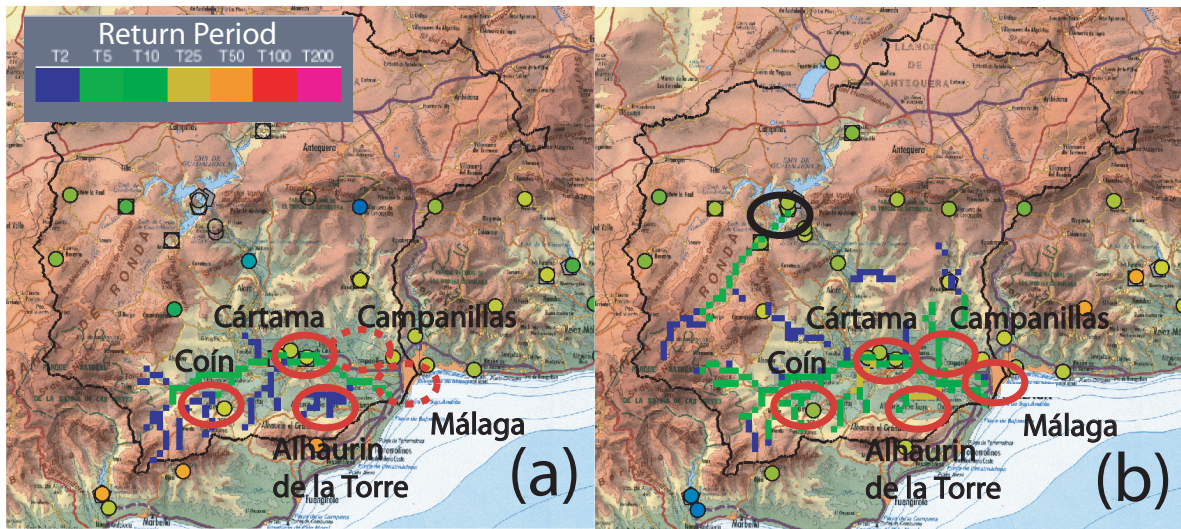
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1020

1021 Figure 4. Flood warnings issued on 7 January 2010 based on: (a) point rainfall at 9:00
 1022 UTC, (b) aggregated rainfall at 10:00 UTC, and (c) simulated discharges at 10:00 UTC.
 1023 This area around Málaga is the one defined by the dotted square in Fig. 3. The circles
 1024 indicate the presence of the rain gauges. The solid red ellipses correspond to the effective
 1025 flooding

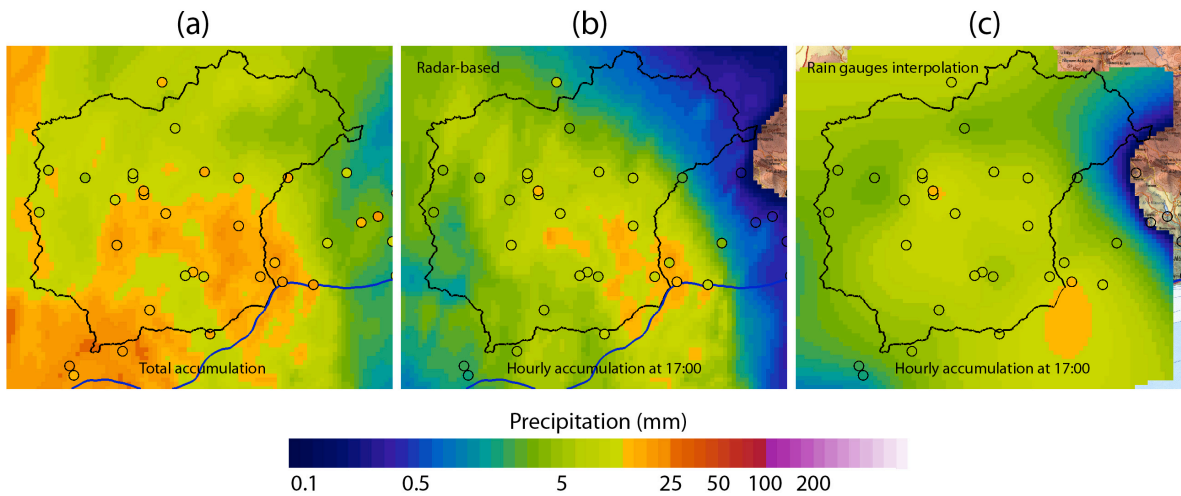
1026



1027

1028 Figure 5. Flood warnings issued on 16 February 2010 based on: (a) Aggregated rainfall at
 1029 6:00, and (b) and simulated discharge at 7:00. Flooded locations are surrounded in red. The
 1030 solid red ellipses correspond to the forecasted flooding and the dotted ellipses to the missed
 1031 flooding. The black ellipse corresponds to the false alarm at Conde Guadalhorce dam.

1032



1033

1034 Figure 6. Results obtained for the 21 April 2011 event: (a) total precipitation accumulated
 1035 from radar-based estimates, (b) hourly rainfall field at 17:00 UTC computed by using radar-
 1036 based estimates, (c) hourly rainfall field at 17:00 UTC interpolated from rain gauges. The
 1037 circles represent the rain gauges and their observed values.

1038

1039 **Table captions**

1040 Table 1

	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8
Qmax [m ³ /s]	44.4	80.7	81.2	27.2	20.8	42.6	22.7	84.3
Rainfall [mm]	59.6	78.6	82.3	57.1	34.4	23.3	24.5	97.5
NE	-0.49	0.70	0.84	-1.80	-0.24	0.76	0.57	0.06

1041

1042 Table 1. Characteristics of the events selected for the calibration of the rainfall-runoff
 1043 model in the Bobadilla watershed. In the table, Qmax is the maximum measured peak flow,
 1044 Rainfall the total amount of precipitation on the sub-catchment, and NE the Nash efficiency
 1045 characterizing the calibration assessment.

1046

1047 Table 2

Event	Bobadilla		Teba		Ardales	
	Qmax [m ³ s ⁻¹]	NE	Qmax [m ³ s ⁻¹]	NE	Qmax [m ³ s ⁻¹]	NE
6-7 January 2010	100	0.69	60	0.53	-	-
15-16 February 2010	80	0.62	65	0.57	33	0.35

1048

1049 Table 2. Characteristics of test case studies and results obtained with the rainfall-runoff
 1050 model at the gauged watersheds. In the table, Qmax is the maximum measured peak flow,
 1051 and NE the Nash efficiency characterizing the calibration assessment. Note that, as
 1052 explained in Section 3.3, Teba and Ardales gauges were not used in the calibration of the
 1053 rainfall-runoff model.

1054