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1 NRCS-CN ESTIMATION FROM ON-SITE AND REMOTE
2 SENSING DATA FOR THE MANAGEMENT OF A RESERVOIR
3 IN THE EASTERN PYRENEES

4
5 Marcos Sanz-Ramos^{1*}, Belén Martí-Cardona², Ernest Bladé³, Irene Seco⁴, Arnau
6 Amengual⁵, Hélène Roux⁶, Romu Romero⁷

7
8 ¹Institut Flumen, Universitat Politècnica de Catalunya – International Center for Numerical Methods in
9 Engineering, Barcelona, Spain – E-mail: marcos.sanz-ramos@upc.edu; ORCID: <https://orcid.org/0000-0003-2534-0039>

10
11 ²Department of Civil and Environmental Engineering, University of Surrey, U.K. – E-Mail: b.marti-
12 cardona@surrey.ac.uk; ORCID: <https://orcid.org/0000-0001-7519-1399>

13 ³Institut Flumen, Universitat Politècnica de Catalunya – International Center for Numerical Methods in
14 Engineering, Barcelona, Spain – E-mail: ernest.blade@upc.edu; ORCID: <https://orcid.org/0000-0003-1770-3960>

15
16 ⁴Institut Flumen, Universitat Politècnica de Catalunya – International Center for Numerical Methods in
17 Engineering, Barcelona, Spain – E-mail: irene.seco@upc.edu; ORCID: <https://orcid.org/0000-0003-0541-2605>

18 ⁵Grup de Meteorologia, Departament de Física, Universitat de les Illes Balears, Palma, Mallorca, Spain – E-
19 mail: arnau.amengual@uib.es; ORCID: <https://orcid.org/0000-0002-6108-2850>

20 ⁶Université de Toulouse, CNRS - Toulouse, France – E-mail: helene.roux@imft.fr; ORCID:
21 <https://orcid.org/0000-0001-7076-5015>

22 ⁷Grup de Meteorologia, Departament de Física, Universitat de les Illes Balears, Palma, Mallorca, Spain – E-
23 mail: romu.romero@uib.es; ORCID: <https://orcid.org/0000-0002-9091-8688>

24
25 *Corresponding author: marcos.sanz-ramos@upc.edu

26
27 **ABSTRACT**

28 On-site and Earth observation (EO) data are used for the calibration of the Natural
29 Resources Conservation Service-Curve Number (NRCS-CN) value in a hydrological simulation
30 model. The model was developed for La Muga catchment (Eastern Pyrenees) highly vulnerable
31 to flood and drought episodes. It is an integral part of a regional reservoir management tool,
32 which aims at minimizing the flood risk, while maximizing the preservation of water storage. The
33 CN values were optimized for five recorded events for the model to match the observed
34 hydrographs at the reservoir, when supported with the measured rainfall intensities. This study
35 also investigates the possibilities of using antecedent moisture conditions (AMC) retrieved from
36 satellite data to inform the selection of the NRCS-CN losses parameter. A good correlation was
37 found between the calibrated CN values and the AMC obtained from satellite data. This
38 correlation highlights the interest in using EO data to update NRCS-CN estimates. This advances
39 in hydrologic-hydraulic coupled modelling combined with new remote sensing datasets present
40 valuable opportunities and potential benefits for flood risk management and water resources
41 preservation.

42
43
44 **Key words:** NRCS-CN, remote sensing, flood risk, reservoir management, hydrological
45 distributed modelling, antecedent moisture condition (AMC), Mediterranean region.

47 1. INTRODUCTION

48 Droughts and floods are recurrent situations in Mediterranean catchments. In this semi-
49 arid region, streams are characterized by intermittent flows due to the irregularity of rainfall and
50 to the seasonal temperature variability. In a large portion of the Mediterranean region, the
51 highly-urbanized areas and the population seasonality due to tourism, increase the water
52 demands and at the same time the flood risk. Periods of water scarcity alternate with periods of
53 frequent flooding that are becoming more severe under the influence of climate change (Arnell
54 1999; IPCC 2014a; Lehner et al. 2006). The management of water resources in these water-
55 stressed areas is therefore complex.

56 Floods are the most catastrophic natural hazard around the world (Fonseca et al. 2018;
57 ISDR 2009; Kron 2005). In the Mediterranean region, according to the EM-DAT (2019) Disaster
58 Database, floods are around 30 % of the natural disasters that occurred in the 20th century. On
59 the other hand, droughts are a cyclic phenomenon in the Mediterranean region. Their
60 management is a challenge for water administrations, especially during the summer season with
61 its higher demand for water resources. The vulnerability of the Mediterranean area to droughts
62 and floods is continually increasing due to the high economic dependency on water resources
63 and to the possible consequences of climate change (GECCC 2016; IPCC 2014b).

64 In this context, dams and reservoirs are essential elements for providing protection
65 against flooding and ensuring the water supply year-round. The complexity of water resources
66 and dam management requires the integration of several disciplines (meteorology, hydrology,
67 hydraulics, etc.) and a deep knowledge of the system characteristics (catchment), inputs
68 (rainfall) and outputs (demands). The use of realistic modelling that considers all these factors
69 can lead to more effective predictions and more effective hazard mitigation.

70 At present, several modelling tools integrate two-dimensional hydraulic modelling with
71 distributed hydrological modelling (Anees et al. 2017; Caro 2016; Cea et al. 2010; Kim et al. 2012;

72 Roux et al. 2011; Viero et al. 2014; Yu and Duan 2017). Integrated or coupled modelling can
73 better represent the real hydrologic and hydraulic processes than using these models
74 independently. Nevertheless, models depend on a large number of parameters (e.g. soil and
75 land characteristics, underground fluxes, etc.) as well as on expertise in their implementation
76 for risk and water resources management applications. The calibration and use of these tools
77 can be complex, as the number of the required parameters depends often on limited data or on
78 data with inadequate quality, and are not always directly physically measurable.

79 In this context, this paper first presents the results of the implementation and calibration
80 of a coupled hydrological and hydraulic model. This model was used as a tool to define and
81 implement management strategies for the Boadella Dam, located in the upper part of La Muga
82 catchment (NE of Spain). This model belongs to a series of methods developed under the PGRI-
83 EPM project (*Forecasting and management of flood risk in the Pyrenees-Mediterranean*
84 *Euroregion*) for the operational management of reservoirs in the region (Roux et al. 2020; Sanz-
85 Ramos et al. 2018). The designed management method is mainly based on modelling in a
86 cascade of the involved processes (short-term precipitation forecast and coupled hydrologic and
87 hydraulic processes). The objective is to minimize the flood risk and, at the same time, to
88 maximize the preservation of water resources during the management of extreme events.

89 The main factors that influence flood generation are related with the rainfall
90 characteristics and the physical and hydrological characteristics of the catchment. The losses,
91 mainly by infiltration and interception, are a determining factor in the rainfall-runoff
92 transformation process. One of the most extended methods for losses estimation is the Soil
93 Conservation Service Curve Number method (SCS-CN; NRCS 2004), also referred as the NRCS-
94 CN method after the Agency was renamed as the Natural Resources Conservation Service. The
95 fact that requires only one parameter for modelling losses has contributed to its success. In the
96 NRCS-CN method, the Curve Number parameter (CN), although not physically-based, is a

97 quantitative descriptor which embodies the complex physical characteristics of the soil type,
98 antecedent soil moisture conditions (AMC), and land use and cover (LULC) in a catchment.
99 Hence, a proper choice of the CN value is essential to achieve realistic rainfall-runoff simulations.

100 The determination of the AMC and thus of the CN value can be improved with the use of
101 remote sensing techniques. These techniques provide spatially distributed retrievals for a wide
102 variety of hydrological parameters (Estévez et al. 2014; Marti-Cardona et al. 2013; Martí-
103 Cardona et al. 2010; Ramos-Fuertes et al. 2013; Torres-Batló et al. 2019; Wu et al. 2018),
104 including surface soil moisture (SM). Also, remote sensing is a powerful tool for the observation
105 of the hydrological processes and a relevant source of information for the calibration of
106 numerical models describing such processes (Li et al. 2019; Ramos-Fuertes et al. 2013). The
107 hydrological modelling community is progressively benefiting from the incorporation of spatial
108 soil moisture measurements, with a varied degree of success (Brocca et al. 2017). Remote
109 sensing has been used for indirect estimation of the CN value by obtaining land use information
110 from satellite images (Tirkey et al. 2014), but also for the adjustment of loss parameters
111 (Silvestro et al. 2015). Rajib et al. (2016) explored the usage of spatially distributed remotely
112 sensed soil moisture in the calibration of a hydrological model.

113 Against this background, this work aims at showing the relevance of remote sensed soil
114 moisture data for the CN estimation within a coupled distributed hydrologic-hydraulic model
115 procedure oriented at water reservoir management. This main objective is achieved through
116 three secondary goals applied on a case study: (i) set up and calibration of the hydrological
117 model; (ii) analysis of the variability of the CN within several registered events and (iii)
118 identification of a relationship between the calibrated CN values and the estimated SM data
119 from EO. The application of this technique in the study case is intended to provide better
120 information for integrated flood risk and water resources management in continuous modelling.

121 2. STUDY AREA

122 2.1. SITE AND CATCHMENT CHARACTERISTICS

123 La Muga is a cross-border basin of 961 km² located at the northeast of Catalonia
124 (northeast Spain) that drains from the south-east Pyrenees to the Mediterranean Sea (Fig. 1a).
125 The basin is partially regulated by the Boadella Dam (182 km²), at the upper-part of the
126 catchment, with 62 hm³ of storage and a regulating capacity of 15 hm³. The basin, which includes
127 some highly developed tourist areas at its lower part (Costa Brava), is highly vulnerable to
128 drought due to excessive water demand (agriculture and human consumption) and to flooding
129 (ACA 2007).

130 The topography of the study area ranges from mountains to lowlands (Fig. 1a) and the
131 rainfall regime in the catchment is significantly influenced by the Mediterranean Sea. The
132 average annual rainfall ranges from 550 mm near the coast to 1200 mm in the upper part. Heavy
133 rainfall episodes tend to concentrate in late summer, autumn and spring, lasting from several
134 hours up to a few days. The variable rainfall frequency and long dry periods cause the area to
135 suffer from severe water scarcity (Llasat and Rodriguez 1992; Martín-Vide 1994).

136 This work focuses on the upper part of La Muga basin, upstream of the Boadella Dam,
137 where there is a single rainfall gauge and one water level gauge (Fig. 1a). The study area has an
138 extension of 181 km² and is mainly characterized by large-forest coverage (above 90 %, Fig. 1b),
139 low permeability and low ground storage capacity (ACA 2007). The reservoir is included in the
140 hydrological analysis and modelling, and it has been calibrated with the measures of water level
141 and their variations during extreme rainfall events.

142 2.2. DATA SET

143 Rainfall and water level

144 A detailed analysis of extreme rainfall events was performed within the PGRI-EPM project
145 (Sanz-Ramos et al. 2018) through which more than 60 significant rainfall episodes registered
146 during the last 100 years were evaluated. From the results of that analysis, five extreme rainfall

147 events were selected for calibration of the proposed model (Table 1). The selected events,
148 occurred between March 2011 and March 2015, are labelled with the starting date and the
149 duration in days. The selected episodes have all mean rainfall intensities above 20 mm/h in
150 5 minutes, and total precipitation volumes over 120 mm in periods between 2 and 4 days.

151 The data of precipitation and water level in the reservoir were provided by the Servei
152 Meteorològic de Catalunya (SMC) and the Agència Catalana de l'Aigua (ACA) respectively. They
153 consisted of 5-minute hyetographs recorded at the Boadella dam station; rasters of 1x1 km
154 spatially distributed hourly rainfall derived from radar (Bech et al. 2005; Corral et al. 2009); and
155 the evolution of the water level in the reservoir (5-minute resolution).

156 Digital terrain model (DTM) and land uses

157 Topographical data were derived from a high-resolution 2x2 m DTM provided by the
158 Institut Cartogràfic i Geològic de Catalunya (ICGC). The DTM includes the bathymetry of the
159 reservoir above 145.0 m.a.s.l. (below the minimum water level during the events).

160 Land use data, obtained from the CORINE project (EEA 2007), was used for the
161 implementation of the surface roughness coefficient (n Manning coefficient). Additional details
162 regarding these data can be found in Table 2.

163 Soil Moisture Data

164 Soil moisture data were obtained from the European Space Agency Climate Change
165 Initiative for Soil Moisture (ESA CCI SM) (Liu et al. 2011, 2012; Wagner et al. 2012). The combined
166 product version 4.2 (ESA et al. 2018) was obtained for the periods covering the selected rainfall
167 events and for some days prior to their onset, with a maximum of 50 days. The product consists
168 of daily rasters of volumetric soil moisture for the soil's top 20 mm. The rasters are provided
169 with a spatial resolution of 0.25° degrees, which for the study area corresponds to
170 approximately 27.5 km.

171 La Muga catchment is encompassed by two resolution cells of the ESA CCI SM product.
172 85 % of the catchment area overlays a raster cell entirely located on the southern Pyrenees,
173 while the remaining 15 % falls within a cell mainly covering the northern Pyrenean side. Moisture
174 data from both cells exhibit a markedly distinctive behavior, as expected from the different
175 precipitation regimes on either side of the mountain range. Since the study catchment belongs
176 to the southern Pyrenees, only the ESA CCI SM moisture records from the southern cell were
177 used, assuming that they would better represent the catchment moisture status than a
178 weighted average of both cells.

179 3. METHODS

180 The cascade workflow presented herein is as follows: 1) building-up a coupled
181 hydrological-hydraulic numerical model balancing the computational cost and the results
182 accuracy; 2) calibrating the numerical model (CN and n) with on-site data, first with rain gauges
183 and then fine-tuning with radar data; and 3) relating the CN values with EO data (SM) aiming to
184 obtain the information needed to continuously support the numerical model for the reservoir
185 management in future events.

186 3.1. NUMERICAL MODEL

187 The coupled distributed hydrological and hydraulic numerical tool Iber (Bladé et al. 2014b;
188 Cea and Bladé 2015) was used for both rainfall-runoff transformation and flow characterization.
189 Iber is based on the dynamic wave solution of the Shallow Water Equations (SWE) with the finite
190 volume method (Cea et al. 2016; Toro 2009), and it includes a specific numerical scheme for
191 overland flow named Decoupled Hydrologic Discretization, DHD (Cea and Bladé 2015). After it
192 was released in 2010, Iber has undergone several improvements. These enhancements allow
193 the model to consider precipitation and losses varying in time and space and improved mesh
194 definition for very shallow flows (i.e. a *fill-sinks-option*) (Bladé et al. 2014a; Caro 2016; Cea et al.
195 2015; Cea and Bladé 2015; Juárez D. et al. 2014).

196 Additionally, Iber implements a specific drying method for hydrological computations,
197 which handling the transition from wet to dry conditions, and vice versa. Briefly, a wet-dry limit
198 (ϵ_{wd}) is used to define the water depth threshold below which a cell is considered to be dry. For
199 drying cells, the scheme uses an adaptation to finite volume numerical schemes of the method
200 used in LISFLOOD (Bates and De Roo 2000), in order to guarantee mass conservation. This
201 method reduces numerical instabilities during simulation and ensures that all mesh cells have a
202 zero or positive depth.

203 3.2. MODEL SETUP

204 The study area was spatially discretized using an irregular triangular mesh of
205 approximately 50,000 elements of area from 150 m² (in rivers) up to 200,000 m² (in hillslopes)
206 (Fig. 2). This discretization is a compromise between accuracy of the results and computational
207 time. The DTM was treated using a *Fill sinks* algorithm, based on the algorithm proposed by
208 Wang and Liu (2006) to ensure a good definition of the flow path removing unreal depressions
209 (Fig. 2). The DHD scheme was used with a wet-dry limit threshold of 10⁻⁴ m.

210 The current set-up configuration allowed the simulation of events that last from 2 to 4
211 days with a computational time between 1 and 3 hours using 1 CPU core (i7 fourth generation
212 to 3.5 GHz). It is worth mentioning that after the end of the project there have been substantial
213 improvements in the computational time of Iber by using Graphics Processing Unit (GPU)
214 computing techniques (García-Feal et al. 2018). With this novelty, the presented simulations
215 would run in about 1 minute, achieving speed-up up to 100.

216 There is only one initial condition imposed to the model which is the water level in the
217 reservoir at the beginning of the simulation events. The river was assumed to be dry at the
218 beginning of the simulations, which is an acceptable assumption as normal discharges are
219 negligible when compared with flood discharges. No boundary conditions were imposed as
220 there are no streams flowing into the study area. Rainfall intensities were applied on the

221 corresponding mesh element. Manning coefficients (n) were associated with each element,
222 based on their land use according to the CORINE map (EEA 2007) (Fig. 1b).

223 The NRCS-CN method was used to evaluate the losses in the rainfall-runoff process. For
224 its application, the initial abstraction (I_a) was linked to the soil potential retention (S) through a
225 0.2 factor ($I_a = 0.2 \cdot S$) as proposed by USDA (1986) and Ponce and Hawkins (1996). Due to the
226 homogeneity of the land uses, soil type and AMC conditions in the study site, where over 90 %
227 of the area corresponds to forest coverage (Fig. 1b), a single value of CN was used for the whole
228 basin. The value of CN was later adjusted within the calibration process.

229 3.3. RELATING CN TO EARTH OBSERVATION SOIL MOISTURE DATA

230 ESA CCI SM data provide information of the soil moisture in the top 20 mm layer of the
231 soil. These measurements are well-correlated with previous rainfall days but might not be
232 representative of the AMC, which have a relevant influence on the CN value. In this study, it was
233 assumed that the evolution of daily surface moisture over several days before the onset of the
234 rainfall event could inform of the water content in deeper soil layers, and hence it could be used
235 as a proxy of the AMC and CN. In order to explore this relationship, daily SM values were
236 averaged for periods ranging from 2 to 40 days before the beginning of the analyzed rainfall
237 event. Then, a correlation between the averaged SM and the calibrated CN values was
238 established.

239 4. RESULTS AND DISCUSSION

240 4.1. HYDROLOGICAL MODELLING AND CALIBRATION STRATEGY

241 The purpose of the calibration process is the adjustment of the values of CN and the
242 terrain roughness (n). The CN mainly influences on the mass balance of the whole event, while
243 the n coefficient is expected to have an effect on the water front propagation and the water
244 elevation evolution.

245 A sensitivity analysis of the Manning's roughness coefficient was carried out. The
246 reference values for the n coefficients were determined following the recommendations from

247 the USGS Guide (Arcement and Schneider 1989). A 0.11 value of n was assumed for the dense
248 forest land use that represents around 75 % of the study area (Fig. 1b). As a result of the analysis,
249 no significant influence on the model response in terms of water front and water elevation in
250 the reservoir was observed under n variations in a range of ± 20 %. Hence, it is assumed that CN
251 is the main calibration parameter. Results obtained by using the dense forest land use data for
252 the n sensitivity analysis are shown in Fig. 3.

253 The CN was adjusted during calibration process to properly represent the evolution of the
254 water stored in the reservoir during the events. For events 20110313_4d and 20130304_3d, rain
255 data were available only from the rain gauge source. For events 20131116_3d, 20141129_2d
256 and 20150320_3d, both data from rain gauges and radar were available and used in the
257 calibration process. For these last three events, the gauge data are used for a first estimation of
258 the CN value and what we called CN_{rg} . This value of CN was later fine-tuned with the radar
259 information calling it CN_r .

260 Table 3 shows the CN value that best fit for all five events taking into account each data
261 source. A seasonal trend could be inferred from these values, with higher values of CN during
262 spring and moderate during autumn, though the number of events is not large enough to take
263 more quantitative conclusions of seasonal variations.

264 In the study area, there are two alternative sources of information for the CN values:
265 CEDEX (2003) and ACA (2019). Both are georeferenced databases available online and provide
266 values of the initial abstraction from which the value of CN can be derived. According to CEDEX
267 the mean CN value for the study area is 64.9 ± 7.6 (standard deviation) while according to ACA
268 it is 62.0 ± 12.8 under so-called normal catchment conditions (neither *wet* nor *dry*). If possible
269 variations due to AMC are considered according to NRCS (2004), the CN values can be updated
270 and varies in a range from 44.5 to 81.1 (initial CN from CEDEX database) and from 41.5 to 79.1
271 from ACA information. Thus, the CN values obtained from the calibration process for this study

272 area and rainfall events are within the limits of values that would be obtained from these data
273 provided by the public administration. However, it should be noted that the CN values provided
274 by the mentioned public entities may be based on an outdated topographic base (Campón et al.
275 2015). Thus, the values that can be obtained by an ad-hoc calibration using hydrological models
276 and real rainfall data should generally provide more representative values of CN.

277 Table 4 shows the total cumulated rainfall and the effective rainfall for each event from
278 rain gauge data and radar data. For the events 20131116_3d, 20141129_2d and 20150320_3d,
279 with radar dataset available, significant differences between the effective rainfall derived from
280 gauge data and from radar were observed. The gauge station registered higher cumulative
281 rainfall than values obtained from the radar source. Thus, in general, the estimated CN_{rg} is
282 smaller than the CN_r in order to reach the same water level in the reservoir. For events
283 20131116_3d and 20141129_2d, the differences between this two CN values can be considered
284 reasonable. However, for the event 20150320_3d, this difference is significant (Table 3).
285 Regarding this, it can be hypothesized that there may have been a highly non-uniformly
286 distributed rainfall. The gauge station probably registered high intensities locally concentrated
287 around the gage's location, which were not representative of the global rain pattern in the
288 catchment during the event. This situation can be corroborated from radar data which are
289 analyzed below.

290 The total rainfall cumulated at the end of the events 20131116_3d, 20141129_2d and
291 20150320_3d is also represented in Fig. 4. The non-uniformity is easily observable in the rainfall
292 spatial distribution recorded by the radar. For the event 20131116_3d, the maximum cumulated
293 precipitation registered by the gage (123 mm) is close to the radar maximum (120 mm).
294 However, this value is observed only locally at the south of the study area, and the average rain
295 depth is lower for the radar source than from the gauge source. For this reason, the CN_r is higher
296 than the CN_{rg} . For the event 20141129_2d, the distribution of radar rainfall shows high

297 accumulations at the east part of the study area (205 mm). However, the average values from
298 gauge and radar are very similar (slightly higher for the rain gauge). Thus, the CN_r for this event
299 is also slightly higher than CN_{rg} . Finally, for the event 20150320_3d the differences are the
300 largest. In this case, the cumulated rainfall from the raingauge source is 200 mm while the radar
301 does not exceed 80 mm (average value). As mentioned before, a high local rainfall was
302 registered by the rainfall station, which is not representative of the rainfall pattern in the basin,
303 which in turn could explain the large differences between the CN_{rg} and the CN_r .

304 Based on what has been observed so far, the calibration process therefore focused on the
305 adjustment of the CN value. The CNs finally selected by event showed in Table 3 were a
306 combination of the calibration process according to the best statistical fitting (Table 5). Thus,
307 the CNs value derived from the calibration process ($CN_{selected}$) range between 55 and 94 (Table
308 3).

309 For the assessment of the fitting between observed and simulated results (water level at
310 the dam) several indicators were used: mean absolute error (MAE); root mean square error
311 (RMSE); and Nash-Sutcliffe model efficiency coefficient (NSE) (Nash and Sutcliffe 1970). Table 5
312 summarizes the performance of the model for both rainfall data sources by event. In general,
313 the simulations performed from radar (r) source data produce a better fit than those obtained
314 with the gauge (rg) data in terms of water front evolution. This statement can be seen in Table
315 5 through the smallest mean differences (MAE and RMSE) and highest values of NSE.

316 Fig. 5 shows the performance of the model for both rain sources with the selected CN
317 value. Events 20110313_4d and 20130304_3d, calibrated with rain gauge data, shown in general
318 a good performance. The modelled water level rise in the reservoir is slightly delayed with
319 respect to the observed data, and the water level at the end of the event was slightly higher
320 than the observed one. A slightly overestimation of the water level was observed at the end of
321 events 20131116_3d and 20141129_2d. For the event 20150320_3d instead, the water level

322 obtained from the rain gauge data rapidly increase exceeding the capacity of the reservoir
323 (160 m.a.s.l), far from the prediction made with radar data. Regarding the inconsistencies using
324 gage data in this last analyzed event, we refer to the non-uniform spatial distribution of the
325 rainfall that may explain this result as was previously explained.

326 It can be seen then that the availability of radar rainfall data can help to improve the
327 hydrological model results since timely rainfall measurements, provided by a rainfall station,
328 might be not enough representative of the complex spatial rainfall variation at the catchment
329 scale. Moreover, rainfall data obtained from radar have a much higher spatial resolution (1 km²
330 in this case) which allow a better spatial representation when modelling.

331 Table 6 shows the results of the mass balance in the reservoir through the differences
332 between observed data and simulation results. The differences in water level (WL_{start} and WL_{end})
333 and stored volume (V_{start} and V_{end}) at the start and end of the simulation period are shown for
334 all the events. In general, good agreement between both observed and simulated results for the
335 simulations performed with either data from the station or radar sources are observed.
336 However, a significant difference is predicted for the event 20150320_3d. For this last event a
337 252 % difference in stored volume can be observed from the simulations carried out using gauge
338 data. As previously hypothesized, significant differences observed using raingauge data could be
339 generated due to high localized rainfall near the gauge location.

340 For event 20110313_4d, the obtained CN value is close to the highest value of the
341 parameter, which would imply that the losses are minimal. This unusually high value can be
342 explained by two possible reasons: 1) the limitations of working with only one gauge and 2)
343 possible errors in the water level records in the reservoir (the water evolution during the days
344 before the event or the lack of data). With respect to the first cause suggested, from the Fig. 5
345 (Event 20110313_4d, dotted line) the water level in the reservoir increases during the first
346 period while there is no rainfall registered by the gauge. This means that either it could have

347 rained heavily during the previous days, or there was rain in some parts of the basin that was
348 not registered by the gauge. Additionally, some errors (lack of data and sudden steps) were
349 detected on the water level records registered in the reservoir. It should be noted that the initial
350 water level was 151 m (constant value during the firsts 3 hours of the simulation period) while
351 after 10 min it increased to 152 m. This difference means 2.67 hm³ in terms of water volume in
352 the reservoir, which is around 12 % of the volume stored during the event. These considerations
353 are presented here as possible reasons that explain the high value for the CN calibrated for this
354 episode.

355 On the other hand, the estimated CN for the event 20130304_3d is 81 also using rain
356 gauge data. As shown in Fig. 5, the delay in the arrival time of the water front into the reservoir
357 is approximately 10 h, but there is a good adjustment in terms of water levels after that. For the
358 mentioned episode, the difference in water level in the reservoir at the end of the episode is
359 lower than 0.03 m.

360 4.2. RELATIONSHIP BETWEEN EARTH OBSERVATION BASED SOIL MOISTURE DATA AND 361 CURVE NUMBER

362 Fig. 6 illustrates the relationship between the five calibrated CNs and the daily EO surface
363 moisture values averaged for different periods prior to the five rainfall events. For clarity, not all
364 analyzed periods are represented in Fig. 6. As the number of averaged days approaches 16, the
365 relationship between CN and the averaged SM converges to a clear linear trend.

366 Fig. 7 depicts the squared linear correlation coefficient between CN and the averaged
367 surface moisture for all analyzed averaging periods and rainfall events. The best fit is achieved
368 when 16 days prior to the rainfall onset are averaged, yielding a high R² value of 0.96. The clear
369 consistency in the correlation coefficient changes as the antecedent period is varied reinforces
370 the validity of this result.

371 The presented relationship between CN and EO based on surface moisture has been
372 obtained for five rainfall events modelled in the small Boadella reservoir catchment. Despite the

373 limited representativeness of the presented case, the quality and consistency of the relationship
374 strongly suggests the potential of EO data to provide updated estimates of the CN value. The
375 accuracy in the estimation of this parameter has crucial implications in the volumes of runoff
376 predicted by hydrological models and, hence, in the flood prevention measures taken by water
377 resources managers.

378 4.3. DISCUSSION: IMPACT OF FLOODING AND POTENTIAL BENEFITS OF MERGING REMOTE 379 SENSING DATA IN WATER RESOURCES MANAGEMENT DECISION SUPPORT SYSTEMS

380 Among the five events presented herein, the events 20110313_4d and 20130304_3d
381 were the ones that caused more flood damages from an economic point of view. The economic
382 evaluation of the flood risk associated to the released discharges, and of the water resources
383 lost or preserved after the extreme rainfall episodes, are part of the outputs of the system
384 developed under the PGRI-EPM project for the operational management of reservoirs in the
385 region (Sanz-Ramos et al. 2018). The application of management measures obtained as outputs
386 from the system for the aforementioned events, would have significant benefits in minimizing
387 the flood risk and maximizing the preservation of water resources. For 20110313_4d for
388 instance, the damages to property would have been reduced by 15 %, expected injury by 62 %
389 and expected fatalities by 48 %, while a volume of 0.9 hm³ of water released from the reservoir
390 would have been preserved. These values represent a reduction of the episode impact of
391 approximately 3.3 M€. For 20130304_3d, material damages would have been reduced by 28 %,
392 injury by 81%, expected fatalities by 58 % and 0.2 hm³ of preserved water volume. In this last
393 case, the reduction of the impact would have been around 2.9 M€ (Bladé et al. 2018).

394 EO data represent a valuable source of information for hydrologic purposes and for water
395 resources management, in general, through mapping water resources and monitoring
396 hydrological parameters. Remote sensing techniques contribute to management systems
397 modelling providing updated estimates of different parameters which can significantly improve
398 the efficiency of such models and their robustness for forecasting. In this case, we focus

399 attention on the benefits that can be obtained in water management modelling through the
400 updated assessment of the CN value after the consideration of remotely sensed soil moisture
401 information as described in previous section 4.2.

402 Once the numerical model is calibrated, the final system is supported up with only two
403 sets of data: quantitative precipitation forecasts and soil moisture from EO. The model is
404 executed continuously, updating the inputs with the last available ESA CCI SM data and
405 precipitation forecasts (Roux et al. 2020). Threshold alerts and pre-established dam operation
406 protocols are included in the model, though the protocols can also be manually adjusted for the
407 assessment of different operations of the dam outflow systems.

408 5. CONCLUSIONS

409 On-site and Earth observation (EO) data were used for the calibration of the NRCS-CN
410 parameter of an Eastern Pyrenees basin, as it is the most important parameter of the
411 hydrological model when correctly assessing water balance so as to evaluate the basin
412 hydrologic response. The model developed for this purpose consists of a coupled fully-
413 distributed hydrological and hydraulic model, which constitutes the central core of an
414 operational system for the Boadella reservoir management. The main aim of the operational
415 system is the prediction of flood risk and final water resources estimates associated to a
416 forecasted extreme rainfall. The use of a distributed model integrating hydraulics and hydrology
417 has been proven to be a robust tool so as to obtain in a single simulation, results of water
418 resources (discharges, reservoir volumes) and flood hazard (depths, velocities).

419 Solid correlations were found between the estimated moisture data and the CN value
420 obtained through numerical modelling forced by ground data, suggesting the potential of
421 available remote sensing data for the updating of the CN values in continuous hydrological
422 models. The optimal averaging period for the SM was, for the present case, 16 days. It would be
423 valuable to check the validity of this period in other basins, which is proposed for future work.

424 The relationship between CN and EO based on surface moisture has been obtained for
425 five rainfall events modelled in the small Boadella reservoir catchment. The accuracy in the
426 estimation of the CN parameter strongly affects the volumes of runoff simulated by the
427 hydrological model and, consequently, the flood mitigation measures informed by those.

428 Thanks to the SM-CN relationship, the information needed to continuously support the
429 operational system for the reservoir management has been reduced to two sets of data:
430 observed meteorological data in raster format, and the observed soil moisture. The consistency
431 of the achieved SM-CN relationship strongly suggests the potential of EO data to provide
432 updated estimates of the CN.

433 The present results of the application to the case study suggest the usefulness of
434 incorporating remotely sensed proxies. This work is a step towards physical descriptors of soils
435 based on remote sensing and its integration in water resources management and flood
436 forecasting systems, thus providing a beneficial direction for future work on optimized
437 management strategies.

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442 Mediterranean Euroregion. The authors also thank to the Agència Catalana de l'Aigua and Servei
443 Meteorològic de Catalunya that provided the "Rainfall and water level" data, as well as its
444 advisement during the project.

445 7. DATA AVAILABILITY STATEMENT

446 The data used during the study, and provided by a third party are listed below:

- 447 • Precipitation data (Table 2), generated by Servei Meteorològic de Catalunya
448 (<https://meteo.cat>), was provided by Agència Catalana de l'Aigua
449 (<http://aca.gencat.cat/ca/inici>) within the PGRI-EPM project.
- 450 • Dam outlet and water level data (Table 2) was provided by Agència Catalana de
451 l'Aigua (<http://aca.gencat.cat/ca/inici>) within the PGRI-EPM project.

452 Direct requests for these materials may be made to the provider.

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621

622 FIGURES & TABLES

623 **Fig. 1.** Location and characteristics of the study area. (a) Topography of La Muga basin, extension
 624 of the study area and location of the Boadella Dam and rain gauge station. (b) Land use map of the study
 625 area. Source: Institut Geològic i Cartogràfic de Catalunya (a), CORINE (b) and own elaboration.

626 **Fig. 2.** Computational mesh of the study area.

627 **Fig. 3.** Sensibility analysis for the Manning coefficient (n) associated with forest-dense land use.
 628 Water level evolution for the events 20130304_3d and 20150320_3d.

629 **Fig. 4.** Representation of a non-distributed (top: rain gauge registrations, triangle: rain gauge
 630 localization) and distributed (bottom: radar observations) rainfall records for events 20131116_3d,
 631 20141129_2d and 20150320_3d.

632 **Fig. 5.** Evolution of the water level in the Boadella reservoir (dam point-check) for the observed
 633 data (dotted line) and the simulations (rain gauge: dashed line; radar: continuous line) using the selected
 634 CN.

635 **Fig. 6.** Scatter plot of CNs calibrated for five events versus Earth observation based soil moisture
 636 measurements averaged for different antecedent number of days.

637 **Fig. 7.** R^2 coefficient of the linear correlation between the calibrated CNs and the Earth observation
 638 based soil moisture averaged for different antecedent periods.

639

640 **Table 1.** Extreme rainfall events registered in the study area used for the model calibration. Rainfall
 641 information sources are identified as: (rg) for rain gauge, (r) for radar images.

| Event ID | Date | season | Source of data | Total rainfall depth | | Maximum intensity | |
|-------------|------------|--------|----------------|----------------------|------|-------------------|--------|
| | | | | [mm] | | [mm/5-min] | [mm/h] |
| | | | | (rg) | (r)* | (rg)** | (r)*** |
| 20110313_4d | March 2011 | spring | (rg) | 127 | - | 62 | - |
| 20130304_3d | March 2013 | spring | (rg) | 181 | - | 30 | - |
| 20131116_3d | Nov 2013 | autumn | (rg), (r) | 123 | 98 | 54 | 9 |
| 20141129_2d | Nov 2014 | autumn | (rg), (r) | 151 | 132 | 61 | 13 |
| 20150320_3d | March 2015 | spring | (rg), (r) | 197 | 77 | 67 | 9 |

*Cumulated rainfall for the study area
 **Intensity registered in 5 minutes at the raingauge
 ***Intensity registered in the study area

642

643 **Table 2.** Summary of the data used for the upper La Muga sub-catchment study case.

| Data type | Characteristics | Source | Data description |
|-----------------------------|--|--|--|
| Digital Terrain Model (DTM) | 2x2 m ASCII raster file | Institut Cartogràfic i Geològic de Catalunya (ICGC) | Elevation data based on LIDAR (RMSE of 0.15 m) |
| Land uses | Shapefile converted into 2x2 m ASCII raster file | CORINE Land Cover project (EEA 2007) | Land uses classification and spatial representation for the year 2012 |
| Soil moisture (SM) | 0.25° degrees spatial resolution | European Space Agency Climate Change Initiative for Soil Moisture (ESA CCI SM) | ESA CCI SM |
| Precipitation | Rainfall intensities | Agència Catalana de l'Aigua (ACA) and Servei Meteorològic de Catalunya (SMC) | Rainfall intensities from 5-minutal raingauge (hyetograph) and 1-hour radar (1x1 km ASCII raster file) |
| Dam outlet / water level | Discharges and water level | Agència Catalana de l'Aigua (ACA) | 5-minutal series of the outlet hydrograph and the water level in the reservoir |

644

645 **Table 3.** CN values resulting from the calibration process.

| Event | season | CN _{rg} | CN _r | CN _{selected} |
|-------------|--------|------------------|-----------------|------------------------|
| 20110313_4d | spring | 94 | * | 94 |
| 20130304_3d | spring | 81 | * | 81 |
| 20131116_3d | autumn | 50 | 55 | 55 |
| 20141129_2d | autumn | 60 | 65 | 65 |
| 20150320_3d | spring | 50 | 85 | 85 |

**No data available on this format*

646

647 **Table 4.** Cumulated and effective rainfall using the selected CN (Table 3) at the end of the event.

| Event | Total rainfall [mm] | | Effective rainfall [mm] | |
|-------------|---------------------|-------|-------------------------|-----|
| | (rg) | (r) | (rg) | (r) |
| 20110313_4d | 127 | * | 109 | * |
| 20130304_3d | 181 | * | 125 | * |
| 20131116_3d | 123 | 98.3 | 16 | 12 |
| 20141129_2d | 151 | 132.3 | 59 | 49 |
| 20150320_3d | 197 | 76.7 | 152 | 41 |

**No data available on this format*

648

649 **Table 5.** Model performance between observed and simulated flow and water balance using the

650 corresponding CN for each rain source.

| Event | MAE (m) | | RMSE (m) | | NSE | |
|-------------|------------|-------|-------------|-------|-------|-------|
| | gauge | radar | gauge | radar | gauge | radar |
| 20110313_4d | 0.735 | * | 0.873 | * | ** | * |
| 20130304_3d | 0.261 | * | 0.389 | * | 0.987 | * |
| 20131116_3d | 0.193 | 0.152 | 0.209 | 0.172 | 0.637 | 0.754 |
| 20141129_2d | 0.770 | 0.371 | 0.948 | 0.532 | 0.518 | 0.848 |
| 20150320_3d | 0.383 | 0.242 | 0.432 | 0.260 | 0.861 | 0.941 |

*No data available on this format

**Statistic not applicable due to lack of data

651

652 **Table 6.** Mass balance at the end of the rainfall event using the selected CN (Table 3).

| Event | GAUGE | | | | | | | |
|-------------|----------------------------|--------------------------|--|--|---------------------|---------------------|----------------------------------|-------------------|
| | WL _{start} [m] | WL _{end} [m] | V _{start} [hm ³] | V _{end} [hm ³] | ΔV (sim) | ΔV (obs) | Difference [hm ³] | Difference [%] |
| 20110313_4d | 151 | 158 | 36.9 | 60.2 | 23.3 | 22.2 | 1.1 | 4.9 |
| 20130304_3d | 147 | 156 | 26.7 | 51.8 | 25.1 | 25.2 | 0.1 | 0.4 |
| 20131116_3d | 151 | 152 | 37.0 | 40.2 | 3.23 | 3.07 | 0.16 | 5.2 |
| 20141129_2d | 149 | 152 | 31.1 | 41.2 | 10.1 | 10.0 | 0.1 | 1.0 |
| 20150320_3d | 155 | 163 | 48.5 | 80.2 | 31.7 | 9.0 | 22.7 | 252 |

| Event | RADAR | | | | | | | |
|-------------|----------------------------|--------------------------|--|--|---------------------|---------------------|----------------------------------|-------------------|
| | WL _{start} [m] | WL _{end} [m] | V _{start} [hm ³] | V _{end} [hm ³] | ΔV (sim) | ΔV (obs) | Difference [hm ³] | Difference [%] |
| 20131116_3d | 151 | 152 | 37.0 | 40.2 | 3.23 | 3.07 | 0.16 | 5.2 |
| 20141129_2d | 149 | 152 | 31.1 | 41.0 | 9.87 | 10.0 | -0.14 | -1.4 |
| 20150320_3d | 155 | 157 | 48.5 | 56.8 | 8.24 | 8.95 | -0.71 | -7.9 |

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