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Spatially distributed flood forecasting in flash flood prone areas: Application to road network supervision in Southern France.

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Abstract

Accurate flood forecasts are critical to an efficient flood event management strategy. Until now, hydro-meteorological forecasts have mainly been used to establish early-warnings in France (meteorological and flood vigilance maps) or over the world (flash-flood guidances). These forecasts are typically limited either to the main streams covered by the flood forecasting services or to specific watersheds with specific assets like check dams, which in most cases are well gauged river sections, thus leaving aside large parts of the territory. This paper presents a distributed hydro-meteorological forecasting approach, which makes use of the high spatial and temporal resolution rainfall estimates that are now available, to provide information at ungauged sites. The proposed system intended to detect road inundation risks had initially been developed and tested in areas of limited size. This paper presents the extension of such a system to an entire region (i.e. the Gard region in Southern France), including over 2,000 crossing points between rivers and roads and its validation with respect to a large data set of actual reported road

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inundations observed during recent flash flood events. These initial validation results appear to be most promising. The eventual proposed tool would provide the necessary information for flood event management services to identify the areas at risk and adopt appropriate safety and rescue measures: i.e. pre-positioning of rescue equipment, interruption of the traffic on the exposed roads and determination of safe access or evacuation routes. Moreover, beyond the specific application to the supervision of a road network, the research undertaken herein also provides also results for the performance of hydro-meteorological forecasts on ungauged headwaters.

Keywords: Flash flood, forecast, distributed model, event management, ungauged watershed

1. Introduction

Europe's Mediterranean region is frequently affected by severe flash floods, which can be characterized by their very fast dynamics. According to Gaume et al. (2009), these so called "flash floods" probably represent the most destructive natural hazard in the Mediterranean zone. The catastrophic flooding that occurred in the Var region in southern France in June 2010 once again illustrates the destructive effects of such floods. Furthermore, the lack of anticipation of these events combined with their very rapid evolution limit the efficiency of event management and rescue operations to a considerable extent. If good preparation is able to help authorities cope with such events, the availability of short-term forecasts could offer a major improvement, which is essential to providing the necessary information for a correct diagnosis of the situation as well as the organization of rescue operations.

Several systems are currently used to produce operational flood warnings in Europe. One recently developed approach consists of introducing Ensemble meteorological predictions as input to hydrological and/or hydraulic models in order to generate river discharge forecasts (Cloke and Pappenberger, 2009). This approach lies at the core not only of the European Flood Alert System (EFAS) developed by the European Joint Research Center (Thielen et al., 2009), but also of the advanced Hydrological Prediction Service proposed by the U.S. NOAA (McEnery et al., 2005) or of the Vigicrue system run by the SCHAPI in France (Tanguy et al., 2005). These methods however mostly apply to gauged sections of relatively large rivers with forecasting lead times of at least 12 to 24 hours and are not suited to flash flood conditions (Borga et al., 2009). Flash flood forecasting must cope with the complex spatio-temporal patterns of the generating rainfall events which significantly limits the accuracy and relevance of meteorological forecasts. Recent improvements in the EFAS approach (Alfiery et al., 2012) have shown that relevant flash flood warnings may be expected for medium-sized watersheds (i.e. greater than 500 km²). Since damage often occurs in headwater catchments a few km² in size (Ruin et al., 2008), it is also necessary to provide information in these areas that are often ungauged. This implies implementing rainfall-runoff models based on distributed rainfall observations, with shorter lead times and limited calibration possibilities.

A variety of methods have been developed to produce short-term flash flood forecasts or alerts on small streams (1 to 500 km²). The most common of these are based on rainfall thresholds associated with risk levels, such as Flash Flood Guidance (Carpenter et al., 1999; Georgakakos, 2006) or

39 Bayesian decision approach (Martina et al., 2006). Other methods, based on
40 distributed rainfall-runoff simulations and discharge thresholds (Reed et al.,
41 2007; Younis et al., 2008; Javelle et al., 2010) have been developed yet based
42 on limited tests and validation at ungauged sites. Moreover, the selected
43 alert thresholds are typically uniform over a given territory, or else deter-
44 mined based on knowledge of the local consequences of flooding. In an ideal
45 case, flood forecasting methods should be combined with an exposure rating
46 method so as to provide valuable outputs at a large spatial scale and not just
47 at a small number of strategic points.

48 More recently, Versini et al. (2010a,b) proposed a prototype of a road
49 inundation warning system (RIWS) adapted to flash floods. This system
50 also relies on distributed rainfall-runoff simulations, though several reasons
51 have led to focusing on road inundations as a specific consequence of flash
52 floods. First, roads are particularly vulnerable: they generally are the as-
53 sets affected first and nearly half of all flash flood victims are car passengers
54 trapped in their vehicles by the rapid rise of water (Drobot et al., 2007; Ruin
55 et al., 2007). Second, the road network is sufficiently dense throughout the
56 territory and moreover inundations are often reported. These reports provide
57 indirect information on flood location and intensity. Third and last, warn-
58 ings of possible road inundations may be of strategic value for emergency
59 services in identifying the areas at risk and selecting safe accesses or evacu-
60 ation routes. The RIWS is intended to provide a real time estimation of the
61 road submersion risk at each intersection between roads and the stream net-
62 work. These intersections mainly correspond to bridges, dams, culverts (for
63 channelized streams) or fords. The computed risk level results from the com-

64 parison of forecasted discharges using a rainfall-runoff model and discharge
65 thresholds established according to the estimated susceptibility to flooding
66 of each single intersection.

67 The initial version of the RIWS has been developed and tested on a ter-
68 ritory with limited areal (240 km², see Figure 1) under relatively favorable
69 conditions: homogeneous hydrological behavior, and the availability of ex-
70 tensive information on road susceptibility to flooding.

71 The work presented herein is aimed at both, extending the RIWS to
72 the entire Gard region (5000 km²), which corresponds to an actual pre-
73 operational test and further developing and testing this tool using a larger
74 data set.

75 A spatial extension of the initial RIWS presents two main difficulties.
76 The first one is the implementation of a rainfall-runoff model at high spatial
77 resolution, mainly on ungauged catchments of a limited area (less than 2 km²
78 on average), and on a territory that features a wide array of hydrological and
79 hydraulic conditions: variability of soil and land use characteristics (in some
80 cases with karstic conditions), a stream network including small upstream wa-
81 tercourses and downstream rivers with broad floodplains. The model should
82 also take into account the spatial heterogeneity of rainfall inputs, with com-
83 putation times being compatible with a real-time application. The second
84 difficulty lies in the definition of the susceptibility of roads to flooding in
85 areas where little or no data on past reported inundations are available, in
86 comparison with the areas initially selected (Versini et al., 2010a).

87 The paper's next section will present the case study and the develop-
88 ments introduced in the initial RIWS methodology in an effort to answer the

89 aforementioned questions. Several tests of the expanded system will then be
90 provided, based on a dataset that includes 10 recent flooding events, which
91 lead to observations of significant disruptions to the road network. These
92 initial results will then be discussed as a preliminary to proposing further
93 system improvements.

94 **2. Presentation of the Gard region and available datasets**

95 *2.1. The Gard region*

96 The Gard region is an administrative jurisdiction located in southeast-
97 ern France. Its boundaries are presented in Figure 1: the northwest part of
98 this area includes the Cévennes Mountains, a medium elevation chain cul-
99 minating at Mont Lozère (1,699 m); on the other hand, the southeast part
100 corresponds to plateaus and plains extending to the Mediterranean coast,
101 with elevations varying between 0 and 200 meters. This region displays typ-
102 ical Mediterranean climate, as revealed by heavy rainfall events during the
103 autumn season. The 10-year daily rainfall accumulation ranges from 100 mm
104 near the Mediterranean coast to more than 270 mm in the Cévennes foothills
105 (CNRS-INPG, 1997).

106 This territory is the French region most frequently affected by flash floods
107 (Gaume et al., 2009). Over the last 25 years three exceptional rainfall events
108 have caused considerable damage and losses. In 1988 the city of Nîmes was
109 completely devastated by a flood associated with rainfall accumulations in
110 excess of 400 mm within 6 hours (Desbordes et al., 1989), causing 9 deaths.
111 The extraordinary flood event of the 8th and 9th of September 2002 affected
112 the entire Gard region, with rainfall accumulations that locally exceeded 600

113 mm in 12 hours, causing 24 deaths in addition to economic losses estimated
114 at €1.2 billion (Delrieu et al., 2004). Lastly, a major event was also observed
115 on September 2005 6th-8th in the southern part of the region, with local
116 rainfall accumulations of about 300 mm on the 6th and 250 mm on the 8th,
117 responsible for significant inundations in Nîmes, but more predominantly in
118 the downstream plains (Maréchal et al., 2007).

119 This region is divided into six main watersheds covering 4/5th of the
120 Gard territory: the Gardon (1858 km²), the Cèze (1355 km²), the Vidourle
121 (798 km²), the Vistre (600 km²), the Hérault (817 km²), and the Dourbie
122 (468 km²) (see Figure 1). Except for the Vistre, these rivers all originate in
123 the Cévennes Mountains, which correspond to primary geological formations.
124 Over their downstream part, the Gardon, the Vidourle and the Cèze rivers all
125 cross a plateau area, characterized by sedimentary bedrock mostly composed
126 mainly of marls and locally of karstified limestone. The extreme southern
127 part of the Gard region corresponding to the Vistre watershed and extreme
128 downstream part of the Vidourle River, is a flat and low elevated plain,
129 covered by thin and diversified Quaternary alluvial formations.

130 2.2. Road network and road inundation inventories

131 The road network considered herein includes all road sections except for
132 local connections at the district scale. Since 2007 this road network has been
133 managed in large part by the Gard Departmental Council whose oversight
134 includes maintenance operations, traffic management and the construction of
135 new road sections. This involvement extends to field surveillance during floods
136 and, if necessary, closing the inundated roads to the traffic, and information
137 dissemination on road traffic conditions to other authorities and to the media.

138 The total number of intersections between roads and rivers depends on the
139 river network definition. This number lies close to 2,200 when the Carthage
140 ¹ hydrographic database is used with an average upstream watershed area of
141 less than 2 km² (Fig. 2). The RIWS will be required to provide an estimated
142 discharge value every 15-min at each of these intersections.

143 One important specificity of the region considered in this analysis is the
144 availability of a relatively thorough information (when compared to other
145 regions) regarding road network susceptibility to flooding. This information
146 relies on two distinct sources.

147 First, a systematic inventory of critical road sections, known from field
148 experience and human memory, was conducted after the major 2002 flood.
149 This initial compilation, called the PICH, basically covers a 40-year period
150 and identifies 160 road sections displaying a potential risk of submersion.
151 This PICH inventory also includes an estimation of the flood return period
152 of each identified vulnerable road section. This compilation however only
153 covers the northwest part of the Gard region, and does not provide event-
154 specific information. The PICH has been used to adjust the susceptibility
155 rating method in the RIWS. Note that only 71% of the points reported in
156 the PICH actually correspond to intersections identified in Figure 2: the
157 remaining 29% may correspond to local road sections not considered herein,
158 or else to inundations that cannot be associated with a river intersection:
159 low points and or lateral overflow of a stream. Consequently, the RIWS will

¹The BD CARTHAGE® database, produced by the French National Geographic Institut, the MEDD (French Ministry of Ecology and Sustainable Development) and the various Water agencies, constitutes the hydrographic reference in France.

160 not be able to detect all types of localized inundations or disruptions but will
161 capture the majority of them.

162 Second, since 2002, inventories of the road disruptions associated with
163 single flood events have gradually been developed. These inventoried road
164 closures are mainly caused by road submersions but might also sometimes be
165 induced by snow, landslides or rock falls, or even road accidents. The most
166 exposed roads may also be closed preventively. This information collection
167 system at the event scale has been progressively implemented and has just
168 recently reached maturity: these inventories have only become systematic
169 since 2007. Ten event reports are ultimately available over the period 2002-
170 2008; they have been presented in Table 1. Nonetheless, this information is
171 heterogeneous and probably far from being exhaustive. The first reports did
172 not indicate the timing or exact locations and causes of the road closures;
173 reports on more recent events tend to be more accurate in space and time.
174 These event reports of road disruptions have still been used to evaluate the
175 RIWS performance.

176 According to both the PICH and the event-specific reports, 528 of the
177 2,172 intersections represented in Figure 2 have been inundated at least once
178 over the last 40 years.

179 *2.3. Rainfall and stream flow data*

180 The Gard region is covered by a relatively dense network of rain gauges
181 (about 1 gauge every 150 km²) and two weather radars providing high spa-
182 tial and temporal resolution quantitative precipitation estimates (QPE). The
183 available operational datasets have been subjected to a thorough quality con-
184 trol and can be considered of above-average accuracy (Boudevillain et al.,

2011). The results presented in this paper are based on an interpolation of rain gauge measurements through simple kriging with a climatological isotropic variogram (Lebel et al., 1987). Radar quantitative precipitation estimates would probably be more appropriate in this context of flash floods. Due however to the evolution in radar data post-processing and to the radar disruptions for certain specific events, radar data of homogeneous quality were only available for 5 out of the 10 reported flooding events selected for this study (see Table 1). A comparison of the RIWS results with various types of rainfall inputs, based on these 5 events (Naulin et al., 2011), showed that the detailed location and levels of risk alarms triggered are significantly modified by the type of inputs (radar-based QPEs or kriged rain gauge data), but that the overall detection performance based on skill scores were not highly altered. The results obtained with the kriged rainfall data were selected for this paper in order to maintain an extensive evaluation dataset with relatively homogeneous rainfall inputs. The generated rainfall fields display a 1-kilometer spatial resolution and a 1-hour temporal resolution: they have been divided into four equivalent 15-minute time steps to match the needs of the rainfall runoff-model.

The Gard region counts 23 stream gauges located for the most part on the major streams. The stream gauge measurements have been used herein to verify the performances of the rainfall-runoff model prior to its application in the RIWS. Nevertheless, these measurements yield little information regarding the accuracy of the rainfall-runoff simulations on the upstream tributaries.

209 2.4. Selection of the flood event dataset

210 The 13 events with a maximum measured point rainfall accumulation
211 exceeding 50 mm/day over the period 2007-2008 were selected in order to test
212 the RIWS. Four additional events from the period 2002-2006 with available
213 event-specific reports of road disruptions were added to the dataset. The final
214 event dataset is presented in Table 1: it includes a wide variety of hydro-
215 meteorological configurations: from exceptional and generalized events, to
216 more localized and/or lower magnitude events. Seven of the selected events
217 did not induce any reported disruptions, while the other events illustrate the
218 features and frequency of floods inducing road inundations across this region.

219 3. Description of the RIWS

220 3.1. General principle

221 Versini et al. (2010a,b) proposed to consider the risk of submersion as
222 the combined consequences of the magnitude of the forecasted discharge in
223 a given river section and the susceptibility to flooding of the corresponding
224 road-river intersection. This susceptibility is determined using the estimated
225 flood return period for the road; it can be compared to the theoretical return
226 period of the forecasted discharge. The RIWS therefore includes three sepa-
227 rate components, namely: i) a rainfall-runoff model producing the forecasted
228 discharges at each intersection, ii) a road-river intersection susceptibility rat-
229 ing method, and iii) a method for estimating the discharge return periods at
230 each intersection (i.e. the SHYREG regional flood frequency method Lavabre
231 et al. (2003)).

232 Since the flood return period depends to a great extent on the local config-
233 uration of each road-river intersection, it might not be determined accurately
234 without specific observations which are generally unavailable. Versini et al.
235 (2010a) therefore proposed to simplify the description of susceptibility and
236 sort intersections into just four susceptibility classes (from high to very low
237 susceptibility), with each class assigned its own distribution of flood return
238 periods. For a given discharge return period, the probability of inundation
239 (i.e. the flood risk level) thus differs for each susceptibility class.

240 Lastly, three inundation risk levels, corresponding to an increased proba-
241 bility of flooding, may be generated by the RIWS at each computation time
242 step and intersection, on the basis of the contingency table 2.

243 The first application presented by Versini et al. (2010a,b) is based on the
244 Cinecar rainfall-runoff model (Gaume et al., 2004), which has been applied
245 using homogeneous production parameters given the limited extent of the
246 considered areas (240 km²). The susceptibility rating method, i.e. the process
247 of sorting intersections into the four susceptibility classes, was based on three
248 morphological parameters: local slope of the river bed, upstream watershed
249 area, and elevation. Versini et al. (2010a) observed that the more vulnerable
250 road sections identified in the PICH inventory were in fact concentrated
251 on smaller slopes and lower elevation areas with large upstream watersheds
252 (Fig. 3). The four susceptibility classes were defined using combinations of
253 thresholds for these three parameters, with the high susceptibility class only
254 containing PICH points and the very low susceptibility class containing no
255 PICH points (see Table 4).

256 In the application presented herein, the general principles of the RIWS

257 have been preserved. The extension of this system to the entire Gard ter-
 258 ritory, which involves a wider variety of local configurations, has however
 259 required introducing some changes into both the rainfall-runoff model and
 260 susceptibility rating method. The next two sections will present in detail
 261 the corresponding methodological evolution. The return periods in Table 2
 262 have remained unchanged. The selected discharge return period estimation
 263 method is based on a stochastic simulation of long rainfall-runoff series, yet is
 264 not directly correlated with the rainfall-runoff model used in the RIWS. This
 265 situation may cause biases; therefore, the RIWS was tested on the 2007-2008
 266 continuous period (including 13 significant rainfall events but only 6 inundat-
 267 ing events) to evaluate the possible system under or over-reaction (Section
 268 4.2).

269 *3.2. Modifications of the rainfall-runoff model*

270 The CINECAR model has once again been selected here to compute the
 271 discharges every 15-min at the 2,172 intersections identified in the Gard re-
 272 gion. This model is distributed and based on a representation of the water-
 273 shed as a ramified series of stream reaches with a rectangular cross-section, to
 274 which both left and right hand hillslopes with schematic rectangular shapes
 275 are connected (Fig. 4).

276 This model only depicts the rapid runoff and is suited for simulating the
 277 rising limb and peak phases of significant flood events. The Soil Conserva-
 278 tion Service - Curve Number (SCS-CN) model has been used to compute
 279 runoff rates and the corresponding effective rainfall on the hillslopes at each
 280 computation time step. The effective rainfall is then propagated on both the
 281 hillslopes and downstream river network using the kinematic wave model,

282 which has been resolved by the method of characteristics according to an
 283 approach proposed by Borah et al. (1980). The model is flexible and its
 284 space and time scales can easily be adapted to meet user needs. Moreover,
 285 the model is capable of accounting for the spatial variability of rainfall. For
 286 this particular application, the hyetographs corresponding to each individual
 287 hillslope have been extracted from interpolated rainfall fields.

288 This model, initially developed to support the hydrological analysis of
 289 data collected after extreme flash flood events, has provided satisfactory re-
 290 sults for reconstructing the floods that occurred in September 2002 in the
 291 Gard (Delrieu et al., 2005; Gaume et al., 2004). Due to model simplicity,
 292 its computation time is limited: less than 60 sec. CPU for a 12-hours event
 293 over the entire Gard region. Moreover, CINECAR has a limited number
 294 of calibration parameters. The widths of river reaches constitute the main
 295 parameters controlling the transfer function. The roughness coefficients are
 296 considered to be constant and their values are set at 0.05 for channels and
 297 0.1 for hillslopes. Channel widths can be determined through field surveys
 298 or an analysis of aerial photographs. For the sake of simplicity, fixed average
 299 channel width values $W_{I,T}$, related to the the Strahler order I of the reach,
 300 and the return period T of the simulated discharge, have been introduced
 301 according to a simple relation:

$$W_{I,T} = W_{1,T} \cdot I^2 \quad (1)$$

302 with $W_{1,T}$ being the channel width for reaches of Strahler order 1 (see Table 3
 303 for the calibrated values in the Gard).

304 Some modifications of the transfer function have been introduced in order

305 to extend the model to the region, namely: a model simulating the effects
306 of the five major check dams, the diffusive wave model and Hayami method
307 (Hayami, 1951; Moussa, 1996) for river reaches with slopes of less than 1%
308 (to simulate the attenuation of the flood waves in the downstream part of
309 the river network).

310 The Curve Number (CN) value is the second important calibration pa-
311 rameter and controls the temporal evolution of runoff rates and, as a conse-
312 quence, the flood magnitude. In the initial version, the CN value was assumed
313 to be homogeneous over the limited application areas; its variation in space
314 has been taken into consideration for the RIWS extension to the entire Gard
315 region. This step is based on the USDA proposed method (USDA, 1986) to
316 determine the CN values as a function of land use, soil types (Corine Land
317 Cover data base and European Soil Database) and during the 5 days pre-
318 ceding rainfall accumulation. As opposed to the conclusions of other recent
319 works (Huang et al., 2007; Soulis et al., 2009), this method has led to satis-
320 factory results, without requiring further adjustments, for the major recent
321 flood events (Table 1) at the 23 gauged sites of the Gard region.

322 Most of the target sites (intersections) are located on small ungauged up-
323 stream watersheds. The hydrological model which has only undergone slight
324 adjustments, has in fact been mostly validated with respect to measured
325 data. No real systematic calibration has been performed. The objective
326 here was to obtain a model that could produce homogenous results at the
327 regional level while avoiding site specific models requiring an intensive cal-
328 ibration phase. As such, the ultimatemodel performance is satisfactory for
329 the major events selected to test the RIWS (Fig. 5): with an average Nash

330 criterion computed for each single event equal to 0.49.

331 These results can be compared with the validation outcome of a concep-
332 tual rainfall runoff model calibrated on each specific stream gauge observed
333 series. The GR4 model, chosen for such a comparison, is a lumped model de-
334 veloped by Edijatno and Michel (1989) and advanced by Perrin et al. (2003).
335 This hourly rainfall-runoff model requires four parameters to be automati-
336 cally calibrated with respect to measured data.

337 A comparative test between Cinecar and GR4 has been conducted for the
338 Anduze stream gauge on the Gardon River: i.e. the largest and highest
339 quality discharge series in the region. A 2-year series was used to calibrate
340 the GR4 model. The obtained Nash score derived over a 6-year validation
341 period reached 0.59, which lies in the average range of values reported in
342 the literature for applications of continuous rainfall-runoff models (Perrin,
343 2002). The corresponding "event-specific" Nash criteria are then compared
344 with the Cinecar criteria for the largest validation floods in Figure 6.

345 Results indicate that while the Cinecar model is less efficient for minor
346 events, the two models present a similar performance for the larger events
347 (i.e. unit peak discharge exceeding $2 \text{ m}^3/\text{s}/\text{km}^2$) which do constitute the
348 focus of the present study and more generally of flood forecasting models
349 for this region.

350 Since the RIWS is based on thresholds and not directly on simulated
351 discharge values, its performance will mainly be controlled by the correct
352 forecast of the magnitude or, more precisely, the correct position of the sim-
353 ulated discharge when compared to the discharge quantiles. Figure 7 shows
354 that the Cinecar model predicts peak discharges with typically the same

355 range of estimated return periods as the observed peak discharges. Except
356 for some few obvious overestimations, the differences between simulated and
357 observed discharges do not exceed one return period class. In considering
358 the additionnal filtering introduced when computing risk levels (Table 2),
359 it is anticipated that these differences will have little impact on the RIWS
360 performance.

361 *3.3. Modifications to the susceptibility rating method*

362 Extending the RIWS to the entire Gard region also required adapting
363 the susceptibility rating method to account for the large spatial variability of
364 observed inundations and geomorphic characteristics throughout the region.

365 The distribution of PICH points into the four susceptibility classes, as
366 presented in Table 4, reveals that the efficiency of a sorting method based
367 on morphological parameters decreases when moving from the initial area
368 considered by Versini to the entire region covered by the PICH inventory
369 (approx. half of the entire Gard region), with the proportion of PICH points
370 in susceptible classes markedly decreasing.

371 A detailed analysis shows that the geographical distribution of PICH
372 points, as presented in Figure 2, is very heterogeneous at the PICH territorial
373 scale. The initial sorting method is not able to capture this variability since
374 it generates susceptibility classes with a relatively homogeneous geographical
375 density. In order to improve the results of the susceptibility rating results,
376 the sorting method has therefore been applied separately to three sub-areas
377 displaying significantly different PICH point densities:

- 378 • the mountainous area, where the density of PICH points is very low
379 (i.e. less than 5 % of the intersections). The ntersections located in

380 this area are only assigned to the low and very low susceptibility classes
381 depending on local slope, altitude and upstream catchment area;

- 382 • the plateau and plain area with an intermediate PICH point density
383 and where the intersection points may be assigned to any of the three
384 lowest susceptibility classes (very low, low and average);
- 385 • the identified flood plains in the plateau and plain area, with a very high
386 PICH point density (exceeding 30 %). In these areas, all intersections
387 are assigned to the high and very high susceptibility classes.

388 The results presented in Table 4 indicate that this application to three
389 homogeneous sub-areas improves the sorting results to a fair extent, which in
390 turn leads to decreasing the proportion of intersections considered as vulner-
391 able (as reflected by an increase in the very low susceptibility class). A higher
392 proportion of intersections is also assigned to the high and average suscepti-
393 bility classes with an equivalent proportion of PICH points in these classes.
394 To validate this evolution in the susceptibility rating method, a comparison
395 of RIWS performances will be presented in Section 5.1 below.

396 Furthermore, the distributions of flooding frequencies for intersections
397 placed in each susceptibility class may be estimated on the basis of the PICH
398 inventory. The dispersion in these distributions, combined with the uniform
399 risk thresholds presented in Table 4, will logically lead the RIWS to generate
400 a significant number of false alarms. Ideal detection rates and False Alarm
401 Ratios of the system (FAR, see definition in Section 4.2) linked to the dis-
402 persion of flooding frequencies in each susceptibility class can be estimated
403 in an *a priori* manner for each risk level, i.e.:

- 404 • Risk level 3: Inundation highly probable (over 40% of the alarms corre-
 405 spond to actual inundations, hence $FAR < 60\%$, i.e. a discharge return
 406 period threshold exceeding the reported inundation return period for
 407 about 40% of all intersections listed in the class);
- 408 • Risk level 2: Inundation possible with a significant probability (over
 409 20% of alarms corresponding to actual inundations, $FAR < 80\%$);
- 410 • Risk level 1: Inundation possible with low probability (over 10% of
 411 alarms corresponding to actual inundations, $FAR < 90\%$);

412 These values will serve as a benchmark for the RIWS performance evalua-
 413 tion. The relatively high theoretical false alarm ratios are due to the difficulty
 414 involved in evaluating the susceptibility of intersections to flooding on the
 415 basis of available data; these figures provide an idea of the possible perfor-
 416 mances of the RIWS performance if the rainfall-runoff forecasts were nearly
 417 perfect.

418 **4. Evaluation of the Road Inundation Warning System (RIWS)**

419 For starters, it is worth noting that over the period 2007-2008, during
 420 which the reports on flood events are certainly comprehensive, the RIWS
 421 only produces warnings (risk levels 1 to 3) for the 6 events with actually
 422 reported road inundations. This finding confirms that the RIWS is neither
 423 under-reacting nor over-reacting and is moreover capable of distinguishing
 424 the most significant flood events. Given these initial results, it seems that the
 425 rainfall-runoff model estimates discharges with the correct order of magnitude
 426 and that the risk thresholds were appropriately selected and estimated.

427 Given this initial positive outcome, the results presented below are mainly
 428 focused on a detailed performance analysis of RIWS during each inundating
 429 event. These results comprise 10 events if the 2002-2006 period is included
 430 (Table 1). The events examined have very distinct characteristics, i.e. vari-
 431 able intensities and total rainfall amounts, more or less concentrated in space,
 432 thus allowing for an in-depth analysis of the RIWS performance.

433 4.1. Evaluation criteria

434 The comparison between computed risk levels and reported floodings will
 435 be based on standard criteria used to evaluate meteorological forecasts, com-
 436 puted based on the contingency Table 5 and then calculated separately for
 437 each risk level.

438 From this table, four scores will be calculated as follows (Schaefer, 1990;
 439 Wilks, 2006):

- Probability of detection (POD) :

$$POD = \frac{H}{H + M} \quad (2)$$

- False Alarm Ratio (FAR):

$$FAR = \frac{Fa}{H + Fa} \quad (3)$$

- Probability of False Detection (POFD) which relates the number of false alarms to the total number of non-flooded points and offers an idea of the legibility of warnings:

$$POFD = \frac{Fa}{Cn + Fa} \quad (4)$$

- The Peirce Skill Score (PSS) has been used as a global score.

$$PSS = POD - POFD \quad (5)$$

A perfect forecasting system should feature both a POD and a PSS equal to 1 and a FAR and a POFD of 0. Yet, the limitations of the road inundation observations must be considered when applying these skill scores to evaluate the RIWS. First, a comparison between simulated stream discharges and reported road disruptions reveals possible inconsistencies along with the lack of exhaustiveness in the reports. Road sections are often reported as closed for relatively moderate floods and not for more intense ones over the considered period, according to the rainfall-runoff simulations. If we were to consider that the rainfall-runoff model, despite its lack of accuracy, is at least able to correctly rank the discharges between events most of the time, this confirms the limitations of available inundation inventories. Such inconsistencies are present in 41% of the reported road disruptions; they have two main potential origins:

- The road closure reports are not likely to be comprehensive.
- The reasons behind road closures are sometimes unknown, hence some road sections present in the inventory may not have been submerged but instead affected by other phenomena (e.g. landslide, snow, accidents).

Furthermore, the inundation location may have imprecisely logged. Reported closures can sometimes be attributed to several intersections; in this situation, if at least one possible corresponding intersection has been targeted by a warning, then all forecasts would be considered as correct (either

461 H or Cn). Otherwise, if no warning had been issued, only one missed alarm
462 would be counted. Such a case is nevertheless rare: this simplification has
463 limited impact on the evaluation criteria.

464 It is also important to note that in the case of events presenting just a few
465 inundated roads, the POD scores are very sensitive to the number of actual
466 detections. For instance, if only 10 roads are reported to be flooded, each
467 detected point increases the POD score by 10%.

468 4.2. RIWS performance

469 Examples of POD and FAR obtained by the system are shown in Figure 8.
470 The false alarm ratios are very high which is clearly correlated with the
471 difficulties involved in defining the susceptibility to flooding of intersections.
472 Section 3.3 pointed out that given the limitations of this susceptibility rating,
473 FAR ratios of about 90% for risk level 1 are to be expected. The FAR ratios
474 observed here lie in this same range (around 90%). Improvements to the
475 rainfall-runoff model can therefore only exert a small impact on the FAR
476 scores.

477 The POD scores depend on the flood event under consideration. A de-
478 tailed analysis shows that the POD is correlated with the total number of
479 reported inundations, which serves as an indicator of the flood magnitude.

480 The POD are very high for the extreme floods of 2002 and 2005, in
481 exceeding or nearing 90%. In such cases, the susceptibility rating plays a less
482 important role since the return period of the computed as well as observed
483 discharges at the affected intersections generally exceeds 10 or even 50 years
484 (Fig. 8). For the less intense events, the discharge values are lower and both
485 the risk level and corresponding warnings are much more dependent on the

486 susceptibility rating of the intersections, which is the weakest part of the
487 RIWS, thus explaining lower and more variable POD values.

488 For risk level 2, Figure 8 also confirms the correlation between the number
489 of reported road closures (and hence the local magnitudes of floods and the
490 POD) and the September 2007 exception, which affected a particularly sus-
491 ceptible area according to the susceptibility rating method: i.e. the southern
492 part of the region at low elevation over an area with expansive floodplains.
493 Once again, FAR values basically match the forecasts of section 3.3 (on the
494 order of 80 %).

495 Some POD scores nevertheless appear to be on the low side. On De-
496 cember 13th 2008, the relatively high number of road closures appears to be
497 inconsistent with the magnitude of floods according to the simulated as well
498 as to the observed discharges. These closures may have been due to other
499 factors than inundation, in particular snow accumulation. This phenomenon
500 has been mentioned in the logs of the road management services with no
501 further details. On December 29th 2008, the limited POD value is related to
502 the underestimation of the discharges as a result of an incorrect evaluation
503 of the initial wetness state of the watershed. A discharge assimilation pro-
504 cedure is under study in order to resolve the initialization problems of this
505 rainfall-runoff model.

506 On the basis of these results, it is now possible to conclude that the
507 RIWS, in its present form, is able to correctly assess not only the magnitude
508 of the floods (with the exception of some particular events) but also the con-
509 sequences of floods in terms of the number of inundated roads and risk levels.
510 On the other hand, RIWS fails to accurately identify the actually affected

511 road/river intersections. Figures 9 and 10 illustrate this last point and the
512 information content in RIWS output. On the whole, the affected areas of
513 the Gard region have been correctly depicted for these two events. The risk
514 levels are clearly contrasted between these two floods, thus indicating local-
515 ized and significant consequences for the September 2007 flood and a larger
516 area affected during October-November 2008, yet with a lower density of high
517 risk warnings (basically limited to the most susceptible areas: i.e. the valleys
518 of the main streams). These forecasts match field observations: localized yet
519 significant inundations in 2007 and sparsely scattered local problems in 2008.

520 It has also been verified that despite the short forecasting lead time (no
521 longer than 15 min. on the headwater catchments given that the system
522 is based on rainfall measurements), the first warnings have for the most
523 part been delivered well ahead of the first field report. Such a system, if
524 operationally implemented, could, for all the aforementioned reasons, be of
525 great utility for the real-time evaluation of situations as well as for organizing
526 the rescue response and managing the road network. It is currently tested
527 by the Gard Departmental Road Management Office and the initial feedback
528 has been positive overall.

529 **5. Discussion of RIWS components**

530 *5.1. Utility of the susceptibility model*

531 Given the limitations of available road inundation inventories, the sus-
532 ceptibility assessment is probably the weakest RIWS component. In order to
533 evaluate its real utility to the system and feasible improvements, two tests
534 have been conducted:

- 535 • The system was run with discharge thresholds of identical return peri-
536 ods for all intersections: without introducing any susceptibility ratings.
537 Risk level 3 has been associated with a 2-year return period, the level 2
538 with a 10-year return period and level 1 with a 50-year return period.
- 539 • Susceptibility has been defined on the basis of the inundations actually
540 observed during the 10 test events: This is the pseudo perfect case.
541 The intersections inundated once have been assigned to the low sus-
542 ceptibility class, those inundated twice to the moderate class and those
543 inundated more than twice to the high class. The intersections not re-
544 ported as inundated have been assigned to the very low susceptibility
545 class.

546 This last procedure does not claim to establish a valid susceptibility layer,
547 but rather has been implemented in order to evaluate the system with a
548 susceptibility assessment close to perfect and moreover to illustrate potential
549 improvements that could be achieved if reported inundations were to be
550 assimilated.

551 System performance was compared using the two susceptibility rating
552 method configurations presented in Section 3.3. The results are shown in
553 Figure 11. Though far from perfect, the susceptibility rating method clearly
554 improves system performance, as the improved susceptibility rating method
555 leads to higher scores. A detailed analysis also indicates that the scores of
556 the system without susceptibility rating appear to be extremely variable with
557 a high POD, but also POFD and FAR scores for high intensity flood events
558 and scores close to zero for less intense events. The susceptibility rating
559 method introduces stability and nuance into the RIWS response, thereby

560 producing warnings for every significant event. The magnitude and location
561 of the floods determine both the warning density and the level of risks (see
562 Fig. 9 and 10) yet have less influence on the detection scores.

563 This "pseudo perfect" configuration furthermore indicates that an im-
564 provement in susceptibility rating, through data assimilation for instance,
565 would clearly improve the overall performance, mainly by reducing the pro-
566 portion of false detections. The room for improvement is indeed significant,
567 given that the PICH inventory used to calibrate of the susceptibility rat-
568 ing method is likely to be far from perfect. As an example, Table 6 lists
569 the number of road sections included in recent event-specific reports of road
570 disruptions that had not been identified in the PICH inventory: 228 road
571 sections are applicable, with 13 of them having been closed more than twice.
572 This finding exposes the probable lack of comprehensiveness in the PICH
573 inventory.

574 5.2. *Comparison of the rainfall-runoff model configurations*

575 The rainfall-runoff model developed for the Gard region has evolved from
576 its first configuration with homogeneous CN parameters to a distributed CN
577 assessment, according to the USDA methodology. The transfer function has
578 also been improved by implementating the diffusive wave model on the down-
579 stream reaches of the river network. These changes have led to improving
580 the Nash criteria computed on the gauged sections (Fig. 5). However the
581 effect of these improvements on the RIWS performance, while not totally
582 undetectable, still appears to be very limited as illustrated in Figure 12.

583 This confirms that only orders of magnitudes of the discharges are nec-
584 essary to deliver relevant alarms in the context of the RIWS. Overall system

585 performance is therefore relatively insensitive, even with significant improve-
586 ments, to the rainfall-runoff model. One positive conclusion drawn is that
587 useful forecasts can be derived from output of hydro-meteorological models
588 affected by significant uncertainties. A more disappointing conclusion how-
589 ever is that the observed local consequences of flood events in ungauged wa-
590 tersheds, like road inundations, do not provide useful indirect measurements
591 of discharges when evaluating rainfall-runoff models.

592 **6. Conclusion**

593 A prototype of a road inundation warning system (RIWS), initially tested
594 on a limited spatial scale, has been extended to an entire French region and
595 has yielded promising results. The resulting system is able to provide warn-
596 ings at 2,172 intersections between roads and rivers every 15 minutes. Tests
597 conducted in batch mode on 10 recent flood events with observed road in-
598 undations have revealed the system's capacity to forecast the location and
599 magnitude of floods and their consequences with relatively good accuracy,
600 yet it remains unable to locate the affected road sections with precision.
601 The main limitation of this system pertains to poor knowledge on the actu-
602 all susceptibility of individual road sections to flooding. A data assimilation
603 method, based on the comparison of field reports and forecasted risk levels, is
604 currently being tested. Early results are encouraging and in time this method
605 could lead to system improvements. For the interested readers, a demonstra-
606 tor (prediflood.lthe.fr/carto.php) has been developed to provide the
607 simulated warnings and field observations for 5 of the tested events.

608 Beyond the specific application to the supervision of a road network, this

609 research has also produced results relative to hydro-meteorological forecasts
610 and monitoring at ungauged sites. It appears that rainfall-runoff models may
611 offer valuable information for flood event management over small space and
612 time scales even on ungauged watersheds. With a limited calibration and
613 validation effort, rainfall-runoff models could at least provide relatively ac-
614 curate flood magnitude forecasts that would certainly be sufficient for many
615 event management decisions as has been illustrated herein. To some extent,
616 the philosophy behind the approach presented in this paper has similarities
617 with the philosophy of the EFAS system (Younis et al., 2008; Thielen et al.,
618 2009; Alfieri et al., 2012) though at different time and space scales and with
619 a focus on flash floods. Such approaches contrast with the traditional fore-
620 casting methods, which are focused on gauged locations and are definitely
621 forging new avenues in the field of hydrological forecasting.

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749 List of Figures

750	1	Gard department (shown in white), main streams and water-	
751		sheds (black), initial test areas of the RIWS (white windows).	38
752	2	Presentation of the PICH inventory and identification of in-	
753		tersections between road and river networks in the Gard region.	39
754	3	Illustration of the susceptibility sorting method applied by	
755		Versini on the 150 intersections of the initial testing areas. . .	41
756	4	Schematic representation of a watershed in the CINECAR	
757		model.	42
758	5	Distribution of the "event-specific" Nash criteria obtained at	
759		the 23 stream gauges for the validation events: A) initial ver-	
760		sion of the CINECAR model with homogeneous CN, B) CN	
761		estimated according to the USDA method, and C) introduc-	
762		tion of the diffusive wave.	43
763	6	Comparison of Cinecar and GR4 model performance at the	
764		gauged Anduze station. The magnitude of the peak discharge	
765		is indicated in the top figure.	44
766	7	Comparison between the return period ranges of the observed	
767		and simulated peak discharges. Q_X stands for the discharge	
768		quantile of return period X	45
769	8	POD, FAR and PSS values obtained for risk levels 1 and 2 . .	45
770	9	September 2007 flood. Map of the maximum forecasted risk	
771		levels and reported inundated roads.	46
772	10	October 2008 flood. Map of the maximum forecasted risk	
773		levels and reported inundated roads.	47

774	11	Box plot of PSS obtained for the risk level 2 with various sus-	
775		ceptibility model configurations: V0) without susceptibility	
776		rating, homogeneous thresholds, V1) initial susceptibility rat-	
777		ing method, V2) modified susceptibility rating method, V3)	
778		pseudo-perfect case, susceptibility determined based on the	
779		10 tested events. The box plots synthesize scores obtained for	
780		the 10 tested events. The average value is indicated by the	
781		point.	47
782	12	Comparison of the PSS distribution obtained with various	
783		rainfall-runoff model configurations for risk level 2: A) ini-	
784		tial version of the CINECAR model with homogeneous CN,	
785		B) CN estimated according to the USDA method, and C) in-	
786		troducton of the diffusive wave.	48

787 List of Tables

788	1	The set of test events for the RIWS.	40
789	2	Contingency table for the determination of inundation risk	
790		levels: 0 (no risk), 1, 2 and 3.	41
791	3	Average widths of river reaches according of their Strahler	
792		order I and return period T of the simulated stream discharge.	42

793	4	Efficiency of the various sorting methods as applied over the	
794		entire PICH inventory territory: A) reference results obtained	
795		with the initial method on the area considered by Versini, B)	
796		initial method applied to the entire PICH territory, and C)	
797		application of the method with a sub-area distinction in the	
798		PICH territory.	43
799	5	Contingency table for the evaluation of the warning system	
800		performance: <i>H</i> (Hits), <i>M</i> (Misses), <i>Fa</i> (False Alarms), and	
801		<i>Cn</i> (Correct negatives).	44
802	6	Proportion of PICH points among intersections identified in	
803		the recent event-specific reports of road disruptions (conducted	
804		since 2002), in areas where the PICH inventory is available. . .	48

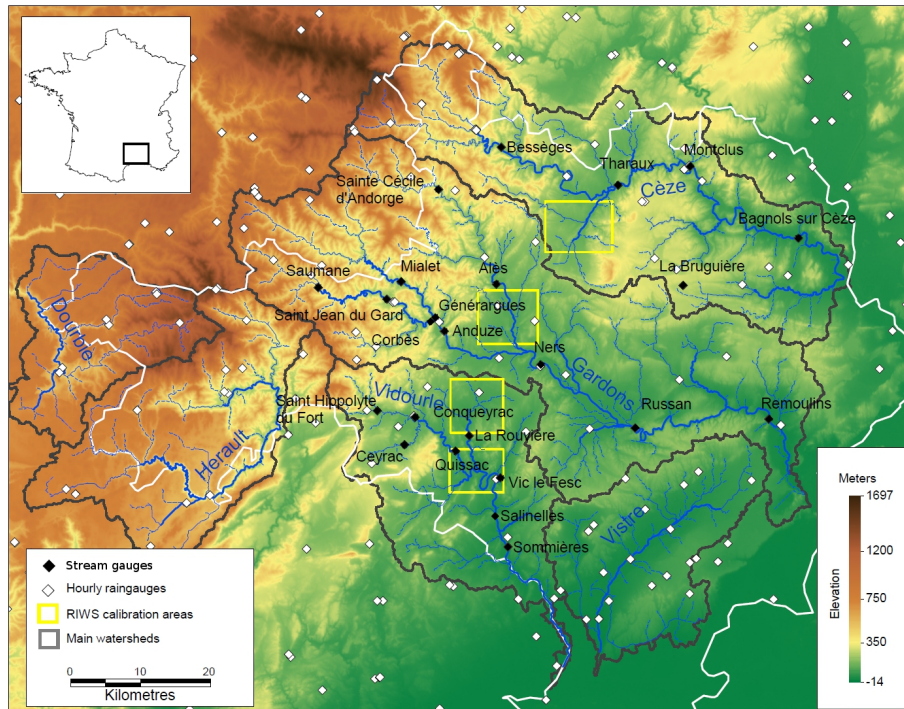


Figure 1: Gard department (shown in white), main streams and watersheds (black), initial test areas of the RIWS (white windows).

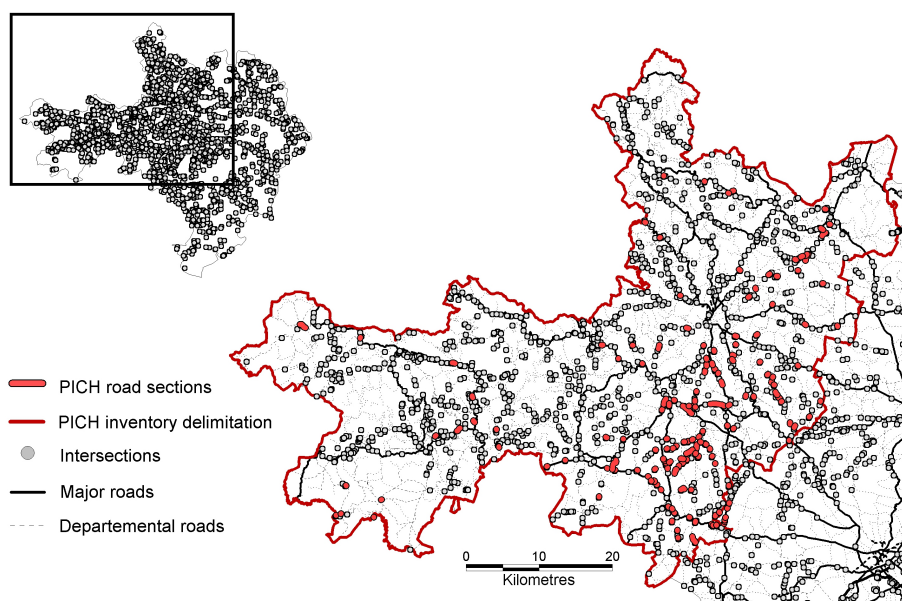


Figure 2: Presentation of the PICH inventory and identification of intersections between road and river networks in the Gard region.

Table 1: The set of test events for the RIWS.

Dates of events	Event	max	%	Nb.
	dura- tion (days)	rain- fall (mm)	area > 200 mm	flooded roads
08-10/09/2002	3	679	74	367
01-04/12/2003	4	380	61	112
02-05/11/2004	4	139	0	11
04-12/09/2005	6	403	76	198
29-30/09/2007	2	204	0	26
19-23/11/2007	5	293	13	14
16-19/09/2007	4	62	0	0
03-11/10/2007	8	100	0	0
06-12/12/2007	7	70	0	0
01-07/09/2008	7	100	0	0
10-15/09/2008	6	60	0	0
07-10/10/2008	4	110	0	0
19-22/10/2008	4	497	15	18
01-02/11/2008	2	514	17	19
10-13/11/2008	4	50	0	0
13-15/12/2008	3	114	0	32
29-31/12/2008	3	218	0.5	54

Table 2: Contingency table for the determination of inundation risk levels: 0 (no risk), 1, 2 and 3.

Susceptibility	Discharge return period (years)				
	0.5	1	10	50	
High	0	2	3	3	3
Medium	0	1	2	3	3
Low	0	0	1	2	3
Very low	0	0	0	0	1

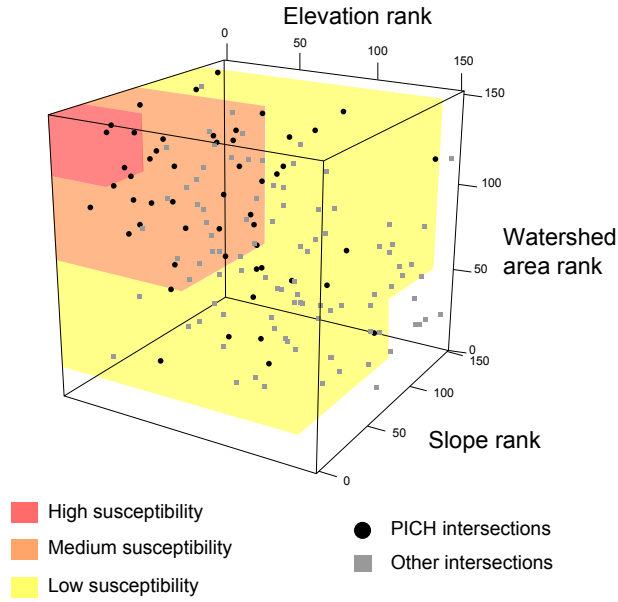


Figure 3: Illustration of the susceptibility sorting method applied by Versini on the 150 intersections of the initial testing areas.

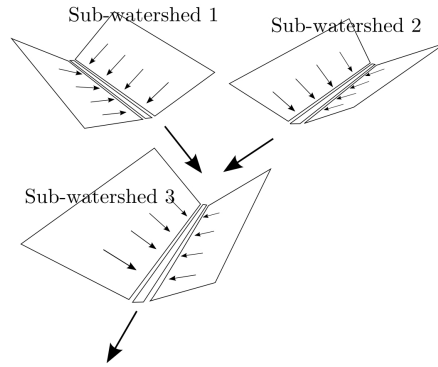


Figure 4: Schematic representation of a watershed in the CINECAR model.

Table 3: Average widths of river reaches according of their Strahler order I and return period T of the simulated stream discharge.

Return period of the discharge Q	Width of the stream (m)				
	I=1	I=2	I=3	I=4	I=5
$Q < Q_2$	4	16	36	64	100
$Q_2 < Q < Q_{10}$	8	32	72	128	200
$Q > Q_{10}$	12	48	108	192	300

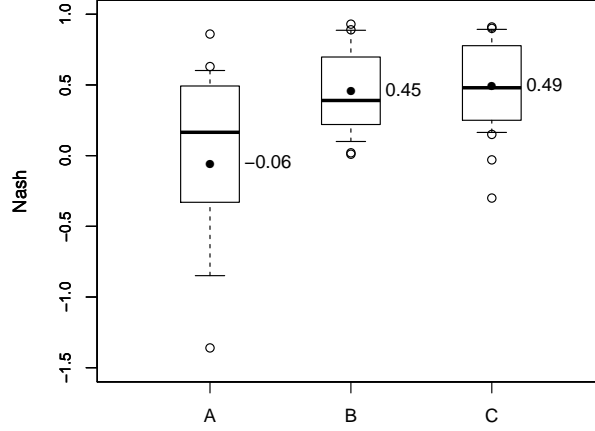


Figure 5: Distribution of the "event-specific" Nash criteria obtained at the 23 stream gauges for the validation events: A) initial version of the CINECAR model with homogeneous CN, B) CN estimated according to the USDA method, and C) introduction of the diffusive wave.

Table 4: Efficiency of the various sorting methods as applied over the entire PICH inventory territory: A) reference results obtained with the initial method on the area considered by Versini, B) initial method applied to the entire PICH territory, and C) application of the method with a sub-area distinction in the PICH territory.

	Susceptibility method	Susceptibility class			
		High	Average	Low	Very low
Distribution of intersections between the susceptibility classes	A	0%	17%	58%	25%
	B	4.5%	9.9%	67.4%	18.3%
	C	6.2%	15.6%	53.3%	24.2%
Proportion of PICH points in each susceptibility class	A	100%	60%	37%	0%
	B	37.7%	25.4%	6.2%	0%
	C	40.1%	23.5%	4%	0%

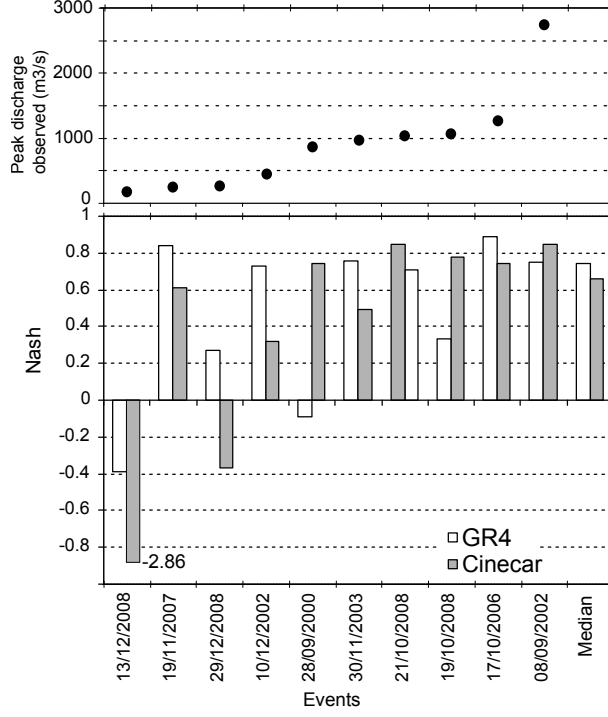


Figure 6: Comparison of Cinecar and GR4 model performance at the gauged Anduze station. The magnitude of the peak discharge is indicated in the top figure.

Table 5: Contingency table for the evaluation of the warning system performance: H (Hits), M (Misses), Fa (False Alarms), and Cn (Correct negatives).

		Reported flooding	
		Yes	No
Risk level reached	Yes	H	Fa
	No	M	Cn

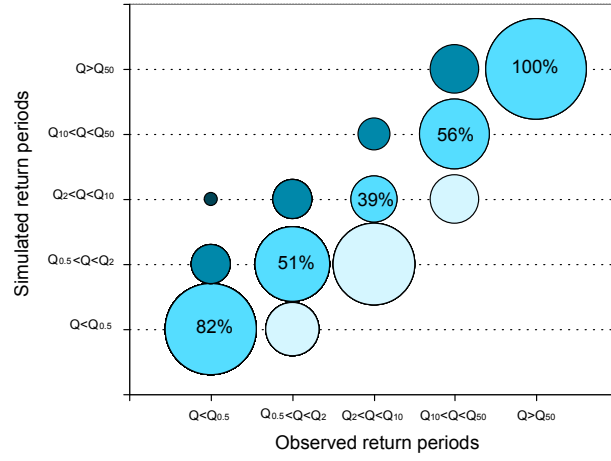


Figure 7: Comparison between the return period ranges of the observed and simulated peak discharges. Q_X stands for the discharge quantile of return period X .

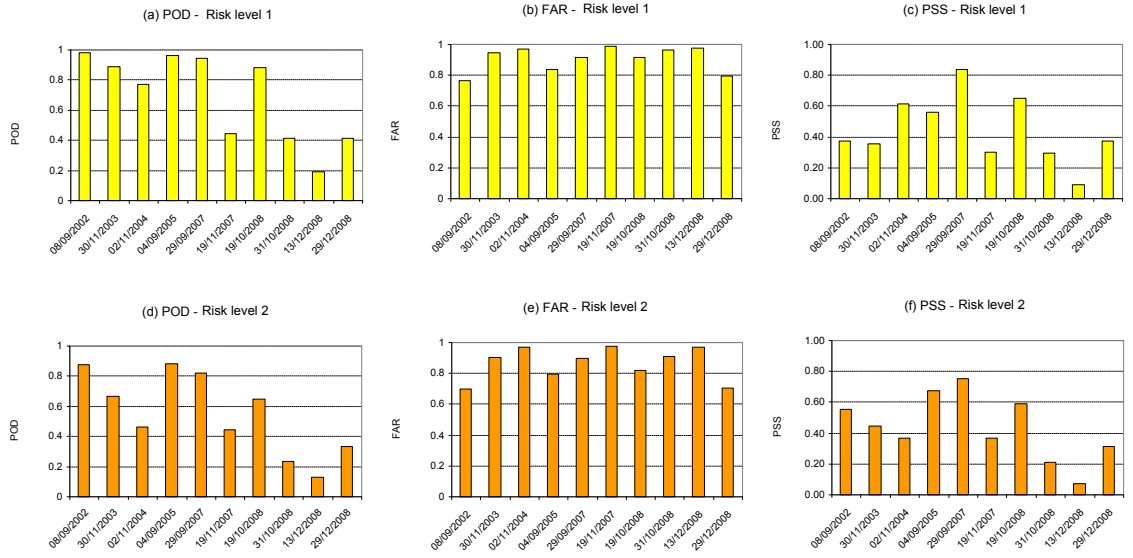


Figure 8: POD, FAR and PSS values obtained for risk levels 1 and 2

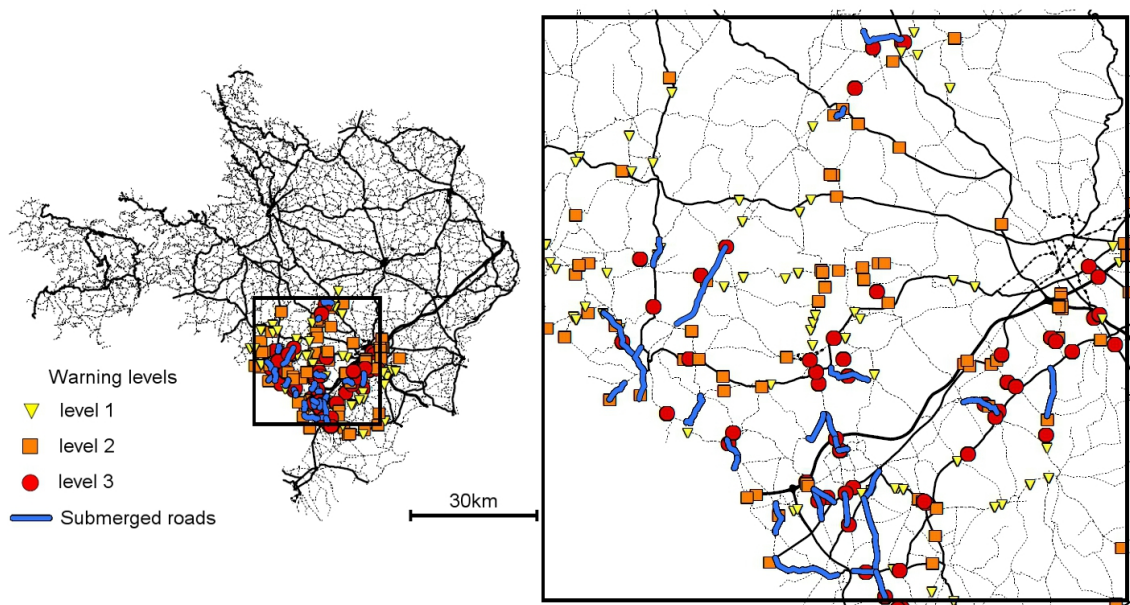


Figure 9: September 2007 flood. Map of the maximum forecasted risk levels and reported inundated roads.

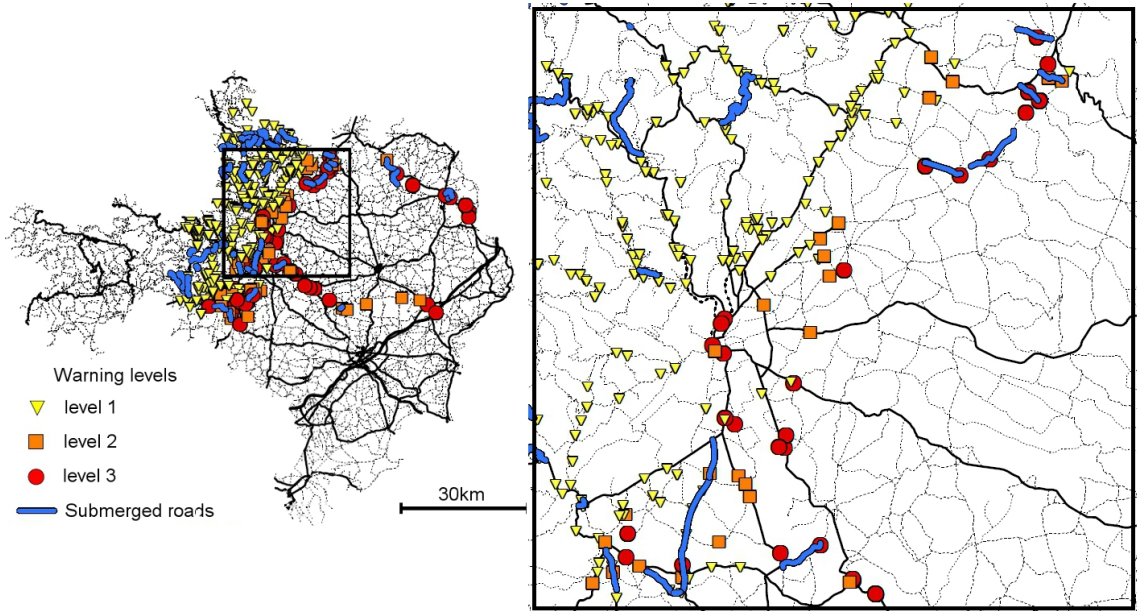


Figure 10: October 2008 flood. Map of the maximum forecasted risk levels and reported inundated roads.

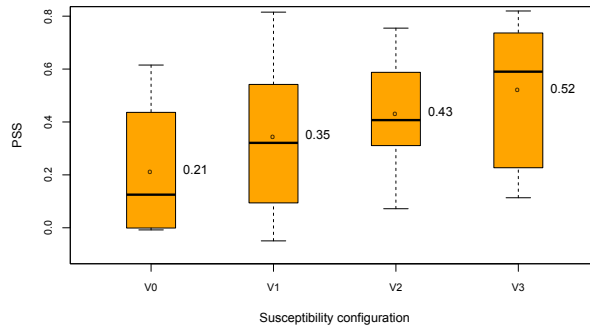


Figure 11: Box plot of PSS obtained for the risk level 2 with various susceptibility model configurations: V0) without susceptibility rating, homogeneous thresholds, V1) initial susceptibility rating method, V2) modified susceptibility rating method, V3) pseudo-perfect case, susceptibility determined based on the 10 tested events. The box plots synthesize scores obtained for the 10 tested events. The average value is indicated by the point.

Table 6: Proportion of PICH points among intersections identified in the recent event-specific reports of road disruptions (conducted since 2002), in areas where the PICH inventory is available.

Number of inundations	Non PICH	PICH
1	189	32
2	26	25
3	6	13
4	6	5
5	1	4
6	0	1
7	0	1
Total	228	81

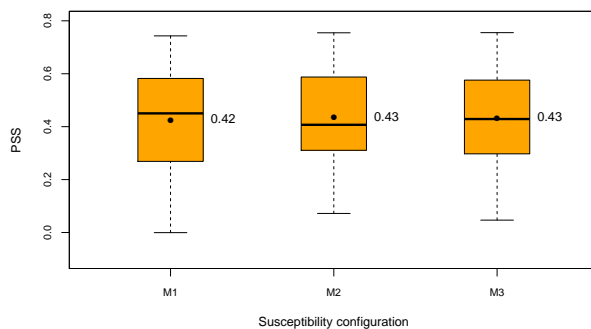


Figure 12: Comparison of the PSS distribution obtained with various rainfall-runoff model configurations for risk level 2: A) initial version of the CINECAR model with homogeneous CN, B) CN estimated according to the USDA method, and C) introduction of the diffusive wave.