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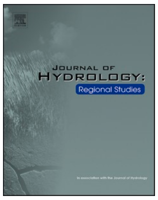

Expanding information for flood frequency analysis using a weather generator: Application in a Spanish Mediterranean catchment

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ABSTRACT

Study region: The proposed methodology has been applied in the Segura River basin (south-eastern Spain) whose hydrological regime has a high anthropic alteration and catastrophic floods have occurred at different times for centuries. The climate is generally semi-arid, with frequent droughts but also floods caused mainly by rainfall associated with mesoscale convective systems.

Study focus: We present a methodology that exploits all available information to obtain reliable low-frequency flood quantiles through the integration of different methods. First, a Weather Generator (WG) was implemented with the results from a regional study of annual maximum precipitation. Second, a rainfall temporal disaggregation procedure was carried out to capture the sub-daily behavior of flood generating storms. Third, a fully-distributed Hydrological Model (HM) was implemented including the role of sediments in extreme events. Finally, the estimation of flood quantiles using plotting positions was validated with systematic and non-systematic information.

New Hydrological Insights for the region: The use of this process-based approach allows to reproduce the main hydrometeorological mechanisms associated with floods in the region studied. Accurate flood quantiles up to 200 years have been possible to obtain, which represents an important advance in the knowledge of the basin since reliable flood quantiles of only 20 years were adequately captured with the current observations. Finally, sediment yield has been proven to be an important factor for the region hydrographs' reconstruction.

1. Introduction

Reliable flood quantile estimations are indispensable for the correct flood risk analysis and management. Despite new approaches for their estimation have been emerging over recent years, the fact is that current flood quantile estimations still present high uncertainty. Flood Frequency Analysis (FFA) methods that can be roughly grouped into the following three categories: statistical or probabilistic, deterministic, and hybrid or mixed (Salazar-Galán et al., 2021). The short length of the available time series and the low

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density of monitoring stations are the main source of uncertainty of the classical statistical methods, especially in arid/semi-arid regions (Metzger et al., 2020). The lack of long-term observations of peak flood discharges has always been one of the concerns of water experts, which has led to the development of various Regional Flood Frequency Analysis (RFFA) models (Allahbakhshian-Farsani et al., 2020). The RFFA models basically derive design flood estimates transferring flood characteristics information from gauged to ungauged catchments. However, these models still present difficulties when applied in arid or semi-arid regions. Zaman et al. (2012) undertook a RFFA analysis for the semi-arid and arid regions of Australia concluding that arid catchments exhibited much steeper flood frequency growth curve than that of the humid region. Smith et al. (2015) showed that arid regional regression models perform poorer than humid regional models, presumably because arid regions are spatially more heterogeneous.

Deterministic procedures, mainly based on the design storm, draw from the uncertain premise that return periods of concurrent rainfall and peak discharge are assumed to be the same. Also, it's assumed that design flood of a given return period can be estimated based on a single rainfall duration that generates the highest peak discharge (Beneyto et al., 2020). As a result of the rapid increase of the computing capacity, combining statistical and deterministic methods in a Synthetic Continuous Simulation (SCS) is becoming one of the most extensively adopted approach for FFA between the scientific community (Winter et al., 2019). Coupling a Hydrological Model (HM) allows the synthetic generation of infinite data series of hydrometeorological variables. Notwithstanding, WGs must be fed with the adequate amount of information to perform correctly, especially when trying to reproduce extremes (Soltani and Hoogenboom, 2003). Actually, Metzger et al. (2020) examined and compared observed and synthetic flood data (i.e., annual maxima series) in different arid/semiarid and non-arid watersheds, reaching to the conclusion that the largest errors in the estimated quantiles were presented in the rivers with a reduced number of flood episodes per year with a large coefficient of variation. This lack of information demands the incorporation of additional flood information (Merz and Blöschl, 2008a, 2008b). This may include; (i) non-systematic data (i.e., historical data and palaeofloods) as in Benito et al. (2020), (ii) regional studies of annual maximum precipitation as in Evin et al. (2018) or (iii) the combination of both as in Beneyto et al. (2020), which considerably reduced the uncertainty of the flood quantile estimations.

Despite SCS addresses the major drawbacks of event-based approaches (i.e. initial conditions of the basin and the spatio-temporal distribution of the precipitation), this approach is limited by the high computational demands required, especially for finer temporal resolutions (Peleg et al., 2017). However, as demonstrated by Ficchì et al. (2016) and Huang et al. (2019), shorter time steps significantly improve streamflow simulations. A common practice to deal with the high computational requirements of sub-daily WGs is to generate daily data and apply disaggregation procedures of the climatic variables for downscaling to finer temporal scales. A review of the different disaggregation methods can be found in Pui et al. (2012), which have been satisfactorily applied in combination with HMs in many flood studies (e.g. Acharya et al., 2022; Mackay et al., 2001; Winter et al., 2019). Another critical aspect of SCS is the choice of the HMs. In the case of Mediterranean catchments, the use of distributed HMs is convenient since it is possible to consider both the effect of the high spatio–temporal variability of storms and the spatial variability of the catchment attributes that together shape the hydrological response (Salazar-Galán et al., 2021).

In the case of the Spanish Mediterranean basins, most of the rivers show an ephemeral behavior, remaining dry most of the time, but with a flashy response to typical intense precipitation events generated by Mesoscale Convective Systems (MCSs) during autumn months (Rigo et al., 2019). These MCS usually take place during the late summer and autumn months. This remarked precipitation pattern along with small catchment sizes with sharply differentiated steep slopes, sparse vegetation, (Marco, 1995) and a large urban growth in flood-prone areas through a deficient spatial planning have led to an increase in the number of floods over the recent years. Consequently, the number of fatalities and economic losses has experienced a strong growth over the last years (López-Martínez et al., 2017). In addition, an intensification of torrential rain events in autumn is to be expected for this region due to climate change (Millán, 2014). The significant spatial and temporal hydrological variability of Mediterranean-climate catchments (Fortesa et al., 2020) along with low flows or no-flow that present the rivers for most part of the year (Cohn et al., 2013) increase even more the difficulty in modeling the hydrological processes and thus their prediction. Increasing the knowledge on the relationship between meteorological events and the impact of floods requires huge spatiotemporal databases (Gil-Guirado et al., 2022), which are rarely available.

Following in the footsteps of the previous work by Beneyto et al., (2020), this paper presents an improved methodology for the adequate estimation of low-frequency flood quantiles based on SCS. Specifically, the enhanced approach presented in this manuscript incorporates the following improvements: (i) the temporal resolution has been lowered to hourly as opposed to daily, both for the precipitation and for the discharges' generation; (ii) a complete ad hoc regional study of annual maximum precipitation has been performed. While in Beneyto et al. (2020) the authors incorporated the information from an existing study published in 1999, this ad hoc study incorporates precipitation records up to 2023, therefore, regional quantile estimations are more accurate; (iii) erosion and sediment yield have also been modeled through the HM; and (iv) the HM has been implemented both in natural regime and in actual (altered) regime for being able to validate the discharges with the non-systematic flood data. This methodological approach has been tested in a case study, namely in the Segura River basin (Spain).

2. Case study

2.1. Study area

The Segura River basin has an extension of 15150 km^2 and is located in southeast of Spain. The headwaters lies in the Sub-Betic system, at an elevation of 2040 m above sea level, flowing into the Mediterranean Sea at Guardamar del Segura (Alicante).

The climate is sub-humid in the headwaters and semi-arid in the middle and lower basin, which represents the 80% of the catchment extension (CHS, 2015). The average rainfall is 375 mm/year, which presents important torrential rain mechanisms and marked daily precipitation concentration in time and high spatial irregularity (Miró et al., 2021). Drought episodes are frequent in the summer months with essentially no rainfall (CHS, 2015) or occasional torrential convective downpours. Heavy rainfalls leading to extraordinary and extreme floods are related to late summer or autumn MCS (Rigo et al., 2019) fed by Mediterranean moisture and enhanced by orographic effect of the Subbaetic Range Mountains close to the coast. For example, the most recent extreme rainfall event in late summer 2019 accumulated up to 500 mm in just 3 days (Fig. 2), causing devastating impacts in the catchment. Similar extreme torrential events were recorded in 1916, 1946, 1948, 1987 and 2016 (Núñez Mora, 2019). Lastly, frontal systems linked to Atlantic zonal flow during winter and spring give the secondary monthly rainfall maximum.

2.2. Data collection

Meteorological records for this research were collected from three different sources: (i) daily precipitation observations were obtained from the State Meteorology Agency (AEMET); (ii) daily precipitation and daily max./min. temperatures were obtained from the Spain02-v5 reanalysis dataset (Herrera et al., 2016; Kotlarski et al., 2017); and (iii) sub-daily precipitation records (hourly records) were obtained from the Automated Hydrological Information Systems (SAIH) of the three River Basin Authorities, namely Júcar, Segura and Guadalquivir basins.

A regional study of annual maximum precipitation was carried out using daily precipitation observations from AEMET, using data from a total of 210 rain gauges (Fig. 3) with at least a 30-year time series. To synthetically generate long precipitation series, data from the Spain02-v5 dataset were used, consisting of 52 grids from 1951 to 2015 (66 years) distributed over the catchment area (Fig. 3). For the temporal disaggregation of daily precipitation, sub-daily records from 59 rain gauges from different SAIH, containing 154 rainfall episodes of at least 30 mm, were used. Runoff data were obtained from the Segura SAIH. The non-systematic flood data were collected from different sources, including documentary datasets (such as the flood chronology database of the Segura River Basin Authority) and palaeoflood studies (Benito et al., 2010; Francés, 1995; Machado et al., 2011).

Lastly, the spatial information for the implementation of the HM was collected from different sources: drainage network, water masses, hydrogeological units and aquifer characteristics were obtained from the Segura River Basin Authority; the digital terrain model (DEM), natural coverage, land use, and geology maps were obtained from the Spanish National Geographic Institute (https://www.ign.es); the information from the SoilGrids250m (https://soilgrids.org) and the 3D Soil Hydraulic Database (Panagos et al., 2012; Tóth et al., 2017) complemented with the layers from CORINE land cover (https://land.copernicus.eu/pan-european/corine-land-cover) at 1:100,000, as well as from the Information System on Land Occupation of Spain (SIOSE) (https://www.siose.es/usos-de-suelo) at 1:25,000, were processed to obtain the hydraulic characteristics of the soil maps; and the data from the European Soil Data Center (https://esdac.jrc.ec.europa.eu) was used to create all necessary maps for modeling the sediment cycle.

3. Methodology

3.1. General Framework

In order to achieve the objective of this study, the following methodology has been proposed:

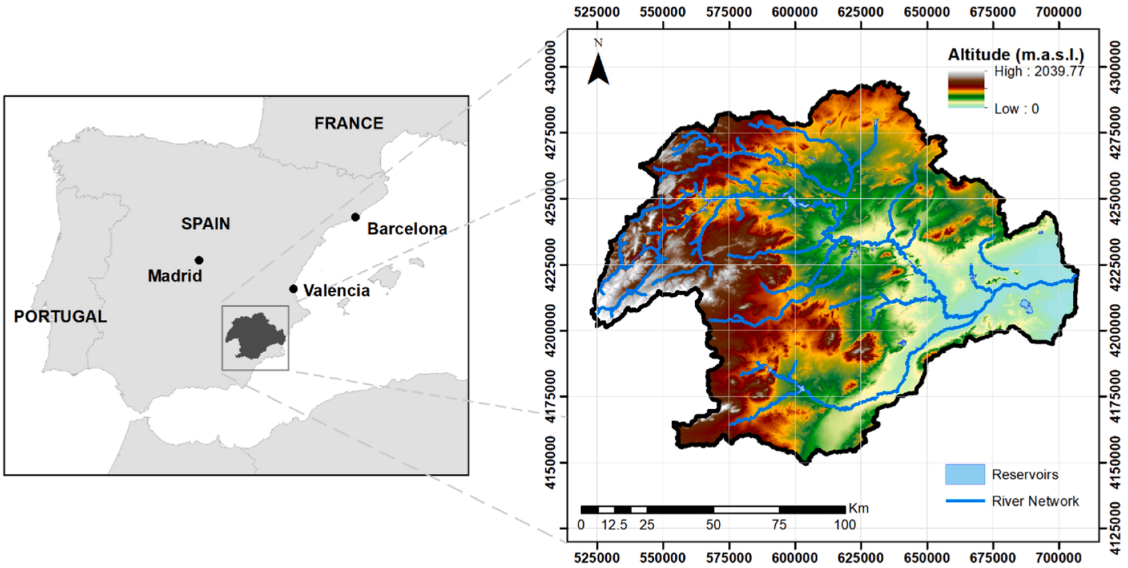

Fig. 1. – Study area: Segura River basin.

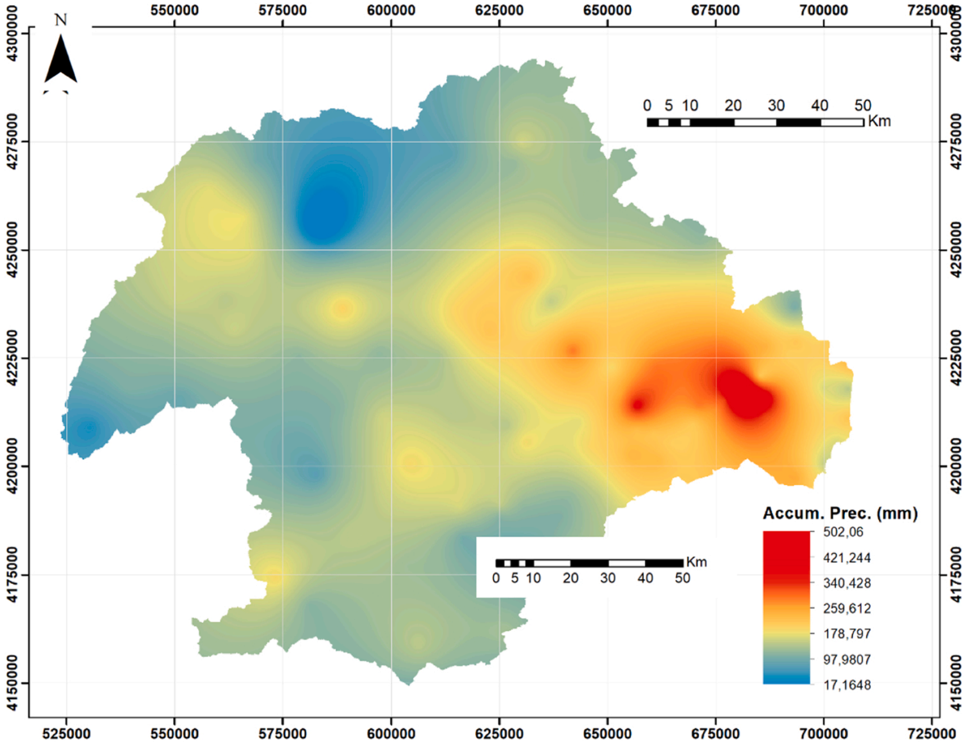

Fig. 2. – Spatial distribution of the total accumulated precipitation in the Segura River basin during the 11–14 September 2019 event.

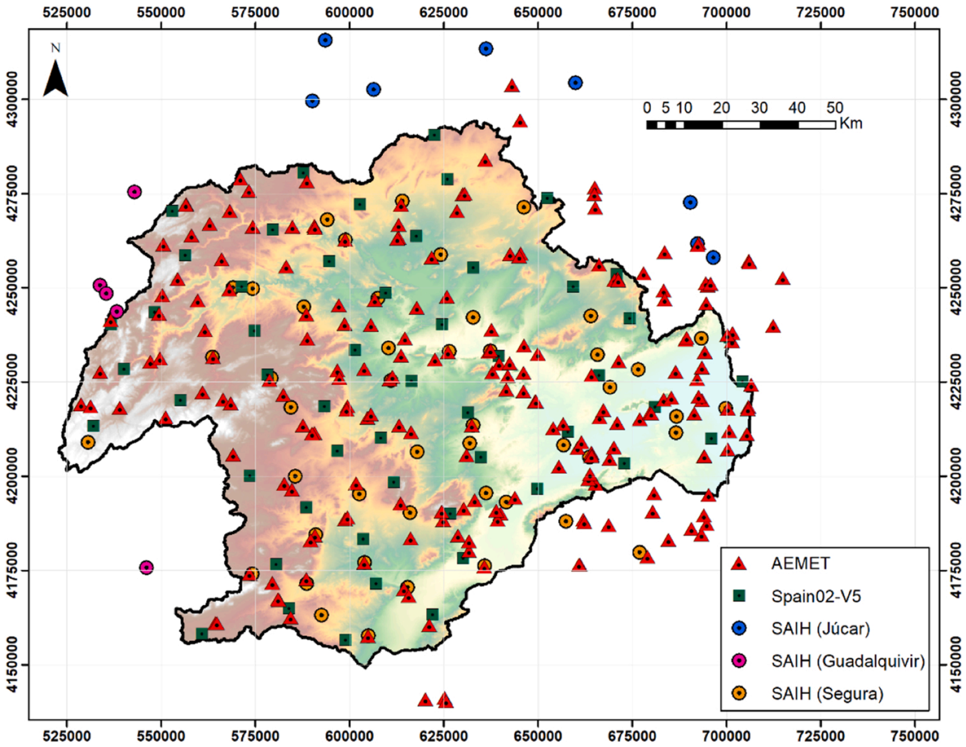

Fig. 3. – Location of daily and sub-daily meteorological information over the Segura River basin.

(1) Perform a regional study of annual maximum precipitation to expand the available information.
(2) Application of a WG for simulating long series of daily precipitation and temperatures with an additional calibration of the parameters related to the extremes using (1) to capture the different spatio-temporal rainfall patterns.
(3) Selection of a number of high magnitude storms as the input of the next step (storm disaggregation). This procedure will depend on the specific characteristics of the study area and the aim of each particular research.
(4) Storm disaggregation to sub-daily (e.g. hourly) temporal resolution and validation with the available observations (e.g., IDF curves, spatial pattern, etc.).
(5) Implementation (parameterization, calibration, and validation) of a fully-distributed HM at hourly temporal resolution to take into account both the temporal resolution of the disaggregated storms and the spatio-temporal variability of hydrological processes.
(6) Simulation of hourly discharges with the fully-distributed HM model from the selected storms, considering a warm-up period of three months to characterize the soil moisture initial conditions of the basin in each storm.
(7) Quantile estimation considering the annual peak flows obtained from HM simulations.
(8) Quantile validation with systematic (flow gauge stations) and non-systematic (historical and palaeoflood information) observations in the points of interest of the catchment.

A workflow diagram with the detailed methodology can be observed in Fig. 4. The following subsections will explain in detail each step of the methodology.

3.2. *Regional study of annual maximum precipitation*

First step of the methodology, if not available, is to perform a regional study of annual maximum precipitation. Results obtained from this study will be used in the implementation of the WG as explained in the following subsection. A comparison of regionalization methods to improve the at-site estimates of daily precipitation can be found in Haruna et al. (2022).

In our case, we performed a regional analysis based on the classical methodology of Hosking and Wallis (1997), (1993), which uses the method of the Index Variable (Dalrymple, 1960) together with linear moments. The first step was to screen the data and define the domain. We defined a 10×10 km^2 grid over our case study and processed the observations from the 210 rain gauges. Only series with

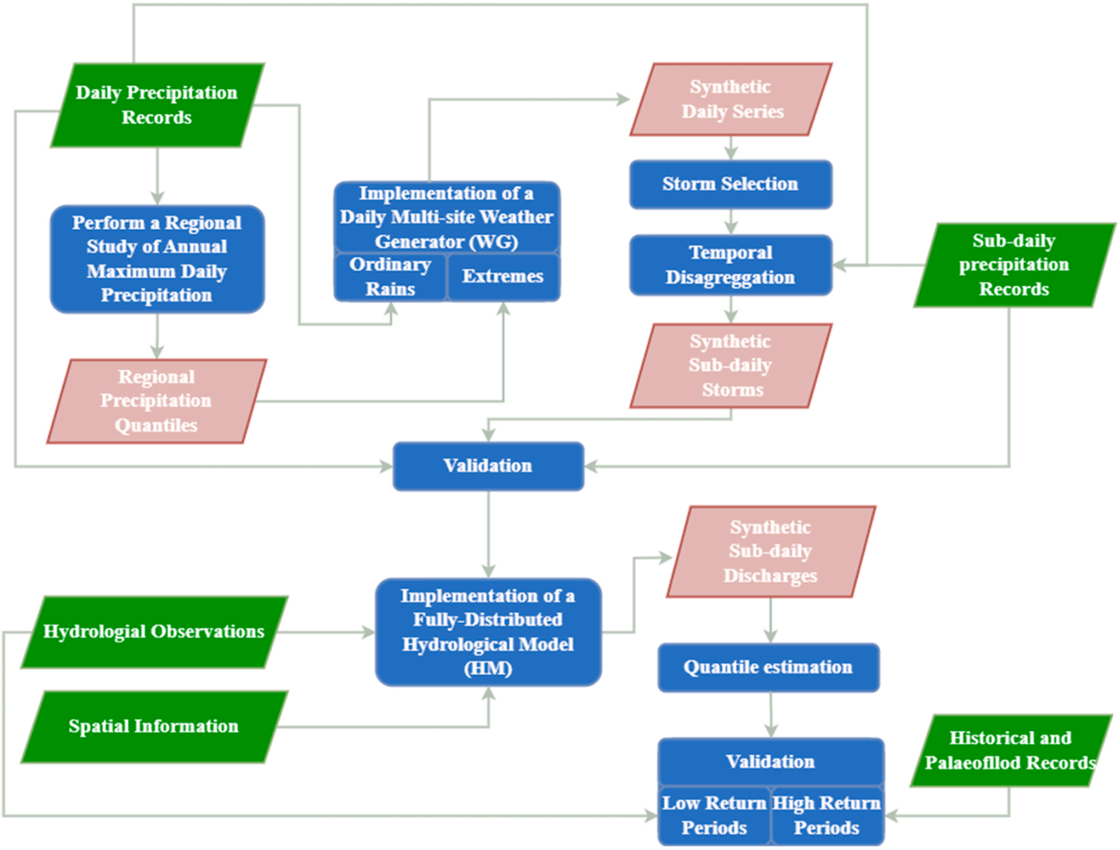

Fig. 4. – Workflow chart of the proposed methodology.

more than 30 years of records were included, and the missing records were filled in with information from other gauges within the same grid. In this way, we generated a continuous equivalent data series in each of the grids.

Secondly, as proposed by Hosking and Wallis (1997), (1993), a Discordance and Homogeneity test based on the series L-moments were performed to identify the homogeneous regions.

Lastly, once the homogeneous regions were identified and following the premises of the Index Variable method (Dalrymple, 1960), the most appropriate probability function was selected for each of them and the regional quantiles were calculated by deregionalization.

3.3. Implementation of a daily weather generator

The WG used in the present study is GWEX (Evin et al., 2018). GWEX is a multi-site WG focused on the adequate reproduction of extreme events. It offers the possibility to model the precipitation amount in 3-day periods and it incorporates the heavy-tailed distribution function Extended Generalized Pareto Distribution (E-GPD) (Papastathopoulos and Tawn, 2013) to model the precipitation amounts. This is a three-parameter distribution function, being the shape parameter ξ the one with the greatest influence in the right tail of the distribution function.

52 grids spread along the catchment extension were obtained from the Spain02-v5 dataset for the synthetic generation of daily precipitation and max/min temperatures. Following the methodology presented by Beneyto et al. (2020), all the WG parameters were firstly estimated from the available observations (i.e. 1950–2015). The shape parameter ξ of the E-GPD is then estimated with the regional quantiles obtained from the regional study of annual maximum precipitation, which is the less uncertain approach to incorporate the information of the regional study into the WG (Beneyto et al., 2023). With all the parameters estimated, long synthetic daily precipitation and max/min temperatures data series were generated at each location.

3.4. Storm selection and temporal disaggregation

From the simulated synthetic data series and interpolation of their areal precipitation using the Kriging method, the events with the largest values were selected for disaggregation. Each of the storms was considered as a sample formed by: (i) the day of the highest precipitation; (ii) the 2 days after the peak to account for the falling limb; and (iii) the 100 previous days in order to consider the initial conditions of the state variables into the fully-distributed hydrological model.

Different models and approaches can be found in the scientific literature for the univariate disaggregation of daily series at a single point. Models based on rectangular pulse point processes (Bartlett-Lewis, Neyman-Scott (Rodriguez-Iturbe et al., 1987)), and later variants (Koutsoyiannis et al., 2003) are especially well known. More recently, the Method of Fragments (MOF) was proposed (Mehrotra et al., 2012; Pathiraja et al., 2012).

The problem with univariate methods is that they produce disaggregation of daily series at each single point independently without considering the spatial dependency, which leads to unrealistic rain fields. Various modeling alternatives are presented in the scientific literature to address this problem (Koutsoyiannis et al., 2003). Among the most recent methods that have raised more interest due to their efficiency and realism is the non-parametric method S-MOF (Spatial-Method of Fragments). This procedure extends the original idea of the aforementioned MOF method to the spatial dimension (Lu and Qin, 2014; Mehrotra et al., 2012; Mezghani and Hingray, 2009; Pathiraja et al., 2012). The most recent contribution corresponds to Breinl and Di Baldassarre (2019), who successfully applied the method in a 6200 km^2 region located in northern Italy. The method applied here essentially follows the scheme proposed by these latter authors, disaggregating the daily synthetic storms to sub-daily data series (hourly), considering the fragments obtained from 154 different rainfall events within the SAIH databases of the three basin authorities. Finally, according to the isolines map proposed by Témez (1987), the disaggregated storms were validated with the torrentiality index.

3.5. Implementation of a fully-distributed HM

The disaggregated storms were converted into discharges with a rainfall-runoff model. In this study, the ecohydrological model TETIS (Francés et al., 2007) was used. It is a conceptual (i.e. tank structure) model, with physically based parameters and fully-distributed in space. Due to the size of the basin, the Segura basin was divided into five sub-basins, with the downstream basins being fed by the outputs of the upstream basins. Since in some cases (e.g., ravines) the solid flow could be a significant percentage of the total flow, sediment submodels were also implemented to determine the sediment flow. Finally, the HM has been implemented under two hypotheses: in the current regime and in the natural regime. For this last case, current land uses and coverages have been considered, but without considering any type of alteration in the flow through reservoirs or transfers (i.e., Abanilla-Santomera and Paretón de Totana). In this way and given the high hydrological regulation of the Segura River basin, it has been possible to compare the results obtained with non-systematic information, in addition to visualizing the current reduction capacity with the operation of all the reservoirs under the considered hypothesis of initial conditions.

3.6. Quantile estimation and validation

Quantile estimation was performed computing the plotting positions of the simulated discharges following the Cunnane formulae (Cunnane, 1978):

$$F_i = \frac{i - \alpha}{N + 1 - 2\alpha} \tag{1}$$

The validation of the quantile estimations was carried out considering two sources of information: the available systematic observations for validating the ordinary discharges; and similarly to Beneyto et al. (2020), historical and palaeoflood information from previous studies (Benito et al., 2010; Francés, 1995; Machado et al., 2011) for validating the exceptional flood episodes.

4. Results

4.1. Regional study of annual maximum precipitation

From all calculated L-moments, it was decided to focus the analysis on the L-CV due to its greater discriminatory capacity compared to the L-CS and L-CC (Hosking and Wallis, 1993). Fig. 5 shows the calculated values of the L-CVs in each cell (blank cells correspond to cells where it was not possible to obtain a data series with the specification mentioned in Section 3.2). As can be observed, there is an important spatial variability, which clearly indicates the impossibility of considering a single homogeneous region. Indeed, the heterogeneity test for the 135 cells that make up the total region yielded a result of H1 = 6.26, a value well above the limit (H < 2 (Hosking and Wallis, 1997)) from which the region must be considered definitively heterogeneous.

After considering different physical descriptors (e.g., altitude or geomorphology), the distance to the coastline was proved to be the only one determinant. Two regions (i.e., Zone 1 and Zone 2) were created with their limits at different distances to the coast (from 30 to 100 km). Means and standard deviations of the regional dispersions were obtained in each case. These were calculated through 500 Monte Carlo simulations assuming a Kappa distribution fitted with the weighted regional sample L-moments. Results shown a clear decrease in the L-CV values in both regions with the distance to the coastline (Fig. 6 right), being the optimal at a 70 km distance, where both regions were homogeneous. Notwithstanding, it was found that the results improved incorporating the geomorphological information in the northern area and thus the delimitation line was modified to include the information in these four cells (Fig. 6 left).

In the current official regional study for the continental Spain, Ferrer Polo and López Ardiles, (1994) found similar satisfactory results for the distribution functions SQRT-Etmax, GEV and TCEV. These authors finally selected the SQRT-Etmax due to its parsimony (only two parameters). For this reason, in this study these three distributions were tested, obtaining the best fit for the GEV and TCEV functions in both regions. Again, the lower number of parameters of the GEV (3) compared to the TCEV (4) at equal goodness-of-fit led to the former being selected as the regional distribution function in the two regions. Finally, local quantiles were obtained in each grid cell by deregionalization.

4.2. Daily weather generator

As mentioned before, the daily WG GWEX (Evin et al., 2018) was used to generate long synthetic data series of precipitation. The local quantiles obtained in the regional study of annual maximum precipitation were incorporated in GWEX for its calibration/validation following the methodology proposed by Beneyto et al. (2020). In this case, estimated local quantiles within each homogeneous region were grouped to form a range of acceptable values (represented as black lines in Fig. 7). From the 52 grids of the Spain02-v5 dataset, 23 fell within the extents of Zone 1 and 29 in Zone 2. To capture quantiles of high return period, 5.000 years of synthetic precipitation were generated at each grid. Firstly, parameter ξ was left as per the WG default value, obtaining a systematic quantile underestimation for both zones (left panel in Fig. 7). Secondly, the shape parameter ξ was estimated for each region and for different periods of the year to make all simulated quantiles fall within the acceptable range. These periods were selected considering the rainfall patterns of the study area: from January to May (JFMAM); from June to August (JJA); and from September to December

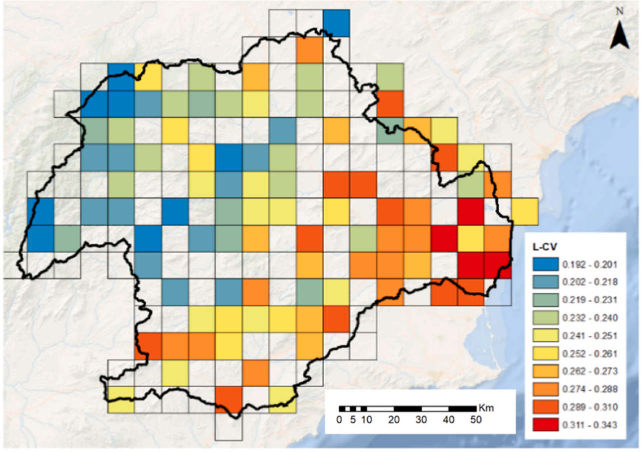

Fig. 5–. Spatial variability of the L-CV.

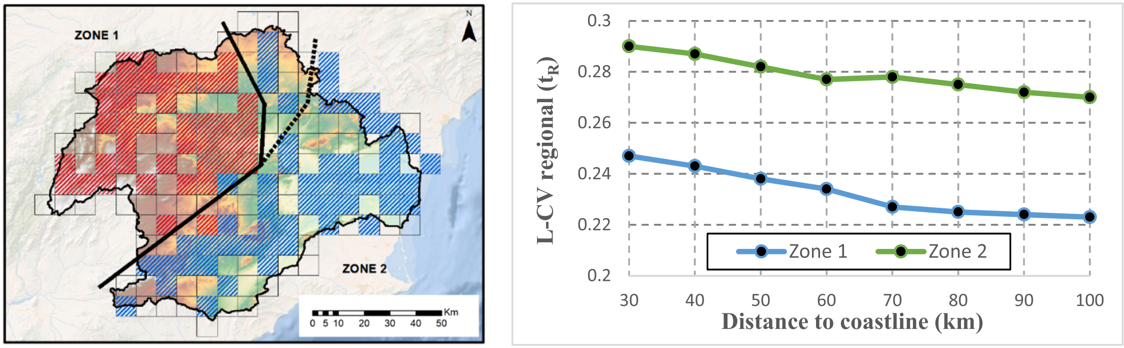

Fig. 6–. Left: regions with a 70 km distance threshold to the coastline before considering the northern area (dashed line) and after (continuous line); and right: variation of the regional L-CV with the distance to the coastline.

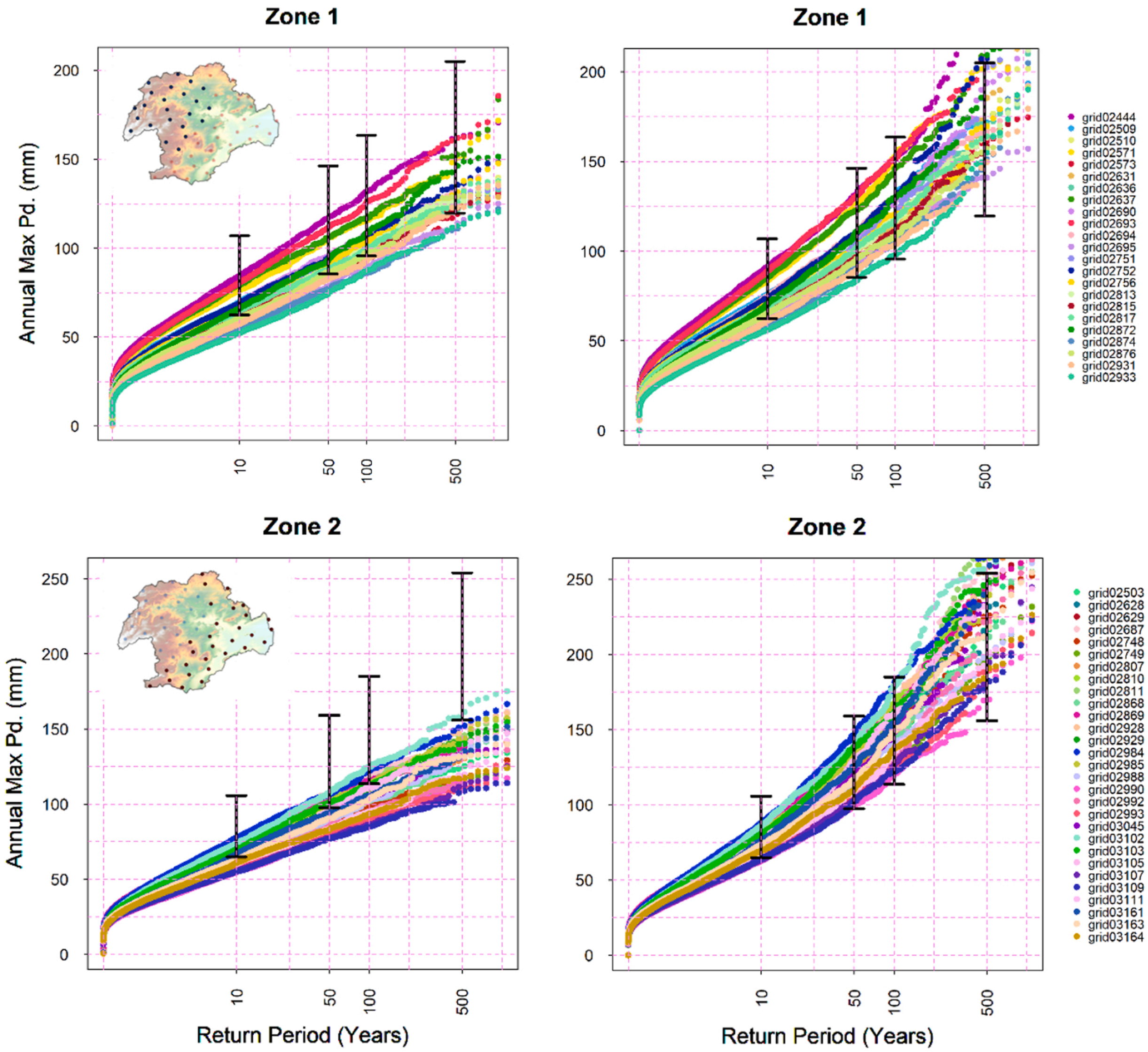

Fig. 7. - WG Calibration: Plotting Positions of simulated precipitation data series before calibrating the shape parameter ξ (left) and after (right) for both regions.

(SOND). (Fig. 7).

Estimated shape parameters ξ for each zone and each period of time are represented in Table 1

4.3. Storm selection, temporal disaggregation, and torrentiality validation

For selecting the highest storms from the 5000 generated years, the basin was split into 9 sub-basins plus the whole basin. Thus, the 200 highest daily precipitation events in terms of areal precipitation in these ten areas were firstly considered. The date of the 2000 resulting storms were crossed up to eliminate duplicated storms, since the same storm could affect more than one sub-basin. This resulted in 698 different storms, each storm composed of 103 daily values (i.e., day of the highest precipitation, the 2 days after and the 100 previous days) in each of the 52 grids.

A temporal disaggregation was then applied using the Method of Fragments (Breinl and Di Baldassarre, 2019) to reduce the temporal scale of the storms from daily to hourly time step. The fragments of a total of 154 daily rain episodes were obtained from the Segura River Basin Authority for the period 09–11–2009 to 24–03–2020, all of them presented accumulated amounts greater than 30 mm in one or more rain gauges. This historical period was carefully selected so that it could contain a large number of relevant daily episodes and, at the same time, sufficiently represented in the spatial distribution of hourly rainfall. The complete duration of the 698 selected storms were then disaggregated, which in turn, will feed the distributed HM to generate the series of discharges. Fig. 8 shows an example of a disaggregated storm.

Finally, the disaggregated storms were validated with the torrentiality index, which represents the relationship between the intensity of precipitation corresponding to one hour of duration and the intensity of daily precipitation (Ministerio de Fomento, 2019). According to the isolines map proposed by Témez (1987), the Segura River basin region should present index values between 10 and 11, which fits perfectly with the results obtained from our synthetic storms as shown in Fig. 9.

4.4. Implementation of a fully-distributed HM

For computational reasons and following hydromorphological criteria, the Segura basin was divided into five models (Fig. 10), being downstream models fed by the discharges at the outlet of the upstream ones. Thus, five different models were implemented in three steps: a first stage where parameter values were estimated at each cell using all available spatial hydrological information (DEM, land cover, soils, River channels and aquifers); in a second step the effective parameters related to the parameter maps and their correction factors (Francés et al., 2007) were calibrated; and a last stage where the models were validated (spatially, temporally and spatio-temporally).

Results from the different implementations considering the systematic records of the extraordinary flood events at sub-daily resolution from the SAIH-Segura monitoring network are summarized in Table 2 below. This table shows various performance indexes that were evaluated in the calibration stage and in the different models' validations, obtaining satisfactory results.

4.5. Quantile estimations and validation

Following the Eq. 1, the plotting positions of the simulated discharges were obtained to estimate the flood quantiles up to the 500-year return period at the various points of interest, assuming these with an acceptable sampling uncertainty.

The validation of the results was carried out using systematic information (data from gauging stations) and non-systematic information (historical and palaeoflood) at three points with severe flood problems. The validation points are located at Valdeinfierno and Puentes reservoirs in the Guadalentin River (main tributary in the lower part of the basin) and at the gauging station located in Orihuela in the main Segura River (downstream of the confluence with the Guadalentín river).

In the case of the Valdeinfierno and Puentes reservoirs, the comparison between the simulated quantiles and the non-systematic information was made in natural regime, assuming no significant anthropogenic effects on their catchment areas. In Fig. 11 it can be seen that the plotting positions of the generated discharges are coherent with the assignment of probability to the reconstructed historical floods.

In the case of the Segura River in Orihuela, it was necessary to compare both with the natural regime (representing the situation previous to the dams' construction), and with the current regime (considering dams). Fig. 12 shows the plotting positions of the systematic data reconstructed at the Orihuela gauging station, completed with the data from Murcia (1912–1993) and the perception threshold of historical floods (Frances et al., 1994) in Murcia. This perception threshold was calculated with the four registered extraordinary events inundating the city of Murcia for the historical period 1825–1911, and presenting a flow greater than 800 m^3/s which is equivalent to a return period of only 21.8 years.

Table 1 –
Values of WG shape parameters after calibration.

	Zone 1	Zone2
JFMAM	0.08	0.16
JJA	0.1	0.08
SOND	0.16	0.23

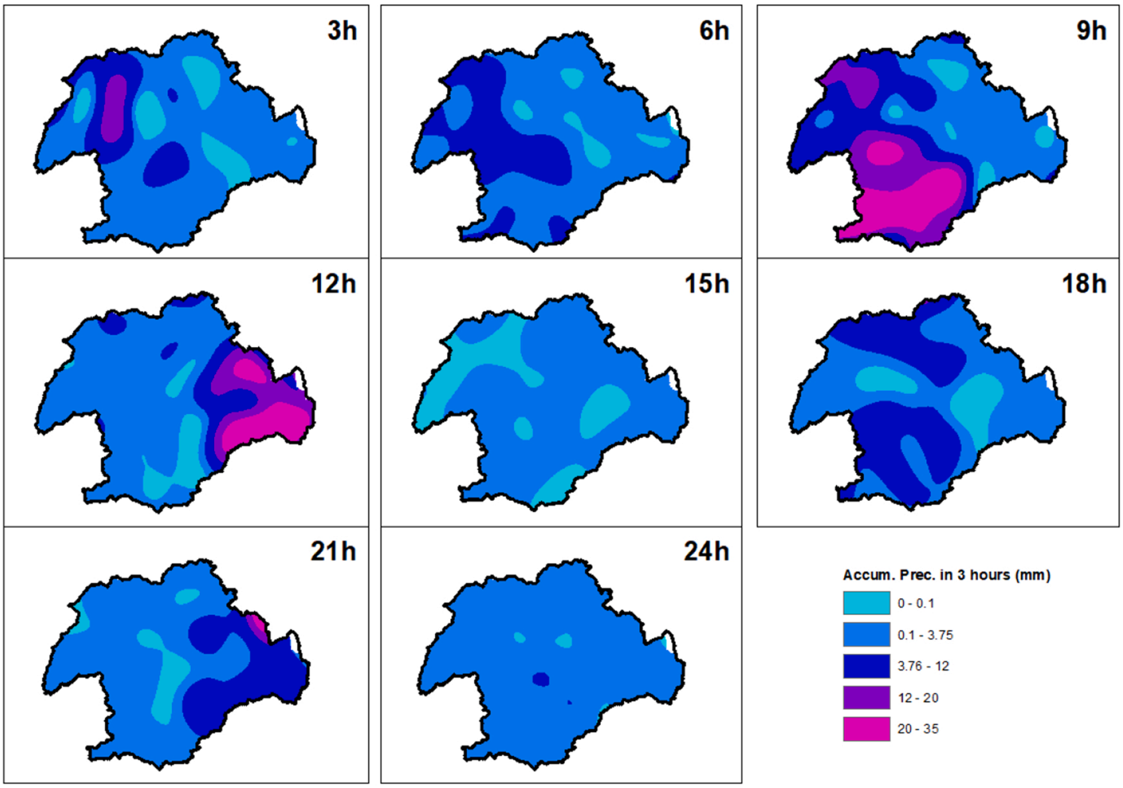

Fig. 8. – Hourly spatial distribution of rainfall field every 3 h for disaggregated storm #384.

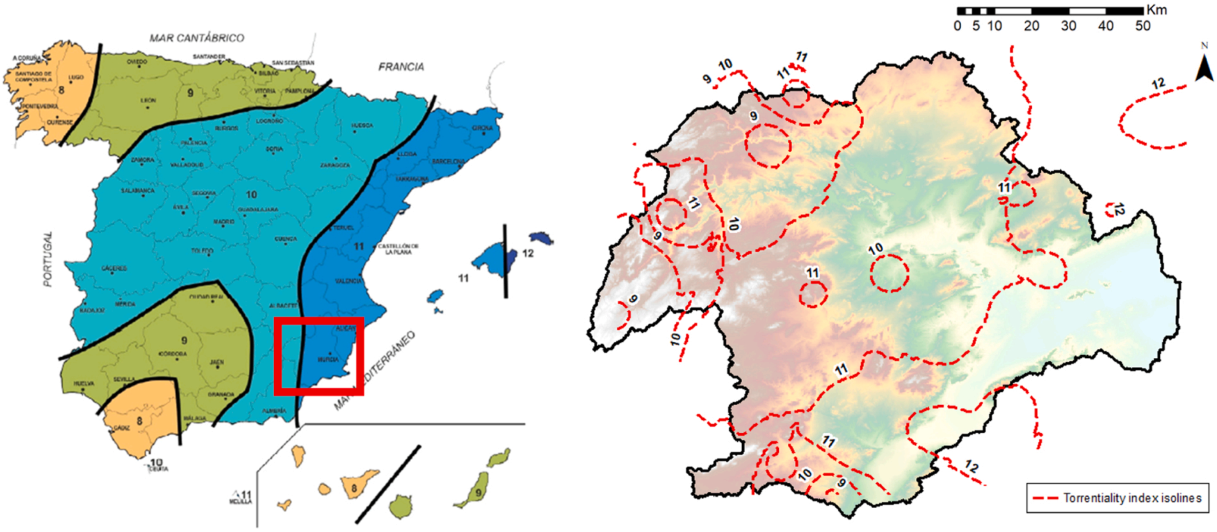

Fig. 9. – Rainfall validation – Left: Torrentiality index map according to Standard 5.2. IC, Superficial Drainage, Order FOM/298/2016. Right: Torrentiality index isolines estimated from the disaggregated synthetic storms.

5. Discussion

5.1. On the added value of expanding information from regional studies of annual maximum precipitation

Arid and semi-arid regions, due to the high spatio-temporal variability of the precipitation and the usual lack of a dense network of gauges with long records, are the regions where it is more difficult to understand the hydrological processes that actually take place

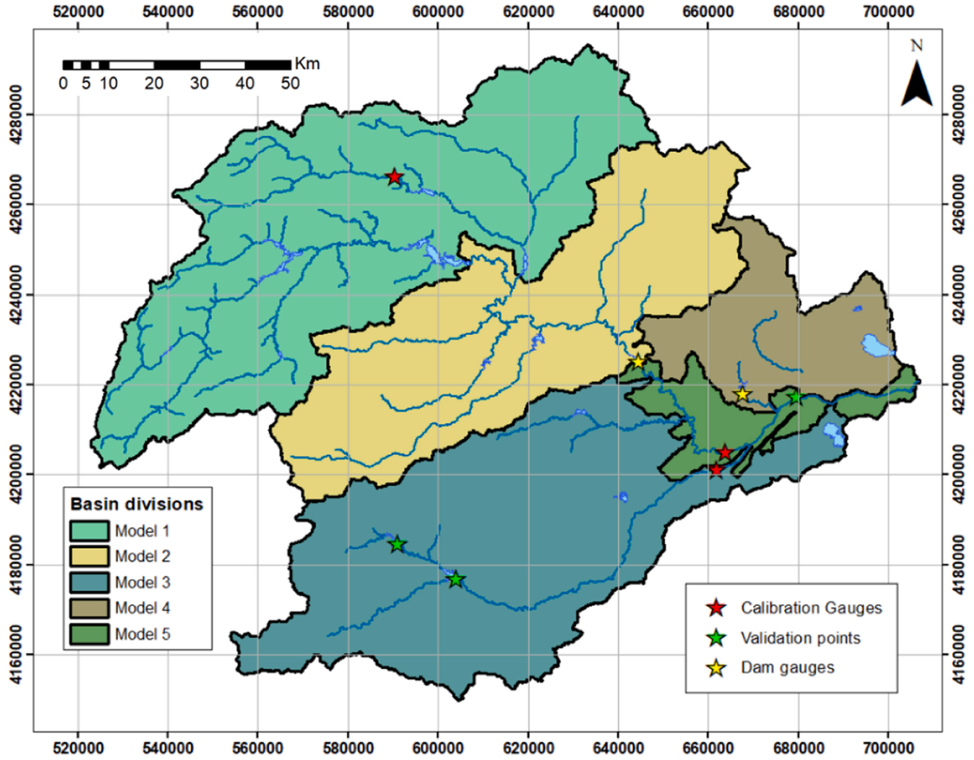

Fig. 10. – Hydrological model basin subdivisions and points of interest.

Table 2 –
Model implementation results in terms of Nash-Sutcliffe Efficiency index (NSE), Relative Mean Square Error (RMSE), and RMSE-observations standard deviation ratio (RSR).

	Stage	RMSE	NSE index	RSR index
Model 1	Calibration (2019)	1.36	0.87	0.36
	Validation (2020)	0.98	0.83	0.41
Model 2	Calibration (2019)	16.4	0.82	0.43
Model 3	Calibration (2019)	5.13	0.90	0.32
	Validation (2020)	1.85	0.70	0.55
	Validation (2016)	1.85	0.70	0.55
	Validation (2012)	6.87	0.75	0.50
Model 4	Calibration (2019)	36.8	0.83	0.41
	Validation (2020)	2.92	0.71	0.53
	Validation (2016)	5.12	0.53	0.69
	Validation (2012)	6.80	0.69	0.55
Model 5	Calibration (2019)	25.89	0.91	0.30
	Validation (2012)	9.61	0.76	0.49

(Zaman et al., 2012). Traditional FFA in these areas have resulted in flood estimates presenting high uncertainty, especially those associated with low-frequency events (Hosking and Wallis, 1993). RFFA have also been demonstrated to perform worse in arid/semi-arid climates than in humid climates (Smith et al., 2015). Furthermore, limited RFFA have been developed for arid or semi-arid climates mainly due to the limited data availability (Zaman et al., 2012).

In this context, the SCS offers the possibility to generate time series of any length, which seems to be a good option for studies of low-frequency extreme events. In addition, unlike the RFFA, the SCS allows full knowledge of the storm hydrographs, which is of great value for flood hazard studies. However, since WGs generate data series based on the statistics of the available observations, long and reliable precipitation datasets are still needed, especially when trying to reproduce extremes. Different approaches can be found in the literature to deal with this problem. For example, Ahn (2020) and Evin et al. (2018) incorporate heavy-tailed distribution functions to model precipitation amounts, while Papalexiou (2022) developed the CoSMoS-2 s rainfall model, assuming that if the fitted boundary describes the rainfall behaviour well, it also reproduces the tail properties. In the case of Beneyto et al. (2020), a regional study of annual maximum precipitation was integrated into the WG parametrization. In the present study, a similar approach as the latter was followed. In this case, rather than comparing quantiles grid by grid, we obtained the range of quantiles within each homogeneous

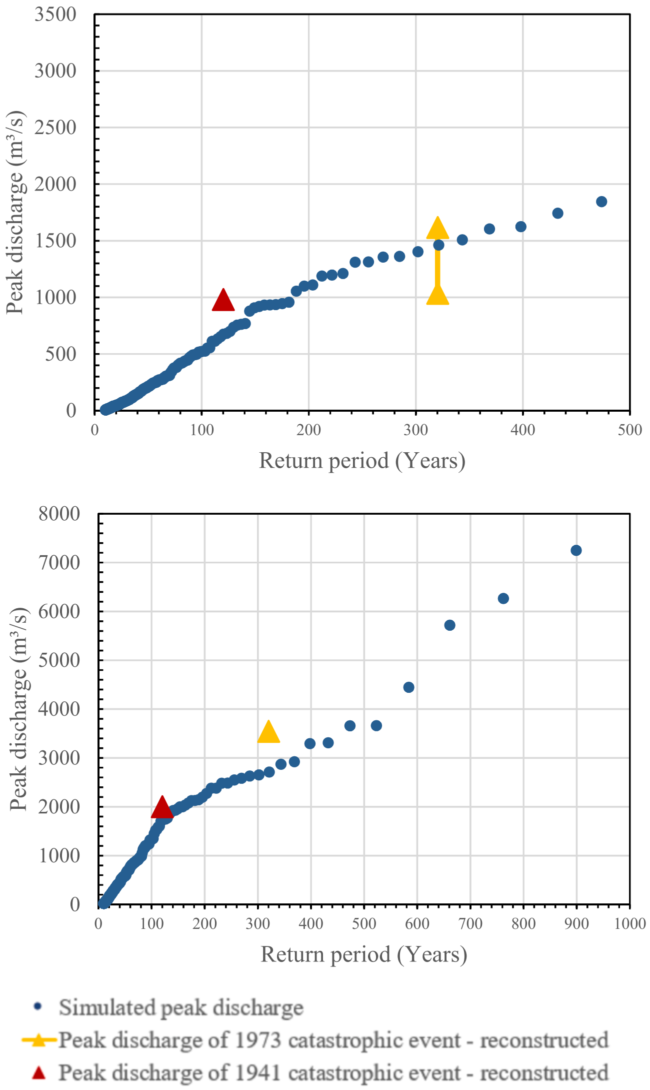

Fig. 11. – Comparison between simulated quantiles in the natural regime and probability assignment to non-systematic events (upper plot: Valdeinfierno reservoir; lower plot: Puentes reservoir).

region for each return period and estimated the group of shape parameters for each grid that made the quantiles fall within the region X_{100} range. As demonstrated in Beneyto et al. (2023), this way of integrating the information from the regional study of annual maximum precipitation significantly reduces the uncertainty of the quantile estimates, as opposed to setting the regional parameters. Additionally, the incorporation of the regional quantiles rather than the regional parameters makes independent the selection of the cumulative distribution function.

Fig. 7 shows how simulated precipitation with the WG systematically underestimated the quantiles obtained from the regional study of annual maximum precipitation if WG parameter estimation was carried out only with the available observations. The calculated quantile ranges were very similar for both regions for low and medium quantiles, only appreciating a significant difference for high quantiles, being Zone 2 region (coast) where the values were higher (i.e., more extreme).

Integrating this information into the WG parametrization process by means of calibrating the shape parameter of the marginal distribution substantially improved the quantile estimates, especially those associated with high return periods. Notwithstanding this and despite high precipitation events fell within the quantile range for the high return periods for both regions, it can be appreciated a slight underestimation for low return period quantiles, which could be explained by the shape of the E-GPD distribution.

5.2. On the adequate representation of storms in the region from the selected model

Although the implementation of the SCS approach would ideally be preferred at a sub-daily scale to represent adequately the hydrological processes during storm events (Breinl and Di Baldassarre, 2019), the high computational requirements this demands

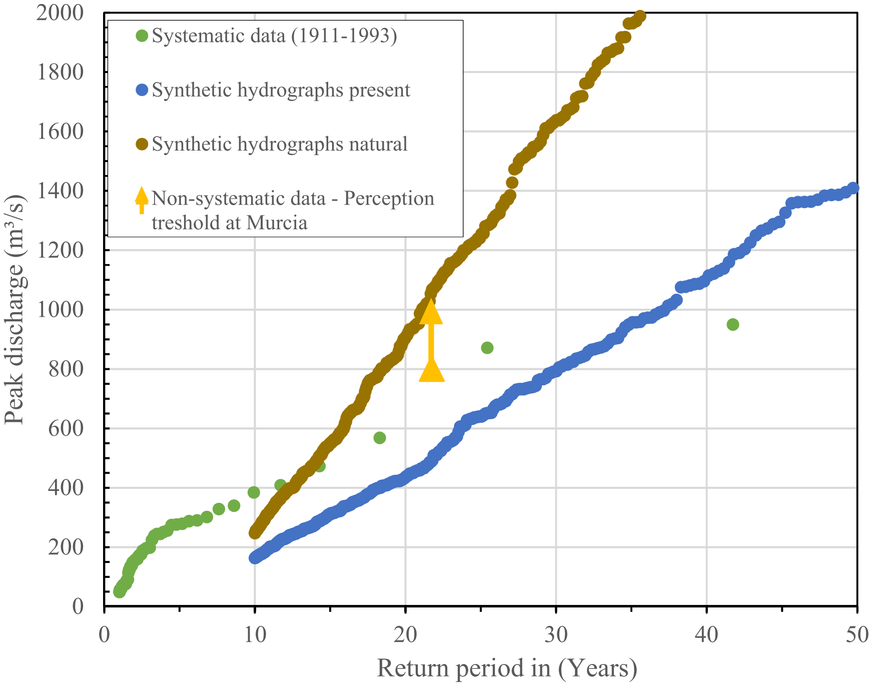

Fig. 12. – Plotting positions of the simulated discharges in Orihuela (natural and present conditions), systematic data and the perception threshold of historical floods in Murcia.

makes it impossible to apply for most practitioners. Only few studies can be found in the literature where SCS is applied to fine temporal resolutions. Grimaldi et al. (2022) evaluated eight rainfall models for sub-daily runoff simulations concluding that all models were capable of simulating realistic runoff time series. However, this study was limited to univariate simulations in small and ungauged basins.

Intermediate solutions have been developed over recent years. These mainly consist in determining from the daily available observations the heaviest storms and disaggregating them to finer temporal resolutions (e.g. Filipova et al., 2019; Winter et al., 2019). In our case, and considering the conclusions by Pui et al. (2012), who posed that the Method of Fragments outperformed other methods such as Cascade Models and the Randomized Bartlet-Lewis Model, we applied the MOF approach. It should be taken into account that feeding the HM only with the event hyetograph might result in errors in the simulated discharges since the initial conditions of the River basin are not considered. For this reason, in our approach each of the 698 disaggregated storms contained the one hundred days leading up to the heaviest precipitation of the storm, which resulted in a compromise solution between computational needs and basin initial conditions error. As observed in Fig. 9, torrentiality indexes obtained from the disaggregated storms fell within the expected range of values posed in the Spanish Drainage Highway Standards (Ministerio de Fomento, 2019), validating the results obtained with this method.

While there is skepticism about the use of WGs, mainly due to the challenge of selecting the most appropriate one and their complexity (Grimaldi et al., 2022), it is important to recognize that their use offers significant advantages. The remarked both temporal and spatial precipitation variability, make WGs a powerful tool capable to “fill in” the spatio-temporal gaps where the local meteorological information is not available.

One of the WGs limitations, however, is the high uncertainty of the low-frequency quantile estimates as a result of the input information being limited. In this study, and similarly to Beneyto et al. (2020), we proposed to address this problem by undertaking (if not available) a regional study of annual maximum precipitation and incorporating it into the WG parametrization. Thus, allowing to improve the systematic underestimations of the low-frequency quantiles estimated only with the available observations. Another problem of WGs is the high computational requirements that they need when dealing with long series (i.e., sub-daily) and the usually high number of parameters involved in the WG implementation. This problem is becoming decreasingly less significant due to the constant technological improvements, but there is still a long way for being available to everybody’s reach. Nevertheless, arid and semi-arid regions as the case study presented, where extreme events duration is typically no longer than 2 or 3 days, with highly intra-daily spatio-temporal variability, and generally poorly observed demands the use of WGs at temporal resolutions lower than daily.

5.3. *On the usefulness of the proposed methodology to obtain reliable quantiles*

The methodology presented in this study builds on different existing methodologies for hydrological modeling that are adequately tailored in an integrated approach to meet the particular needs of arid and semi-arid regions. Beyond the paradigm of the Design Storm approach, with its inherent limitations (i.e., fixed initial conditions of the catchment and simple spatio-temporal distribution of the storm), our approach exploits the latest scientific and technical advances in precipitation modeling. Specifically, it combines the use of stochastic WGs for generating long and spatially dense synthetic data series with temporal disaggregation procedures, adapting the temporal resolution of the data series to the particular needs of the region or climate.

Rainfall-runoff transformation with a HM is an extended approach to obtain reliable discharge data series since they simulate the natural hydrological processes that lead to the eventual transformation of rainfall into runoff (Ali et al., 2011). When HMs are fed with the large meteorological data series simulated with a WG, the respective low-frequency discharges are not possible to be directly validated with the plotting positions obtained in one or several flow gauge stations, since available systematic records are not sufficiently long. In order to handle that practical limitation, historical and palaeoflood information, gathered from the analysis of historical flood records and sedimentary evidence, can extend the available discharge observations beyond the instrumental records. By incorporating data from past extreme flood events, it is possible to gain a more comprehensive understanding of the full range of potential flood magnitudes and frequencies. Benito et al. (2020) found differences of 15–50% between estimated quantiles (>50 years) from palaeoflood-gauged data compared to those based only on instrumental data. In the research conducted by Francés, (1998) in the Turia River basin, it was concluded that inaccuracies in the quantile estimation diminished as the volume of data employed to estimate the 1000-year flood quantile increased. The analysis indicated that the incorporation of historical data led to a reduction of roughly 50% in estimation errors.

In the present study, the incorporation of historical and palaeoflood information and the use of a fully-distributed model allowed the entire methodology to be validated on the basis of the simulated peak discharges at three locations. In Orihuela (Fig. 12), the plotting positions of the systematic data between return periods of 10 and 40 years fell within the natural and the current regime. Non-systematic data is close to the simulated plotting positions in natural regime (although this being slightly lower, given the difference in the basin size between Murcia and Orihuela). In the case of Valdeinfierno and Puentes reservoirs (Fig. 11), non-systematic data allowed to validate discharges up to return periods higher than 200 years, as opposed to return periods of approximately 40 years obtained only with the systematic records, obtaining satisfactory results.

Finally, it is interesting to note that the "dog-leg" effect of the flood plotting positions (first described by Potter, (1958) is clearly reproduced with this methodology (as in Fig. 11). This “dog-leg” effect is especially characteristic of the Mediterranean Rivers in the region and can be reproduced by a TCEV distribution, as suggested by Francés (1998).

6. Conclusions

There is a general lack of long-term and spatially fully-distributed sub-daily hydrometeorological information, which results in inaccurate flood quantile estimations when applying traditional purely statistical FFA approaches. Deterministic procedures assume uncertain hypothesis and do not account for the initial conditions of the basin. Instead, the use of WGs coupled with fully-distributed HMs can provide a realistic approach resolving the issues of the previously mentioned methods. However, it requires of the adequate amount of input information to return reliable quantile estimations. Expanding the input information beyond the available systematic observations is key for a better characterization of the FFA, empowering hydrological modelers to improve their assessments of flood risk, develop more resilient infrastructure, and formulate effective flood mitigation strategies.

The methodology presented in this paper was applied in the Segura River basin, a strongly altered and with a relatively large area (15150 km^2), integrating different sources of information generated from meteorological models with an adequate spatio-temporal discretization. Specifically, this paper presents an innovative approach to FFA that combines several pre-existing methods to improve the estimation of low-frequency flood quantiles. In particular, it has used (i) a daily stochastic WG, (ii) a temporal disaggregation procedure to reduce the temporal scale of simulated daily synthetic rainfall to the resolution required by the hydrological modelling of floods, and (iii) an integration of historical and paleoflood information to validate the quantile results and thus the methodology.

As demonstrated in previous studies, just relying on the available observations, especially in arid and semi-arid climates, is not enough for the adequate modeling of low frequency quantiles. We conducted a regional study of annual maximum precipitation, which was introduced in the WG parametrization, allowing for a better reproduction of all quantiles but especially those associated with low frequency ($T > 50$ yrs), where the bias was more evident. Indeed, in Zone 2 of the presented case study, where the precipitation regime is more extreme than in Zone 1, practically all grids presented quantile underestimations X_{10} when the WG was fitted only with the available observations. Thus, integrating this additional information from a regional study clearly reduces the uncertainty of quantile estimations.

Moreover, the lack of long and consistent sub-daily records to directly generate sub-daily synthetic data series along with the high computational requirements was resolved by disaggregating the daily synthetic precipitation to hourly data. This procedure allows reducing the temporal resolution and allowing for an appropriate spatio-temporal characterization of the typical storms in these types of climates, which was demonstrated comparing the calculated torrentiality indexes with those proposed in the Spanish Highway Drainage Standards.

Finally, simulated discharges with a fully-distributed HM were validated with both systematic and non-systematic (recorded, historical and palaeoflood) information, allowing to validate the estimated flood quantiles up to return periods higher than 200 years, as opposed to the highest quantile of $T = 21.8$ obtained only with the available systematic observations.

The integrated use of stochastic modelling with fully-distributed HM has allowed the estimation of representative extreme hydrometeorological events typical of the southeastern Mediterranean. This was possible by considering the spatio-temporal variability of the main flood-generating processes of the studied region. With this integrated approach, it is possible to move forward of classical approaches of FFA, expanding the input information beyond the available systematic observations. It is of paramount importance to obtain reliable synthetic process-based hydrographs at any point of the catchment, which is possible through the use of fully-distributed HMs, in order to both improve the results into the flood risk analysis and to serve as a baseline to formulate effective flood mitigation strategies.

These results have important implications towards a more accurate flood modeling. While the approach described in this paper has been satisfactorily implemented in a particular case study to validate its conceptual variability, its adaptability to any study area is sustained by at least the following five main reasons:

- There exists a wide range of WGs and HMs with different conceptualizations, enabling users to choose those that best perform in any specific location.
- Daily precipitation data are available for any location on the planet, allowing a regional study of annual maximum precipitation in any basin.
- The use of a fully-distributed HM allows the estimation of flood quantiles at any location across the study catchment. This approach consistently incorporates the spatial heterogeneity of rainfall patterns and catchment characteristics.
- Combining different sources of available flood data (systematic and non-systematic) allows for the validation of the results of the FFA, and the methodology itself.
- This methodology is also applicable in the context of ungauged catchments since it is based on the adequate representation of the main processes involved in flood generation.
- This methodology does not involve high computational requirements giving the hybrid nature of the proposed solution to handle the temporal resolution of models (daily and sub-daily).

CRediT authorship contribution statement

Carles Beneyto: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Sergio Salazar-Galán:** Writing – review & editing, Resources, Methodology, Investigation, Data curation, Conceptualization. **José Ángel Aranda:** Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Eduardo Albentosa:** Software, Resources, Formal analysis, Conceptualization. **Rafael Garcia-Bartual:** Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Félix Francés:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

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