Comparison of stage/discharge rating curves derived from different recording systems: consequences for streamflow data and water management in a Mediterranean island

J. Fortesa^{ab}, J. García-Comendador^{ab}, A. Calsamiglia^{ab}, J.A. López-Tarazón^{abcd}, J. Latron^e, B. Alorda^f and J. Estrany^{ab*}

^a*Mediterranean Ecogeomorphological and Hydrological Connectivity Research Team (<http://medhycon.uib.cat>), Department of Geography, University of the Balearic Islands, Carretera de Valldemossa Km 7.5 07122, Palma, Spain*

^b*Institute of Agro-Environmental and Water Economy Research –INAGEA, University of the Balearic Islands, Carretera de Valldemossa Km 7.5 07122, Palma, Spain*

^c*Institute of Earth and Environmental Science, University of Potsdam, Karl-Liebknecht-Straße 24/25, 14476 Potsdam-Golm, Germany*

^d*Fluvial Dynamics Research Group, Department of Environment and Soil Sciences, University of Lleida, Av. Alcalde Rovira Roure, 191, 25198 Lleida, Spain*

^e*Institute of Environmental Assessment and Water Research (IDAEA), Spanish Research Council (CSIC), Jordi Girona 18, 08034 Barcelona, Spain*

^f*Department of Physics, University of the Balearic Islands, Carretera de Valldemossa Km 7.5 07122, Palma, Spain*

*Corresponding author: joan.estrany@uib.cat; Tel.: +34 971172362

Abstract

Obtaining representative hydrometric values is essential for characterizing extreme events, hydrological dynamics and detecting possible changes on the long-term hydrology. Reliability of streamflow data requires a temporal continuity and a maintenance of the gauging stations, which data are affected by epistemic and random sources of error. An assessment of discharge meterings' and stage-discharge rating curves' uncertainties were carried out by comparing the accuracy of the measuring instruments of two different hydrometric networks (i.e., one analogical and one digital) established in the same river location at the Mediterranean island of Mallorca. Furthermore, the effects of such uncertainties were assessed on the hydrological dynamics, considering the significant global change impacts beset this island. Evaluation was developed at four representative gauging stations of the hydrographic network with analogic (≈40 years) and digital (≈10 years) data series. The study revealed that the largest source of uncertainty in the analogical (28 to 274%) and in the digital (17-37%) networks were the stage-discharge rating curves. Their impact on the water resources was also evaluated at the event and annual scales, resulting in an average difference of water

yields of 183% and 142% respectively. Such improvement on the comprehension of hydrometric networks uncertainties will dramatically benefit the interpretation of the long-term streamflow by providing better insights into the hydrologic and flood hazard planning, management and modelling.

Keywords: hydrometric networks; stage-discharge; metering; uncertainty; error propagation.

1 Introduction

River catchments are considered one of the more sensitive earth-systems to global change, due to the combination of climate change (e.g. increase of extreme storm events; Borga et al., 2010) and direct human influence (e.g. changes on land uses; García-Ruiz et al., 2011). Under this context, the hydrometric data reliability of surface water resources requires a temporal continuity and an inspection and maintenance system of the gauging stations (Shaw, 1994) to effectively detect changes. However, uncertainties in hydrological systems frequently derive from many different factors and are non-stationary because of the non-linearity of the hydrological processes (Westerberg et al., 2011; Bayazit, 2015). Due to the stochastic nature of these processes, long time series (i.e., 30 years) are required to obtaining representative hydrometric values (i.e., accurate and reliable) for characterizing extreme events, hydrological dynamics and detecting possible changes. Conversely, short data series may lead to unrepresentative values, especially in the calculation of mean flow in ephemeral and intermittent hydrological regimes (Westerberg et al., 2011). From the mid-forties to the sixties of the last century, most of the hydrometric networks used very simple measuring instruments; i.e., limnigraphs (e.g., Ward, 1967). Over the years, a substantial improvement in instrumentation has been achieved due to technological advances, allowing a higher temporal resolution monitoring (i.e., minutal intervals) of several variables (Le Coz, 2008, Volkmann et al., 2010). Despite technological advances, many of these hydrometric networks have not adopted such improvements, causing high levels of error (Mishra and Coulibaly, 2009).

The reliability of hydrometric data is affected by the transformation of water stage (hereinafter WS; m) to discharge (hereinafter Q; $\text{m}^3 \text{s}^{-1}$) through the stage/discharge rating curves (hereinafter SDRC) into the

qualitative range (from low to high Q conditions) of the hydrological dynamics (Gravelle, 2015). Power (Herschy, 1978; Pappenberger et al., 2006) and also polynomial (Yu, 2000) equations, characterised by physical-based parameters, are broadly used to elaborate SDRCs. This is not a unique or invariant relationship, as it is affected by different sources of error that generate uncertainty in the flow calculation (Pelletier, 1987, McMillan et al., 2012). These errors are classified according to the source that originates them, and may be random –generated by incorrect monitoring of WS , Q and/or cross-sections (Di Baldassarre and Montanari, 2009, McMillan and Westerberg, 2015)– and epistemic –related with the absolute lack of knowledge in the SDRC– due to morphological changes in the stream, seasonal vegetation growth and extrapolation of the SDRC (Rantz, 1982, Petersen-Øverleir et al., 2009, Westerberg et al., 2011).

A full comprehension of the uncertainty that affects the SDRC method requires a description of the procedure itself (Di Baldassarre and Montanari, 2009). Several methods have been used to assess the SDRC uncertainty. Le Coz et al. (2014) used a Bayesian analysis to determine the uncertainties generated by the hydraulics controls in the SDRC and the Q meterings. Reitan and Petersen-Øverleir (2011) assessed the SDRC uncertainty through a Bayesian and Markov chain Monte Carlo simulation techniques. McMillan and Westerberg (2015) assessed the uncertainty where epistemic uncertainty sources included weed growth, deposition of the bed gravels and unconfined high flows through a statistical likelihood function. It is necessary to quantitatively assess the reliability of data series generated by the hydrometric networks under non-stationarity conditions to define the best strategies in hydrological modelling and water balance calculations. Hence, Tomkins (2014) developed an analysis of the deviations in Q meterings from the SDRC, a simple robust empirically based method that can provide substantial information on SDRC uncertainty and the reliability of flow data. Despite this, few studies have investigated Q meterings and

SDRC uncertainties also comparing the accuracy of measuring instruments of two hydrometric networks established in the same river reaches.

The present study carries out that type of assessment, in which the first network is controlled by analogical instruments (Analogical Hydrometric Network; hereinafter AHN) and compiles data series < 40 years, while the second network is controlled by digital devices (Digital Hydrometric Network; hereinafter DHN) with data series ≈ 10 years. The main aim of this paper is to analyse the reliability of the measured discharge by calculating the total uncertainty of the streamflow data and then quantify the individual contribution of the main different sources of uncertainty. As some of the AHN and DHN stations are located in the same gauging site, it is possible to compare their flow records, hence to evaluate the importance of their uncertainty in the quantification of the surface water resources. Such evaluation is performed at four different gauging stations of two contrasted catchments (i.e. two gauging stations per catchment) through: (1) a comparison of WS measurements from AHN and DHN recording systems; (2) an assessment of the uncertainty of the Q meterings; (3) an assessment of the uncertainty of their SDRCs; and, (4) an assessment of the SDRC effects on the water yield dynamics in the Mediterranean island of Mallorca. Finally, the global uncertainty, understood as the sum of Q meterings and SDRC uncertainties, is also assessed.

2. Material and methods

The assessment of Q metering's and SDRC's is performed by applying a multi-method approach focused on the integration of hydraulics and uncertainties evaluation on the surface water resources estimation (Fig. 1).

2.1 Study area

The island of Mallorca (3,640 km²; Fig. 2a) is a Mediterranean region where fluvial systems are mainly under ephemeral/intermittent hydrological regimes resulting from the combination of geology and

103 Mediterranean climate, with a significant intra- and interannual variability as well as high recurrence of
104 severe flash-flood events (Estrany and Grimalt, 2014). It is characterised by a basin-and-range
105 topographical configuration mainly constituted by limestone geology (Jenkins et al., 1990). The
106 hydrographic network (Fig. 2b) is formed by small catchments; only 7 exceed 100 km², and the largest
107 accounts for 456 km². In mountainous areas, streams are short and very steep in headwaters; catchments are
108 small and receive a medium-high annual precipitation (i.e., 700-1,200 mm; Pardo and Olsen, 2004). These
109 mountainous streams represent 20% of the hydrographic network total length. In lowland areas, where
110 annual precipitation is lower (400-600 mm), streams have gentler slopes with lengths representing 63% of
111 the hydrographic network. The remaining 17% of the river streams are located on impervious materials
112 allowing different degrees of intermittency and even punctually perennial hydrological regimes.

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114 ***2.2 Monitoring systems and validation***

115 The monitoring of surface hydrology on the Mallorca Island is carried out by means of the AHN (1965-
116 2014), managed by the Autonomous Government of the Balearic Islands (Fig. 2b). The network design
117 responds to the initial objective of assessing the hydrological potential of selected catchments to construct
118 reservoirs, just 2 of the many planned were finally built and located in different river catchments to those
119 studied here. The network was composed at 2014 of 32 stations equipped with analogical instruments (i.e.,
120 7 limnigraphs and 25 limnimeters). All the gauging stations were built with concrete weirs which keep a
121 uniform flow (Table 1). Limnigraph temporal resolution is 1 hour and the vertical 0.01 m. The lack of
122 maintenance and the structural deficiency of the AHN led the University of the Balearic Islands to
123 implement the DHN, which has been developed in different phases since 2004 (Fig. 2b). The DHN is
124 currently composed of 34 stations with digital pressure capacitive probes ([Druck PDCR-1830-3](#) controlled
125 by [Campbell data-loggers CR200](#); [Hobo Water Level U20L-04](#) and [TruTrack WT-HR 250](#) water level
126 loggers) to measure the WS by readings of 1 minute accumulating 15-minute average values providing

127 continuous records.

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129 *2.2.1 Selected gauging stations*

130 One of the components of the uncertainty assessment was performed by comparing the WS and the Q
131 collected by AHN with those obtained from DHN in gauging stations placed in the same location. For this
132 purpose, four representative gauging stations of the hydrographic network of Mallorca with long data series
133 (40 years) were selected. Two of these official stations (i.e., Comafreda and Sant Miquel; hereinafter M1-
134 Mountainous 1- and M2-Mountainous 2-, respectively) are located in the mountainous and forested Sant
135 Miquel catchment (Fig. 2b) whereas the other two (i.e. Sa Vall and Ses Pastores; hereinafter L1-Lowland 1-
136 and L2-Lowland 2-, respectively) are located in the lowland and agricultural Na Borges catchment (Fig.
137 2b). Table 1 summarizes catchment characteristics of precipitation, land uses, average annual runoff, and
138 gauging stations recording systems type and channel bed characteristics. Further details can be read in the
139 [Experimental catchments web page](#).

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141 To validate the hydrometric values generated by the recording systems it was necessary to obtain a
142 representative range of flow rates to encompass all the situations that occur in the natural hydrological
143 dynamics. Low, intermediate, high and extreme WS and Q were obtained using two types of field
144 measurements. On the one hand, WS was measured manually *in situ* using a line gauge at the same time as
145 the pressure probe and limnimeter recorded the WS. On the other hand, Q meterings using the float method
146 or the area-velocity-method were carried out under a range of different magnitudes (see Table 2 and
147 Annex), from low (baseflow) to high flows (flood events). All SDRCs obtained by DHN were based on a
148 larger number of Q meterings (Fig. 3) performed from the center of the channel. However, these
149 measurements were carried out from the river banks for high-Q conditions (i.e., $WS > 1$ m) due the
150 impossibility of measuring the flow velocity from the channel-center at M1 and M2 stations.

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2.3 Stage-discharge rating curves elaboration

The low and unrepresentative Q meterings carried out at AHN forced to the development of theoretic SDRCs based only on the specific hydraulic formulae of the gauging sections. Therefore, AHN SDRCs were derived theoretically based on Manning formulae (Limerinos, 1970) for the different WS levels. The design of the low-flows channel coupled with the low gradient slope of the stream at L2 gauging station caused the impossibility to measure the flow velocity for WS levels < 0.50 m with the available OTT C31 current meter. Accordingly, some intervals of the SDRCs were elaborated by applying the Manning procedure (Limerinos, 1970) in these stations. The n roughness coefficient was determined following Arcement and Schneider (1990) and the average stream gradient slope by using a topographic equipment ([dGPS Leica 1200](#)) along a longitudinal river section established 100 m up- and downstream of the gauging station. The *WinXSPRO* software (Hardy et al., 2005) was applied to analyse stream channel cross section data for geometric and hydraulic parameters. This software supports four alternative resistance equations for computing boundary roughness and resistance to flow. With the topographic channel cross sections and the determination of n roughness coefficient, the *WinXSPRO* was applied to obtain Q values. It is worth to note that the Q meterings carried out during low- Q conditions were used to calibrate the Manning coefficient for the computation of the flow for the high- Q conditions, but taken into consideration the lower impact of the Manning coefficient on high flows, when the influence of the gauging structure is almost negligible. That issue could represent an additional source of uncertainty which could not be assessed on the present paper. Finally, it must be assumed that the equation is valid for these river sections under concrete weirs, despite changing conditions during flood events, as gauging sections were cleared regularly of debris and vegetation >100 m up- and downstream.

2.4 Computation and data analysis

2.4.1 Water stage level

WS levels obtained from DHN instruments (i.e. pressure probes) were calibrated with WS measurements carried out simultaneously during fieldwork to assess their functioning accuracy. WS levels measured by AHN could not be validated at any stations as the records which were provided by the Autonomous Government of the Balearic Islands never coincided on time with fieldwork; i.e., it was not possible to measure the real WS level at the same time when an AHN device was registering. Nevertheless, in the unique gauging station where a pressure probe (DHN) and a limnigraph (AHN) were simultaneously recording (i.e., M2), the WS levels obtained from DHN were compared with those obtained by AHN to assess their differences.

2.4.2 Global uncertainty assessment

Di Baldassarre and Montanari (2009) observed that the main sources of error affecting Q are the error in Q meterings (hereinafter ε_1); and the error due to SDRC uncertainty (hereinafter ε_2) which in turn is induced by its interpolation and extrapolation error, the presence of unsteady flow conditions, seasonal changes of roughness. These authors assumed that the global uncertainty can be obtained by:

$$\varepsilon(Q(x,t)) = \pm \varepsilon_1(Q(x,t)) + \varepsilon_2(Q(x,t)) \quad (1)$$

Traditional approaches are used in this study to infer ε_1 , while original techniques are developed to evaluate the rating curve uncertainty ε_2 . The latter is a difficult task as the methodology depends on the available information. In practical applications, the lack of information related with ε_2 , led us to assess the SDRC uncertainty by using the deviation of the Q directly estimated from the Q meterings (hereinafter Q_g) from the predicted Q from the SDRCs (hereinafter Q_{re}).

- Uncertainty assessment of discharge meterings (ε_1)

198 The initial source of error results from the Q meterings. In order to quantify this uncertainty, the *European*
 199 *ISO EN Rule 748* (1997) offers a methodology to quantify these errors at a 95% confidence level:

$$200 \quad X'_Q = \pm \sqrt{X_A^2 + \frac{1}{m} (X_e^2 + X_c^2 + X_B^2 + X_d^2 + X_p^2)} \quad (2)$$

201 where X'_Q is the error of the Q metering (%); X_b is the uncertainty affecting the measurement of the cross-
 202 section width; X_d is the uncertainty that affects to the WS measurement; X_e is the uncertainty of the flow
 203 velocity related to the duration of the measurement; X_p is the uncertainty of the flow velocity in function of
 204 the number of measurement points along each of the performed vertical sections, when at least 5 have been
 205 performed; X_c is the uncertainty of the flow velocity associated with the calibration of the measuring
 206 instrument; and, X_A is the uncertainty in the flow velocity depending on the number of vertical sections.
 207 Each singular uncertainty has been calculated by following the formulae stated by Herschy (1970).

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209 - *Discharge uncertainty assessment in the stage-discharge rating curves (ϵ_2)*

210 SDRC uncertainty is based in the concept that WS is uncertain through its own measurement errors.
 211 Tomkins (2014) analysed the SDRCs uncertainty in the Q values directly estimated from the Q meterings
 212 and their correspondence within the SDRCs. In this way, the relative deviation of the measurements
 213 (hereinafter D) from the corresponding SDRC was estimated to obtain the uncertainty between Q values:

$$214 \quad D = [(Q_g - Q_{rc})/Q_{rc}] \times 100 \quad (3)$$

215 This relative D (%) indicates the fitting degree between Q directly estimated from Q meterings and Q
 216 predicted from the SDRC for each single measurement. The results can be classified as good for $D = \pm$
 217 10%; acceptable ± 11 -20%; doubtful ± 21 -50% and underestimated or over-estimated $\geq \pm 50\%$ (Tomkins,
 218 2014). At the M1 and M2 station, the AHN and DHN SDRCs were analysed using their respective Q
 219 metering. However, at the L1 and L2 station, this analysis was performed for both the AHN and DHN using
 220 only the Q meterings from the DHN, because no field measurements were carried out for the AHN.

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2.4.3 Stage-discharge rating curves effects on hydrological dynamics

Finally, SDRCs for AHN and DHN were applied and the resulting Q-series compared at the event and annual scales (i.e. 2007-08 hydrological year at L1 and L2 and 2013-14 hydrological year at M1 and M2) to assess the propagation of errors in the quantification of surface water resources. Selected parameters at the event scale were: $Q_{\max}$, Q_{average} and event water yield (E_{wy} , hm^3), while at the annual scale, such parameter were: Q_{average} and the annual water yield (A_{wy} , hm^3). Additionally, the uncertainty computed in previous section 2.4.2 was applied to calculate an associated Q (and related parameters) uncertainty band both at the event and annual scale.

3 Results and Discussion

3.1 Calibration and comparison of water stage measurements

A basic calibration and comparison of the instruments accuracy between AHN and DHN systems were initially performed. The comparison was only carried out at M2 station due that it is the only station where the contiguous installation of a limnigraph for AHN and a pressure probe for DHN allowed measuring WS simultaneously.

DHN-pressure probe at M2 was calibrated based on 15 *in situ* measurements of WS in a representative range (0 to 1.52 m), therefore determining also the accuracy of the device (Fig. 4a). Likewise, in order to determine the uncertainty of the AHN records used in the historical data series at M2 station, 48 values of WS (from 0.00 to 1.03 m) obtained simultaneously from the pressure probe and the limnigraph were compared (Fig. 4b), resulting a mean difference of 0.08 ± 0.07 m, being a 23% higher in AHN. This comparison revealed a worse functioning of the limnigraph, especially for low flow measurements, even observing that AHN measured WS values of 0.05 m (or higher) when the stream was actually dry (i.e., field observation) and the DHN-pressure probe was measuring (correctly) a WS of 0 (Fig. 4b). This error was

246 very high if compared with the WS uncertainty review carried out by McMillan et al. (2012). Additionally,
247 the instrumental precision in the vertical resolution of the WS (0.01 m for the AHN and 0.0001 m for the
248 DHN) inherently caused higher uncertainty in the Q computation of AHN records. According with Sauer
249 and Turnipseed (2010), AHN main sources of uncertainty in WS are probably driven by some of the sources
250 listed by such authors, so called: stage sensor errors related to the instrument performance, measurement
251 conditions, water surface-to-sensor-to-recorder errors, mechanical problems, intake of the stilling well).
252 Those errors have to be classified as systematic (i.e., generated by a sensor drift or inaccurate calibration)
253 and should not be neglected at all (Horner *et al.*, 2018).

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255 ***3.2 Global uncertainty assessment at the analogical and digital hydrometric networks***

256 The application of the procedure proposed by Di Baldassarre and Montanari (2009) estimated the total error
257 as the sum of Q meterings (ϵ_1) and SDRC (ϵ_2) uncertainties, being their detailed results discussed as
258 follows.

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260 ***3.2.1 Uncertainty assessment of discharge meterings (ϵ_1)***

261 At L1 and L2, the error of Q meterings from which the AHN SDRCs were elaborated could not be assessed
262 as no Q metering was performed throughout the historical series. At M1 and M2, after applying the *ISO EN*
263 *Rule 748* (1997), the Q values obtained by AHN were based on a higher error than those obtained by DHN
264 (Table 3). This fact can be attributed to the number of segments in which each gauging section was
265 subdivided for the velocity measurements (i.e. only 2 to 4 in M1; 6 to 11 in the case of M2) because as
266 higher is the number of segments across the gauging section, the more representative are the flow velocity
267 data. Despite different measurement methods can increase an order-of-magnitude the transmission errors
268 (Hamilton and Moore, 2012), the largest errors occurred using AHN in these two last stations were
269 generated because the SDRC calibrations were not performed by means of Q meterings nor by the

270 application of, for example, a Manning procedure for the Q estimation.

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272 3.2.2 Uncertainty assessment in the stage-discharge rating curves (ϵ_2)

273 The errors derived from the direct Q meterings were propagated towards the elaboration of the SDRCs.
274 Therefore, the comparison of the deviations (D) analysis of those direct measurements (Q_g) with the
275 predicted Q values (Q_{rc}) in each SDRC (applying the method developed by Tomkins, 2014; see Annex for
276 further details) showed larger differences in the D values derived from the AHN SDRCs at all the stations
277 compared with the DHN SDRCs (Table 3).

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279 The Tomkins (2014) method is simple to apply if compared to others (Reitan and Petersen-Overleir, 2008;
280 Morlot et al., 2014). It basically makes no assumptions about the data or distributions, using the readily
281 available meta-data more fully. It only requires a dataset of Q meterings not dependent on fitting a single
282 mathematical function allowing a more accurate definition of the SDRC. Tomkins (2014), in a comparative
283 study of historic SDRCs of 36 gauging stations in Australia, indicated that D between Q_g and $Q_{rc} \geq \pm 50\%$
284 should be classified as poor values. Accordingly, when the D values obtained for all the AHN and DHN
285 SDRCs are analysed, it is clear that DHN performed generally better than AHN (Table 3). Then, the AHN
286 SDRCs were constructed with only 16% of adjusted or acceptable deviations and 85% doubtful or
287 overestimated. However, DHN SDRCs were elaborated with 65% of adjusted and acceptable (i.e., $D \leq$
288 20%) deviations and 34% doubtful, underestimated or overestimated ($D \geq 21\%$). However, Tomkins (2014)
289 method presents some weaknesses which also exist in other rating curve uncertainty approaches (McMillan
290 et al., 2012) as can be: (1) a high degree of overfitting between nearest Q meterings; (2) a few number of Q
291 meterings or located too distant between them can modify the curvature of the SDRC; (3) the residuals must
292 be interpreted in the lower part of the SDRC because small differences in absolute values can be
293 transformed in high deviations (which are not always meaning a worse SDRC); and, (4) the confidence

limits can vary according the expertise of the scientist and the availability or difficulty to obtain Q meterings. Furthermore, the D value only allows to develop a single stationary uncertainty band in Q values while there are many other tools (e.g. [BaRatin](#) and [HydraSub](#)) which allow to compute and draw multiple flow uncertainty series (McMillan et al., 2017).

Finally, it should be noted that the opposite curvature of the SDRCs reflexed differences in the Q values at different WS, especially for their lower values, which represent another source of uncertainty. Such uncertainty for low WS and Q is related to the shape of the SDRC function and whether they fit or not from the origin of coordinates (i.e., 0, 0 point). Then, the SDRCs which are not fitted tot that (i.e., M2, L1 and L2 from AHN and L1 from DHN) present residues in their equations and, consequently, zero values of WS do not produce zero values of Q. Such values had to be adjusted to 0 manually.

3.2.3 Global uncertainty calculation

Lately, studies on hydrological uncertainties are mainly based on the evaluation of the SDRCs construction and development but they use ignoring the importance of WS or just assume that its related uncertainty is negligible. However, the relative contribution of WS to the global uncertainty depends on the degree of the SDRCs uncertainty and on the management of the hydrometric network (e.g., maintenance, sensor calibration). It has been proved that the uncertainties directly related with WS could increase up to 10% the SDRC uncertainty, especially in small catchments under ephemeral/intermittent regimes (Hornet *et al.*, 2018), as it is the case of the present paper.

After applying the method developed by Di Baldassare and Montanari (2009), results reveal that the main source of errors lied in the SDRCs uncertainty (ϵ^2 ; Table 3), even though AHN did not include the error of field measurements because not any single Q metering was carried out. It should be noted that D were

318 higher using AHN's SQRCs than using DHN's, especially in L1 and L2, with just very few single values
319 performing $\geq \pm 50\%$ for DHN's at both sections, which could be considered as outliers (e.g., 105% in L1;
320 see Annex) or generated due to the extremely low Q values from which they were calculated (e.g., $Q_g =$
321 $0.009 \text{ m}^3 \text{ s}^{-1}$ and $Q_{rc} = 0.006 \text{ m}^3 \text{ s}^{-1}$ in L2). However, higher D values do not always mean a worse SDRC
322 elaboration. In the case of DHN, the largest total error (38%) was observed in L2, mainly due to the
323 inadequate construction design of the gauging section, which is located in a very flat section of the main
324 stream (i.e., 0.0014% of slope). As a consequence, the DHN SDRC in L2 was partially built following the
325 Manning approach, a method that presents an intrinsic uncertainty of $\pm 15\%$ to $\pm 35\%$ in the Q calculations
326 (Slade, 2004).

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328 Several authors have previously analysed and quantified the uncertainty for low Q, obtaining errors between
329 -43% to 73% (Westerberg et al., 2011), and between 50-100% (McMillan et al., 2012), as well as for the
330 intermediate and high flows, which was estimated in a range between 10-40% (McMillan et al., 2012), and
331 between 6.2% to 42.8% (Di Baldassare and Montanari, 2009). Moreover, McMillan et al. (2018)
332 summarized the results obtained from the literature on hydrologic data uncertainty. They classified such
333 studies, based on their coefficient of variation, into low (0-10%) and medium (10-40%) uncertainty, which
334 places AHN (108%) and DHN (25%) within the very high and medium range respectively. Nevertheless, it
335 must be stated that the Q values uncertainty in a gauging station can vary highly depending on the method
336 which is applied (Kiang et al., 2018). These authors compared the SDRC uncertainties obtained from seven
337 different methods at three river locations and they ranged for low flows between 28-101%, for median
338 between 3-17% and for high flows between 41-200%, so that must be taken into account when working
339 with Q derived from SDRCs.

341 *3.3 Effects of the application of stage-discharge rating curves at analogical and digital hydrometric*

networks over hydrological dynamics

The hydrological effects of applying AHN and DHN SDRCs are here assessed comparing the SDRCs obtained from both hydrometric networks at event and annual scales.

3.3.1 Event scale

Figure 5 and Table 4 illustrate the derived Q dynamics at AHN and DHN for selected representative events of high and low magnitude at the gauging stations, excepting for M1, where the event scale could not be assessed due to the limnimeter's measuring frequency (i.e. daily).

In the case of M2, many differences are observed if AHN or DHN data are considered. For the selected high magnitude event (Fig. 5a), AHN recorded higher WS than DHN both at the beginning and at the end of the event. $Q_{\max}$ was registered with a delay of 15 minutes in AHN, and WS decreased more sharply in the falling limb in DHN than in AHN. $Q_{\max}$ and E_{wy} were also higher in DHN than AHN. Oppositely, for the low magnitude event (Fig. 5b), the rising limb and $Q_{\max}$ in AHN were delayed (i.e. 15 and 45 minutes respectively) compared to DHN, and WS decreased more sharply in DHN than in AHN. In addition, differences of up to one order of magnitude in $Q_{\max}$ and E_{wy} were observed (Table 4). In the case of L1, the high magnitude event (Fig. 5c) evidenced that $Q_{\max}$ obtained by DHN was one order of magnitude higher than that obtained for AHN. Q_{average} and E_{wy} were very similar, presenting the smallest differences between both networks (Table 4). For the low magnitude event (Fig. 5d), $Q_{\max}$, Q_{average} and E_{wy} obtained by DHN were three times lower than those of AHN. Finally the high magnitude event chosen at L2 (Fig. 5e) showed that $Q_{\max}$, Q_{average} and E_{wy} obtained by AHN were twice as high as those of DHN, while in the low magnitude (Fig. 5f), $Q_{\max}$, Q_{average} and E_{wy} obtained by AHN were three times higher than those of DHN.

As a result, the two events selected at M2 and the high magnitude one in L1 showed a clear underestimation

of the Q values after the application of the AHN's SDRCs compared to the DHN's. Conversely, the low magnitude event in L1 and the two events in L2 presented an overestimation of the Q values of up to three times through the application of the AHN's SDRCs. Furthermore, the Q values obtained for the uncertainty bands and measured discharge reflected significant differences, ranging from 17 to 336% (Table 4), despite the drawn uncertainty bands do not overlap at M2 (Fig. 5a and 5b) and L1 (Fig. 5d), and presented a minimum overlap in L2 (Fig. 5f). Such values are even more remarkable when compared with the literature; Westerberg et al. (2011) found differences between two datasets ranging from -60 to 90% for low flows and $\pm 20\%$ for medium and high flows.

3.3.2 Annual scale

Figure 6 performs the Q dynamics according to AHN and DHN SDRCs, whilst Q_{average} and the annual water yield (A_{wy}) were used for comparing relatively the results in the quantification of surface water resources at both hydrometric networks (Table 5). At M1, the differences of up to one order of magnitude (in favour of DHN) which were observed between Q_{max} , A_{wy} and Q_{average} at the annual scale (Table 5) due to the different temporal resolution of the hydrometric networks, being daily in the case of AHN and 15-min for DHN. Thus, as AHN can only register daily values, it was impossible to accurately record a flood event because WS was recorded once per day reading a limnimeter at 8.00 h in the morning. Accordingly, more flood peaks were also recorded (Fig. 6a) when DHN was applied (i.e., 9 peaks, for only 5 peaks using AHN). Such differences were that large that the uncertainty boundaries of AHN and DHN do not overlap.

In M2, the A_{wy} (2013/14) varied between 9.412 hm^3 following AHN and 15.587 hm^3 by using the DHN one. The main difference in the hydrographs (Fig. 6b) was again that observed for Q_{max} , which was three times larger for DHN compared to AHN (Table 5). Furthermore, the application of AHN generated longer recessions and a wrong continuous record of baseflow from December to May, as WS levels higher than 0

were systematically registered despite that the stream was mostly dry during the whole period. Such sources of uncertainty are associated to the malfunctioning of the AHN recording system (Fig. 4b) and to the presence of residues in the SDRC equation (Fig. 3c). However, despite AHN and DHN uncertainties overlapped in simultaneous peaks, AHN recessions presented larger uncertainties than DHN.

The A_{wy} (2007/08) at L1 was double in AHN than DHN (Table 5). The Q_{max} during events was very different too, ranging from 1.350 to 6.910 $m^3 s^{-1}$ in L1 AHN and from 0.507 to 11.332 $m^3 s^{-1}$ in L1 DHN (Fig. 6c). These differences in Q_{max} peaks increased where uncertainty bands were applied, special in low to intermediate Q values, Uncertainties overlapped in Q values higher than 2 $m^3 s^{-1}$.

At the L2 station, the inadequate design of the low-waters channel in a cross-section of the stream with a very gentle slope (0.014%) caused a wrong transformation of WS to Q throughout the flow range. Therefore, Q was largely overestimated for the AHN SDRC for all WS as it is reflected in the annual Q_{max} , A_{wy} and also in the $Q_{average}$ (Table 5). The AHN uncertainty in Q values was reflected in all the WS range (Fig. 6d). For DHN stations, L2 presented the highest uncertainty. Nevertheless, DHN procedure in meterings and SDRC elaboration allowed to reduce the uncertainty compared to AHN. The difference between AHN and DHN in the Q_{max} during events was the highest of all stations, with relative differences ca. >200%.

4. Conclusions

The analysis of Q meterings and SDRCs deviations carried out at the present paper has been proved as a valid method for the assessment of the reliability of the data obtained from two independent hydrometric networks (i.e., AHN and DHN) with different data collection and recording systems, time series, maintenance and SDRCs management. Results allowed the discrimination of the stations presenting the

largest monitoring limitations, evidencing that AHN is way more problematic and limited than DHN. In addition, the analysis of the Q data registered for both hydrometric networks at different time scales (i.e., event and annual scales) has evidenced (and evaluated) the propagation of errors of such data from the field measurements to the final computations of the annual contribution. Those errors have showed differences of up to two orders of magnitude between the Q values measured for each hydrological network. Nevertheless, such values have been used anyway for decades for the quantification of the surface water resources in the Balearic Islands, as well as for hydrological and flooding-hazards prevention, planning, management and modelling.

The main source of uncertainty has been identified as that derived from the construction of SDRCs. The relative contribution of this to the general uncertainty ranged from 68 to 94% in AHN and from 72 to 87% in DHN. Q meterings general uncertainty had a relative contribution lower than 20%. Nevertheless, that contribution increased up to 32% in AHN due to the generally wrong procedure in the Q meterings. Furthermore, the assessment of the performance of AHN (i.e. implemented over 40 years) and DHN (i.e. 10 years of implementation) regarding total water yields resulted in a propagation of errors with contrasted and remarkable consequences for the quantification of the surface water resources in Mallorca. The impact was evaluated at each station and resulted in an average difference in water yield values of up to 183% at the event time scale and 142% at the annual scale, which represents an under/overestimation up to 6 and 22 hm³ respectively in the annual water yield. Such differences represent a third part of the historic AHN average value (underestimation scenario) or even larger than the major annual water yield contribution registered by AHN (overestimation scenario).

The differences between recording systems (especially in the case of M1) have been proved to be decisive in the provision of WS values, which are essential for a reliable computation of hydrological processes in

catchments characterised hydrologically by flash-floods (Gallart *et al.* 2008), as it is exactly the case of Sant Miquel and Na Borges catchments. Consequently, having an accurately measured WS record is essential for a proper estimation of the water resources, making practically impossible to amend historical records which were wrongly gauged (e.g. WS measured historically at AHN cannot be amended afterwards thus the proper rating curves created for DHN could not be either applied for a better estimation of the water resources).

It is well known that a poor maintenance of recording systems without a systematic field calibration for an optimum management of SDRCs leads to a lack of representativeness and validity of the data and, hence, to a loss of continuity of correct data in the historical series. Then, it is clear that fieldwork procedures for obtaining water stage and Q meterings are required as a non-stop maintenance of the digital system. If those procedures are not carried out, the recorded values will be never valid even if they have been obtained by means of a continuous hydrological process monitoring. Furthermore, computing streamflow uncertainties can reduce project costs and improve stakeholders' decisions (McMillan et al., 2018), so studies like the aforementioned (no matter if they have been carried out at global or regional scales) are needed and essential. Such studies provide clues to improve the planning and management of the scarce water resources (and flood hazards) in the Mediterranean, and particularly in an island, where these resources are eco-sociologically crucial (Kent et al. 2002) especially under the current global change context.

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Figures captions.

Fig. 1. Methodological workflow of the research study.

Fig. 2. Map of the Mallorca Island representing the analogic (AHN) and digital (DHN) hydrometric networks as well as the location of the Sant Miquel and Na Borges basins within the fluvial network of the island. Left set map represents the location of Mallorca in the Western Mediterranean Sea. Bottom and right set figures are upstream views of the selected gauging stations.

Fig. 3. Stage-discharge rating curves at M1 - Comafreda for (a) AHN and (b) DHN; at M2 - Sant Miquel for (c) AHN and (d) DHN; at L1 - Sa Vall for (e) AHN and (f) DHN; and at L2 - Ses Pastores for (g) AHN and (h) DHN. MP are Measured Points; TP are Theoretic Points; LMP are Low/intermediate Q measured points; LTP are Low/intermediate theoretic points; HMP are Intermediate/high Q measured points and HTP are Intermediate/high theoretic points.

Fig. 4. Accuracy assessment of instruments at M2 - SantMiquel gauging station: (a) calibration of digital records collected by a pressure probe with in situ fieldmeasurements of theWS and (b) comparison of analogic records collected by a limnigraph with digital records.

Fig. 5. Application of stage-discharge rating curves forAHNand DHNthrough hydrographs in high and lowmagnitude events at (a and b)M2- SantMiquel, (c and d) L1 - Sa Vall and (e and f) L2 - Ses Pastores gauging stations. The Q uncertainty band is also plotted in each of the hydrographs.

Fig. 6. Annual hydrograph for the (a)M1 - Comafreda, (b) M2- Sant Miquel, (c) L1 - Sa Vall and (d) L2 - Ses Pastores gauging stations according to each SDRC elaborated for AHN and DHN. The Q uncertainty band is also plotted in each of the hydrographs.

- AHN station
- AHN - DHN coincidence station
- DHN station
- Fluvial network
- ▭ Mountainous Sant Miquel catchment
- ▭ Lowland Na Borges catchment

AHN

M1 - Comafreda

DHN

(c)

M2 - Sant Miquel

(d)

(e)

L1 - Sa Vall

(f)

(g)

L2 - Ses Pastores

(h)

(a)

(b)

Table 1. Main characteristics of selected catchments as well as average runoff and type of recording systems at gauging stations.

Catchment	Precipitation	Land uses	Gauging station	Average annual runoff (AHN)	Recording systems	Weirs types
Mountainous Sant Miquel 152 km ²	1,262 mm (1993-2011, Lluc AEMET station)	Forest and agricultural	M1 - Comafreda 31 km ²	48 mm $\pm$ 144% (1977-2015)	AHN: Limnimeter DHN: Water height probe	Rectangular broad-crested at low and high-flow channels
			M2 - Sant Miquel 52 km ²	373 mm $\pm$ 81% (1968-2015)	AHN: Limnimeter DHN: Water height probe	Rectangular broad-crested
Lowland Na Borges 320 km ²	572 mm (1974-2006, Boscana Nou AEMET station)	Agricultural	L1 - Sa Vall 264 km ²	157 mm $\pm$ 89% (1971-2009)	AHN: Limnimeter DHN: Water height probe	Rectangular broad-crested at low and high-flow channels
			L2 - Ses Pastores 316 km ²	4 mm $\pm$ 177% (1976-2015)	AHN: Limnimeter DHN: Water height probe	

Table 2. Number and type of metering's, instruments and stage-discharge rating curves characteristics at each gauging station.

Gauging station	SDRC	Readings and WS range (m)	Q metering's and WS range (m)	Sampling frequency	Type of Q metering's	Instrument, velocity measurement range and accuracy for Q metering's	SDRC type	SDRC segments	Equation	n Manning	Slope
M1 - Comafreda	AHN	0	5 (0.07 - 0.38 m)	Current measurements since 1960s	Float method	--	Theoretic	1	Power regression	-	-
	DHN	11 (0.00 - 0.70 m)	14 (0.04 - 2.15 m)	Every 2 months and during flood events	Area-velocity-method	OTT MF PRO [0 to 6.09 m s ⁻¹ accuracy of 2% (0 to 3 m s ⁻¹) and 4% (3 to 5 m s ⁻¹) for measured values $\pm$ 0.015 m s ⁻¹ (SD)]	Experimental and Manning formulae for high Q	1	Polynomic	0.060	1.28·10 ⁻²
M2 - Sant Miquel	AHN	0	6 (0.20 - 0.90 m)	Current measurements since 1960s	Area-velocity-method	OTT C31 (0.025 to 10 m s ⁻¹ accuracy of 2%)	Theoretic	2 (0.05 - 0.55 m // 0.55 - 2.00 m)	Exponential	-	-
	DHN	12 (0.00 - 1.52 m)	11 (0.11 - 1.25 m)	Every 2 months and during flood events	Area-velocity-method	OTT MF PRO [0 to 6.09 m s ⁻¹ accuracy of 2% (0 to 3 m s ⁻¹) and 4% (3 to 5 m s ⁻¹) for measured values $\pm$ 0.015 m s ⁻¹ (SD)]	Experimental and Manning formulae for high Q	1	Polynomic	0.065	1.55·10 ⁻²
L1 - Sa Vall	AHN	0	0	Without measurements	--	--	Theoretic	2 (0.00 - 0.33 m // 0.33 - 1.22 m)	Exponential and lineal	-	-
	DHN	67 (0.00 - 0.90 m)	32 (0.09 - 0.83 m)	Every 2 months and during flood events	Area-velocity-method	OTT C31 (0.025 to 10 m s ⁻¹ accuracy of 2%)	Experimental	2 (0.00 - 0.21 m // 0.21 - 2.50 m)	Polynomic and lineal	-	-
L2 - Ses Pastores	AHN	0	0	Without measurements	--	--	Theoretic	1	Polynomic	-	-
	DHN	0	5 (0.50 - 1.60 m)	Every 2 months and during flood events	Area-velocity-method	OTT C31 (0.025 to 10 m s ⁻¹ accuracy of 2%)	Experimental and Manning formulae for high Q	1	Potential	0.029	1.42·10 ⁻⁴

Table 3. Proportion of gauges and its category classification and the global uncertainty components such as Q metering's (ϵ_1) and error due to stage-discharge rating curve uncertainty (ϵ_2) for AHN and DHN at M1 - Comafreda, M2 - Sant Miquel, L1 - Sa Vall and L2 - Ses Pastores stations.

Category	Percentage of deviation	M1 - Comafreda		M2 - Sant Miquel		L1 - Sa Vall		L2 - Ses Pastores		TOTAL	
		AHN	DHN	AHN	DHN	AHN	DHN	AHN	DHN	AHN	DHN
Good	0-10	0	36	0	55	13	47	0	10	8	40
Acceptable	11-20	0	21	50	18	3	31	0	20	8	25
Suspect	21-50	0	7	33	9	31	19	30	50	28	19
Poor	>50	100	36	17	18	53	3	70	20	57	15
Uncertainty components											
ϵ_1		16.4	5.9	13.3	5.7	---	6.8	---	5.6		
ϵ_2		274	28.3	28.3	22.4	48.8	17.3	64.0	37.3		
Total		290.4	34.2	41.6	28.1	48.8	24.1	64.0	42.9		

Table 4. Maximum and average discharge as well as total contribution at event scale in the M2 - Sant Miquel, L1 - Sa Vall and L2 - Ses Pastores gauging stations applying the discharge transformation according to the stage-discharge rating curves and its uncertainty band of AHN and DHN.

Magnitude type of the events	Gauging station	Event	Rating curve	Maximum water stage (m)	$Q_{\max} \text{ (m}^3 \text{ s}^{-1}\text{)}$			Measured AHN - DHN ratio	$Q_{\text{average}} \text{ (m}^3 \text{ s}^{-1}\text{)}$			Measured AHN - DHN ratio	$E_{\text{wy}} \text{ (hm}^3\text{)}$			Measured AHN - DHN ratio
					Low band	High band	Measured		Low band	High band	Measured		Low band	High band	Measured	
High	Sant Miquel	29/09/2014	AHN	1.03	4.960	12.110	8.552	35	0.444	1.084	0.838	24	0.051	0.125	0.087	31
			DHN	1.15	17.780	31.633	24.694		2.511	4.468	3.488		0.206	0.366	0.286	
	Sa Vall	28/11/2007	AHN	2.13	3.524	10.283	6.910	61	1.800	5.252	3.688	92	0.468	1.366	0.856	92
			DHN		8.613	14.064	11.332		2.816	4.599	3.988		0.733	1.196	0.926	
	Ses Pastores	22/11/2007	AHN	1.62	4.288	19.533	11.911	253	0.597	2.720	1.658	281	0.311	1.415	0.861	281
			DHN		2.686	6.735	4.713		0.337	0.844	0.591		0.175	0.439	0.307	
Low	Sant Miquel	04/11/2014	AHN	0.09	0.154	0.377	0.267	17	0.091	0.222	0.156	17	0.005	0.011	0.008	40
			DHN	0.19	1.110	1.975	1.542		0.656	1.168	0.912		0.014	0.025	0.020	
	Sa Vall	20/02/2008	AHN	0.59	0.651	1.898	1.276	276	0.389	1.135	0.763	315	0.008	0.025	0.016	315
			DHN		0.351	0.573	0.462		0.184	0.300	0.242		0.004	0.006	0.005	
	Ses Pastores	05/10/2007	AHN	0.42	0.199	0.908	0.554	317	0.053	0.243	0.148	335	0.015	0.067	0.041	336
			DHN		0.100	0.250	0.175		0.025	0.063	0.044		0.007	0.017	0.012	

Table 5. Annual water contribution, maximum and average discharge as well as relative difference at the M1 - Comafreda, M2 - Sant Miquel, L1 - Sa Vall and L2 - Ses Pastores gauging stations applying the stage-discharge rating curves and its uncertainty band from AHN and DHN.

Gauging station	Rating curve	$Q_{\max} \text{ (m}^3 \text{ s}^{-1}\text{)}$				$Q_{\text{average}} \text{ (m}^3 \text{ s}^{-1}\text{)}$				$A_{\text{wy}} \text{ (hm}^3\text{)}$			
		<i>Low band</i>	<i>High band</i>	<i>Measured</i>	<i>Measured AHN-DHN ratio</i>	<i>Low band</i>	<i>High band</i>	<i>Measured</i>	<i>Measured AHN-DHN ratio</i>	<i>Low band</i>	<i>High band</i>	<i>Measured</i>	<i>Measured AHN-DHN ratio</i>
M1 - Comafreda	AHN	--	2.324	0.801		--	0.025	0.007		--	0.776	0.267	
	DHN	13.879	28.220	21.028		0.043	0.087	0.065		1.354	2.752	2.051	
M2 - Sant Miquel	AHN	4.960	12.110	8.552		0.183	0.446	0.312		5.767	14.079	9.412	
	DHN	17.780	31.633	24.694	35	0.356	0.633	0.494	63	11.223	19.967	15.587	60
L1 - Sa Vall	AHN	3.524	10.283	6.910		0.195	0.569	0.382		6.165	17.986	12.088	
	DHN	8.613	14.064	11.332	61	0.145	0.237	0.191	200	4.587	7.490	6.035	200
L2 - Ses Pastores	AHN	3.910	17.939	10.850		0.374	1.704	1.039		11.827	53.881	32.854	
	DHN	2.430	6.093	4.624	235	0.201	0.505	0.353	294	6.367	15.961	11.170	294

1 **Table 6.** Annual water contribution, maximum and average discharge as well as relative difference at the
2 M1 - Comafreda, M2 - Sant Miquel, L1 - Sa Vall and L2 - Ses Pastores gauging stations applying the stage-
3 discharge rating curves of AHN and DHN.

Gauging station	Rating curve	A_{wy} (hm ³)	Measured AHN - DHN ratio	Q_{max} (m ³ s ⁻¹)	Measured AHN - DHN ratio	$Q_{average}$ (m ³ s ⁻¹)	Measured AHN - DHN ratio
M1 - Comafreda	AHN	0.267	13	0.801	4	0.007	11
	DHN	2.051		21.028		0.065	
M2 - Sant Miquel	AHN	9.412	60	8.552	35	0.312	63
	DHN	15.587		24.694		0.494	
L1 - Sa Vall	AHN	12.088	200	6.910	61	0.382	200
	DHN	6.035		11.332		0.191	
L2 - Ses Pastores	AHN	32.854	294	10.850	235	1.039	294
	DHN	11.170		4.624		0.353	

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