Programa de Doctorado en Ingeniería del Agua y Medioambiental

On the use of weather generators for the estimation of low-frequency floods under a changing climate

Doctoral Thesis

Ph.D. CANDIDATE:

CARLES BENEYTO IBAÑEZ

SUPERVISORS:

Prof. D. Félix Ramón Francés García

Prof. D. José Ángel Aranda Domingo

March 2024

En primer lugar, me gustaría agradecer a mis directores de tesis, D. Félix Francés García y D. José Ángel Aranda Domingo, por todo el conocimiento y consejos que me han aportado durante todo este tiempo, por su dedicación y su extraordinario esfuerzo para la preparación de esta tesis

A la Universitat Politècnica de València, por darme esta gran oportunidad. Al personal del Departamento de Ingeniería Hidráulica y Medio Ambiente, por su continua ayuda y su buena predisposición siempre. Al Prof. Rafa García Bartual, quien, desde que empecé mis estudios universitarios, siempre ha estado ayudándome, aconsejándome, y motivándome para seguir adelante.

A todo el grupo del GIMHA, especialmente a Cristina, Vicente, Sergio y Carlos, por haber hecho mis días en el despacho más llevaderos, por todo lo que he aprendido de vosotros, por vuestra ayuda incondicional, por las risas, por permitirme conocerlos más allá de la oficina.

A mis amigos, quienes siempre me han apoyado y confiado en mí, estando siempre conmigo en las buenas y en las malas.

Por último, a mi familia, a mis padres, a mis hermanos, por creer siempre en mí y darme ánimos y apoyo en todo momento. Su confianza ha sido el cimiento sobre el cual he construido mis sueños y aspiraciones. En los momentos de triunfo, han sido mis mayores celebrantes, y en las adversidades, mis más sólidos pilares. Cada logro que he alcanzado lleva consigo una parte de su dedicación, porque han sido mis guías incondicionales, impulsándome a superar obstáculos y a perseguir mis metas con determinación.

Muchas gracias a todos

ABSTRACT

Most scientific studies predict an increase in the frequency and magnitude of extreme precipitation events as a consequence of climate change effects. Furthermore, it is expected that within 50 years, 80% of the global population will reside in flood-prone areas. This heightened risk, vulnerability, and exposure to intense rainfall hazards signify a significant rise in the flood risk, already elevated. It underscores the urgent need to implement measures to reduce vulnerability and develop methodologies capable of accurately estimating the magnitude and probability of occurrence of these potential extreme events. This doctoral thesis is directed towards this objective, presenting a new methodology based on the use of stochastic weather generators for estimating the frequency of extreme floods in both current and climate change scenarios.

Beyond the Design Storm paradigm and traditional Flood Frequency Analysis studies, the methodology proposed in this thesis relies on continuous synthetic simulation: stochastic weather generator + spatially distributed hydrological model. The use of stochastic weather generators for Flood Frequency Analysis is becoming increasingly common within the hydrological community. However, reliable quantile estimates for high return periods require long and complete observations. The innovation introduced by the proposed methodology lies in the integration of regional studies of maximum precipitation into the implementation of the weather generator, significantly reducing uncertainty in quantile estimates (especially those associated with low-frequency events) due to the typically short and limited hydrometeorological records available to date.

This thesis is presented as a compilation of five publications already published in journals indexed in the Journal Citation Report. These documents narrate the progression of the methodology through various stages to its final approach. Initially conceived for the current climate at a daily scale, the methodology was later adapted to a subdaily scale and ultimately developed for application in future climate scenarios. Throughout this process, uncertainty

studies were addressed concerning the amount of information involving both precipitation and flood quantile estimates.

The methodologies have been implemented in two case studies: Rambla de la Viuda (Castellón) and the Segura River basin, with results demonstrating the robustness and effectiveness of the methodologies. In the field of meteorological modeling, the results have been consistent and satisfactory, showcasing the methodology's ability to accurately represent the complexities of climate patterns. Likewise, in the hydrological domain, the methodology has exhibited effective capabilities in representing and simulating processes related to the water cycle, offering coherent and satisfactory results in the estimation of flows and flood events in both current and future climates. This consistency in the robustness of the methodology, both in meteorological and hydrological modeling, supports its applicability and reliability in diverse environmental and climatic conditions.

RESUMEN

La mayoría de los estudios científicos pronostican un incremento en la frecuencia y magnitud de los episodios de precipitaciones extremas como consecuencia de los efectos del cambio climático. Además, se espera que en un plazo de 50 años el 80% de la población mundial viva en zonas propensas a inundaciones. Este incremento en la peligrosidad, vulnerabilidad y en la exposición al peligro de lluvias intensas supone un aumento significativo en el riesgo de inundaciones, ya de por si elevado, que manifiesta la urgente necesidad de tomar medidas encaminadas a reducir la vulnerabilidad y desarrollar metodologías capaces de estimar con la mayor precisión posible la magnitud y la probabilidad de ocurrencia de estos posibles fenómenos extremos. En esta última dirección va dirigida la presente tesis doctoral, presentando una nueva metodología basada en el uso de generadores meteorológicos estocásticos para la estimación de la frecuencia de avenidas extremas tanto en escenarios de clima actual como de cambio climático.

Más allá del paradigma de la tormenta de diseño y de los estudios tradicionales de análisis de frecuencia de inundaciones, la metodología propuesta en esta tesis se basa en la simulación sintética continua: generador meteorológico estocástico + modelo hidrológico espacialmente distribuido. El uso de generadores meteorológicos estocásticos para el análisis de frecuencia de inundaciones es una práctica cada vez más común dentro de la comunidad hidrológica. Sin embargo, es necesario disponer de observaciones largas y completas para obtener estimaciones de cuantiles confiables para altos períodos de retorno. La novedad que introduce la metodología propuesta se basa en la integración de estudios regionales de precipitación máxima en la implementación del generador meteorológico, lo que reduce considerablemente la incertidumbre en las estimaciones de cuantiles (especialmente aquellos asociados a eventos de baja frecuencia) debida a los usualmente cortos y escasos registros hidrometeorológicos de los que se dispone hasta la fecha.

Esta tesis se presenta como un compendio de cinco publicaciones: tres de ellas ya publicadas y dos en proceso de revisión en revistas indexadas en el Journal Citation Report. Estos documentos narran la progresión de la metodología a lo largo de diversas etapas hasta llegar al enfoque final. Inicialmente concebida para el clima actual a escala diaria, la metodología fue posteriormente adaptada a escala subdiaria y finalmente desarrollada para su aplicación en escenarios de clima futuro. A lo largo de este proceso, se abordaron estudios de incertidumbre asociados a la cantidad de información que involucran tanto las estimaciones de cuantiles de precipitación como de inundación.

Las metodologías se han implementado en dos casos de estudio: Rambla de la Viuda (Castellón) y; la cuenca del río Segura, cuyos resultados han evidenciado la solidez y eficacia de las metodologías. En el ámbito de la modelización meteorológica, los resultados han sido consistentes y satisfactorios, demostrando la capacidad de la metodología para representar con precisión las complejidades de los patrones climáticos. Asimismo, en el ámbito hidrológico, la metodología ha exhibido una eficaz capacidad para representar y simular los procesos relacionados con el ciclo del agua, ofreciendo resultados coherentes y satisfactorios en la estimación de caudales y eventos de inundación tanto en clima actual como en clima futuro. Esta consistencia en la robustez de la metodología, tanto en la modelización meteorológica como hidrológica, respalda su aplicabilidad y confiabilidad en entornos y condiciones climáticas diversas.

RESUM

La majoria dels estudis científics pronostiquen un increment de la freqüència i la magnitud dels episodis de precipitacions extremes a conseqüència dels efectes del canvi climàtic. A més, s'espera que en un termini de 50 anys el 80% de la població mundial habite en zones propenses a inundacions. Aquest acreixement en la perillositat, vulnerabilitat i exposició al perill de pluges intenses suposa un augment significatiu del risc d'inundacions, ja de per si elevat, que manifesta la urgent necessitat de prendre mesures encaminades a reduir la vulnerabilitat i desenvolupar metodologies que permeten estimar amb la major precisió possible la magnitud i la probabilitat d'ocurrència d’aquests possibles fenòmens extrems. En aquesta última direcció va dirigida la present tesi doctoral, que presenta una nova metodologia basada en l'ús de generadors meteorològics estocàstics per a l'estimació de la freqüència d'avingudes extremes, tant en escenaris de clima actual com de canvi climàtic.

Més enllà del paradigma de la tempesta de disseny i dels estudis tradicionals d'anàlisis de freqüència d'inundacions, la metodologia proposada en aquesta tesi es basa en la simulació sintètica contínua: generador meteorològic estocàstic + model hidrològic espacialment distribuït. L'ús de generadors meteorològics estocàstics per a l'anàlisi de freqüència d'inundacions és una pràctica cada vegada més comuna dins de la comunitat hidrològica. No obstant això, és necessari disposar d'observacions llargues i completes per a obtindre estimacions de quantils de confiança per a alts períodes de retorn. La novetat que introdueix la metodologia proposada es basa en la integració d'estudis regionals de precipitació màxima en la implementació del generador meteorològic, la qual cosa redueix considerablement la incertesa en les estimacions de quantils (especialment d’aquells associats a esdeveniments de baixa freqüència) a causa dels usualment curts i escassos registres hidrometeorològics dels quals es disposa fins a la data.

Auqesta tesi es presenta com un compendi de cinc publicacions: tres d'elles en ja publicades i dos en procés de revisió en revistes indexades en el Journal

Citation Report. Aquests documents narren la progressió de la metodologia al llarg de diverses etapes fins arribar a l'enfocament final. Inicialment concebuda per al clima actual a escala diària, la metodologia va ser posteriorment adaptada a escala subdiària i finalment desenvolupada per a la seua aplicació en escenaris de clima futur. Al llarg d'aquest procés, es van abordar estudis d'incertesa associats a la quantitat d'informació que involucren tant les estimacions de quantils de precipitació com d'inundació.

Les metodologies s'han implementat en dos casos d'estudi: Rambla de la Vídua (Castelló) i; la conca del riu Segura, els resultats del qual han evidenciat la solidesa i eficàcia de les metodologies. En l'àmbit de la modelització meteorològica, els resultats han estat consistents i satisfactoris, ja que han demostrat la capacitat de la metodologia per a representar amb precisió les complexitats dels patrons climàtics. Així mateix, en l'àmbit hidrològic, la metodologia ha exhibit una eficaç capacitat per a representar i simular els processos relacionats amb el cicle de l'aigua, i ens ha oferit resultats coherents i satisfactoris en l'estimació de cabals i esdeveniments d'inundació tant en clima actual com en clima futur. Aquesta consistència en la robustesa de la metodologia, tant en la modelització meteorològica com en la hidrològica, recolza la seua aplicabilitat i confiabilitat en entorns i condicions climàtiques diverses.

TABLE OF CONTENTS

List de figures

List de tables

1. Introduction

Precipitation, a fundamental component of the Earth's hydrological cycle, assumes a critical role as a resource that profoundly shapes the dynamics of our environment. Embracing various forms such as rain, snow, sleet, and hail, these diverse manifestations of water play a pivotal role in nourishing the earth and sustaining life in its innumerable forms. As the primary source for replenishing freshwater resources, precipitation becomes the lifeblood of ecosystems, threading an intricate network through rivers, lakes, and underground aquifers. These water sources, like lifelines, not only sustain the diverse flora and fauna but also form the spine of human communities. The precipitation patterns, marked by its intensity, frequency, and seasonal variations, shape not only the biological diversity within ecosystems but also the cultural diversity of societies relying on these water resources.

In tandem with its indispensable role as a life-sustaining resource, precipitation presents itself as a formidable force that can pose significant risks to both natural environments and human settlements. The very characteristics that make precipitation a vital component of ecosystems and agricultural cycles - its intensity, variability, and patterns - also render it capable of triggering hazardous conditions. Prolonged periods of low precipitation, for instance, may result in droughts, jeopardizing water supplies, agricultural productivity, and the overall resilience of communities and ecosystems. Conversely, excessive rainfall can lead to devastating floods, disrupting landscapes, submerging communities, and causing economic and human life losses. In fact, according to the United Nations Office for Disaster Risk Reduction (UNDRR), river floods caused about 7 million fatalities in the 20th century, with a direct global average annual loss estimated at US$ 104 billion (UNDRR, 2015), and only in the last decade of the 20th century floods killed about 100,000 persons and affected over 1.4 billion people (Jonkman, 2005).

Additionally, the global temperature is experiencing a continuous increase since the Industrial Revolution. As shown in Figure 1, this is not just as a consequence of the natural climate variability of the Earth but due to anthropogenic factors, mainly related to the exponential growth in the consumption of fossil fuels and the consequent increase in the atmospheric concentrations of key greenhouse gases (Höök and Tang, 2013).

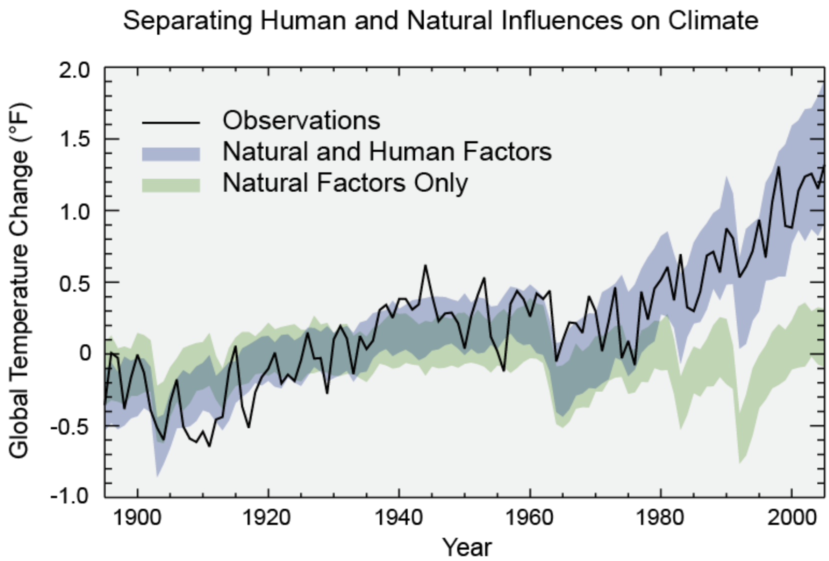


Figure 1 – Global temperature change (United States Environmental Protection Agency, 2005)

This increase in the global temperature has direct influence on practically all Earth's natural processes, producing shifts in the current distribution of climatic conditions (Loarie et al., 2009) in a widely well-known climate change. The effects of this climate change, that many authors consider irreversible (e.g., Solomon et al., (2009)), impact directly on precipitation patterns (e.g., Dai et al., 2018; Dore, 2005; Sohoulande Djebou and Singh, 2016; Trenberth, 2011). Increased heating leads to greater evaporation and thus surface drying, thereby increasing the intensity and duration of drought. However, since the water holding capacity of air increases by about 7% per 1C warming (Zhang et al., 2017), storms, supplied with increased moisture (i.e., more energy accumulated in the atmosphere), produce more intense precipitation events (Trenberth, 2011). This is the same conclusion in which practically all available research point out: changes in the precipitation patterns with longer droughts and more frequent and severe heavy precipitation events (e.g., Cardoso Pereira et al., 2020;

Guhathakurta et al., 2011; Rajczak et al., 2013; Simon J. Mason et al., 1999; Tabari, 2020). Also, change in the timing and magnitude of subsurface drainage processes and streamflow under a warmer global climate can occur through direct changes in evapotranspiration and snow (or glacier) accumulation, melt rates, and timing (Tague and Grant, 2009). Undoubtedly, these shifts in the precipitation and snow patters result in changes in the hydrological response of rivers. It is expected that climate change accelerates the hydrological cycle with an increasing intensity of rainfalls and frequency of extreme weather events (Milly et al., 2008). Moreover, more intense precipitation events combined with drier and crusted soils after prolonged periods without rain (that can rapidly convert rainfall to runoff because the runoff coefficient is higher), will result in heavier flash floods (Kundzewicz et al., 2014). On the other hand, higher temperatures will imply higher rates of evapotranspiration, which could partially compensate the increase in precipitation in certain climates (Bussi et al., 2014).

All these, combined with the expectation that within 50 years 80% of the world's population will live in flood-prone areas (De Wrachien et al., 2011), project an increase of losses due to fluvial floods from US$208 billion in 1976-1995 to US$597 billion in 2016-2035 (Willner et al., 2018), which evidences the need for precise modeling and prediction of extreme floods, enabling timely responses and effective mitigation against the potentially devastating impacts of current, and future severe floods. In fact, these studies are necessary for the correct sizing of major key hydraulic infrastructures, such as dams and spillways, flood protection works, and nuclear power plants (Singh et al., 2018).

Notwithstanding, being able to precisely predict where and when an extreme precipitation event is going to occur is not an easy task. Technological advances have permitted us to know with exact precision how an asteroid millions of kilometers away from the Earth is going to move. However, if we drop a leaf in a river, we are incapable to know exactly the position of that leaf 25 meters downstream. In fact, if we drop the same leaf ten times exactly in the same location, the leaf will appear in ten different locations 25 meters downstream. The problem when dealing with meteorological variables lies with the multitude of conditions and variables that simultaneously come into play across extensive regions, with many of these factors interacting and influencing each other. Weather prediction extends beyond merely chasing a moving target, and its perfect prediction would involve solving an infinitive number of non-linear equations which, to date, is not possible. In fact, current knowledge of meteorological or climatological phenomena is limited to a few days or even hours (depending on the type of front). If predicting when, where, in what form, and for how long a precipitation event is going to last is not an easy task, estimating river flows (mainly feed but these precipitation events) and potential flood events are even more complicated, with many more variables and equations to be added on top. Instead, Flood Frequency Analysis (FFA), based on the available records of discharges collected at stream gauges, has been preferred for flood studies over physics-based equations due to practical reasons: FFA relies on historical streamflow data, which is often more readily available than detailed basin characteristics required by physics-based models; FFA simplicity and assumption of stationarity make it a practical choice, especially when dealing with data from ungauged basins and; the highly variable and complex nature of hydrological processes, coupled with computational intensity in physics-based models.

FFA has evolved over time, with various methods emerging and shaping our understanding of flood occurrences. Historically, FFA has been rooted in statistical approaches, leveraging historical records and observed data to estimate the probability of different flood magnitudes. Early methods often relied on simple statistical distributions and assumed stationarity, treating past flood events as indicative of future patterns. Later, deterministic procedures, mainly based on the design storm, were introduced. This approach draws from the premise that return periods of concurrent rainfall and peak discharge are assumed to be the same and that the design flood of a given return period can be estimated based on a single rainfall duration that generates the highest peak discharge (see the classical Chow et al., (1998); or the Flood Estimation Handbook Houghton-Carr, (1999)). However, we now know that this approach is uncertain since peak discharges and hydrographs are strongly dependent on the spatio-temporal distribution of the precipitation (Emmanuel et al., 2017) and on the initial conditions of the basin (Pathiraja et al., 2012).

As hydrological science progressed, more sophisticated techniques, such as the Regional Frequency Analysis of extremes (RFA), were developed to account for the complexities of different hydrological regions and poorly monitored catchments, and augmenting the limited temporal data at a gauging site of interest with spatial data (Hine and Hall, 2010). With the advent of computer technology, hydrologists began employing simulation, and to expand models and advanced statistical methods. Contemporary approaches often blend traditional data-driven methods with advanced modeling techniques, fostering a more comprehensive understanding of flood frequency dynamics and improving the accuracy of estimations.

In recent years, different continuous hydrologic modeling approaches have emerged (see, for example, Grimaldi et al., (2020)). An alternative method widely adopted is to combine statistical and deterministic methods in a Continuous Synthetic Simulation (CSS). The procedure involves the generation of synthetic discharge data series obtained from a Stochastic Weather Generator (WG) combined with a Hydrological Model (HM). WGs are computer models that produce long synthetic series of meteorological data that have similar statistical properties to the observed data (Chen et al., 2010). Furthermore, while observed time series represent only one realization of the climate, WGs can generate many realizations, which provide a wider range of feasible situations (Khazaei et al., 2021). These have been extensively used in recent years and the thrive of open-source libraries for stochastic rain-fall generation such as in Kossieris et al., (2012) or in Diez-Sierra et al., (2023) are a good prove of it.

Current WGs can be broadly divided into parametric or nonparametric (or resampling; see Ailliot et al., 2020; Rajagopalan and Lall, 1999). Most existing WGs are of the parametric type since parameters can be altered to simulate different weather scenarios and thus facilitate climate change studies (Wilks, 2009). Both types of WGs perform reasonably well in terms of reproducing average characteristics of some variables, but mainly those parametric WGs have been extensively used coupled with hydrological and environmental models (e.g., Beneyto et al., 2020; Brocca et al., 2013; Cameron et al., 1999; Cowpertwait et al., 2013; Dai and Qin, 2019) and more recently as a tool for climate downscaling, increasing the resolution of climate projections by linking their parameters to the climate model outputs (e.g., Chun et al., 2013; Khazaei et al., 2021; Li and Babovic, 2019). Therefore, CSS procedures can generate long series of discharges where flood quantiles can be easily interpolated from the empirical plotting positions rather than having to parameterize the discharges data series as in the traditional FFA (Beneyto et al., 2020). Nevertheless, WGs require representative data series of observed extreme precipitation in order to perform adequately (Soltani and Hoogenboom, 2003). In most of the cases, there may not be sufficient extreme rainfall records, meaning that results from stochastic WG may not generate reliable extreme floods (Cavanaugh et al., 2015; Verdin et al., 2015).

Extensive efforts have been made, particularly within the hydrological community, to statistically model high precipitation amounts. Cowpertwait, (1998) applied a method for deriving high-order moments to obtain the third-moment function for the observed precipitation time series. Evin and Favre, (2012) refined the Neyman-Scott model structure by introducing the concept of transient storm arrival rate. Other efforts, with much evidence of the precipitation amount distribution being heavy-tailed, have been dedicated (Furrer and Katz, 2008). In this sense, several WGs incorporating heavy-tailed distribution functions have emerged in recent years (e.g., Ahn, 2020; Evin et al., 2018; Hundecha et al., 2009). More recently, Papalexiou, (2022) developed a two-state rainfall model, CoSMoS-2s, highlighting the importance of selecting an appropriate distribution to describe nonzero rainfall and stating that if the fitted marginal describes the behavior of rainfall well, then it reproduces the tail properties too and thus the behavior of extremes. However, although a distribution might appear to describe the observations well, this does not guarantee that its tail precisely reproduces extremes (Papalexiou, 2022). Notwithstanding this, the primary source of uncertainty still lies with the observed rainfall time series (Merz and Blöschl, 2008; Salazar-Galán et al., 2021).

Furthermore, as commented above, climate studies predict an increase in the frequency and magnitude of extreme events (e.g., Alfieri et al., 2017; Paprotny and Morales-Nápoles, 2017), which combined with the global socioeconomic development will lead to an increased flood losses resulting from extreme precipitation events in the near future (IPCC, 2022). All this further highlights the need to develop methodologies that reduce the uncertainty in the flood estimates under a changing climate, especially those associated with low probability of occurrence. Generally, most of the studies currently carried out to estimate future flood quantiles are broadly based on the use of the available products from the Global Circulation Models (GCM), downscaled to finer scales and bias corrected (Ehret et al., 2012), obtaining the flow series through a HM (e.g., Roudier et al., 2016; Soriano et al., 2020; Yin et al., 2018). 30-year climate projections are usually used in these studies that, according to the "World Meteorological Organization", are of sufficient length to smooth out the variations from one year to the next (WMO, 2017). This could be true for specific studies and for some meteorological variables, however, flood quantile estimation requires longer datasets or, more importantly, additional procedures to reduce the tremendous uncertainty in flood levels' estimates, especially if we are focused on adequately modelling extremes, that to date, are not deeply developed.

Notwithstanding, most of the developed countries such as Finland, United Kingdom or Italy, given their simplicity, are still recommending in their standards and regulations the use of either statistic or/and deterministic methods based on the available observations, and only suggesting incorporating the effects of climate change, without specifying how. For example, the Spanish Standard "*Norma técnica de seguridad para el proyecto, construcción y puesta en carga de presas y llenado de embalses*" (BOE, 2021), requires determining the hydrographs of the foreseeable avenues to the reservoir, together with the statistical characterization of its probabilities of occurrence, considering the available knowledge about the possible long-term changes in the hydrological conditions of the basin and, in particular, to the extent that scientific and technical knowledge allows it, the possible repercussions of climate change. Taking into account that, depending on the category they fall, dams could require design return periods of up to 10,000 years (Table 1), and although not being specifically specified in the standards, these studies are clearly demanding information beyond the local systematic records, either through regional studies or through the stochastic synthetic generation.

Table 1 - Return periods considered for dam construction in Spain (in years)

Dam category*	Standard project flood	Maximum flood level	
		Concrete dam	Loose material dam
A	1,000	5,000	10,000
B	500	1,000	5,000
C	100	500	1,000

**Classification according to the damage induced by a possible breakage of the dam*

In fact, recent standards or guidance documents, such as the methodological guidance for the development of the National Flood Zone Mapping System (Ministerio de Medio Ambiente y Medio Rural y Marino, 2011) or the draft of the new guidance for the elaboration of hydrological studies of floods for dams (CEDEX, 2023), start to incorporate in their methodologies the concepts of synthetic storms or stochastic generation, which appears to set the direction in which flood frequency studies must head in the very near future.

1.1. Main objectives

This research thesis aims to develop a new methodology that integrates different sources of information generated from hydrometeorological models at an appropriate spatiotemporal scale and fed with the amount of information necessary to achieve an adequate characterization of the main variables that must be considered in the FFA under climate change scenarios, achieving a reduction of the uncertainty of low-frequency quantile estimates. Specifically, the proposed methodology integrates: (1) the use of a stochastic multi-site WG to generate long series of daily precipitation and maximum and minimum temperatures, incorporating the results from a regional study of annual maximum daily precipitation in the WG parameterization for both current and future climate to account for the short length of the available data and thus to reduce the uncertainty of quantile estimates; and (2) a fully-distributed HM, allowing the discharge information at any point of the catchment to be known unlike in the case of lumped or semi-distributed HMs.

Partial objectives have been needed to achieve the main purpose of this research thesis. The main partial goals are listed next:

- Undertake an extensive literature review of the existing WGs and their different typologies.
- Select the most appropriate WG considering the main objectives of the research (i.e., adequately characterize extremes).
- Develop a methodology to estimate extreme flood quantiles in current climate based on the use of WG.
- Evaluate and quantify how the integration of regional quantiles in the WG parameterization under different practical scenarios of available information, and under different precipitation regimes, climate extremality, and basin hydrological characteristics affect the estimated precipitation and flood quantiles in terms of reduction of uncertainty.
- Understand historical and palaeoflood information as source for validating low-frequency flood quantiles.
- Undertake an extensive literature review of current climate projections, bias-correction procedures and existing methodologies for the estimation of future flood quantiles.
- Develop a methodology to estimate extreme flood quantiles in future climate based on the use of WG.

1.2. Methodology

The final methodology has been progressively being shaped with the results achieved in the different abovementioned partial objectives. The result is a robust methodology that can be generalized to any study area, independently of the climate or the catchment extension, and with basic computational requirements. This section of the thesis summarizes the steps followed to develop the final methodology and the elements and procedures of which it consists of. Finally, a brief description of the main tools involved is presented.

1.2.1. General framework

Firstly, a new approach to estimate extreme flood quantiles with a WG in current climate was developed. An existing regional study of annual maximum daily precipitation from CEDEX, (1994) was integrated in the WG implementation by means of modifying the shape parameter of the marginal distribution dealing with precipitation amounts so that the different 100-year return period population precipitation quantiles ($X_{100,P}$) from the regional study fit those simulated with the WG. Thus, it is possible to expand the independent amount of available information by incorporating the data from neighbor rain gauges (space for time trading). The generated synthetic precipitation series fed a distributed HM, the results of which were validated with the available observations (ordinary floods) and with historical and palaeoflood information (high return period floods). Figure 2 below shows a workflow diagram with this initial methodology to estimate extreme floods in current climate.

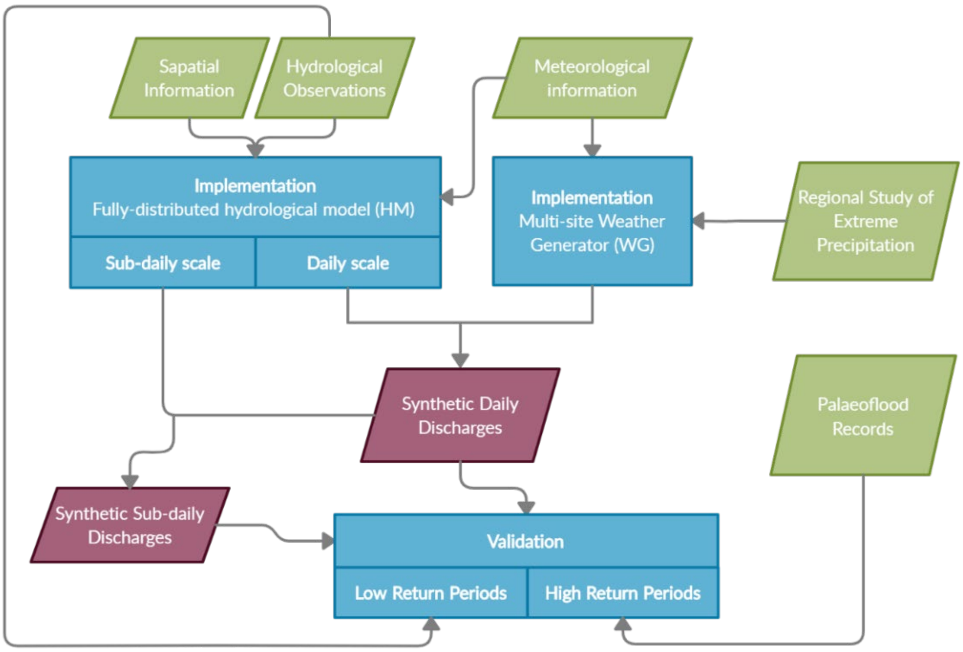


Figure 2 - Workflow diagram of the methodology in current climate.

The results obtained shown a clear reduction of the uncertainty of the flood quantile estimates. However, this reduction was not quantified at this point, which was precisely the objective of the next steps. In this case, and from different synthetic populations, a Monte Carlo simulation study was performed with 50 x 60-year samples estimating the WG marginal shape parameters ξ as:

- if additional information were not available and;
- if there existed a regional study of annual maximum daily precipitation.

Uncertainty of estimated precipitation quantiles was measured through the Relative Root Mean Square Error (RRMSE), Relative Bias (RB) and the Coefficient of Variation (CV), which were computed and analyzed for both the simulated quantiles and for the ξ parameters.

This analysis was the basis to perform the following study. Now, the objective was to assess how this reduction of uncertainty propagates through the HM and how different precipitation regimes, climate extremality, and basin hydrological characteristics of the basin could affect in the uncertainty of the flood quantiles estimates. Similarly, a Monte Carlo simulation was performed from samples extracted from synthetic populations. With the results of the previous analysis, the different population 100-year return period precipitation quantiles ($X_{100,P}$) were introduced in the WG for its parametrization to simulate long series of precipitation, which in turn fed a fully-distributed HM with two different hydrological regimes (i.e., permanent regime and ephemeral regime) to obtain the discharges and the corresponding flood quantiles. Figure 3 below shows a workflow diagram of how this Monte Carlo study was performed.

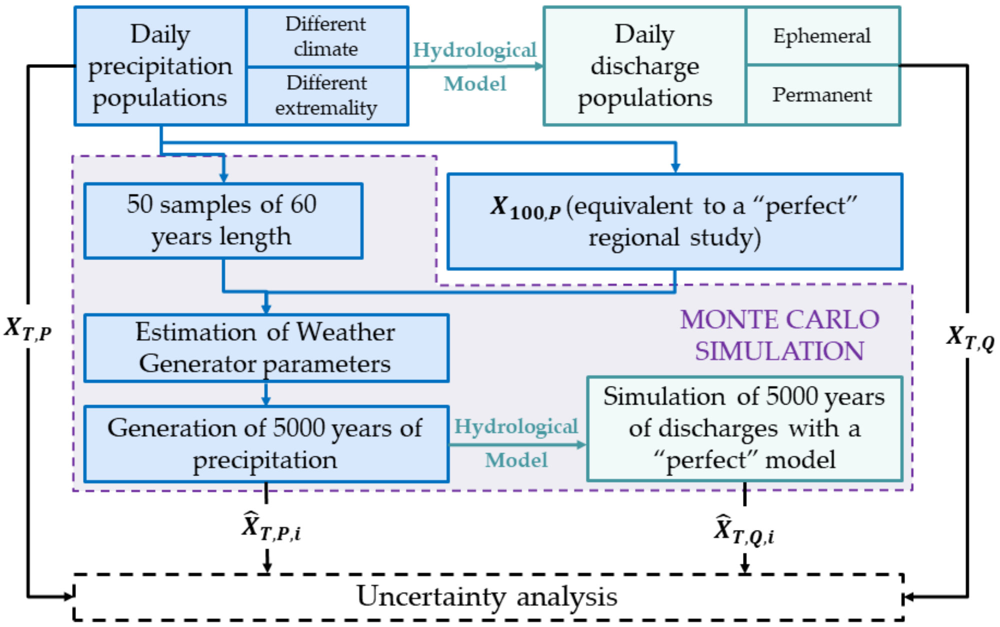


Figure 3 - Workflow diagram of the methodology to quantify the uncertainty reduction of the flood quantile estimations. $X_{T,P}$: Population precipitation quantile. $X_{T,Q}$: Population flood quantile. $X_{T,Q/Pi}$: Precipitation/flood quantile of each realization.

With all this progress made and all the knowledge acquired, coinciding with a collaboration agreement with the Segura River Basin Water Authority, the proposed methodology was applied in a case study, the whole Segura River Basin (15,150 km^2). In this case, however, the outputs from the study were required to be at sub-daily resolution (i.e., 60 minutes). Therefore, the methodology was slightly amended to obtain discharges at 60-min temporal resolution. This was achieved by selecting a set of representative high return period storms from the generated synthetic precipitation with the WG and disaggregating the daily precipitation using the Method of Fragments (Breinl and Di Baldassarre, 2019). Figure 4 shows the workflow diagram of the methodology proposed for the

Segura River Basin, which is basically the same as the proposed in Figure 2, but incorporating the temporal disaggregation of the precipitation.

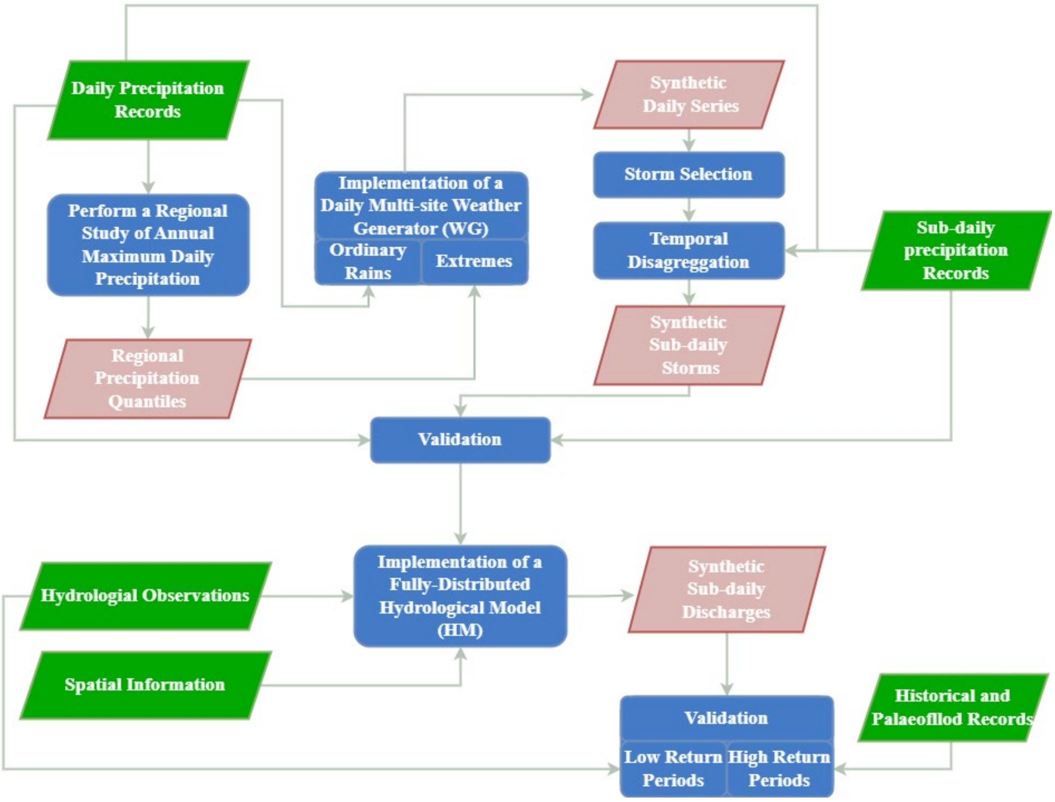


Figure 4 - Workflow diagram of the methodology applied in the Segura River Basin case study.

Lastly, having established a methodology to estimate extreme floods in current climate, both in daily and sub-daily temporal resolutions, last step consisted in incorporating the potential effects of climate change in future flood quantiles. Climate projections were obtained from the “Coordinated Regional Downscaling Experiment for Europe” (EURO-CORDEX) (https://www.euro-cordex.net/). A total of 12 different combinations of Global Circulation Models (GCM) and Regional Circulation Models (RCM) were used in this study (Table 2). These data included: (1) a control period (1971-2000), which was used to perform a bias correction based on the non-parametric statistical transformation of empirical quantiles or “quantile mapping” (Gudmundsson et al., 2012) and also considering the adaptation of the frequency of wet/dry days proposed by Themeßl et al., (2012): and (2) a medium-term projection (2035-2064), and a long-term projection (2065-2094). Both projections used in this study correspond to the Radioactive Concentration Pathways (RCP) 8.5, which represents the most pessimistic scenario, with continuous emissions of CO_2 throughout the 21st century (Meinshausen et al., 2011).

Table 2 - EUROCORDEX models.

Model	GCM	RCM	Institute
1	MPI-M-MPI-ESM-LR	COSMO-crCLIM-v1-1	CLMcom-ETH
2	CNRM-CERFACS-CNRM-CM5	CCLM4-8-17	CLMcom
3	CNRM-CERFACS-CNRM-CM5	RACMO22E	KNMI
4	ICHEC-EC-EARTH	COSMO-crCLIM-v1-1	CLMcom-ETH
5	ICHEC-EC-EARTH	RACMO22E	KNMI
6	IPSL-IPSL-CM5A-MR	RACMO22E	KNMI
7	MOHC-HadGEM2-ES	CCLM4-8-17	CLMcom
8	MOHC-HadGEM2-ES	RACMO22E	KNMI
9	MPI-M-MPI-ESM-LR	CCLM4-8-17	CLMcom
10	MPI-M-MPI-ESM-LR	KNMI-RACMO22E	KNMI
11	MPI-M-MPI-ESM-LR	REMO2009	MPI-CSC
12	NCC-NorESM1-M	COSMO-crCLIM-v1-1	CLMcom-ETH

Once the models were bias corrected, a regional analysis of maximum precipitation was performed for each of the models and both for control period and for the two projections following the methodology developed by Hosking and Wallis, (1993, 1997), which uses the Index Variable method (Dalrymple, 1960) together with linear moments. Once again, the obtained regional quantiles were incorporated in the calibration of the WG, both for the control period and for the projections. Generating a long series of precipitation with the WG for each model and estimating the flood quantiles, it was possible to obtain the climate change signal (or delta Δ) the models were yielding, which applied to the observed flood quantiles provided the future flood quantiles. A full workflow diagram of the methodology can be observed in Figure 5.

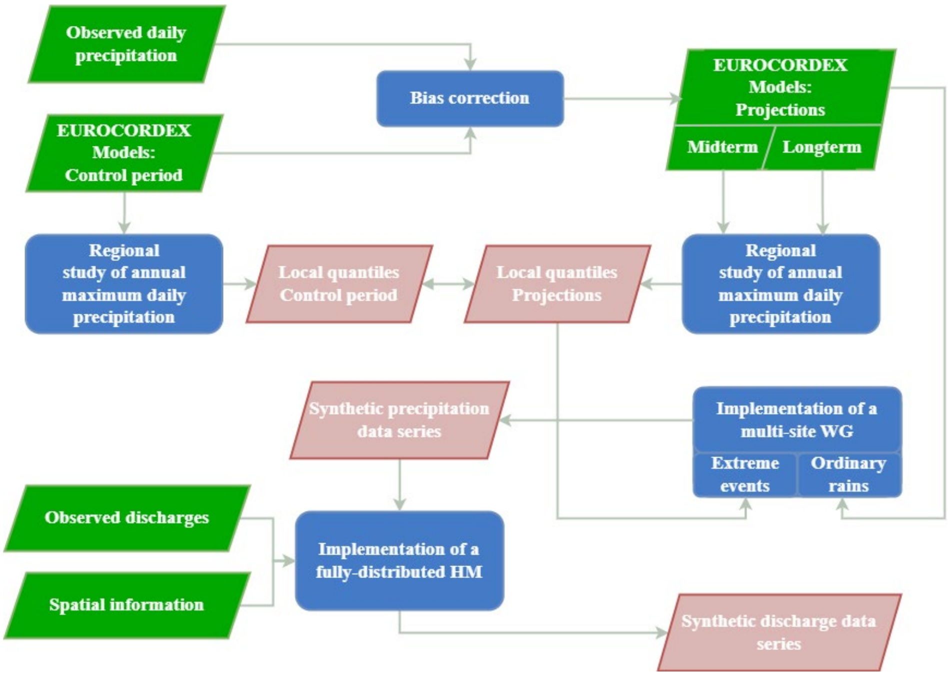


Figure 5 – Workflow diagram of the full methodology.

1.2.2. Weather generator

The WG used to carry out these studies was GWEX, developed by Evin et al., (2018). It is a multi-site stochastic WG focused on the adequate modeling of extreme events. Among the many characteristics that can be highlighted of this WG, for the purposes of this research thesis it is worth mentioning that it incorporates the Extended Generalized Pareto Distribution (E-GPD) function (Papastathopoulos and Tawn, 2013), which is basically obtained by raising the Generalized Pareto Distribution to a power of k>0.

$$F(x;\lambda) = \left[1 - \left(1 + \frac{\xi x}{\sigma}\right)_+^{-1/\xi}\right]^{\kappa}, \qquad x > 0 \tag{1}$$

being λ = (k, σ, ξ) a vector of parameters, where k controls the shape of the lower tail, σ is a scale parameter, and ξ controls the decay rate of the upper tail (Naveau, 2016), 2016). This decay can be observed in Figure 6, which shows the plotting positions for different values of ξ having fixed the values of k and σ.

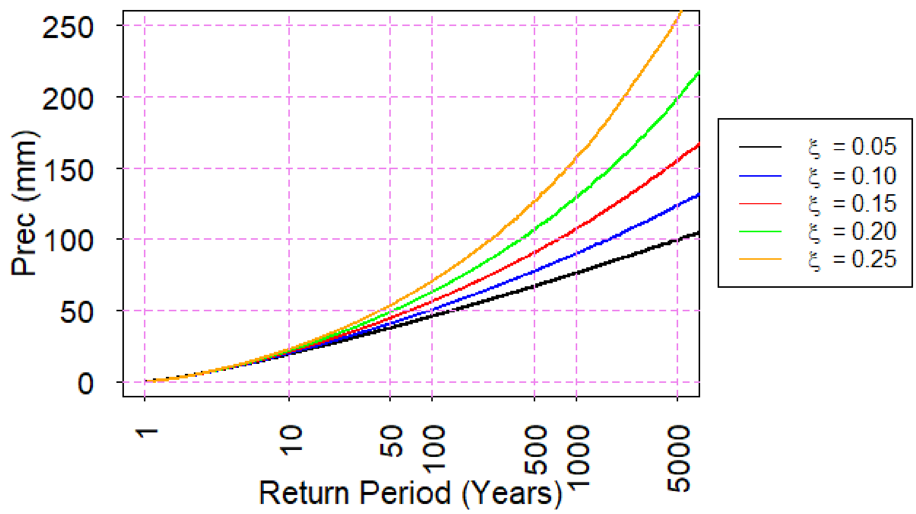


Figure 6 - E-GPD upper tail decay for different ξ values.

Additionally, in GWEX it is possible to simulate precipitation in 3-day periods for then being disaggregated to a daily scale by the Method of Fragments. This latter feature was particularly interesting for our case studies, given that the extreme events that usually take place in our study areas last between 2 and 3 days on average.

1.2.3. Hydrological model

In the present research thesis, the TETIS ecohydrological model was used (Francés et al., 2007; Vélez et al., 2007). It is a conceptual model (i.e., tank structure), with parameters physically based and fully-distributed in space (Figure 7). It is a parsimonious model thanks to the incorporation of a split-parameter structure that allows a significant reduction in the number of variables to be calibrated (only nine corrective factors), facilitating the calibration stage of the model through an optimization algorithm (Francés et al., 2007; Vélez et al., 2007).

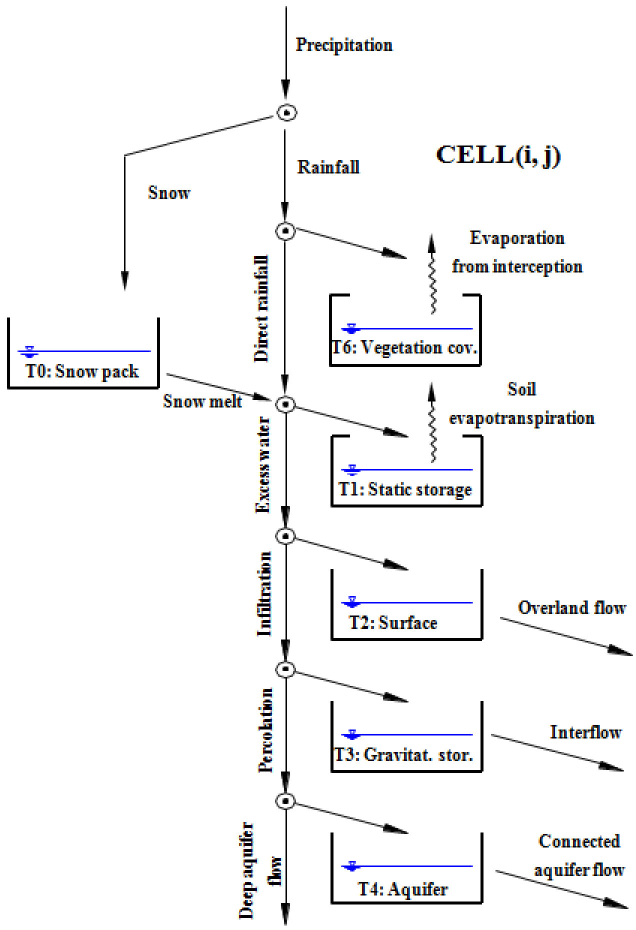


Figure 7 - Conceptual schema of the TETIS model at cell scale.

Several maps were used to feed the ecohydrological models with the geomorphological characteristics of the basins, such as slope, flow directions and flow accumulation, which were obtained from digital elevation models with a resolution of 100 m obtained from the Institute of National Geographic (IGN). Soil hydraulic conductivity was obtained from the European Soil Database (ESDB). The capillary water storage capacity of the upper soil was estimated from ESDB and reclassifying the CORINE land use map. The saturated hydraulic conductivity of the rock stratum (used for the percolation capacity) was estimated using the map of the Geological and Mining Institute of Spain (IGME) reclassified to lithological units. The two models (i.e., Rambla de la Viuda and Segura River basin) were implemented obtaining satisfactory results in terms of Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) both in calibration and in temporal, spatial and spatio-temporal validation.

1.3. Thesis structure

This thesis is written as a compendium of research papers. For this reason, and following the regulations established by the Doctoral School of the Polytechnic University of Valencia, the document is divided into four main blocks: a first block containing a general overview of the motivation, objectives and the contribution of this thesis; a second block composed of five chapters with the author's version of the research papers that encompass the thesis: a third block where the main findings of the thesis are presented and discussed and; a last block presenting the main conclusions and the potential future research lines. All the papers that encompass this research thesis, and that are cited below, have been published or submitted in peer review journals indexed in the Journal Citation Report (JCR).

- Beneyto, C., Aranda, J.Á., Benito, G., Francés, F., 2020. *New approach to estimate extreme flooding using continuous synthetic simulation supported by regional precipitation and non-systematic flood data*. Water (Switzerland) 12, 1-16.
- Beneyto, C., Ángel, J., Francés, F., 2023. *Exploring the uncertainty of Weather Generators' extreme estimates in different practical available information scenarios*. Hydrological Sciences Journal 000, 1-10.
- Beneyto, C.; Vignes, G.; Aranda, J.Á.; Francés, F., 2023. *Sample Uncertainty Analysis of Daily Flood Quantiles Using a Weather Generator*. Water (Switzerland) 2023, 15, 3489.
- Beneyto, C., Ángel, J., Francés, F. *Expanding Information for Flood Frequency Analysis Using a Weather Generator: Application in a Spanish Mediterranean Catchment*. Journal of Hydrology: Regional Studies. 2024, 53, 101826
- Beneyto, C., Ángel, J., Francés, F. *On the Use of Weather Generators for the Estimation of Low-Frequency Floods Under a Changing Climate*. Water. 2024, 16, 1059

2. New approach to estimate extreme flooding using continuous synthetic simulation supported by regional precipitation and non-systematic flood data.

Carles Beneyto[a], José Ángel Aranda[a], Gerardo Benito[b] and Félix Francés[a]*

[a]*Research Institute of Water and Environmental Engineering, Universitat Politècnica de València, Camino de Vera s/n, E-46022 Valencia, Spain*

[b]*Department of GeologyGeology Department, National Museum of Natural Sciences-CSIC (CSIC-Universidad Complutense de Madrid), c/José Gutiérrez Abascal, 2, E-28006 Madrid, Spain.*

* Correspondence: carbeib@alumni.upv.es; Tel.: +34-963-877-000 (ext. 76152)

Beneyto, C., Aranda, J.Á., Benito, G., Francés, F., 2020. *New approach to estimate extreme flooding using continuous synthetic simulation supported by regional precipitation and non-systematic flood data*. Water (Switzerland) 12, 1-16.

This is the author version of the paper published in the scientific journal Water (Switzerland) in 2020 (https://doi.org/10.3390/w12113174/).

2.1. Abstract

Stochastic weather generators combined with hydrological models have been proposed for continuous synthetic simulation to estimate return periods of extreme floods. Yet, this approach relies upon the length and spatial distribution of the precipitation input data series, which often are scarce, especially in arid and semiarid regions. In this work, we present a new approach for the estimation of extreme floods based on the continuous synthetic simulation method supported with inputs of (a) a regional study of extreme precipitation to improve the calibration of the weather generator (GWEX), and (b) non-systematic flood information (i.e., historical information and/or palaeoflood records) for the validation of the generated discharges with a fully-distributed hydrological model (TETIS). The results showed that this complementary information of extremes allowed for a more accurate implementation of both the weather generator and the hydrological model. This, in turn, improved the flood quantile estimates, especially for those associated with return periods higher than 50 years but also for higher quantiles (up to approximately 500 years). Therefore, it has been proved that continuous synthetic simulation studies focused on the estimation of extreme floods should incorporate a generalized representation of regional extreme rainfall and/or non-systematic flood data, particularly in regions with scarce hydrometeorological records.

Keywords: weather generator; palaeoflood; regional extreme precipitation study; ephemeral river; fully-distributed hydrology; flood quantiles; Rambla de la Viuda.

2.2. Introduction

Accurate estimates of extreme and rare floods have been a fundamental problem in flood hydrology since pioneer work by Foster, (1924), and it is still present among the scientific and engineering communities in numerous papers and reports. Stedinger and Griffis, (2008) evaluate critical issues on flood frequency methods, recommending practical developments, among others, on:

(i) extending flood records with historical and non-standard flood data (e.g., palaeofloods), which can be called non-systematic information (Francés, 1998); (ii) generation of flood data from rainfall records using conceptually based and spatially fully-distributed watershed models; and (iii) advances in setting realistic physical limits on precipitation and flows in a given catchment. These research topics seek to gain knowledge about the tail of the frequency distribution describing the extremes, particularly in data-poor regions, either by using regional flood methods (Francés, 1998), extending the flood registers (Stedinger and Cohn, 1986), and improving parameter estimates related to the distribution shape with upper bounds (e.g., (Botero and Francés, 2010)) or identifying low outliers in flood data (Cohn et al., 2013). Traditional flood studies (e.g., for the design of sensitive infrastructures) were based in either flood frequency analysis (FFA) for gauged basins or deterministic procedures, mainly based on the design storm, for ungauged basins. This latter approach draws from the premise that return periods of concurrent rainfall and peak discharge are assumed to be the same and that the design flood of a given return period can be estimated based on a single rainfall duration that generates the highest peak discharge (see the classical Chow et al., (1998) or the Flood Estimation Handbook (Houghton-Carr, 1999)). However, we now know that this approach is uncertain since peak discharges and hydrographs are strongly dependent on the spatio-temporal distribution of the precipitation (Emmanuel et al., 2017) and on the initial conditions of the basin (Pathiraja et al., 2012). In recent years, different continuous hydrologic modeling approaches have emerged (see, for example, Grimaldi et al., (2020)). An alternative method widely adopted is to combine statistical and deterministic methods in a continuous synthetic simulation (CS). The procedure involves the generation of synthetic discharge data series obtained from a stochastic weather generator (WG) combined with a hydrological model (HM). Many studies can be found in the literature following this approach with different nuances. In an early work, Cameron et al., (1999) combined a modified WG developed by Eagleson, (1972) with the semi-distributed HM TOPMODEL. Other examples include WG synthetic datasets from Neyman-Scott rectangular pulse (Brocca et al., 2013) or spatiotemporal Neyman-

Scott processes (Cowpertwait et al., 2013) integrated on semi-distributed or fully-distributed hydrological models. A review of different continuous synthetic simulation approaches can be found in Boughton and Droop, (2003).

Continuous synthetic simulation procedures can generate long series of discharges where flood quantiles can be easily interpolated from the empirical plotting positions rather than having to parameterize the discharges data series as in the traditional flood frequency analysis. Nevertheless, WGs require representative data series of observed extreme precipitation in order to perform adequately (Soltani and Hoogenboom, 2003). In most of the cases, there may not be sufficient extreme rainfall records, meaning that results from stochastic WG may not generate reliable extreme floods (Cavanaugh et al., 2015; Verdin et al., 2015). This problem has been addressed by several authors who have proposed different alternatives to improve the WG performance. For example, Furrer and Katz, (2008) distinguished the type of precipitation by fitting low to moderate intensities to a gamma distribution and high intensities to generalized Pareto distribution. Evin et al., (2018) proposed the use of a heavy-tailed distribution function (E-GPD) and the integration of information from more extensive regional studies for the parametrization of the WG.

In the context of Mediterranean ephemeral rivers, WG and FFA implementation involve a number of practical problems, mostly related to frequent zero or very small flows for the entire year, a large variability of flood peak discharges, and often-short observation records (Cohn et al., 2013). In arid/semiarid rivers, Metzger et al., (2020) applied synthetic flood records to FFA, concluding that streams with a small number of events per year and a large coefficient of variation of the flood peaks produced the largest errors in the estimated quantiles. Regional regression models were used to improve at-site frequency curves (Zaman et al., 2012), but their performance in arid/semiarid environments is not as satisfactory as in humid regions because of the higher degree of hydrological variability. The fact that longer records provide less biased estimates, as indicated by Metzger et al., (2020), calls for the inclusion of historical and other non-standard flood data (Merz and Blöschl, 2008a, 2008b).

These include historical observations, interval data (estimates of flood peaks within specified ranges of magnitude and time), and palaeoflood records (Benito et al., 2020). Palaeoflood data provide physical evidence of flooding over secular time scales and typically consist of fine-texture sediment layers accumulated on valley sides (Baker, 1987) and durable botanical evidence, such as scars produced by impacting floating debris and stones on riparian trees (Ballesteros-Cánovas et al., 2013). By providing information beyond the systematic records, it is generally possible to extend the observations beyond the 100-year return period and therefore reduce the estimated quantile uncertainty (e.g., England Jr. et al., 2019; Frances et al., 1994; Stedinger and Baker, 1987).

The main objective of this paper was to develop a methodology for a better estimation of extreme flooding based on a daily multisite WG and a fully-distributed HM supported by a regional extreme precipitation study and non-systematic flood information, validating its results in a case study. Although we integrated both sources of additional information in this research, different variants of this methodology can be applied if only one source of information is available, which will depend on the type of information available.

Under- or overestimation of flood quantiles has always been a problem in flood modeling studies. The main reason behind this is the short length of the available hydrometeorological data series. Most of the former works based in the CS approach do not account for this problem and, although solving the abovementioned issues of the initial conditions of the river basin and the characterization of the spatio-temporal distribution of the precipitation, the estimated higher quantiles still present high uncertainties. This methodology aims to contribute in this sense, obtaining better estimates of the higher flood quantiles and reducing their uncertainty by adding two extra sources of additional information for the implementation of the WG and the validation of the resulting discharges.

2.3. Case Study and Data Collection

The proposed approach was implemented and evaluated in the catchment of Rambla de la Viuda, a typical Mediterranean ephemeral river located in eastern Spain. The river is ca. 36 km in length and 1513 km2 in catchment surface, and it originates at the confluence of River Montlleó and Rambla Carbonera, flowing into River Millars near its mouth in the Mediterranean Sea (Figure P1 - 1).

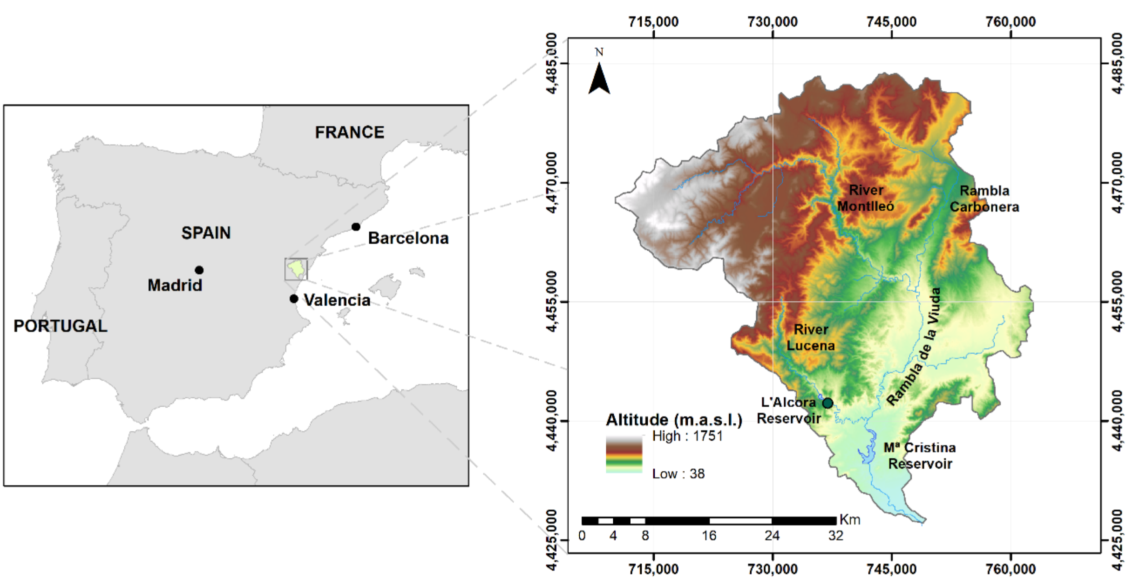


Figure P1 - 1- Study area: Rambla de la Viuda catchment.

Their headwaters are located at the Iberian Range Mountains at an elevation of 1750 m above sea level, with a substrate dominated by Jurassic and Cretaceous limestones and marls affected by the Alpine tectonic reactivated during the Neogene (Simón et al., 2013). This bedrock lithology favors karstification processes, leading to high infiltration and percolation rates into a deep karst aquifer disconnected from the stream channels. The lower part of the catchment is located in the coastal plain where the Rambla joins the Millars River to find its way to the Mediterranean Sea. This coastal plain consists of alluvial fan deposits (mainly gravels) of Tertiary and Pleistocene age. In the upper catchment, the river channel is embedded in deep and narrow valleys, whereas in the lower part, it develops a wide alluvial channel bed, with a width-to-depth ratio of ~100 times (Camarasa Belmonte and Segura Beltrán, 2001).

The observed average annual rainfall is approximately 550 mm. The precipitation annual pattern consist of (i) autumn rains (September to November) recording the highest daily and monthly rainfall amounts; (ii) frontal systems linked to Atlantic zonal flow during winter (December to January) and spring (March to May), with spring giving the secondary monthly rainfall maximum; and (iii) occasional convective storms in summer, which is mostly dry (Camarasa Belmonte and Segura Beltrán, 2001; Mateu, 1974). Rambla de la Viuda streamflow patterns are strongly marked by the Mediterranean rainfall regime, high bedrock permeability due to the dominance of karstified limestones, and high channel transmission losses. As a result, streamflow occurs with an average of 31 days per year, often lasting only 2-3 days and associated with accumulated rainfall amounts larger than 70 mm (Camarasa Belmonte and Segura Beltrán, 2001).

Large floods are a significant element of this irregular hydrological regime, producing up to 80% of annual discharge volume (Segura and Camarasa, 1996). Heavy rainfalls leading to extraordinary and extreme floods are related to autumn mesoscale convective systems (MCSs) (Llasat and Puigcerver, 1990) fed by Mediterranean moisture and enhanced by orographic effect of the Iberian Range Mountains close to the coast. For example, the rainfall event of October 1962, recorded ca. 300 mm in 24 h that led to severe flash flooding with a peak flow of 1500 m3s−1 at Maria Cristina Dam. This floodwater overflowed the spillway (capacity for 600 m3s−1) and spilled over the dam wall with a depth of 0.7 m. Comparable large floods overflowing the dam took place in 1920 (during dam construction), 1962, 1969, and 2000.

Meteorological records were obtained from different sources. The daily max. and min. temperatures as well as the daily precipitation series were obtained from the Spain02-v5 reanalysis dataset (Herrera et al., 2016). A total of 20 grid points (Figure P1 - 2) covering the catchment area with daily records from 1951 to 2015 (66 years). Sub-daily temperature and precipitation records (5-min) for 13 stations were obtained from the Júcar River Basin Authority (CHJ) through the

Júcar Automatic Hydrological Information System (SAIH), which started recording sub-daily measurements from 1991.

In terms of hydrological data, these were recorded in four points with available daily and 5-min discharge information directly from the CHJ and from the SAIH, respectively, namely two continuous flow gauges (Vall d'Alba and Montlleó) and two stations at dams (Alcora and Maria Cristina) where discharges were estimated from the balance of the reservoir level and the outflow records (Figure P1 - 2). The length of the daily discharge series ranged between 57 years at Maria Cristina dam and 14 years at Montlleó flow gauge. With regards to the 5-min records, only three high flow events (i.e., 2000, 2015, and 2018) were registered from 1991. In addition, 5-min discharge records at both Vall d'Alba and Montlleó showed strong inconsistencies and therefore they were only used to validate dry/wet conditions on the river channel.

Further information on extremes was obtained from a regional study of maximum daily precipitation (Ministerio de Fomento. Dirección General de, 1999) that was used for the additional calibration of the weather generator. In addition, non-systematic flood data were collected from documentary datasets and palaeoflood studies (Benito et al., 2020; Machado et al., 2017) in two sites, which were integrated for the validation of the GW-hydrological model methodology.

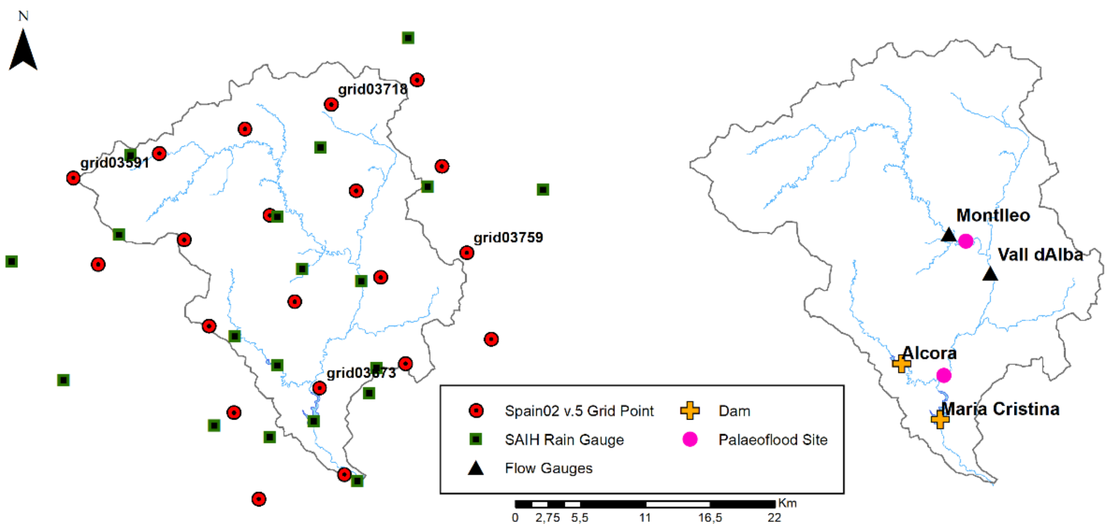


Figure P1 - 2 - Location of hydrometeorological information.

2.4. Methodology

The methodology consisted of four steps: (1) application of a weather generator for simulating daily precipitation and temperatures with an additional calibration of the parameters related to the extremes using a regional annual maximum rainfall study to deal with the limited length of precipitation records; (2) implementation at a daily and sub-daily scale of a fully-distributed hydrological model that can cope with the spatial variability of rainfall and catchment characteristics; (3) simulation of daily flows of the synthetic rainfall dataset in the fully-distributed rainfall-runoff model; (4) comparison of the performance of flood frequency analysis from observed and synthetic flood series; and (5) incorporation of palaeoflood discharge estimates covering the past 500 years to validate synthetic discharges for high return periods in other ungauged locations but with non-systematic information. A workflow diagram of the methodology can be observed in Figure P1 - 3.

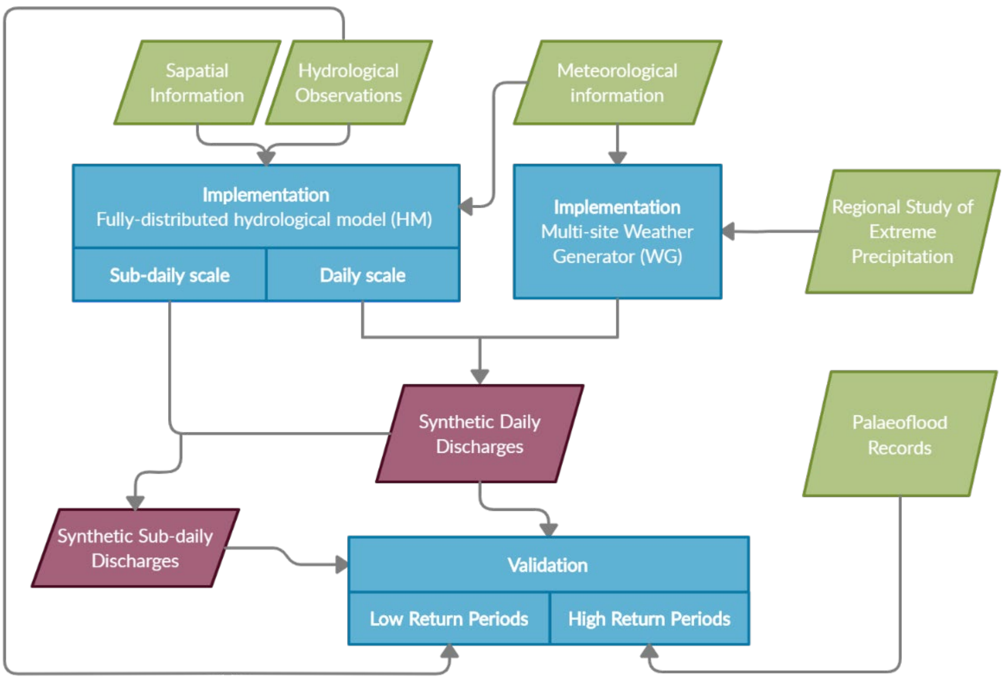


Figure P1 - 3 - Workflow diagram of the methodology.

In the present study, the eco-hydrological model TETIS (Francés et al., 2007) was used. It is conceptual (i.e., tank structure) but with physically based parameters, and fully-distributed in the space. It is a parsimonious model thanks to the incorporation of a split effective parameter structure that allows a significant reduction in the number of variables to be calibrated (only nine correction factors) facilitating the model calibration stage using an optimization algorithm (Francés et al., 2007). Several maps were used to feed the model with the catchment geomorphological characteristics, such as slope, flow directions, and flow accumulation, which were obtained from a digital elevation model with a 100-m resolution obtained from National Geographic Institute (IGN). The hydraulic conductivity of the soil was obtained from the European Soil Database (ESDB). Capillary water content capacity of the upper soil was estimated from ESDB and by reclassifying the CORINE land use map. Hydraulic conductivity of saturated rock (used for the percolation capacity) was estimated using the map reclassified to lithological units from the Spanish Geological and Mining Institute (IGME).

Model implementation was carried out at two temporal resolutions. On the one hand, the model was implemented on a daily scale, and this was used to obtain the long data series of discharges. On the other hand, a 5-min temporal resolution model was also implemented. This allowed the relation between peak and daily discharges at any point in our study area to be obtained.

With regards to the WG, after testing different models, GWEX (Evin et al., 2018) was selected. This WG was designed to focus on extreme events and incorporates a heavy-tailed distribution function for the precipitation amounts: the E-GPD (Papastathopoulos and Tawn, 2013). It offers the possibility to introduce a tail dependence between at-site extremes by using a student copula to represent the dependence structure of innovations. Additionally, and what is more important, it is possible to simulate precipitation in 3-day periods for then being disaggregated to a daily scale by the method of fragments. This latter feature was particularly interesting for our case study given that the extreme events that take place in our study area last between 2 and 3 days on average.

Long synthetic data series of precipitation and temperatures were generated. These, in turn, fed the daily hydrological model obtaining the resulting discharge data series. Finally, the results were validated in two stages: (1) comparison of the flows associated with low quantiles with the observed flows at Maria Cristina Dam; and (2) comparison of the quantiles of the upper part of the distribution function with the non-systematic records previously converted into daily values.

As previously mentioned, non-systematic data were collected from previous studies reporting documentary floods and palaeoflood analysis (Benito et al., 2020; Machado et al., 2017). Historical floods were collected from scientific and technical reports; local history books and non-systematic compilations by historians, such as Balbás, (1892), Fogués, (1931), and Fontana Tarrats, (1978); and from recent compilations by Camarasa Belmonte and Segura Beltrán, (2001), Sánchez Adell et al., (1993), and Beltrán Manrique (1958). The Rambla de la Viuda documentary flood evidence reports a total 19 large floods since CE1378, although continuous and homogeneous data started in 1959. Palaeoflood records were reconstructed on the basis of sedimentary evidence at two sites (Figure P1 - 2), namely in Rambla de la Viuda upstream of the Maria Cristina Reservoir (Machado et al., 2017) and in the Monlleó River (Benito et al., 2020). Palaeoflood data result from the analysis of palaeostage indicators consisting of stratigraphic sequences of fine-flood sediments (mainly sand and silt), each representing an individual flood event (Machado et al., 2017). Hydraulic studies were performed to relate the elevation of sediment layers to palaeoflood discharges, and flood age was obtained by geochronological analysis (see Ballesteros-Cánovas et al., (2013)). In Rambla de la Viuda, the palaeoflood record contains a total of 17 floods above a threshold of 500 m^3s^{-1} since CE1378, whereas in the Monlleó River, it comprises 10 floods above a threshold of 470 m^3 s^{-1} since CE1475.

2.5. Results

2.5.1. Fully Distributed Hydrological Model

The following paragraphs describe the implementation of the hydrological model at both the daily scale and 5-min temporal resolutions.

Daily Implementation

For the daily scale model, six extreme flow events were selected from the available records in the SAIH (1959-2015) at Maria Cristina dam: 1962, 1969, 1989, 2000, 2006, and 2015. The model was fed with hourly and daily rainfall from the grid points shown in Figure P1 - 2. The calibration process was especially complex due to two specific particularities of this case study: the asynchrony between meteorological and hydrological daily data and the difficulties to evaluate flow transmission losses into the karstic and alluvial aquifers. Firstly, during the calibration process, it was observed that the maximum flow appeared one day after the maximum precipitation event occurred; however, the area of the basin was not large enough for its concentration time to be one day. Different aggregation intervals of precipitation and flow were detected, as weather stations measure daily time blocks from 07:00 to 07:00, whilst the flows are recorded at the dam from 19:00 to 19:00. If it rains in the early hours of the morning or between the afternoon and the night of any given day, with a residence time of 7 or 8 h according to the size of the Rambla de la Viuda basin, the flow can be transferred to the next day (Vélez and Botero, 2011). The solution, thus, consisted of advancing by one day the time series corresponding to the hydrological information, making the event of maximum precipitation and the peak flow coincide on the same day, improving the model performance in both the calibration and validation stages.

After the correction of the time lag, it was noted that during certain periods of time and despite the fact that there were registered rains, there were simulated small peak flows where the observed hydrograph did not show them. This was considered as a clear indicator of the existence of transmission losses in the basin as a consequence of the effects of karstification and the existence of reaches where the streamflow was directly connected into the groundwater system.

TETIS allows for the introduction and extraction of external flows to the basin to consider the effects of external demands, such as irrigation channels, as well as the input of external flows from transfers. Using this characteristic and by looking into the zero-probability events, flow losses of ~8 m^3s^{-1} were estimated and accordingly extracted at specific reaches of the model. This removed the simulated small peaks and improved the model performance.

Lastly, and considering that the main purpose of this methodology is to estimate flood quantiles, the daily hydrological model was validated comparing the plotting positions of the 57-year period of observed annual maximum daily flows and the 66-year period of simulated ones (Figure P1 - 4). In this case, instead of comparing the flow events one-to-one, the two complete data series of observed and simulated flows were compared. However, since neither the length of both data series is the same and consequently nor are the associated probabilities, the observed and simulated flows cannot be directly related one-to-one. The used plotting position formulation was proposed by Cunnane (1978):

$$F_i = \frac{i - \alpha}{N + 1 - 2\alpha} \quad (1)$$

where i is the position, N is the length of the data series, and α is a coefficient. Since this study was focused on extremes, a value of α = 0.44 was adopted (Gringorten, 1963).

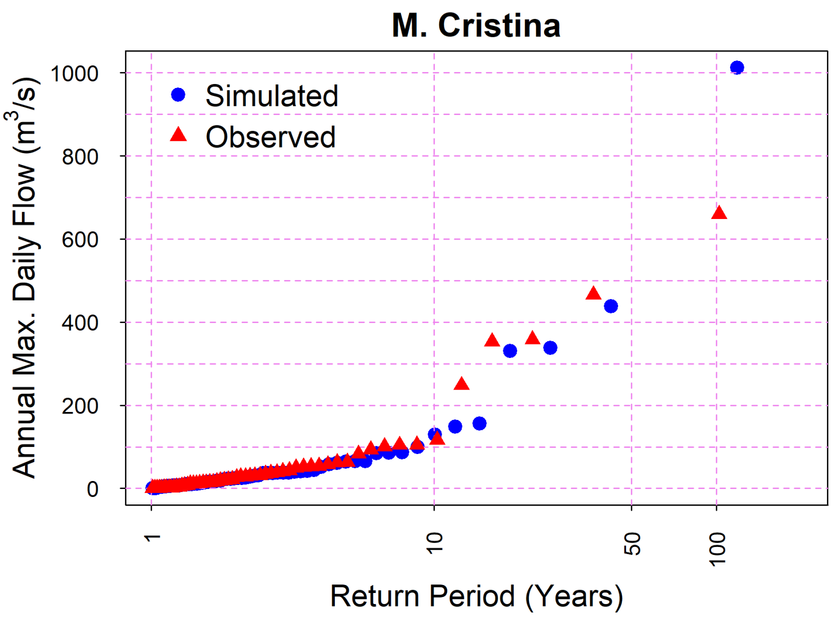


Figure P1 - 4 - Plotting positions of simulated and observed annual maximum daily flows in Maria Cristina dam.

Sub-Daily Implementation

For the sub-daily implementation of TETIS, three high flow events were selected (2000, 2015, and 2018) with available records at 5-min time-steps of precipitation and temperature as well as information of observed flows and reservoir levels from the SAIH network.

In this case, a cross-calibration was performed at Maria Cristina dam, obtaining the best results in terms of the Nash-Sutcliffe index (NSE (Nash and Sutcliffe, 1970)) when calibrating in the 2018 event (Figure P1 - 5). For this calibration period, an NSE index of 0.7556 was obtained, whilst an NSE index of 0.6293 and 0.3684 was obtained for the 2000 and 2015 validation periods, respectively.

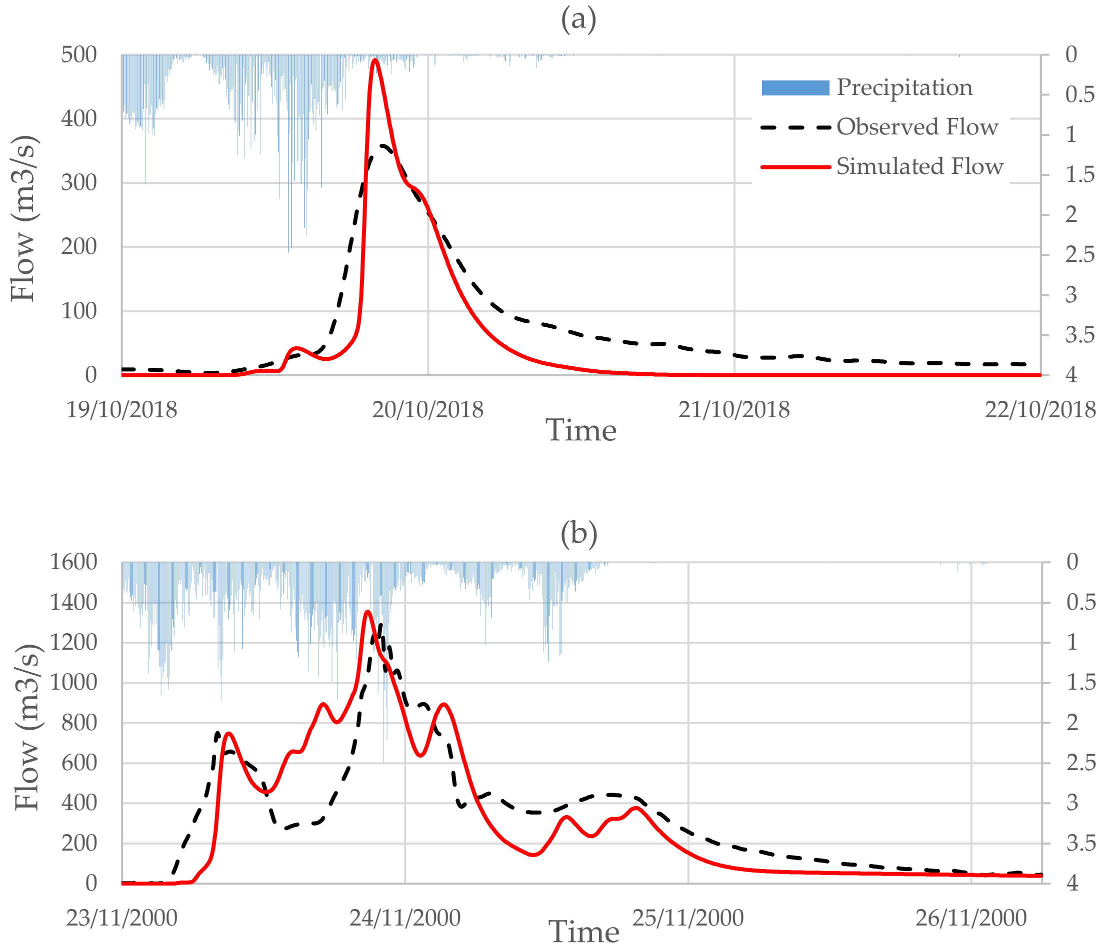


Figure P1 - 5 - Observed and simulated sub-daily hydrographs for the calibration in the 2018 event (a), and temporal validation in the 2000 event (b) at Maria Cristina dam.

2.5.2. *Stochastic Daily Weather Generator*

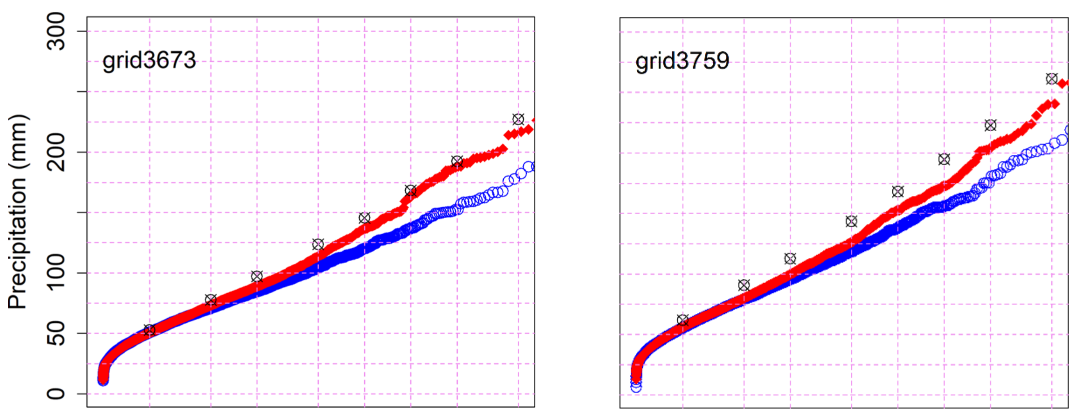
The GWEX model (Evin et al., 2018) was used for simulating long data series of both precipitation and temperatures. The next section discusses the way the parameters of the WG were estimated and presents the results of the implementation.

Parameter Estimation

A similar approach to that proposed in Evin et al. (Evin et al., 2018) was carried out. A regional study of Spanish maximum daily precipitation (CEDEX, 1994) was used to compare the simulated flow quantiles in two steps. In this study, the coefficient of variation was regional, and the mean was local, which was used for the regionalization. The region this catchment belongs to had more than 30 years of precipitation records, which means that the estimated coefficient of variation has high reliability. Therefore, we maintained the regional coefficient of variation and only updated the local means.

Firstly, an estimation of the WG parameters was made only considering the observed precipitation and compared with the information from the regional study of maximum daily precipitation.

Secondly, due to the systematic quantile underestimation (as shown in Figure P1 - 6), the regional study of maximum daily precipitation was used to calibrate the shape parameter ξ of the marginal distribution function E-GDP. The final value adopted was the one that which minimized the mean root mean square error (RMSE) between the observed and simulated quantiles. For this second calibration, it was decided to split the precipitation into two groups: (1) a first group that included the ordinary precipitations, that is to say, the precipitation that fell outside the autumn months, where the shape parameter was left as per default (ξ = 0.05); and (2) the precipitation falling during autumn months (SON), i.e., comprising all heavy precipitation events. Since the catchment dimensions can be considered small and with no great differences in terms of annual precipitation between the upper and lower parts, it was deemed appropriate to consider the catchment as a single unit. Therefore, one value of the shape parameter ξ was estimated for all the rain gauges. After several iterations, the value of ξ that minimized the RMSE was ξ = 0.16.



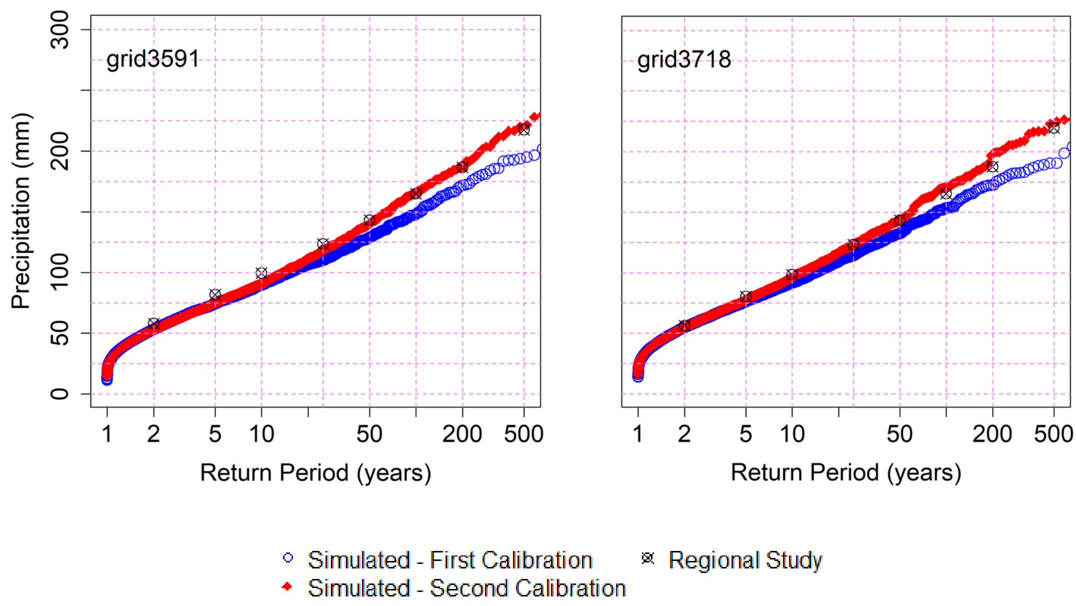


Figure P1 - 6 - Results of WG calibration in four representative grid points.

2.5.3. Peak Discharge Transformation

The palaeoflood information in this case study, and very often, is presented as lower limits of the peak floods, without knowing the exact value of the peak. Therefore, there is a need for conversion between peak (Q_p) and daily discharges (Q_d) in order to exploit this information using the HM implemented at a 5-min temporal resolution (Section 4.1.2).

A set of 50 high flow events were synthetically generated by scaling the available records of precipitation and modifying the initial soil moisture. From these, 33 and 21 episodes respectively were selected to proceed with the analysis. Daily discharges were calculated by grouping the sub-daily data for each event at both locations where palaeoflood information was available and compared against the simulated peak discharges with the 5-min HM (Figure P1 - 7). The fitted potential equations have a coefficient R of Sperman higher than 0.8 at both locations. Finally, palaeoflood information from Benito et al., (2020) and Machado et al., (2017) was converted into daily values using the fitted potential relationship.

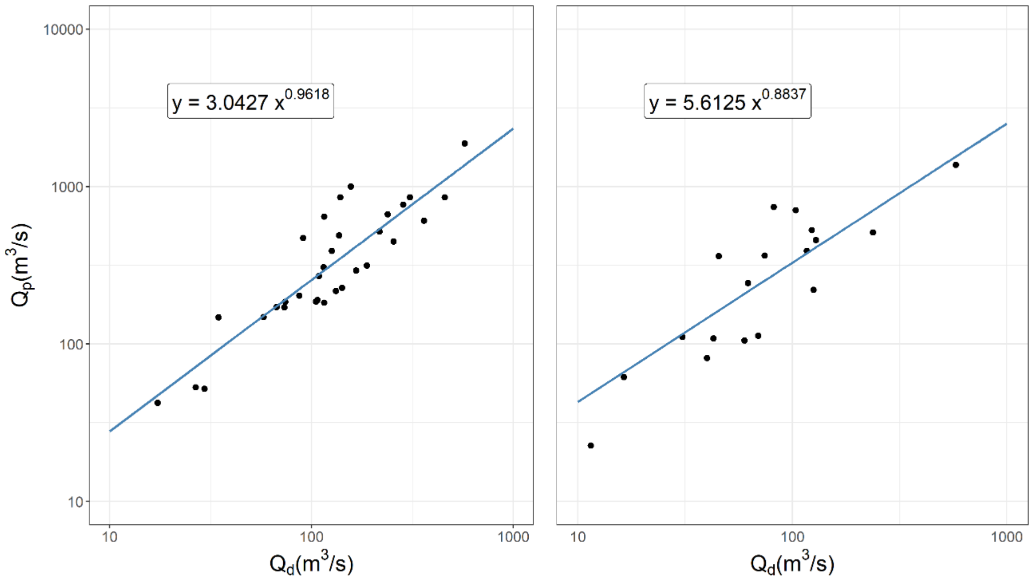


Figure P1 - 7 - Potential regression between daily (Q_d) and simulated peak discharges (Q_p) at palaeoflood sites: Left, Rambla de la Viuda NS site; Right, Montlleó NS site.

2.5.4. Validation with the Palaeoflood Information

Figure P1 - 8 shows the plotting positions (given by Equation (1)) of the 10,000 simulated annual maximum daily discharges at Rambla de la Viuda and Montlleó palaeoflood sites. The plotting positions of the palaeoflood information can be used for the validation of the methodology. However, this non-systematic information must be statistically classified as binomial censored (Frances et al., 1994), and only can be computed the plotting position of the common censoring threshold (represented by a triangle in Figure P1 - 8) and the plotting position of the lower bound of the maximum flood (represented by an arrow in Figure P1 - 8), where the data length includes the systematic and non-systematic periods.

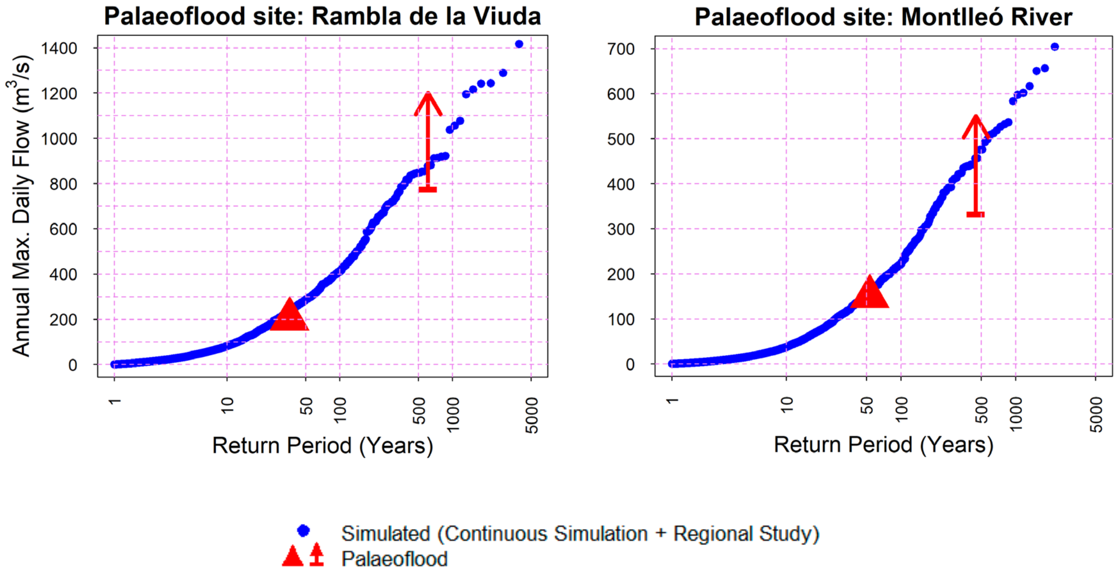


Figure P1 - 8 - Plotting positions of 10,000 simulated annual maximum daily flows and palaeoflood information used for validation at Rambla de la Viuda and Montlleó River.

2.6. Discussion

2.6.1. Flood Frequency with Weather Generators and A Regional Precipitation Study

Available discharge and precipitation records are still far from being sufficiently robust for an adequate estimation of extreme events with a high return period. Traditional purely statistical studies using systematic records have been proved to involve high uncertainty, resulting in either over- or underestimations of the simulated flood quantiles (Haktanir and Horlacher, 1993) and, in any case, they can only be applied in the location of the flow gauge station.

Later studies focusing on individual synthetic storms have been used for many years for infrastructure design (Chen, 2019). Again, great uncertainty surrounded these studies since not necessarily the biggest storm should result in the highest flows, and these would depend upon the spatio-temporal distribution of the storm and the initial conditions of the catchment, which these studies do not rigorously account for.

A continuous synthetic simulation approach using a WG and a fully-distributed HM seems to be becoming one of the potential candidates to deal with this challenge and its use is rapidly increasing over recent years (Lamb et al., 2016). The possibility of extending the records beyond the available ones using a WG reduces the uncertainty of the calculated flood quantiles. Yet, the quality of the precipitation input data series (length, spatial density, reliability, and completeness) is critical to obtain reliable results and, therefore, extra tools and additional information must be integrated to complement their current short length and improve the performance of the WG. For example, in our case study, taking into account that the characteristic high precipitation events have an approximate return period of 7/8 years on average, and these are of extreme magnitude every 20/30 years, 66 years of observed precipitation was not enough information for the WG to satisfactorily reproduce extreme events.

Traditionally, WGs have used light-tailed distribution functions to model precipitation amounts, such as the exponential, gamma, or combinations of both. However, these types of distribution where the tails exponentially decay result in underestimations in the precipitation of the most extreme events (Cavanaugh et al., 2015). GWEX, instead, incorporates a heavy-tailed distribution function for modeling the precipitation amounts. This, along with the 3-day precipitation amounts modeling, improved the performance of the WG, reducing the underestimations of the higher flows, and, as demonstrated in the present study, could be considered as a good option when dealing with arid/semiarid climates where most of the precipitation is concentrated in few days, as in the case of the Spanish Mediterranean coastal catchments (Camarasa Belmonte and Segura Beltrán, 2001; Mateu, 1974).

Evin et al., (2018) suggest that robust studies are needed to adequately estimate certain weather generator parameters, particularly when trying to capture extremes. In our case and following the same approach, we incorporated the information from an available regional study of maximum annual precipitation from CEDEX (1994) for a better calibration of the shape parameter ξ. This regional study substantially improved the performance of the WG, especially for high return periods, where the underestimation was more evident (Figure P1 - 6).

The better reproduction of precipitation data series was also reflected in the results obtained with the HM (Figure P1 - 8). However, it would not have been possible to validate the low-frequency events only with the observed discharge information, since with a systematic flood records' length of 57 years in the case of Maria Cristina dam, only flood quantiles up approximately T = 50 years would have been possible to obtain with a minimum of confidence. The integration of palaeoflood records was key to validate the upper tail of the distribution function.

2.6.2. Non-Systematic Information

Palaeoflood information provides data on individual extreme hydrological events. Robust palaeodischarge estimations were obtained from sedimentological evidence of floodwater elevations reached by past floods (Benito and Thorndycraft, 2005). By providing information beyond systematic records, it is generally possible to extend the flood frequency curve over the 50-year return period and, therefore, reduce the uncertainty of the highest quantiles. In the study carried out by Francés (1998) for the Turia river basin, it was concluded that errors in the estimation decreased as the amount of information used to estimate the flood quantile of 1000 years increased, observing that the use of historical information reduced the estimation error by approximately 50% in his case study. Lamb et al., (2016) concluded that the uncertainty associated with estimated discharge for the 100-year return period flood was reduced by more than 50% when including palaeoflood information.

In the present study, the analysis of the reduction of the uncertainty associated with the flood quantile estimates was not in the scope. Nevertheless, the reliability of the calculated flood quantiles decreases as the return period increases Botero and Francés, (2010). In our case, only with the observed precipitation (66 years), despite being able to calculate the plotting position up to approximately T = 50 years, the uncertainly surrounding return periods higher than 10 years was too high to deem them valid.

However, the palaeoflood records from the studies of Benito et al. (2020) and Machado et al., (2017) provided extra information at the upper tail of the probability function. Specifically, the plotting position of the common censoring threshold (represented by a triangle in Figure P1 - 8), which was calculated with the number of high flow events exceeding a threshold of 470 and 500 m3s−1, allowed more robust estimates of the flood quantiles of T = 36 years and T = 53 years, respectively, to be obtained. Furthermore, it was also possible to obtain the plotting position of the lower bound of the maximum flood (represented by an arrow in Figure P1 - 8), with associated return periods of approximately T = 500 years at both sites.

On the other hand, palaeoflood information is usually related to the peak of the flood. Therefore, daily data series of generated flows must be converted into instantaneous flows or vice versa in order to be able to compare the results. Traditionally, this transformation has been based on empirical methods as in Fuller (1914) or in deterministic methods (Linsley et al., 1968; Sangal, 1983). Fathzadeh et al., (2017) compared four different approaches, concluding that, although some of the tested methods (i.e., adaptive neuro-fuzzy inference systems and artificial neural networks) could obtain better results, it is necessary to have a robust subset of data to train more sophisticated models. In other words, the existence of robust datasets is more important than the method used.

Since these were not available in our study area, it was decided to implement the HM in a sub-daily temporal resolution (5-min). Simulating different synthetic rain events, it was possible to obtain for each the relation between daily and peak discharges at both locations where palaeoflood information was available. All these values were fitted to a potential function, obtaining satisfactory Pearson's correlation coefficients (i.e., 0.8174 and 0.8207) (Figure P1 - 7).

2.6.3. A Holistic Methodological Approach to Estimate Extreme Floods

The methodology presented in this case study is an extension of the continuous synthetic simulation model. Apart from the benefits of this approach discussed before (i.e., initial conditions of the catchment and spatio-temporal distribution of the storm), we propose the integration of additional information to deal with the estimation bias on the flood quantile resulting from the short length of the existing hydrometeorological data series. This methodology can be implemented in any region regardless of its size or its climate; however, the more remarked climate variability, the greater the need to add extra sources of information due to their erratic hydrology.

In our case, an existing regional study of extreme precipitation was used to improve the calibration of the WG and palaeoflood records were included to validate the discharge series. However, this is not the only option; it is possible to apply the present methodology only having one source of information. In the case of having only the regional study of extreme precipitation, the WG can be calibrated with this; however, the resulting discharges cannot be validated. Conversely, in the case of only having palaeoflood records, although not being so straight forward, the WG can be calibrated by comparing the resulting discharge series with the palaeoflood records.

Additionally, due to their ephemeral or temporary nature, most of the streams that lead to catastrophic floods over the months of SON in the Mediterranean coast are either ungauged or only equipped with sensors capable of detecting flow for flood warning purposes. The selection of a deterministic (fully-distributed and physically based) HM here was of upmost importance to capture local infiltration losses and gains. TETIS, being a fully-distributed HM where the parameters are physically based, preserves the spatiotemporal distribution of the storm and allows the discharge information at any point of the catchment to be known unlike in the case of lumped or semi-distributed HMs. Thus, fully-distributed models allow improvement of the understanding of flood extreme regimes in parts of the catchment where discharge records are not available, leading to better estimations of extreme floods, which, in turn, could result in improvements on the flood design of sensible infrastructures or early flood warning protocols. Furthermore, integrating them is an indispensable condition if palaeoflood information is to be incorporated, since this is limited to certain parts of the river where these records can be obtained and usually not in the same location where the flow gauge stations are located.

It is a fact, however, that many of the extreme precipitation events could have a duration lower than a day (i.e., flash floods) and some can argue that lower temporal scales are needed in order to account for these phenomena. However, simulating long series of precipitation and discharges at sub-daily temporal resolution is, to date, not operational for medium and large catchments due to the lack of appropriate WGs and the need in any case of supercomputers, which are not to everyone's reach. Nevertheless, the case study presented in this paper showed that a daily temporal resolution could produce satisfactory results, especially in those areas where extreme event duration is typically longer than one day as in the Spanish Mediterranean coast.

2.7. Conclusions

The reliability of flood estimates depends upon long and trustworthy input data series (i.e., precipitation and/or discharges). Most ephemeral rivers worldwide lack long-term and spatially fully-distributed hydrometeorological information, which leads to inaccurate estimations of flood quantiles, especially those associated with high return periods. Continuous synthetic simulation models have been gaining ground over recent years to the detriment of statistical or deterministic approaches. The use of continuous stochastic meteorological models coupled with a fully-distributed hydrological simulation provided a realistic approach, enabling the recreation of multiple and different situations at any point within the catchment, thus completing the frequency distributions of discharges along with the whole river network. Yet, though, long and reliable input data series of precipitation and discharges are necessary for the correct implementation of the WG and the HM, which in practice are rarely available.

The methodology presented in this paper was applied in a typical Mediterranean ephemeral river and combined a long synthetic meteorological data series within a continuous synthetic simulation approach, with the additional inclusion of a regional study of extreme precipitation and palaeoflood data, with the objective of improving the flood quantile estimations, especially those associated with low probabilities.

Our results show that the integration of more robust precipitation studies for the WG implementation clearly improved its performance. In our case, the integration of an existing regional study of annual maximum precipitation allowed reproduction of the precipitation quantiles with high return periods, where the bias was more significant.

This improvement was transferred to the simulation of discharge data series with the fully-distributed HM. Here, the available palaeoflood records gave extra flood information up to T = 500 years as opposed to the highest quantile of T = 50 years obtained only with the systematic information. By having this extra information at the upper tail of the distribution, it was possible to validate the simulated extreme discharges and, at the same time, the proposed methodology.

Moreover, these estimates are not limited to the sites where flow gauge stations are located or where the palaeoflood information is available. The fully-distributed HM provides reliable data on extreme flood discharges at any point of the catchment, thus leading to better knowledge of its hydrology compared with the traditional methodologies based on at site flood frequency analysis of recorded discharges or the HM modeling of a design storm.

Finally, the importance of incorporating two different sources of additional information in the methodology when trying to estimate extreme flooding was demonstrated. Whilst adding one source of additional information is essential for a better calibration of the WG, adding a second one allows for validation of the simulated discharges, thus improving the robustness of the methodology and providing higher confidence in the flood quantile estimates. These findings have important implications towards a more efficient and balanced flood risk management in general, but especially in poorly monitored catchments with high variability in their flood regime.

Funding: This research was funded by the Spanish Ministry of Science and Innovation through the research projects TETISCHANGE (RTI2018-093717-B-100) and EPHIMED (CGL2017-86839-C3-1-R), both cofounded with FEDER European funds.

Acknowledgments: The authors wish to acknowledge support from Confederación Hidrográfica del Júcar, for providing the hydrological data used in the research.

3. Exploring the uncertainty of Weather Generators' extreme estimates in different practical available information scenarios

Carles Beneyto[a], José Ángel Aranda[a] and Félix Francés[a]*

[a]*Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Camino de Vera s/n, E-46022 Valencia, Spain*

* Correspondence: carbeib@upv.es; Tel.: +34-963-877-000 (ext. 76152)

Beneyto, C., Ángel, J., Francés, F., 2023. *Exploring the uncertainty of Weather Generators' extreme estimates in different practical available information scenarios*. Hydrological Sciences Journal 000, 1-10.

This is the author version of the paper published in the scientific journal Hydrological Sciences Journal in 2023 (https://doi.org/10.1080/02626667.2023.2208754/).

3.1. Abstract

Stochastic weather generators are powerful tools capable to extend the available precipitation records to the desired length. These, however, rely upon the amount of information available, which often is scarce, especially in arid and semi-arid regions. No studies can be found dealing with the uncertainty associated with these estimates related to the amount of information used in the weather generation calibration process, which is precisely the aim of the present study. A Monte Carlo simulation from a synthetic population was performed, evaluating the uncertainty of the simulated quantiles in different practical available information scenarios. The results showed that incorporating a regional study of annual maximum daily precipitation in the model parametrization clearly reduced the uncertainty of all quantile estimates. In addition, it has been proved that the uncertainty of these estimates increases with the population extremality, thus, remarking the importance of integrating additional information in regions with extreme precipitation patterns.

Keywords: Weather generator; uncertainty; regional; extreme precipitation study; Monte Carlo simulation; quantile.

3.2. Introduction

Extreme precipitation events leading to major floods are one of the natural disasters causing the higher economic losses and the higher number of fatalities around the world. In addition, climate change projections predict an increase in their frequency and magnitude (e.g., Alfieri et al., 2017; Paprotny and Morales-Nápoles, 2017), which combined with the global socio-economic development will lead to an increase in the frequency and severity of flood losses resulting from extreme precipitation events in the near future (IPCC, 2022). Having a better understanding of these events and, thus, being able to better predict them would result in extensive improvements in early warning flood protocols and in a better sizing of future infrastructures (or resizing the existing ones), which is key to reduce future losses.

Yet though, the high spatio-temporal variability of these extreme precipitation events, and particularly the short available precipitation records, make it difficult to obtain reliable quantile (X_T) estimates when modeling these events, particularly those X_T associated with high return periods. This problem becomes more evident in arid and semi-arid climates, where most of the rainfall is concentrated in short periods of time (mostly in the form of heavy rainfall episodes), and these are followed by long drought conditions.

A reasonably recent widely adopted solution to this problem is the use of Stochastic Weather Generators (WGs). Weather generators are computer models that produce synthetic long series of meteorological data that have similar statistical properties as that of observed data (Chen et al., 2010). Furthermore, while observed time series represent only one realization of the climate, WGs can generate many realizations, which provide a wider range of feasible situations (Khazaei et al., 2021).They have been extensively used coupled with hydrological and environmental models (e.g., Beneyto et al., 2020; Cowpertwait et al., 2013; Dai and Qin, 2019), and more recently as a tool for climate downscaling, increasing the resolution of climate projections by linking their parameters to the climate model outputs (e.g., Khazaei et al., 2021; Chun et al., 2013; Li and Babovic, 2019).

Although first developed WGs were mostly univariate, single-site and at a daily temporal resolution (e.g., Richardson, 1981; Richardson and Wright, 1984; Wilks, 1998), the need for long data series of multiple weather variables, at multiple locations, and at finer time resolutions has brought an exponential growth of new WGs integrating all these demands over the recent time.

Current WGs can be broadly divided into parametric or non-parametric (or resampling, see Rajagopalan and Lall, 1999) (Ailliot et al., 2020). Most of the existing WGs, however, are of the type parametric since parameters can be altered to simulate different weather scenarios and thus facilitate climate change studies (Wilks, 2009). Both types of weather generators perform reasonably well in terms of reproducing average characteristics of some variables. Past issues related to the inter-annual variability of monthly precipitation means (Ailliot et al., 2015; Sharif and Burn, 2006; Wilks and Wilby, 1999) have been addressed in recent years. Papalexiou (2018) proposed to simulate processes that explicitly reproduce the long-term persistence autocorrelation structure or disaggregating the annual/monthly time series that preserve the desired variability (Papalexiou et al., 2018) to deal with this issue Notwithstanding this, since the statistical properties of the generated meteorological variables are expected to be similar to those of the observed weather records and the length of the current registers is relatively short (i.e., very little information on extremes), the performance of WGs reproducing high return period estimates is still limited. Thus, even extending the precipitation records with a WGs, the higher estimated X_T still present high uncertainty (Khazaei et al., 2021).

Extensive efforts have been devoted, particularly within the hydrological community, to statistically modeling high precipitation amounts. Cowpertwait (1998) applied a method for deriving high-order moments to obtain the third-moment function for the observed precipitation time series. Evin and Favre (2012) refined the Neyman-Scott model structure by introducing the concept of transient storm arrival rate. Other efforts with much evidence of the precipitation amount distribution being heavy-tailed have been dedicated (Furrer and Katz, 2008). In this sense, severeal WGs incorporating heavy-tailed distribution functions have emerged in recent years (e.g., Ahn, 2020; Evin et al., 2018; Hundecha et al., 2009). More recently, Papalexiou (2022) developed a two-state rainfall model CoSMoS-2s, highlighting the importance of selecting an appropriate distribution to describe nonzero rainfall and stating that if the fitted marginal describes the behavior of rainfall well, then it reproduces the tail properties too and thus the behavior of extremes. However, although a distribution might appear to describe the observations well, this does not guarantee that its tail precisely reproduces extremes (Papalexiou, 2022). Notwithstanding this, the source of uncertainty still lies with the observed rainfall time series (Merz and Blöschl, 2008; Salazar-Galán et al., 2021). Focusing on this, other authors such as Beneyto et al., (2020) proposed the incorporation of more robust studies (e.g., regional precipitation studies) for the parametrization of the WG similarly as in Evin et al., (2018), which clearly reduced the uncertainty of low-frequency discharge estimates, however this reduction of uncertainty was not within the scope of their work.

Recent studies are mostly focused on climate change impact studies, assessing the uncertainty introduced by WG-based downscaling when applied to projections of future climate (e.g., Chen et al., 2011; Sharafati & Pezeshki, 2020; Vesely et al., 2019). However, the fact is that no studies were possible to be found in the literature by these authors with the aim of quantifying the uncertainty of low-frequency quantile estimates generated with WGs lying with the amount of available information.

The main objective of the present paper is to quantify the uncertainty of the higher precipitation X_T estimates generated by a stochastic weather generator in four different practical available information scenarios. These can be broadly divided into two groups: two scenarios where the only available information are the observations, and; two scenarios incorporating information from a regional study of annual maximum daily precipitation. A synthetic study area was created from one existing rain gauge located in the Spanish Mediterranean coast (i.e., semi-arid climate). Monte Carlo simulations using a WG focused on extreme events were conducted, evaluating three performance indices for both the simulated X_T and for the shape parameter of the marginal distribution: Relative Root Mean Square Error (RRMSE), Relative Bias (RB), and Coefficient of Variation (CV).

Under- or overestimation of precipitation X_T has always been a problem, especially in modern flood modeling studies where hydrological models are fed with precipitations generated by weather generators. The main reason behind this is the short length of the available meteorological data series, which hinders WGs from appropriately capturing low-frequency events. This study aims to be a contribution in this field, assessing the importance of robust precipitation data series and the incorporation of additional information as inputs for Weather Generators, leading to better X_T estimations and reducing their uncertainty.

3.3. Synthetic case study

3.3.1. Location and available meteorological data.

Rather than making up a completely fictitious study area, our synthetic study area was built from information obtained from one rain gauge located in the Spanish Mediterranean coast, which was considered representative of a semiarid climate after carrying out a statistical analysis of different rain gauges of the area. Daily precipitation records were obtained from 1951 to 2015 from the Spain02-v5 dataset (Herrera et al., 2016; Kotlarski et al., 2017): a series of interpolated precipitation and temperature dataset in a 0.11º rotated grid. Climate in this region can be considered as semi-arid, despite of registering an annual mean precipitation of 570 mm, more than 75% of days are dry and precipitation is mostly concentrated during the autumn months, highly influenced by the effects of mesoscale convective systems (MCSs) (Llasat and Puigcerver, 1990), that lead to torrential precipitation events. These rains account for approximately 40% of the annual rainfall. Spring (25%) and winter (20%) are characterized by the passage of frontal systems linked to Atlantic zonal flow whilst most of the precipitation registered over the summer months (15%) is originated in isolated convective storms (Camarasa Belmonte and Segura Beltrán, 2001; Mateu, 1974). A table with the basic observation statistics is shown in Table P2 - 1.

Table P2 - 1 - Observations' statistics.

Variable	Statistic	Value
Daily prec. (Pd)	Mean	1.56 mm
	Sd	6.81 mm
	Nº Pd > 0.1	24.77 %
	Max.	206.94 mm
Annual Prec. (Pa)	Mean	569.86 mm
Annual max. daily prec. (Pa_m)	Mean	73.35 mm
	CV	0.56
	Coeff. Skewness	1.43
	Coeff. Kurtosis	1.66

Additionally, the mean monthly precipitation amounts along with the number of annual daily max. occurrences by month can be observed in Figure P2 - 1.

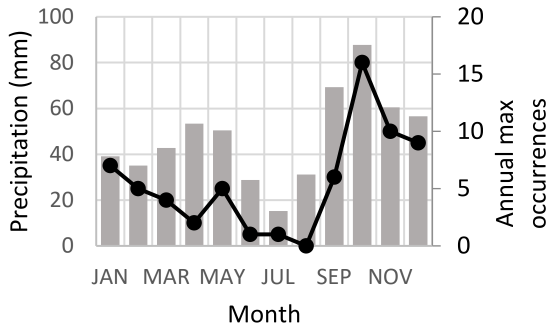


Figure P2 - 1 - Monthly mean precipitation (grey) and number of annual max. occurrences by month (black dots).

3.3.2. Stochastic weather generator: GWEX

The multisite Weather Generator used in this work was GWEX (Evin et al., 2018), developed by the Centre National de la Recherche Scientifique (CNRS) and first presented in 2018. This WG, was devised to focus on extreme events and it follows the Wilks approach (Wilks, 1998), where precipitation occurrence and amount are modeled separately. Thus, the at-site occurrence process at each location is defined by a p-order Markov chain and the spatial dependence of the precipitation states is modeled using an unobserved Gaussian stochastic process. With regards to the intensity process, GWEX model generates the amount of precipitation by using: a tail-dependent spatial distribution; an autocorrelated temporal process; and a marginal heavy-tailed distribution for each rain gauge and each month of the year. This distribution is the Extended Generalized Pareto Distribution (E-GPD), which was first proposed by Papastathopoulos and Tawn (2013) and has been proved to model adequately both low and high precipitation intensities (Naveau, 2016). This distribution function is obtained by raising the Generalized Pareto Distribution to a power of k>0:

$$F(x) = \left[1 - \left(1 + \frac{\xi x}{\sigma}\right)_+^{-1/\xi}\right]^k, \quad x \geq 0 \tag{1}$$

where k controls the shape of the lower tail, σ is a scale parameter, and ξ controls the rate of upper tail decay (Naveau, 2016) (Figure P2 - 2). All three need be estimated for each station and each month of the year.

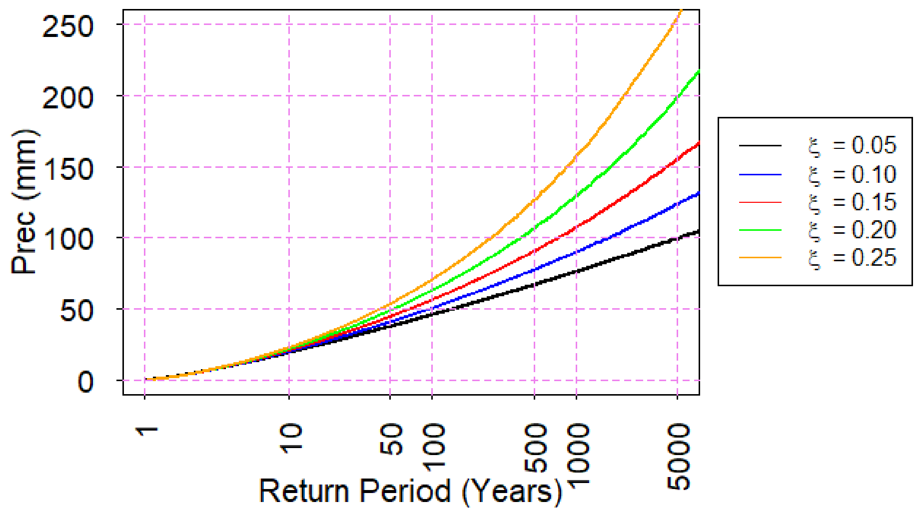


Figure P2 - 2 - E-GPD upper tail decay for different ξ values.

Lastly, both the spatial and temporal dependence of precipitation amounts are represented simultaneously using a multivariate autoregressive model of order 1. Furthermore, to introduce a tail dependence between at-site extremes, GWEX allows to introduce a Student copula to represent the dependence structure of innovations ε_t (Evin et al., 2018).

3.4. Methodology

A synthetic "base" population was created from the 66-years sample described in Section 2.1 for one rain gauge. All parameters defining this population were estimated with GWEX. Additionally, a ξ value of 0.11obtained from an existing regional study was assigned for all months of the year for the sake of simplicity. In order to adequately capture their base X_T, 15,000 years were simulated with GWEX replicating the main statistics in Figure P2 - 1.

From this population, a Monte Carlo simulation study was performed with 50 x 60-year samples, which is reasonable with the current extent of daily precipitation records. For each sample, all WG parameters related with the precipitation occurrence, amount and its temporal correlation were firstly fitted from the sample records for then, according to the information scenarios, estimating the shape parameter ξ as follows:

- No additional information
  (1) For each realization, the ξ parameter value was set to 0.05 (default) as proposed in Evin et al. (2018).
  (2) For each realization, the value of the parameter ξ was estimated by fitting an E-GPD to the X_100 estimated from the available observations.
- There exists a regional study of annual maximum daily precipitation.
  (1) Parameter ξ was estimated with one high T regional quantile for each realization (if not regional E-GPD).
  (2) The parameter ξ was set to the regional value for each realization (if regional E-GPD).

For simplicity, it was assumed that the regional study of annual maximum daily precipitation was "perfect" (i.e., no uncertainty). Therefore, the regional X_T was assumed to be the population X_T and the regional ξ the population ξ.

Uncertainty was measured through the Relative Root Mean Square Error (RRMSE), the Relative Bias (RB) and the Coefficient of Variation (CV), which were computed and analyzed for both the simulated X_T and for the ξ parameter.

Additionally, sensitivity analyses were conducted for the calibration X_T, the population ξ value and for the sample length.

3.5. Results

3.5.1. Information Scenarios

The first analysis carried out was aimed to find out the information scenario presenting the best quantile estimations. Figure P2 - 3 shows the boxplots of the simulated quantiles of the 50 realizations for different return periods and for the four information scenarios.

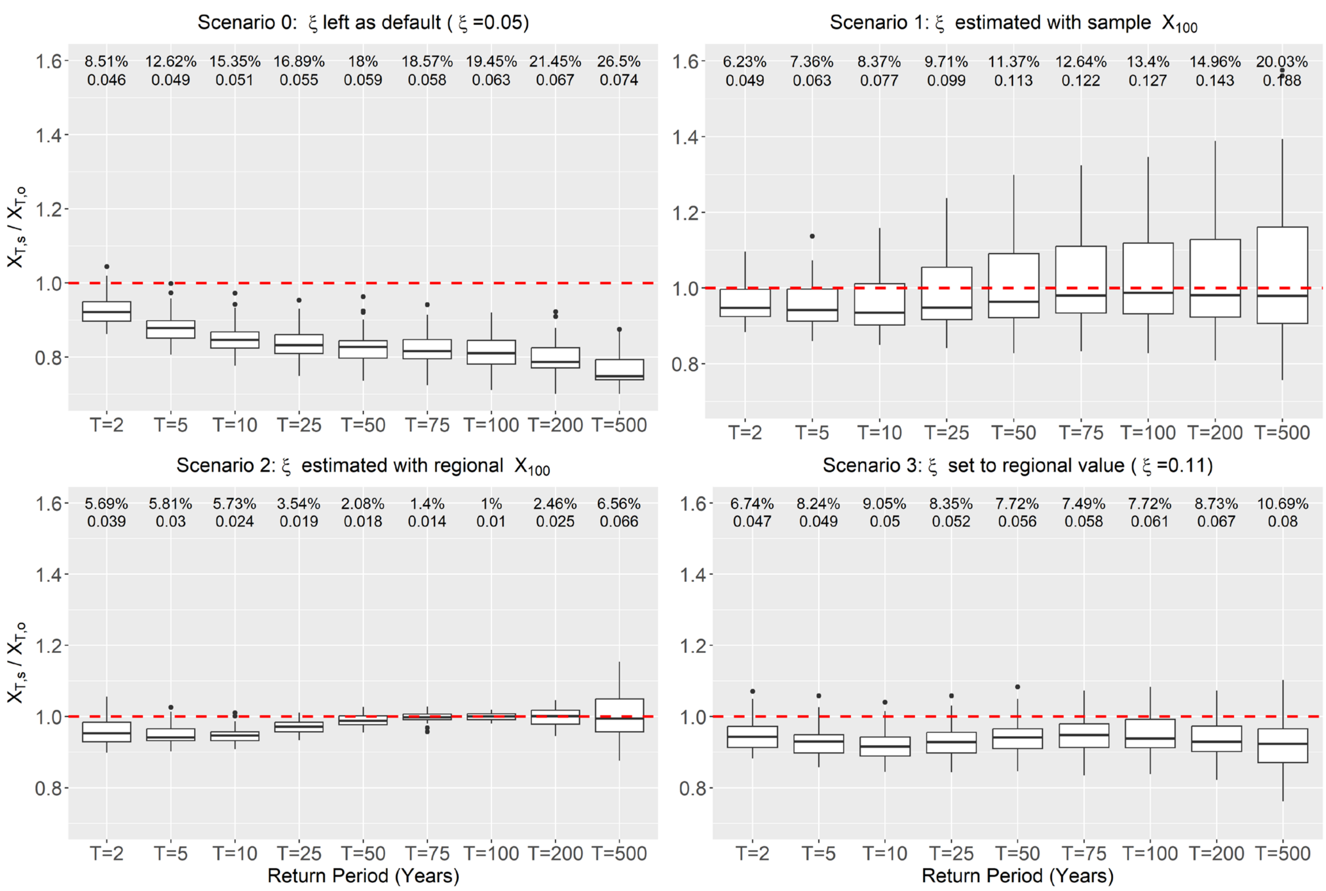


Figure P2 - 3 - Boxplots of the estimated quantiles (standardized with the population quantiles) for the four information scenarios. Both the RRMSE (expressed in %) and the CV are shown on top of each boxplot for each T

The value of the simulated quantiles (standardized with the population quantile) is represented on the X-axis and the different return periods on the Y-axis. Upper plots (i.e., scenario 0 and scenario 1) present the results when no extra information is added in the WG calibration whereas the lower plots (i.e., scenario 2 and scenario 3) integrate the information from a regional study of annual maximum daily precipitation in the calibration process. At first glance, from Figure P2 - 3 it can be observed that the WG performs better when extra information is incorporated for its calibration. In scenario 0, where ξ is left as default, quantile estimations show a systematic underestimation for all quantiles, being this more evident as we move to higher quantiles. In the case of scenario 1, where the ξ parameter is estimated with the simple X_{100}, a slight improvement can be appreciated for all quantile estimates, however, still significant values of RRMSE are obtained, especially for high return periods. CV values increase considerably compared to scenario 0, which is explained by the sample variability.

Moving to scenario 2 and scenario 3, where a regional study of annual maximum daily precipitation is integrated for the estimation of the parameter ξ, a clear improvement can be appreciated. Estimating the parameter ξ with the regional X_{100} (i.e., scenario 2) leads to a significant reduction for both RRMSE and CV for all quantiles. Giving that in this case the parameter ξ was calibrated with the regional X_{100}, low values for both metrics were expected for this quantile, however, it can also be observed satisfactory results for X_{200} and X_{500} estimations, with RRMSE values of 2.46% and 6.56% respectively, which means a reduction on the RRMSE of 89% and 75% respectively compared to scenario 0 (Figure P2 - 4). Still an underestimation on the high frequency quantiles is presented, this is due to the fact that the parameter ξ does not significantly affect the shape of the lower part of the distribution function (Figure P2 - 2).

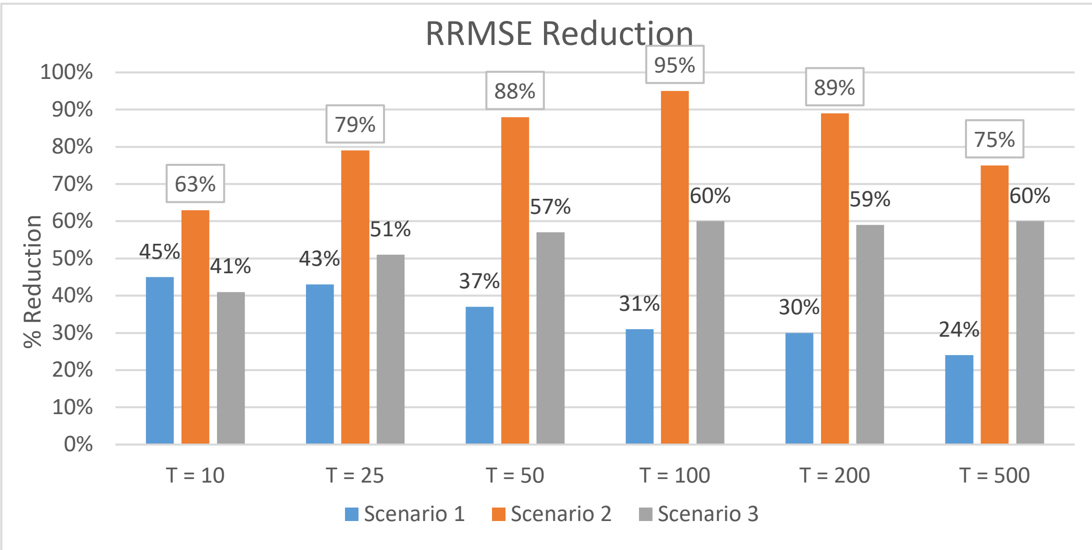


Figure P2 - 4 - Reduction of RRMSE for the three scenarios compared to scenario 0 (parameter ξ set to 0.05.

Lastly, applying the regional parameter to all realizations (scenario 3), contrary to what it could be expected, it was observed a systematic negative relative bias for all quantile estimations, which could be attributed to the own uncertainty of the method. Nevertheless, the reduction of both the RRMSE and the CV is evident compared to both scenarios where no extra information is incorporated, however, this reduction is higher in the case of estimating the parameter ξ with the regional X_{100} (Figure P2 - 4). For this reason, only scenario 2 is presented in further analyses.

3.5.2. Calibration $\boldsymbol{X_T}$

Having demonstrated that the best approach was to estimate the parameter ξ with the regional X_T, an analysis to evaluate how the selection of the single X_T could affect in the WG performance was performed. To do this, again, a Monte Carlo simulation study was performed with 50 x 60-year samples calibrating the parameter ξ with different regional X_T (i.e., X_{10}, X_{50}, X_{100}, X_{500}) and compared. Figure P2 - 5 shows the results for each implementation. Moreover, since each realization estimates a value of the parameter ξ, an individual analysis of the variations of this parameter was carried out for each implementation (Figure P2 - 6).

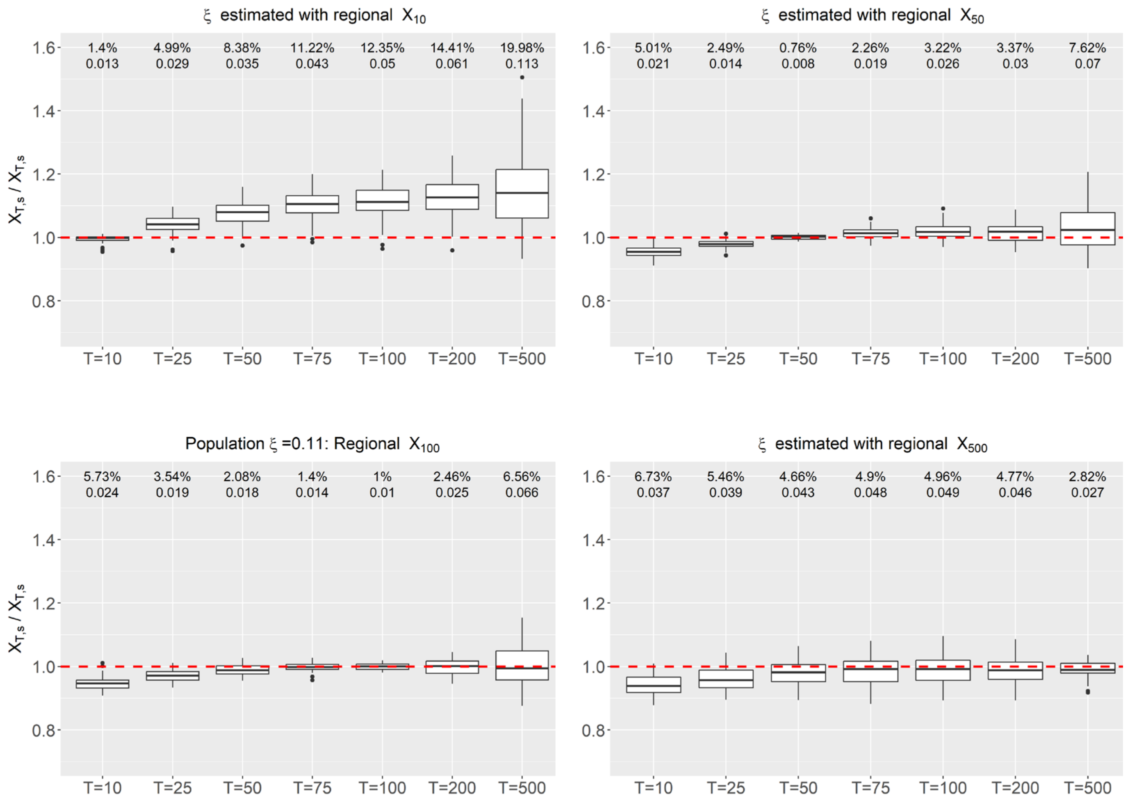


Figure P2 - 5 - Boxplots of the estimated quantiles (standardized with the population quantiles) for different calibration X_T in scenario 2.

Typical values of X_T obtained from regional studies of annual maximum daily precipitation range between those associated with return periods of 50 years and 200 years. Considering quantiles beyond a return period of 200 years does not have much sense since the available precipitation records rarely allow for certain estimations of these quantiles. Notwithstanding and for the sake of this analysis, X_{10} and X_{500} were also considered in this study.

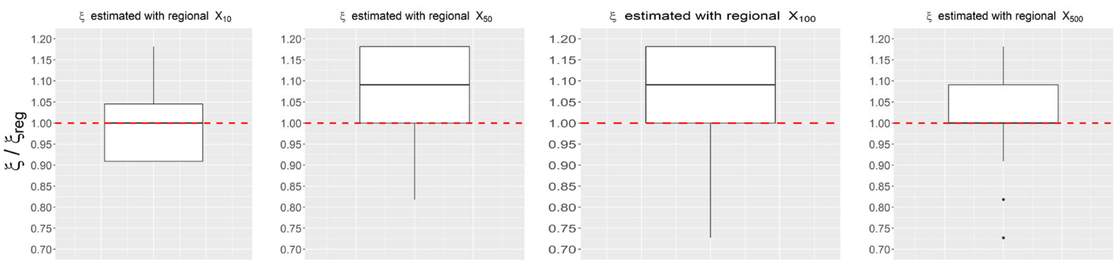


Figure P2 - 6 - Boxplots of the ξ values for different calibration X_T in scenario 2.

As it can be observed in Figure P2 - 5, using X_{10} to calibrate the WG results in overestimations of all quantiles, with RRMSE values up to 14.4% and 20% for return periods of 200 years and 500 years respectively. Both X_{50} and X_{100} significantly reduced both the RRMSE and the CV for all quantiles, obtaining satisfactory results especially in the case of the low-frequency quantiles (i.e., X_{200} and X_{500}). It is worth noting here that, as commented previously, slight underestimations can be observed for those X_T lower than the calibration X_T. In the case of X_{500}, however, the underestimation seems to be systematic for all quantiles, although the values of RRMSE are fairly satisfactory. The Boxplots of the parameter ξ obtained for each calibration X_T are represented in Figure P2 - 6.

3.5.3. Population extremality

The objective of this analysis was to evaluate if the extremality of the population could have an influence in the performance of the WG. Parameters k and σ were proved to do not have much influence on the upper part of the distribution function, therefore, four synthetic populations were created by means of increasing the value of the parameter ξ {0.09, 0.11, 0.13 and 0.25}. A Monte Carlo simulation study was performed with 50 x 60-year samples calibrating the parameter ξ with the regional X_{T100} of each population. Results in Figure P2 - 7 shows an increase of the relative bias and the interquartile range with the extremality, evidencing that the more extreme the climate is, the worse the WG performs. This decay is more evident for high return periods, being near imperceptible for return periods lower than 50 years.

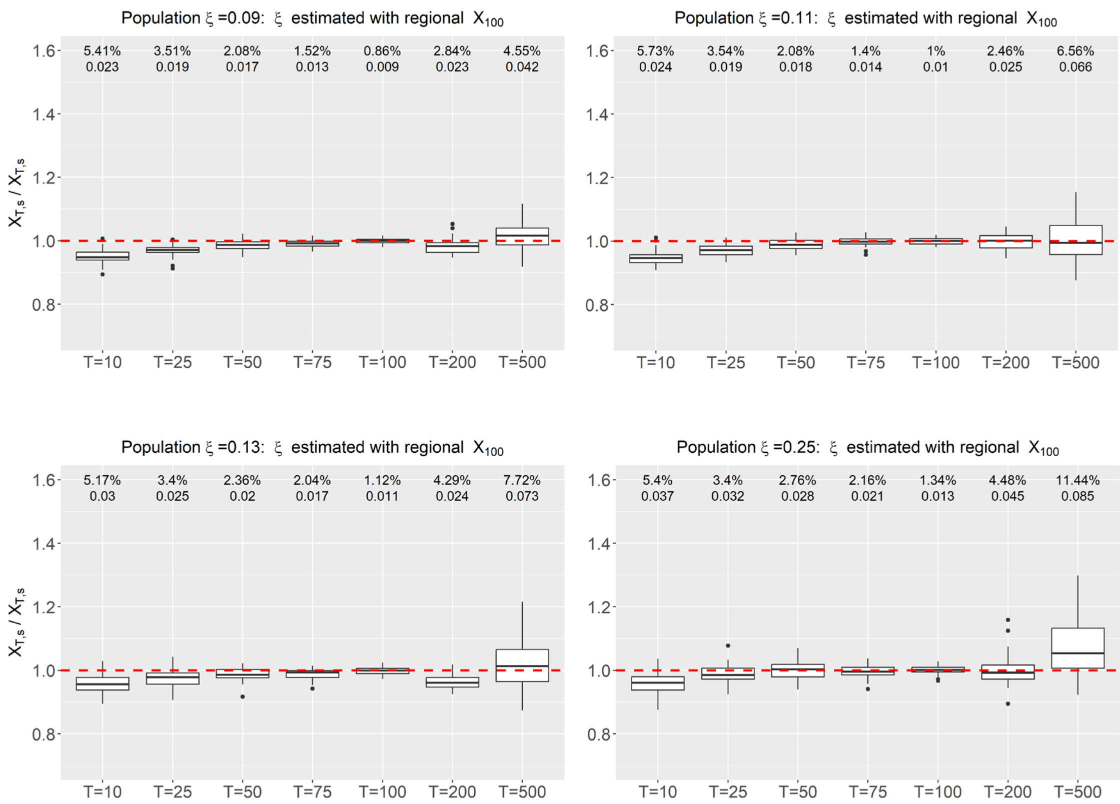


Figure P2 - 7 - Boxplots of the Monte Carlo Simulation calibrated with the regional X_{100} for populations with different extremality (i.e., ξ values of 0.09, 0.11, 0.13 and 0.25).

3.5.4. Sample length sensitivity.

Lastly, a sensitivity analysis to the sample length was conducted in order to assess whether having a longer precipitation data set could improve the performance of the WG or not. Sample lengths of 60, 90 and 120 years were evaluated through 50 realizations for all return periods via Monte Carlo Simulations. Figure P2 - 8 shows the results for T = 10, T = 50, T = 100 and T = 500 years for scenario 3 (ξ set to 0.11). A slight reduction on both RRMSE and CV is appreciable. In this scenario, having sixty years larger samples is translated into RRMSE reductions of 14%, 14%, 18% and 20% respectively, obtaining similar reductions in terms of CV.

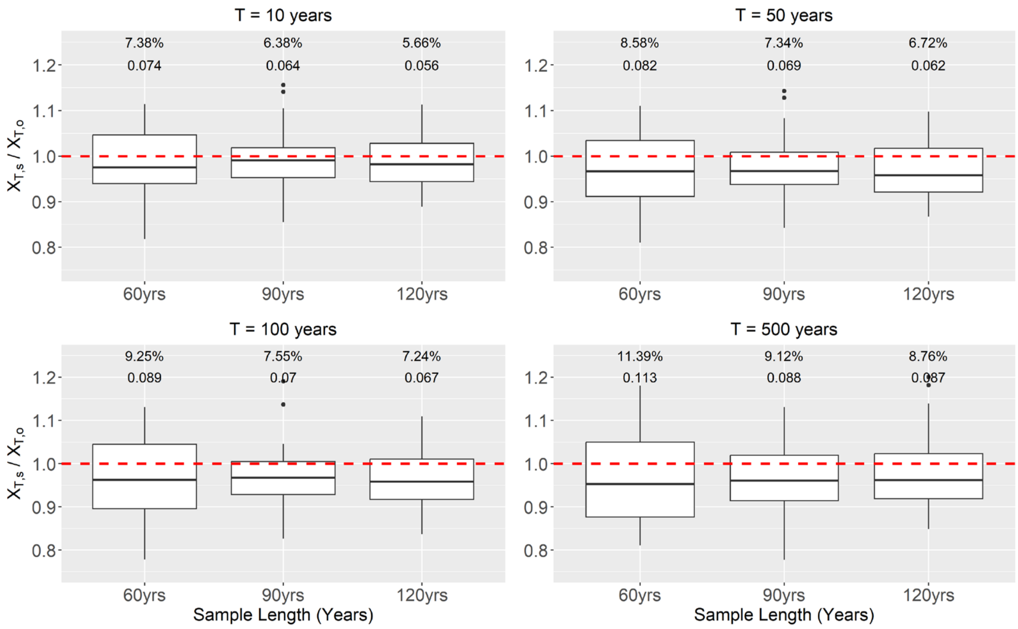


Figure P2 - 8 - Boxplots of the Monte Carlo Simulation from 60, 90 and 120-yrs samples - scenario 3 (ξ set to 0.11).

3.6. Discussion

Recorded precipitation datasets are still too short to provide reliable estimations of low-frequency quantiles. The limited number of extreme events recorded within the available observations difficult their adequate estimation with traditional approaches such as statistical or deterministic methods, leading to uncertain quantile estimations. Extending the precipitation records is a widely adopted solution over recent years. Weather Generators are tools capable to extend the existing precipitation records to an unlimited length based in the statistics of the observations. Notwithstanding this, the uncertainty of the estimations will still depend upon the amount of information available. Many applications derived from the use of WGs can be found nowadays in the literature such as for climate downscaling or for hydrological modelling, by means of feeding hydrological models with the precipitation generated by WGs in what is known as continuous synthetic simulation approach. Despite it has been demonstrated that WGs can satisfactorily reproduce ordinary precipitations, the fact that so little extraordinary precipitation events can be found within the available observations makes it difficult for WGs to adequately reproduce extreme events, thus, low-frequency quantile estimations still present today high uncertainties. This uncertainty is even higher in arid and semi-arid climates, where usually these extreme events are of larger magnitude and take place with less frequency.

Many authors have proposed the use of different heavy-tailed distribution functions for modeling the precipitation intensity process, which has been proved to improve substantially the quantile estimations. Others, such as Evin et al. (2018) argue that, apart from the available in-situ observations, more robust studies are needed to adequately estimate certain weather generator parameters, particularly when trying to capture extremes. Beneyto et al. (2020) presented a methodology for a better estimation of flood quantiles where the WG was calibrated with the information obtained from a regional study of annual maximum daily precipitation obtaining satisfactory results, however, the quantification of the quantile uncertainty reduction was not within the scope of their work. The fact is that no literature could be found by these authors assessing the uncertainty surrounding the quantile estimations generated by a WG, which it precisely is the aim of this work.

Results from Figure P2 - 3 show that, in those studies where a regional study of annual maximum daily precipitation is not available (upper plots), quantile estimates tend to be systematically underestimated, especially the low-frequency ones. Instead, incorporating a regional study of annual maximum daily precipitation for estimating certain WG parameters (lower plots) clearly improves the performance of WGs, especially when focusing on extremes, obtaining a substantial reduction of both CV and RRMSE. This reduction is more evident for scenario 2, which suggests that using a regional X_T for the WG calibration provides better results than using the regional ξ. This result, although not expected, constitutes an advantage, since using the regional ξ for the WG calibration is only limited to those studies where the WG and the regional study of annual maximum daily precipitation incorporate the E-GDP distribution function.

When no additional information is available, calibrating the WG with the simple X_{100}, in general, provides better results than leaving the ξ parameter as default, however, the CV increases substantially as a result of the sample variability.

Different calibration X_T have been tested for scenario 2; X_{10}, X_{50}, X_{100}, X_{500} (Figure P2 - 5). Given the actual length of the available precipitation records, usual reliable quantile estimates do not go beyond the T = 200 years (in the best case), thus, using X_{100} seems to be the most reasonable option to calibrate the WG. Notwithstanding, the abovementioned calibration X_T were tested for the sake of the analysis. It must be taken into account that the calibration X_T cannot be considered for comparison since they have been forced to the regional value. Using X_{10} for calibration leads to systematic overestimations of all quantile estimates. This is explained by the behavior of the E-GDP distribution function; changes in the shape parameter ξ translates into increases or decreases of the estimated quantiles at a different rate. Both X_{50} and X_{100}, however, considerably reduced RRMSE and CV values of all quantiles, especially for those of high return period. It is worth noting here that a slight underestimation in all X_T below the calibration quantile is observed. This is explained by the use of a heavy-tailed distribution function (i.e., E-GPD), which it has been demonstrated that these types of distributions perform well for extremes, but these usually do not capture appropriately low or moderate precipitation events (Caron et al., 2009). X_{500} performed poorly compared to X_{50} and X_{100}, slightly underestimating all quantiles and increasing the value of both RRMSE and CV.

Having set scenario 2 as the information scenario providing the best results in terms of reduction of the uncertainty and X_{100} the most reasonable option as a reference quantile, a sensitive analysis was conducted to the population extremality. Since parameters k and σ were proved to do not affect substantially the upper tail of the E-GPD, this extremality was introduced in the synthetic population by means of increasing the value of the parameter ξ {0.09, 0.11, 0.13 and 0.25}. Figure P2 - 7 shows the results of the Monte Carlo simulation for each of the synthetic populations. It can be appreciated that both the RRMSE and CV tend to increase with the value of the parameter ξ, being this more important in the case of low frequency X_T, which, in line with the conclusion from Breinl et al., (2017), means that the more extreme the climate is, the worse the WG performs. This reinforces the idea that stochastic generation of daily precipitation should be tailored toward climatic conditions (Li and Shi, 2019).

Additionally, a sensitivity analysis to de sample length was conducted. A 30-year period was set as a standard reference period by the World Meteorological Organization (WMO, 2011) and it has been a common practice in most climate related studies. However, and as commented previously, WG generation is based on the observed statistics of the available observations, therefore, allegedly longer samples should lead to better quantile estimations (less uncertainty). Since we drew from a 66-year sample, a standard sample length of 60 years was selected for all analysis. Not considering the potential issue of the nonstationary of longer samples sizes, we repeated the Monte Carlo simulations for three different sample lengths (i.e., 60, 90 and 120 years) for scenario 0 and scenario 3. Although a slight reduction in both RRMSE and CV could be appreciated in the case of scenario 3, which it was imperceptible for scenario 0, no major improvements can be highlighted even doubling the length of the observations. This, at least for semi-arid climates, means that the 30-years assumption might not be enough to capture climate normal. Incorporating a regional study of annual maximum daily precipitation, however, clearly adds more information in the calibration process than the length of the available observations. Therefore, these results indicate that, even in 50 years' time, observations on their own will not be sufficient to appropriately estimate extreme precipitation quantiles, still other sources of information will be needed to be incorporated in the WG calibration process, and regional studies of annual maximum daily precipitation have been proved in this study to be a very good option in this sense.

3.7. Conclusions

The use of Weather Generators has been becoming a common practice among the hydrological community in order to extend the available meteorological records. Yet, this approach is very much dependent on the available observations, especially in arid and semi-arid climates, due to their characteristic precipitation patterns. The short available records and the high spatio-temporal variability of these extreme events makes it difficult for WGs to obtain reliable low-frequency quantile estimates since the main source of uncertainty still lies with the amount of information available.

This study presented an analysis of the uncertainty of the quantile estimates generated by a WG in different practical available information scenarios, with the focus on extreme events. An already tested WG obtaining satisfactory results (see Beneyto et al., 2020) was selected to undertake the analysis, integrating the different information scenarios by means of modifying the parameter ξ of the marginal distribution function. The aim of the study was not to assess the performance of the WG but the potential reduction of the uncertainty of the higher quantile estimates lying with the available information for the model calibration.

Our results show that, even WGs incorporating new approaches for a better capturing of extreme events (a heavy-tailed distribution function to model precipitation amounts in our case), if no additional information is integrated in the model calibration process, low-frequency quantile estimates still present high uncertainty as a consequence of the uncertainty lying with the limited length of the current available records. Using only the available observations lead to systematic underestimations of all quantile estimates, which increase with the return period. A different approach when no additional information is available (i.e., calibrating the WG with the simple X_{100}) has been tested obtaining slightly better results, although retuning high values of CV explained by the sample variability.

The importance of incorporating additional information in the model calibration when the input data is limited has been demonstrated. Furthermore, calibrating the WG with the regional X_T provided better results than using the population ξ, which represents a clear advantage since the latter is limited to those studies where the WG and the regional study of annual maximum daily precipitation share the same distribution function.

Different calibration X_T were tested concluding that, X_{100} was the most appropriate quantile to use. Lower X_T lead to overestimations of low-frequency quantiles due to the sensitivity of the parameter ξ to the lower quantiles whereas higher quantiles did not provide a significant reduction on the uncertainty of the estimations.

Moreover, climate extremality was proven to be a key factor in the uncertainty of the quantile estimations, being this more evident for low-frequency quantiles, which evidences the special need to integrate additional information in the WG calibration process in these types of climates (i.e., arid and semi-arid climates), where most of the annual rainfall is concentrated in short extreme episodes, as in the case of the Spanish Mediterranean coast.

Finally, no significant reduction in the uncertainty of the estimations was found when analyzing different sample lengths compared to the reduction obtained when incorporating additional information, which means that integrating a regional study of annual maximum daily precipitation provide more information than having an input data series thirty or sixty years longer.

These findings reveal that, independently of the WG, only relying on current or in the short- and medium-term available observations, might lead to systematic underestimations of quantile estimates, especially those associated with low probabilities and, therefore, there is an evident need to incorporate further information in the calibration process of the WG when estimating low-frequency quantiles, particularly in arid or semi-arid climates. In this study, it has been demonstrated that integrating a regional study of annual maximum daily precipitation is a good practice to deal with the lack of information of the available observations, providing satisfactory results in terms of reduction of uncertainty of the higher return period quantile estimates.

Acknowledgements

This work was supported by the Spanish Ministry of Science and Innovation through the research project TETISCHANGE (RTI2018-093717-B-100).

4. Sample Uncertainty Analysis of Daily Flood Quantiles Using a Weather Generator

Carles Beneyto[a], Gloria Vignes[b], José Ángel Aranda[a] and Félix Francés[a]*

[a]*Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Camino de Vera s/n, E-46022 Valencia, Spain*

[b]*Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), Alma Mater Studiorum—University of Bologna, 40126 Bologna, Italy*

* Correspondence: carbeib@upv.es; Tel.: +34-963-877-000 (ext. 76152)

Beneyto, C.; Vignes, G.; Aranda, J.Á.; Francés, F. *Sample Uncertainty Analysis of Daily Flood Quantiles Using a Weather Generator*. Water 2023, 15, 3489.

This is the author version of the paper published in the scientific journal Water (Switzerland) in 2023 (https:// doi.org/10.3390/w15193489/)

4.1. Abstract

The combined use of weather generators (WG) and hydrological models (HM) in what is called synthetic continuous simulation (SCS) has become a common practice for carrying out flood studies. However, flood quantile estimations are far from presenting relatively high confidence levels, which mostly relate to the uncertainty of models' input data. The main objective of this paper is to assess how different precipitation regimes, climate extremality, and basin hydrological characteristics impact the uncertainty of daily flood quantile estimates obtained by SCS. A Monte Carlo simulation from 18 synthetic populations encompassing all these scenarios was performed, evaluating the uncertainty of the simulated quantiles. Additionally, the uncertainty propagation of the quantile estimates from the WG to the HM was analyzed. General findings show that integrating the regional precipitation quantile ($X_{T,P}$) in the WG model calibration clearly reduces the uncertainty of flood quantile estimates, especially those near the regional $X_{T,P}$. Basin size, climate extremality, and the hydrological characteristics of the basin have been proven not to affect flood quantiles' uncertainty substantially. Furthermore, it has been found that uncertainty clearly increases with the aridity of the climate and that the HM is not capable of buffering the uncertainty of flood quantiles, but rather increases it.

Keywords: weather generator; hydrological model; uncertainty; Monte Carlo simulation; daily flood quantile

Beneyto, C.; Vignes, G.; Aranda, J.Á.; Francés, F. *Sample Uncertainty Analysis of Daily Flood Quantiles Using a Weather Generator*. Water 2023, 15, 3489.

This is the author version of the paper published in the scientific journal Water (Switzerland) in 2023 (https:// doi.org/10.3390/w15193489/)

4.2. Introduction

Accurately designed flood estimation is required to make the best decision possible in various applications including infrastructure construction, land-use management, and risk assessment (Kidson and Richards, 2005; Kim et al., 2017). Flood frequency analysis (FFA) includes all techniques that aim to decipher the natural random processes that drive the occurrence and magnitude of flood events (Gaume, 2018). Traditional techniques are based on fitting the available annual maxima discharge data to a distribution function for gauged basins or deterministic approaches for ungauged basins. The main problem of these methods is the lack of long systematic observations, mainly concerned with hydrometric measurements, which characterize runoff processes (Grimaldi et al., 2021).

More recently, hybrid methods based on the use of the two abovementioned approaches, either through their combination or by adding other sources of information or techniques (Salazar-Galán et al., 2021), appear to be gaining an important audience. In this vein, a widely adopted approach is the generation of long synthetic flood data series by combining the use of a stochastic weather generators (WG) coupled with a hydrological model (HM) in what is called synthetic continuous simulation (SCS). This approach addresses the issue of the short length of the available observations at the same time as it eliminates the problem of the determination of the initial conditions of the basin and the characterization of the spatiotemporal distribution of the precipitation in the case of deterministic methods such as design storms.

Despite the invaluable contribution that this approach makes to flood estimation, it is true that quantile estimates still present high uncertainty, which becomes magnified when dealing with low-frequency events (Cavanaugh et al., 2015; Verdin et al., 2015). WGs rely on the amount of information available, meaning they require representative data series of observed extreme precipitation in order to perform adequately (Soltani and Hoogenboom, 2003). The lack of this has led practitioners to seek potential solutions to reduce the uncertainty of quantile estimations. In this sense, some WG developers have opted for the use of heavy-tailed distribution functions to model precipitation amounts, including Evin et al. (Evin et al., 2018) and Ahn (Ahn, 2020). Beneyto et al. (Beneyto et al., 2020) proposed the incorporation of more robust and reliable studies (e.g., regional precipitation studies) for the parameterization of WGs, obtaining a clear reduction in the uncertainty of the low-frequency precipitation quantile estimates, although not quantifying this uncertainty reduction. The quantification of hydrological prediction uncertainty is crucial in water resource decision-making processes (Tegegne et al., 2019).

Major sources of uncertainty in hydrological modeling include input and calibration data, model structures, and parameters (Pluntke et al., 2014), with model input data being the primary source of uncertainty (Faramarzi et al., 2013), especially in regions with limited data availability such as arid and semi-arid regions (Metzger et al., 2020). Moges et al. (Moges et al., 2021) categorized uncertainty analysis methods into six broad classes: (i) Monte Carlo analysis, (ii) Bayesian statistics, (iii) multi-objective analysis, (iv) least squares-based inverse modeling, (v) response surface-based techniques, and (vi) multi-modeling analysis. Based on Monte Carlo analysis, Beneyto et al. (Beneyto et al., 2023) evaluated reductions in the uncertainty of the integration of a regional study of annual maximum daily precipitation in the WG parametrization entailed in the precipitation quantiles, concluding that integrating these studies provides more information than longer input data series.

In terms of discharges, many studies have focused on the quantification of input data uncertainty. Sun et al. (Sun et al., 2000) calculated flood hydrographs for the Finniss River basin in Darwin, Australia using different approaches to estimate the input rainfalls from the available radar and rain gauge data. Bardossy and Das (Bárdossy and Das, 2008) investigated the influence of the spatial resolution of the rainfall input on the model calibration and application. Moulin et al. (Moulin et al., 2009) built, calibrated, and validated a realistic error model on mean areal precipitation (MAP) estimates and undertook a detailed analysis of the links between MAP estimation uncertainties, basin area, and streamflow simulation uncertainties. This latter study concluded that a large part of the rainfall runoff modeling errors could be explained by the uncertainties in rainfall estimates, limiting their operational use for flood forecasting.

Therefore, reliable precipitation data series is key to obtaining accurate flood quantile estimates. In the SCS approach, since the sample statistics set the generated precipitation patterns, the precipitation regime may have a direct influence on the flood quantile estimations. That is, flood quantile estimations in arid or semi-arid climates, with effectively no rain over the year with occasional intense precipitation events, might present different degrees of uncertainty than in the case of humid climates, with less skewed and more homogeneous precipitation.

In this context and following in the footsteps of the previous work of Beneyto et al. (Beneyto et al., 2023), the main objective of this paper is to quantify the uncertainty of flood discharge quantile estimates obtained by SCS in a wide range of hydro-climatic scenarios through the combination of: (1) different precipitation regimes, (2) different climate extremality, and (3) different hydrological characteristics of the basin. In other words, we are trying to analyze the influence of hydro-climatic conditions on the uncertainty of the flood quantiles obtained with the SCS approach presented in Beneyto et al. (Beneyto et al., 2023). Additionally, a simple sensitivity analysis for the basin size was conducted, as well as an assessment of the uncertainty transmission from the precipitation to the discharge quantiles. We propose a framework that accounts for all these different scenarios, which are represented by synthetic populations considered as 'truth', and used as benchmarks to evaluate the sample uncertainty through Monte Carlo simulations.

Since the objective is the uncertainty of the proposed SCS methodology independently of the selected models, and for the sake of simplicity, we will assume that both the meteorological and the hydrological model do not introduce any type of uncertainty beyond the methodology itself. Specifically: (i) the WG does not present structural uncertainty and (ii) the HM perfectly reproduces the reality. In any case, this unconsidered uncertainty is much smaller than that corresponding to the precipitation information usually available.

4.3. Methodology

4.3.1. Simulation Framework

Different daily precipitation populations were created with different climates and different precipitation extremality, being the latter understood as the number of registered extreme precipitation events per year. These populations were created from existing observations and by handling the adequate WG parameters in order to increase or reduce the annual precipitation, the annual maximum daily precipitation, and the number of wet days per year. A Monte Carlo simulation was performed with 50 packages of 60-year samples extracted from each of the populations. Following the approach in Beneyto et al. (Beneyto et al., 2023), and assuming the population precipitation quantile ($X_{T,P}$) to be perfect (i.e., no uncertainty), the population $X_{100,P}$ was introduced in the WG for its parametrization. Long series of precipitation and both maximum and minimum temperature were then simulated, which in turn fed a fully-distributed HM with two different hydrological regimes (i.e., permanent regime and ephemeral regime) to obtain the discharges and the corresponding flood quantiles. Both basin hydrological regimes were obtained varying the HM Correction Factors (CF) as will be explained in the following sections

Precipitation and discharge population quantiles X_{10}, X_{100} , and X_{500} were compared with those of the 50 packages, analyzing the uncertainty through the Relative Root Mean Square Error (RRMSE), the Coefficient of Variation (CV), and the Relative Bias (RB).

Finally, the transmission of uncertainty from the WG to the HM was also evaluated. A workflow diagram of the methodology can be seen in Figure P3 - 1.

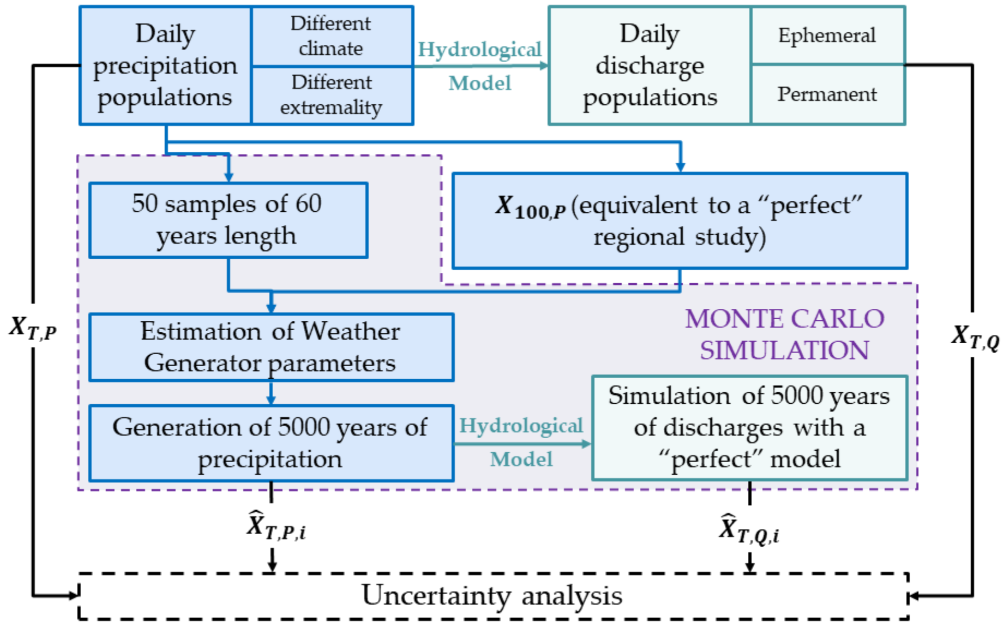


Figure P3 - 1 - Workflow diagram of the methodology. $X_{T,P}$: Population precipitation quantile. $X_{T,Q}$: Population flood quantile. $X_{T,Q/Pi}$: Precipitation/flood quantile of each realization.

4.3.2. Stochastic Weather Generator: GWEX

The WG used to perform this study was GWEX (Evin et al., 2018), a stochastic multi-site WG focused on extreme events. Among the many features this WG presents, and for the purposes of the present study, it should be highlighted that it incorporates the Extended Generalized Pareto Distribution (E-GPD) function (Papastathopoulos and Tawn, 2013) for modeling the precipitation amount, which is basically obtained by raising the Generalized Pareto Distribution to a power of k>0:

$$F(x;\lambda) = \left[1 - \left(1 + \frac{\xi x}{\sigma}\right)_+^{-1/\xi}\right]^{\kappa}, \qquad x > 0 \tag{1}$$

being λ= (k, σ, ξ) a vector of parameter, where k controls the shape of the lower tail, σ is a scale parameter, and ξ controls the rate of the upper tail decay (Naveau, 2016) as demonstrated in Beneyto et al. (Beneyto et al., 2023).

This latter parameter was therefore set to three different values {0.05, 0.11, and 0.25} to generate precipitation populations with different extremality, being the population with a ξ value of 0.05 the less extreme and the one with a ξ value of 0.25 the most extreme. Similarly, this parameter was estimated in the WG calibration process for each realization to obtain the closest value of the simple $X_{P,100}$ to the population one.

4.3.3. Eco-Hydrological Model: TETIS

The TETIS eco-hydrological model (Francés et al., 2007) is a conceptual (tank structure) model with physically-based parameters and fully-distributed in the space. It incorporates an effective split-parameter structure that facilitates the model implementation process, presenting only nine CFs to be calibrated for the hydrological module. Rather than calibrating the value at each cell, the estimated value of each of these CFs is multiplied by the value of each cell in the corresponding input raster map. This considers the spatial and/or temporal scale effects, the model or input errors, and allows for a quick and simple (manual or automatic) calibration of the different processes represented, taking advantage of the information used in the parameter estimation. The CFs of the TETIS model are as follows: CF1. Static storage; CF2. Evapotranspiration; CF3. Infiltration; CF4. Overland flow; CF5. Percolation; CF6. Interflow; CF7. Deep aquifer flow; CF8. Connected aquifer flow; and CF9. Kinematic wave velocity.

In our case, and starting from an implemented model in previous studies, two different synthetic basins with a different hydrological behavior were built-up: ephemeral and permanent. These basins were created by setting the values of CF3, CF5, CF6, CF7 and CF8 based on the authors' expertise. It is worth highlighting that, for the purposes of our study, we consider our model to be "perfect", that is to say, no uncertainty is introduced in the quantile estimations by the model.

4.4. Synthetic Case Study

4.4.1. Basin Description

The synthetic basin, obtained from an actual one to guarantee its natural behavior, has a drainage area of approximately 180 km^2. The altitude of the basin ranges from 1.061 m.a.s.l. at the headwaters to 226 m.a.s.l. at the outlet, presenting a main stream of 28.5 km length and several short tributaries pouring on both sides of the main course (Figure P3 - 2).

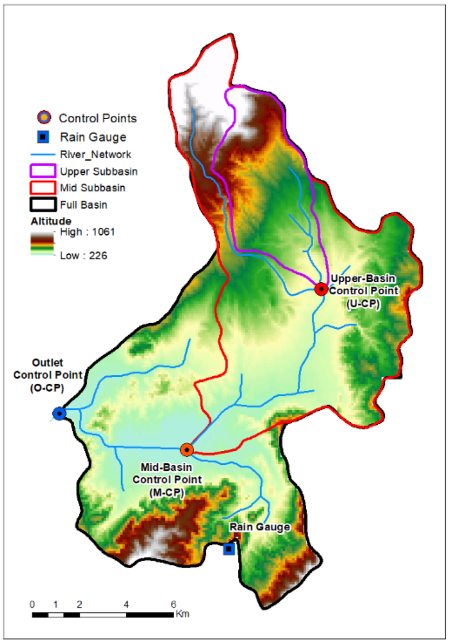


Figure P3 - 2 - DEM of the synthetic basin (north arrow not shown given the synthetic nature of the basin).

Three synthetic flow gauges (hereafter Control Points (CP)) were defined within the basin as follows: the Upper basin Control Point (U-CP), collecting the waters of an approximately 24 km^2 headwater tributary just before its confluence with the main stream; the Mid basin Control Point (M-CP), with a basin area of 101.5 km^2; and the Outlet Control Point (O-CP), at the outlet of the full synthetic basin (Figure P3 - 2).

Two different hydrological characteristics of the basin were analyzed to test the basin response. The first one, reproducing an ephemeral regime, is characterized by 70% of overland flow and 30% of interflow, being the aquifer disconnected. This regime is typical of arid or semi-arid regions, were rivers only present flow after high precipitation events, remaining dry for most of the year. The second hydrological regime represents a permanent discharge regime, typically found in humid climates where rivers never dry up independently the time of the year. This latest is characterized by 30% of overland flow, 40% of interflow and the remaining 30% feeds the aquifer or reach the river channel.

Both hydrological responses were achieved by setting the abovementioned CFs, which basically translates into increasing or decreasing the values of the hydraulic conductivity of the soil maps (obtained from the European Soil Database (ESDB)). Additionally, the infiltration capacity map (obtained from the ESDB), and the percolation capacity map (obtained from the Spanish Geological and Mining Institute) were also slightly amended. Slope, flow directions, and flow accumulation maps, derived from a digital elevation model with a 100-m resolution obtained from the National Geographic Institute, are common for both hydrological regimes.

4.4.2. Climate Description and Statistics

Two grid points from the Spain02-v5 reanalysis dataset (Herrera et al., 2016; Kotlarski et al., 2017) were initially used to create the synthetic populations. Specifically, “grid3715”: representative of a Spanish Mediterranean coast semi-arid climate, and “grid3314”: representative of a northern Spanish humid climate. From this information, six different 15,000-yrs populations were created by modifying the WG parameters associated with the extremality and the percentage of dry/wet days. Table 1 shows the basic statistics of the nine precipitation populations.

Table P3 - 1 - Populations' precipitation statistics.

Variable	**Statistic**	**Semi-Arid**			**Humid**			**Extremely Humid**			**Units**
		0.05	**0.11**	**0.25**	**0.05**	**0.11**	**0.25**	**0.05**	**0.11**	**0.25**	
Daily Precipitation (P_d)	Mean	1.57	1.57	1.56	2.05	2.05	2.05	3.60	3.60	3.60	mm
	Mean if P_d > 0.1 mm	6.32	6.32	6.29	6.59	6.54	6.42	6.20	6.21	6.20	mm
	Standard Deviation (SD)	6.19	6.35	6.90	5.69	5.82	6.35	7.15	7.34	8.05	mm
	SD if P_d > 0.1 mm	11.16	11.52	12.73	8.61	8.86	9.91	8.49	8.76	9.78	mm
	% P_d > 0.1 mm	24.79	24.79	24.79	31. 91	31. 91	31.91	57.95	57.95	57.95	%
	Max	249.51	373.15	846.69	173.80	238.80	805.50	208.37	263.20	677.65	mm
Annual Precipitation	Mean	572.46	572.62	569.76	748.94	748.91	748.23	1313.27	1315.27	1313.08	mm
Annual max. Precipitation	Mean	59.56	62.96	70.77	47.61	50.88	60.88	53.51	58.07	72.18	mm
	Coeff. Variation	0.43	0.48	0.67	0.33	0.39	0.60	0.31	0.36	0.57	-
	C. Skewness	1.55	2.02	3.53	1.36	1.75	4.53	1.41	1.81	3.63	-
	C. Kurtosis	7.25	10.68	27.61	6.25	8.62	52.26	6.91	9.54	30.82	-

All populations' annual mean daily temperature and annual mean daily precipitation were checked against De Martonne's aridity index (De Martonne, 1926), each of them falling within the climate type of Semi-Arid, Humid, and Extremely Humid, respectively.

In summary, considering the two different basin hydrological regimes, the three different climates, and the three different climate extremality, eighteen possible combinations were considered in the present study. Figure P3 - 3 below outlines all these considered combinations, which represent eighteen synthetic discharge populations with significantly different hydro-climatic characteristics.

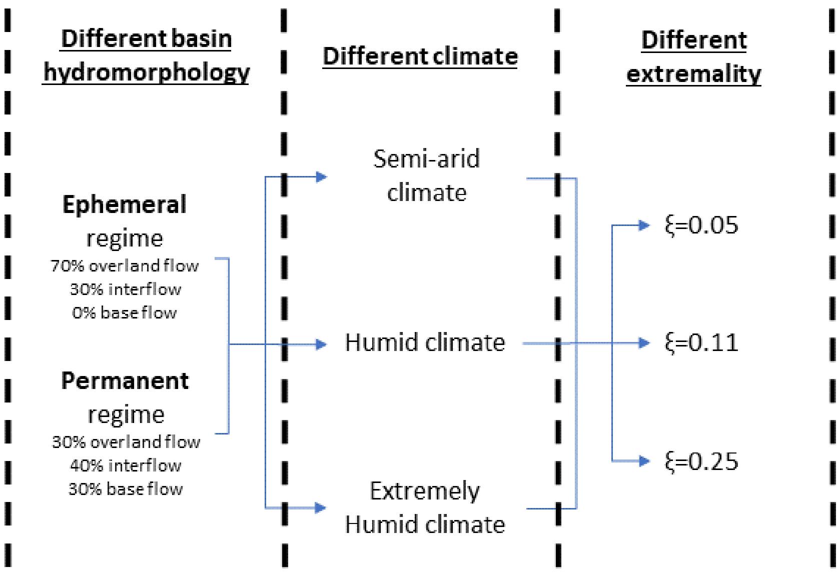


Figure P3 - 3 - Synthetic populations outline.

4.5. Results

This section presents the results of the uncertainty analysis of flood quantile estimates in the three different scenarios considered: different basin hydrology, different climate, and different climate extremality. Flood quantiles for return periods of 10, 100, and 500 years were analyzed, representing moderate, low, and very low probability of occurrence.

Additionally, the results of a preliminary analysis assessing the influence of the basin size in the quantile estimates are presented. Finally, the uncertainty transmission through the HM from the precipitation quantile estimates to the flood quantile estimates was also analyzed and quantified.

For a better clarity, all RRMSE, RB, and CV values (expressed in percentage) are shown at the end of the section.

4.5.1. Preliminary Analysis

This analysis was firstly undertaken to find out whether the size of the drainage area has an influence in the flood quantile uncertainty or not. The analysis was carried out considering a semi-arid climate, medium extremality ($\xi = 0.11$), and an ephemeral behavior of the basin. Results in the three CPs (24 km^2, 101.5 km^2, and 180 km^2, respectively) are shown in Figure P3 - 4, where each boxplot represents the relation between the population quantile and the simulated quantiles for the 50 realizations. A similar negative value of the RB was obtained for $X_{10,Q}$ and $X_{100,Q}$ for all three CPs, being again similar but positive in the case of $X_{500,Q}$. This latter quantile presented the higher errors, with RRMSE and CV values of up to 8.19% and 6.10%, respectively.

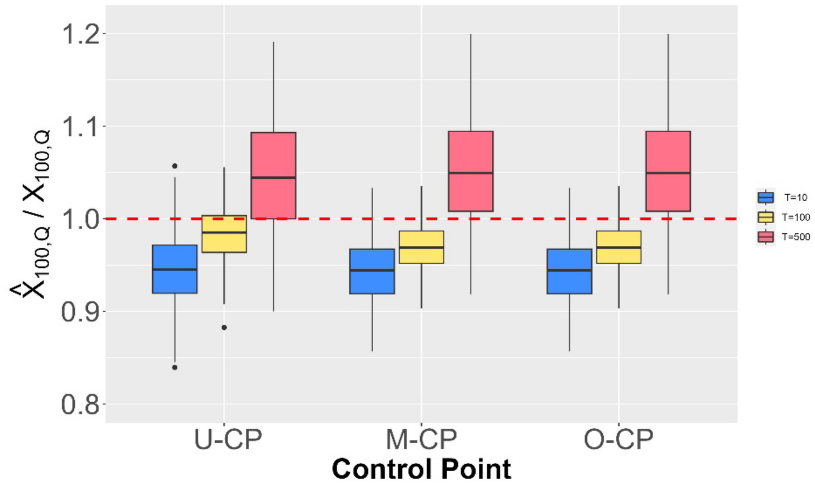


Figure P3 - 4 - Boxplots of flood quantile estimates in the three CPs for return periods of 10, 100, and 500 years, considering a semi-arid climate, medium extremality (ξ=0.11), and an ephemeral regime.

Nevertheless, these values tend to vary slightly with the basin size and without a clear pattern. These variations are almost negligible, and they could be attributable to the sample variability or the methodology uncertainty itself. Therefore, only the CP located at the basin outlet (i.e., O-CP) will be considered in further analyses.

4.5.2. Hydrological Characteristics of the Basin

Two different hydrological characteristics of the basin were analyzed, reproducing an ephemeral (i.e., 70% of overland flow and 30% of interflow) and a permanent discharge regime (i.e., 30% of overland flow, 40% of interflow and 30% feeding the aquifer or reaching the river channel).

The aim of this analysis was to evaluate if the basin behavior could have a significant influence in the uncertainty of quantile estimations. Similarly to the previous analysis, Figure P3 - 5 represents the boxplots for the quantile estimates in a semi-arid climate for medium extremality (ξ = 0.11), both for an ephemeral and a permanent regime. Although flood quantiles in a permanent river present slightly lower values of RRMSE and CV for all three return periods, again, no significant differences in terms of uncertainty can be found between both discharge regimes. Additionally, quantiles for return periods of 10 and 100 years tend to be underestimated (negative RB) whereas quantiles for a return period of 500 years are overestimated (positive RB).

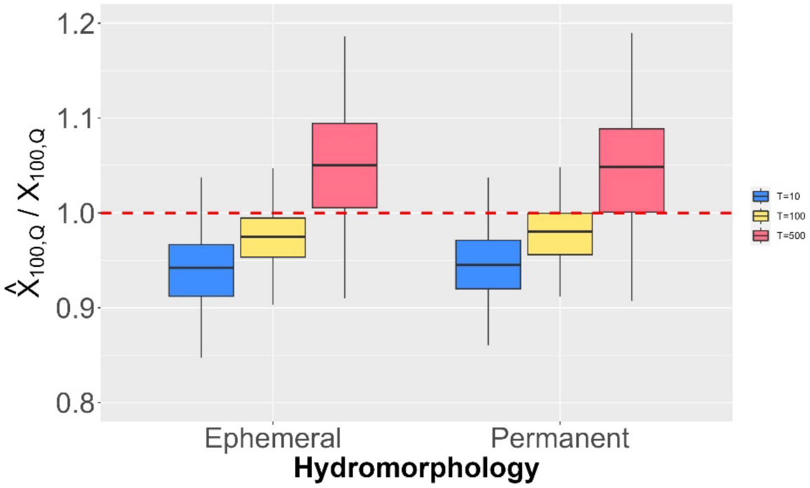


Figure P3 - 5 - Boxplots of flood quantile estimates in a semi-arid climate and medium extremality (ξ=0.11) for return periods of 10, 100, and 500 years in two different hydrological basin characteristics.

It can be concluded that the hydrological characteristics of the basin are not a significant factor in terms of quantile estimates' uncertainty, thus, only results for the ephemeral regime will be presented in successive analysis.

4.5.3. Precipitation Regime

Having set the river regime as ephemeral, three rainfall regimes according to De Martonne's aridity index were analyzed: semi-arid, humid, and extremely humid. As shown in Table 1, the main differences between all three climates relate to the percentage of wet days (ca. 25%, 32%, and 58%, respectively) and the mean annual precipitation (ca. 570 mm, 750 mm and 1300 mm, respectively). Figure P3 - 6 shows the boxplots of the quantile estimates in an ephemeral river with medium climate extremality (ξ = 0.11) for the three climates. In this case, significant differences can be observed. Flood quantiles for return periods of 10 years and 100 years present less uncertainty as climate turns more humid, reducing the values of RRMSE from 7.31% in a semi-arid climate to 4.59% in a very humid climate and from 4.17% to 1.42%, respectively. Similar reduction can be observed for the values of the CV, being this more evident in the case of a very humid climate. Conversely, for return periods of 500 years, both values of RRMSE and CV increase rapidly as climate turns less arid, reaching values of up to 24.75% and 4.60%, respectively. While $X_{100,Q}$ is fairly well represented, especially in the case of a very humid climate, $X_{10,Q}$ is systematically underestimated and $X_{500,Q}$ presents a positive RBs for all three climates.

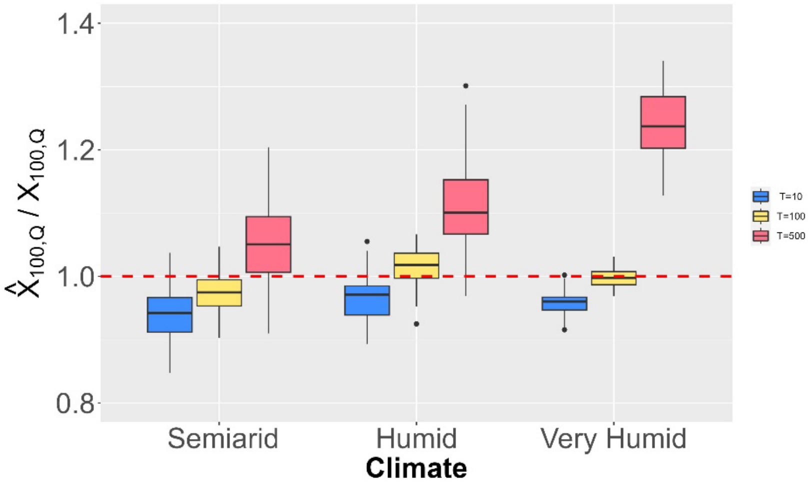
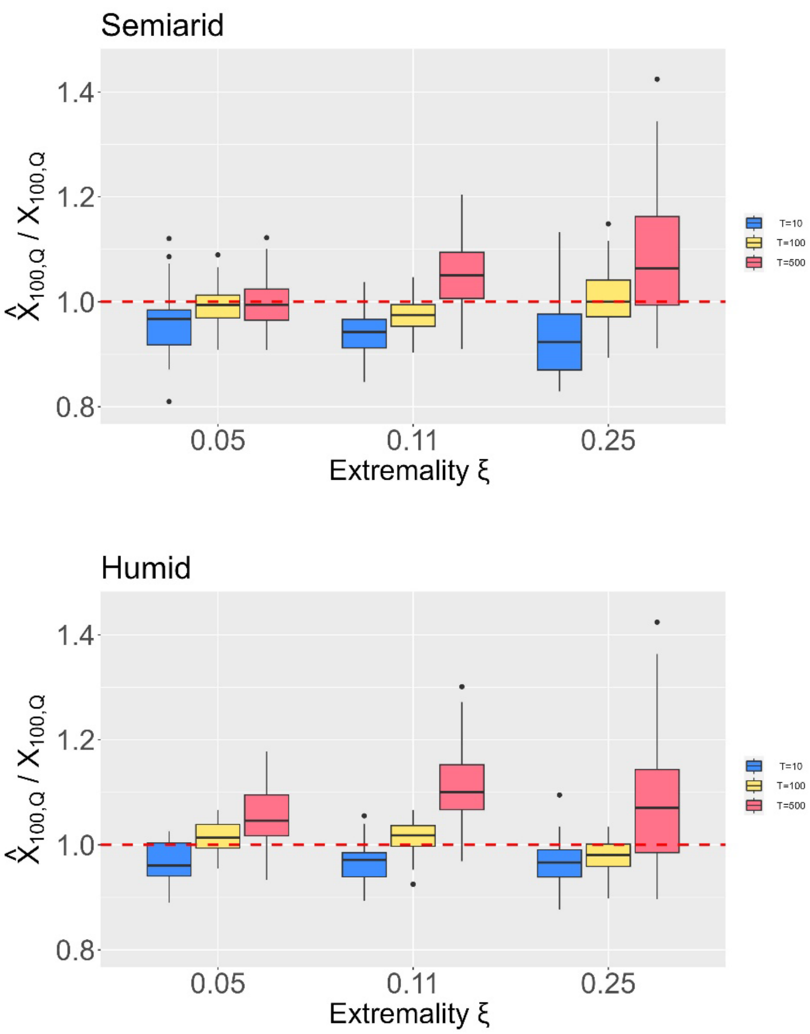


Figure P3 - 6 - Boxplots of flood quantile estimates for an ephemeral river with medium climate extremality (ξ=0.11) for return periods of 10, 100, and 500 years in the three analyzed climates.

4.5.4. Climate Extremality

The aim of this analysis is to assess whether the extremality of the population has an impact on the flood quantile estimations. This extremality, understood as the number of registered extreme precipitation events per year, has been synthetically introduced in the populations by means of modifying the shape parameter ξ of the E-GPD, obtaining three climate extremality: low extremality (ξ=0.05); medium extremality (ξ=0.11) and; high extremality (ξ=0.25). Figure P3 - 7 shows the boxplots of the quantile estimates for an ephemeral river for return periods of 10, 100, and 500 years in the three analyzed climates before, and the three climate extremality. Results show that $X_{100,Q}$ are generally well estimated independently of the climate extremality, albeit RRMSE and CV values slightly increase as the climate is more extreme. Still, RRMSE values range from 1.42% to 4.17%, which indicates a very good estimation. $X_{10,Q}$ are underestimated for all three climate extremality, presenting RRMSE values quite similar for all climates and climate extremality, except for the semi-arid climate, where the value increases considerably. In the case of $X_{500,Q}$), and with the only exception of the semi-arid climate with low extremality where the RRMSE value is satisfactory (i.e., 4.66%), quantile estimates systematically overestimate the population quantiles. This is more evident as the population is more extreme, and especially as the climate becomes more humid, reaching RRMSE values of up to 37.43% and CV values of up to 10.50%.



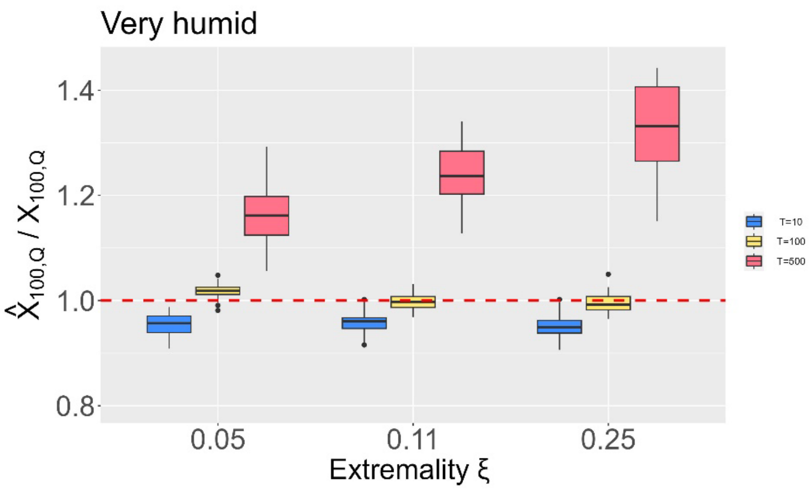
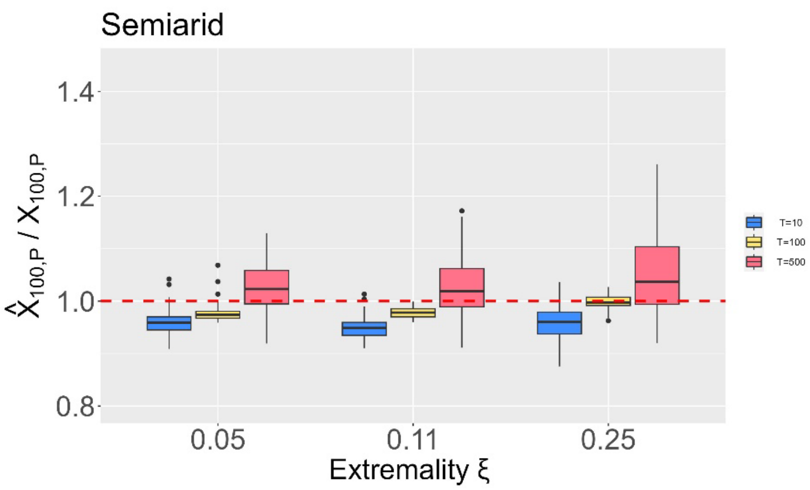
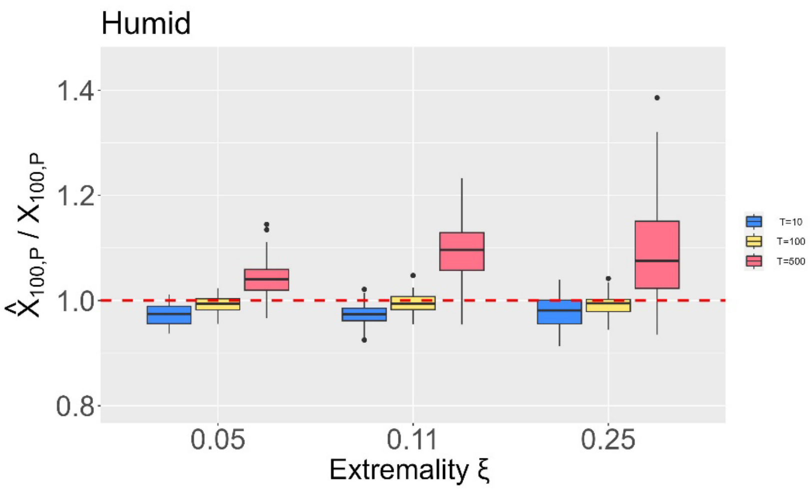


Figure P3 - 7 - Boxplots of flood quantile estimates for an ephemeral river for return periods of 10, 100, and 500 years in the three analyzed climates and climate extremality.

4.5.5. Uncertainty Propagation

This section analyzes the uncertainty propagation of the quantile estimates from the WG to the HM. Respective precipitation quantiles to those flood quantiles shown in Figure P3 - 7 are now represented in Figure P3 - 8.





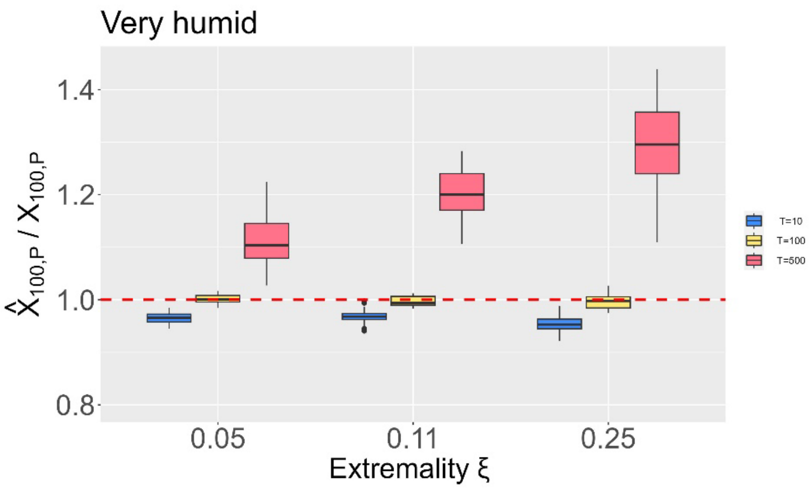


Figure P3 - 8 - Boxplots of precipitation quantile estimates for an ephemeral river for return periods of 10, 100, and 500 years in the three analyzed climates and climate extremality.

At first glance, it can be appreciated how the size of the boxplots and the distance to the red dashed line is lower, which means that, in general, $X_{T,P}$ present lower uncertainties than their respective $X_{T,Q}$. Table P3 - 2 shows the RRMSE, CV, and RB values for precipitation and flood quantiles for all analyses undertaken in this research. As it can be observed, there is a systematic increase (or decrease in the case of negative RB) for all scenarios, which means that uncertainty clearly propagates through the HM. Therefore, it can be concluded that the rainfall-runoff transformation, far from acting as a buffer, it increases the uncertainty of the flood quantile estimates.

Table P3 - 2 - RRMSE, CV, and RB values for the estimated precipitation and flood quantiles for return periods of 10, 100, and 500 years, the three climate extremality (ξ = 0.05, 0.11, and 0.25), and the three analyzed climates.

			RRMSE		CV		RB	
Climate	ξ	**Return Period (Years)**	**Precipitation (%)**	**Discharge (%)**	**Precipitation (%)**	**Discharge (%)**	**Precipitation (%)**	**Discharge (%)**
Semi-arid	0.05	10	4.8	7.1	2.8	6.0	−4.0	−4.3
		100	2.9	3.8	1.9	3.7	−2.2	−0.9
		500	5.2	4.7	4.5	4.7	2.5	−0.1
	0.11	10	5.5	7.3	2.4	4.8	−5.0	−5.8
		100	2.4	4.2	1.0	3.4	−2.2	−2.6
		500	6.9	8.2	6.0	6.1	3.2	5.2
	0.25	10	5.4	12.4	3.7	9.5	−4.1	−9.1
		100	1.4	5.3	1.4	5.3	−0.1	0.8
		500	9.7	13.9	8.0	10.8	5.0	7.8
Humid	0.05	10	3.4	5.0	2.0	3.8	−2.7	−3.4
		100	1.7	3.3	1.5	2.9	−0.7	1.5
		500	5.8	7.5	3.7	5.1	4.3	5.3
	0.11	10	3.3	5.0	2.2	3.8	−2.6	−3.4
		100	1.9	3.3	1.8	2.9	−0.6	1.5
		500	11.1	13.7	5.4	6.9	9.5	11.4
	0.25	10	3.5	5.5	2.9	4.4	−2.1	−3.5
		100	2.2	3.8	2.1	3.2	−0.7	−2.1
		500	13.5	13.5	9.3	10.5	9.0	7.5
Extremely humid	0.05	10	3.6	4.8	1.0	1.9	−3.4	−4.4
		100	0.8	2.2	0.8	1.3	0.1	1.8
		500	12.2	17.1	4.0	4.6	11.3	16.2
	0.11	10	3.5	4.6	1.3	2.0	−3.3	−4.2
		100	1.0	1.4	0.9	1.4	−0.3	−0.2
		500	20.9	24.8	4.1	4.6	20.3	24.1
	0.25	10	4.9	5.3	1.6	2.0	−4.7	−5.0
		100	1.3	1.8	1.3	1.8	−0.4	−0.5
		500	31.5	37.4	6.8	6.9	30.3	36.2

In a more illustrative way, Figure P3 - 9 shows the mean (considering all scenarios) value of RRMSE, CV, and RB for both precipitation and flood quantile estimates for the three considered return periods. RRMSE, CV, and RB values are considerably lower for return periods of 100 years as expected, since $X_{100,P}$was used for the WG calibration. However, it can be seen an increase in RRMSE and CV for all return periods. In the case of the RB, this presents an increase for return periods of 500 years and a decrease for return periods of 100 years, which are indicating an increase in the uncertainty. Lastly, the almost negligible mean RB values are explained by the WG calibration procedure.

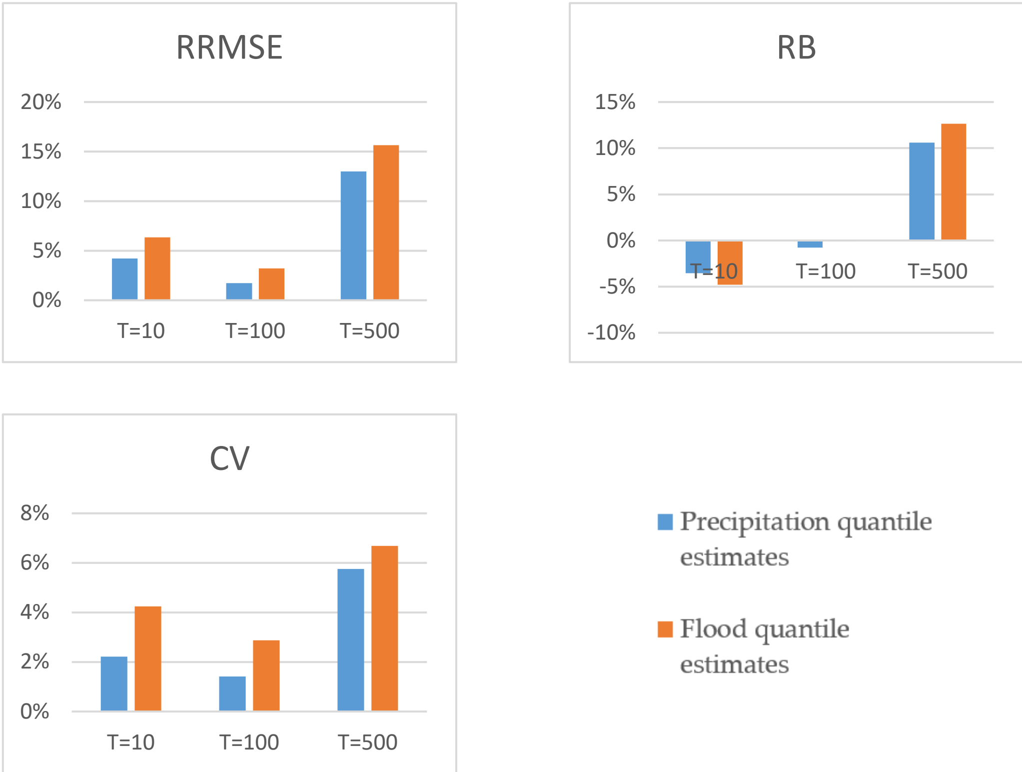


Figure P3 - 9 - Difference between mean (considering all scenarios) RRMSE, CV, and RB values for the estimated precipitation and flood quantiles.

4.6. Discussion

SCS is a widely adopted hybrid approach to determine flood quantile estimates, which resolves the issues of former purely statistic or deterministic methodologies (i.e., characterizing the initial conditions of the basin and adequately representing the spatio-temporal distribution of the precipitation) (Cameron et al., 1999). Nevertheless, low-frequency flood quantile estimates still present high uncertainty. The length of the input data series and the low density of monitoring stations constitute the main source of uncertainty and one of the main challenges to be faced in FFA, especially in arid and semi-arid regions (Metzger et al., 2020). Longer available input data series would ideally contribute to reduce estimates' uncertainty but, unfortunately, this is something that only the passage of time can mitigate. Instead, incorporating additional sources of information or improving the model set-up can lead to considerably improvements in the reliability of flood estimates. Moreover, quantifying the uncertainty is required for decision makers in order to understand the implications of limited data, model uncertainties, changes in the flooding system over the long term, incommensurate scales of appraisal, and potentially conflicting decision objectives (Hall and Solomatine, 2008). Recognizing this importance, no studies could be found in the literature by these authors quantifying the uncertainty of quantile estimates by SCS associated with the amount of available input information, which is precisely the objective of this paper. Being aware of the different precipitation patterns and basin characteristics around the world, and drawing from the previous research by Beneyto et al. (Beneyto et al., 2023), this study intends to elucidate how different precipitation regimes, climate extremality or basin hydrological characteristics impact on the uncertainty of the flood quantile estimates.

Results initially obtained in three CPs of the basin through Monte Carlo simulations with samples of 60 years, which double the 30-year period set as a standard reference by the World Meteorological Organization (WMO, 2011), shown no major differences in terms of quantile estimates' uncertainty. This follows the line of the results obtained in Moulin et al. (Moulin et al., 2009), and it can be concluded that the basin size has no major influence in the accuracy of the estimations.

An ephemeral and perennial river were also compared. Far from these authors' initial thoughts, results shown again that no significant differences could be found with regards to the quantile estimates accuracy. Ephemeral rivers, usually located in less populated arid or semi-arid areas, pose unique challenges to researchers and practitioners due to the generally limited data records, these being poorly gauged, and usually sporadically active, which result in the most hazardous types of floods (Metzger et al., 2020; Ortega et al., 2014). In view of the results obtained, the difficulties to accurately model ephemeral rivers stem from the gauge data availability rather than the few no-zero observations, since it has been proven that, under the same conditions (i.e., same sample size), flood quantile estimates in ephemeral rivers present the same degree of uncertainty as in the case of permanent rivers.

In arid and semi-arid areas, with long periods of drought conditions with no flow followed by short intense precipitation events leading to flash-floods, few models are considered adequate for modeling hydrologic processes due to the difficulty in effectively modeling infiltration-excess runoff processes as the dominant generation mechanism (Pilgrim et al., 1988). Compared to humid regions, where the information on the internal state of the basin is obtained from streamflow records, most models perform well, mainly because the dominant runoff generation mechanism is saturation excess runoff (Dunne and Black, 1970; Hongwei et al., 2009). For this reason, the hydrological prediction is more challenging for arid or semi-arid regions than for humid regions (Bafitlhile and Li, 2019). The results obtained in the present study analyzing three different climates according to De Martonne's index: semi-arid, humid, and very humid, point in the same direction. As shown in Figure P3 - 6, both values of RRMSE and CV decrease as climate turns more humid. This is more evident in the case of the CV, which is explained by the higher precipitation homogeneity of humid and very humid climates, where the internal basin fluxes remain more stable than in semi-arid climates. An exception is found here for $X_{500,Q}$, which is systematically overestimated for all return periods, especially as climate becomes wetter. In fact, this problem originates from the meteorological modeling (Figure P3 - 8) and it is dragged into discharges. After different analysis, it was determined that the problem laid with the high number of non-zero precipitation, and especially with the shape of the E-GPD. Humid and very humid climates, with much more days of low precipitation events than in semi-arid climates, added more information to the left tail of the distribution functions, which resulted in these data governing the fit in detriment of the right tail observations, thus and given the shape of the E-GPD, misrepresenting the higher quantiles.

In terms of climate extremality, three different populations with different extremality were analyzed. This analysis was repeated for the three abovementioned climate types (Figure P3 - 7). Apart from the already commented overestimations of $X_{500,Q}$, in general, RRMSE and CV values remain similar for three climates. There are not much differences between the uncertainty obtained in $X_{10,Q}$ and $X_{100,Q}$ for low extremality and medium extremality (i.e., ξ=0.05 and ξ=0.11, respectively), however, for high extremality (ξ=0.25), RRMSE and CV values increase considerably, which means that the more extreme the climate is the more uncertainty the flood quantile estimates present.

It is worth noting that, following the same methodology as in Beneyto et al. (2023), WG calibration was made using the regional $X_{100,T}$. This is the reason why the best results in terms of flood quantile uncertainty are presented for $X_{100,Q}$. Practitioners willing to better capture higher flood quantiles should use a different $X_{T,Q}$ for the WG calibration (e.g., $X_{500,Q}$).

It is expected that for a well-calibrated HM that adequately represents the important runoff processes within the basin, the major factor contributing to the uncertainty in the predicted flows is the uncertainty in rainfall (Butts et al., 2004). In our case, having a “perfect” HM, the intention of the analysis was to assess if the uncertainty of the estimated precipitation quantiles propagates through the HM, evaluating if the HM could buffer the uncertainty of flood quantiles. In similar studies, Butts et al. (Butts et al., 2004) determined the propagation of uncertainty due to uncertainties in the measured rainfall using a Monte Carlo approach, using a total of 200 samples. They concluded that a 50% relative standard deviation in the precipitation estimate (R = 0.5) has only a limited impact on the accuracy of the hydrological simulation when compared to the flow measurement uncertainty and the other sources of uncertainty. Gabellani et al. (Gabellani et al., 2007) explored the impact of uncertainties in the spatial-temporal distribution of rainfall on the prediction of peak discharge in a typical mountain basin, reaching to the conclusion that uncertainties in the small-scale statistical properties of forecasted rain fields propagate along the rainfall-runoff chain and affect the prediction of peak discharge. In our case, and as observed in Figure P3 - 8, similar results were obtained: RRMSE, CV, and RB values systematically increased for all nine precipitation populations, indicating that the HM, far from acting as a balance component in the SCS approach, magnified the uncertainty of the estimates.

4.7. Conclusions

SCS has increasingly gained popularity as a means to extend the existing limited hydro-meteorological records. However, this approach heavily relies on the available observations, which in practice are rarely sufficiently long. This may lead to systematic under- or overestimation of flood quantiles, particularly when trying to model adequately extreme events in basins with lack of hydro-meteorological data.

In a previous study carried out by Beneyto et al. (2023), it was proven the necessity to incorporate additional information in the WG calibration process, especially when estimating low-frequency precipitation quantiles. This former work presented the reduction in uncertainty in the precipitation quantile estimates based on the available information used for the model calibration. The present paper presents an extension of this work, aimed to analyze the uncertainty of flood quantiles estimated by SCS in different scenarios: (1) different precipitation regimes, (2) different climate extremality, and (3) different hydrological characteristics of the basin. Thus, eighteen “base” populations were used as benchmarks to analyze the flood quantile uncertainty using Monte Carlo simulations.

The findings of this study highlight the significant influence of the precipitation regime on the estimated flood quantile uncertainty. While it appears that the basin size and the hydrological characteristics of the basin do not substantially impact on flood quantiles’ uncertainty, it has been found that uncertainty clearly increases with the aridity of the climate, which should be considered by practitioners when dealing with flood studies in arid and semi-arid climates. Climate extremality has been proven not to be as significant as expected, however, very low-frequency flood quantiles presented higher degree of uncertainty when the climate was more extreme. Finally, flood quantiles presented higher uncertainty than their precipitation quantile counterparts, indicating that the HM does not act as a balance component in the SCS approach as it was expected. Additionally, despite the aim of this study was not to evaluate the performance either of the WG or of the HM, some doubts have emerged as to the use of the E-GPD distribution function, which will be studied in further research. General findings of this research reveal that low-frequency flood quantile estimates by SCS are still far from presenting adequate levels of uncertainty for flood studies if additional information is not integrated in the WG implementation. Integrating a regional $X_{T,P}$ (with a relatively high reliability) in the WG model calibration clearly reduces the uncertainty of flood quantile estimates independently the climate, the extremality, the drainage area and, the hydrological characteristics of the basin (i.e., in a broad range of hydro-climatic conditions). This uncertainty reduction is greater for flood quantiles with return periods near the regional precipitation quantile used $X_{T,P}$.

These findings carry significant implications for advancing in the efficiency of flood risk management, particularly in areas with lack of hydro-meteorological data, and in arid and semi-arid climates, characterized by substantial variability in their flood patterns. Results from this research will help practitioners using SCS to obtain more accurate flood quantiles should they are working on an extreme arid climate or on a mild continental humid region.

Funding: This work was supported by the Spanish Ministry of Science and Innovation through the research projects TETISCHANGE (RTI2018-093717-B-100) and TETISPREDICT (PID2022-141631OB-I00). Funding for the Open Access charge has been provided by Universitat Politècnica de València.

Acknowledgments: The authors thank AEMET and the UC for the data provided to carry out this work (Spain02 dataset).

5. Expanding Information for Flood Frequency Analysis Using a Weather Generator: Application in a Spanish Mediterranean Catchment

Carles Beneyto[a], José Ángel Aranda[a], Sergio Salazar-Galán[a, b], Rafael Garcia-Bartual[a], Eduardo Albentosa[a] and Félix Francés[a]*

[a]*Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Camino de Vera s/n, E-46022 Valencia, Spain*

[b]*Agroecosystems History Laboratory, Pablo de Olavide University, Carretera de Utrera km 1, E-41013 Sevilla, Spain*

* Correspondence: carbeib@upv.es; Tel.: +34-963-877-000 (ext. 76152)

Beneyto, C., Aranda, J. A., Salazar-Galán, S., García-Bartual, R., Albentosa, E., Francés, F. *Expanding Information for Flood Frequency Analysis Using a Weather Generator: Application in a Spanish Mediterranean Catchment*. Journal of Hydrolgy: Regional Studies 2024. 53, 101826.

This is the author version of the paper published in Journal of Hydrolgy: Regional Studies (2024).

5.1. 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.

Keywords: synthetic continuous simulation; quantile; palaeoflood; regional study of annual maximum precipitation; fully-distributed hydrological model

5.2. 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 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).

5.3. Case study

5.3.1. Study area.

The Segura River basin has an extension of 15150 km2 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).

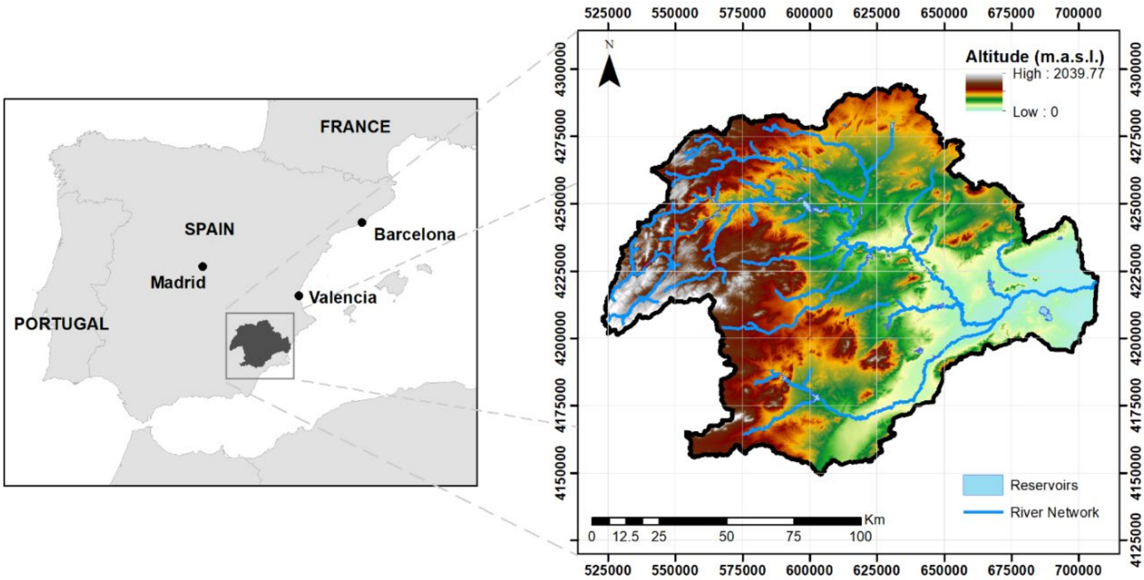


Figure P4 - 1 - Study area: Segura River basin.

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 500mm in just 3 days

(Figure P4 - 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.

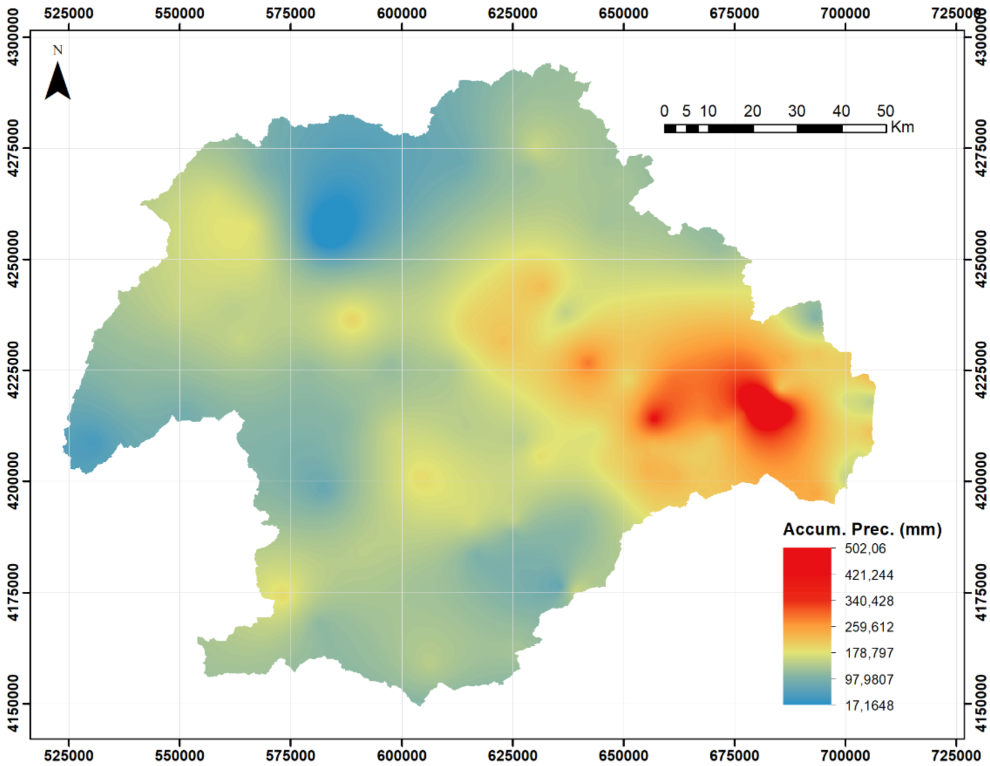


Figure P4 - 2 - Spatial distribution of the total accumulated precipitation during the 11-14 September 2019 event.

5.3.2. 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 (Figure P4 - 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 (Figure 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).

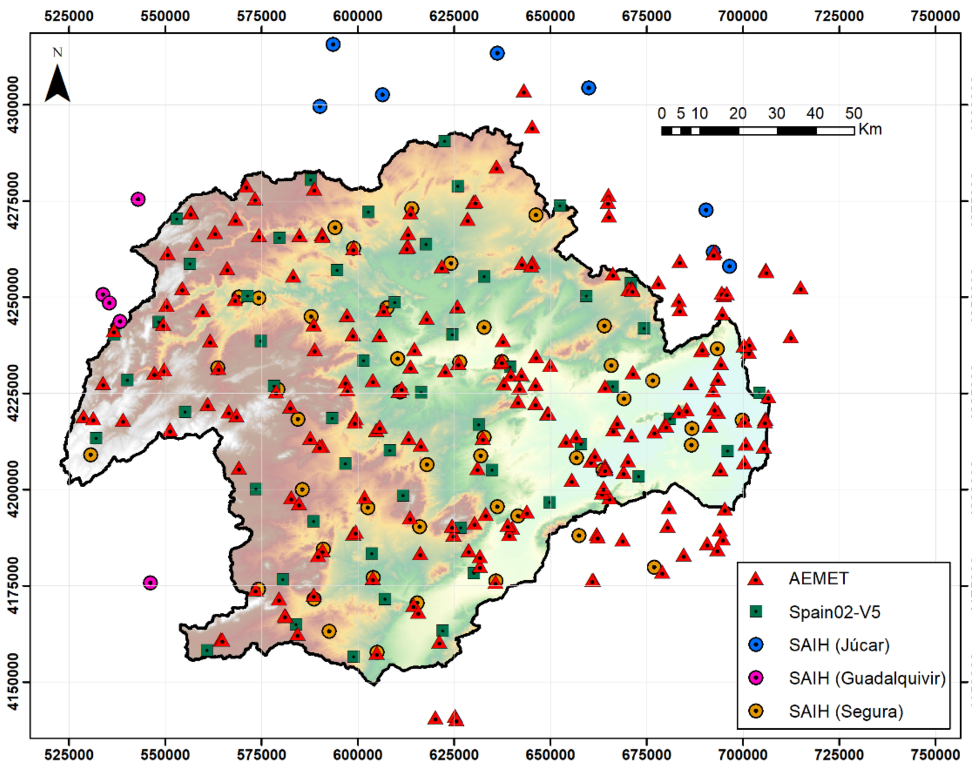


Figure P4 - 3 - Location of daily and sub-daily meteorological information over the Segura River basin.

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.

5.4. Methodology

5.4.1. General Framework

The proposed methodology for a general case consisted of five steps:

- In order to achieve the objective of this study, the following methodology has been proposed:
- Perform a regional study of annual maximum precipitation to expand the available information.
- 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.
- 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.
- Storm disaggregation to sub-daily (e.g. hourly) temporal resolution and validation with the available observations (e.g., IDF curves, spatial pattern, etc.).

- 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.
- 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.
- Quantile estimation considering the annual peak flows obtained from HM simulations.
- 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 Figure P4 - 4. The following subsections will explain in detail each step of the methodology.

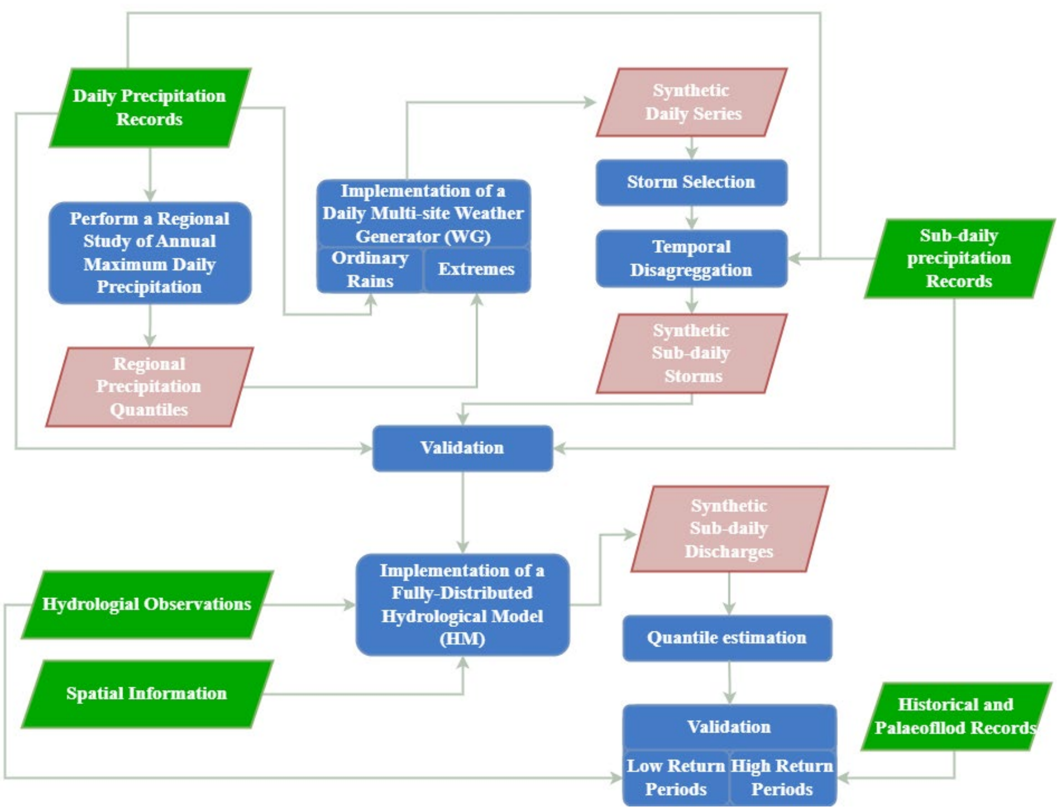


Figure P4 - 4 - Workflow chart of the proposed methodology.

5.4.2. Regional study of annual maximum daily 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 10x10 km2 grid over our case study and processed the observations from the 210 rain gauges. Only series with 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.

5.4.3. 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..

5.4.4. 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 km2 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.

5.4.5. 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.

5.4.6. Quantile estimation and validation

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

$$F_i = \frac{i - \alpha}{N + 1 - 2\alpha} \quad (1)$$

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.

5.5. Results

5.5.1. Regional study of annual maximum daily 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). Figure P4 - 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.

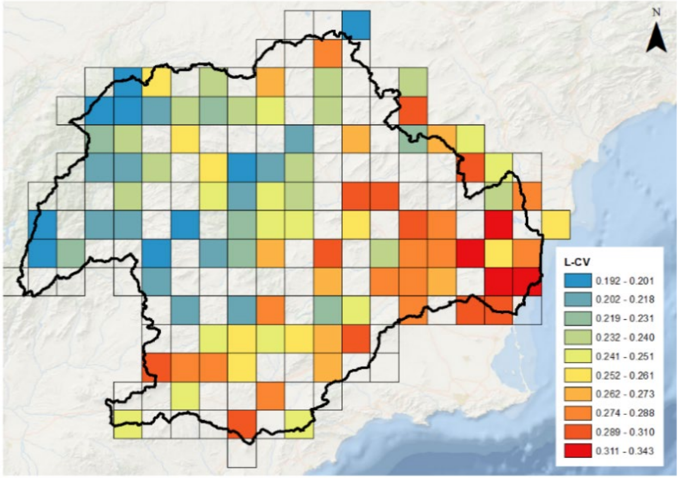


Figure P4 - 5 - Spatial variability of the L-CV.

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 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 (Figure P4 - 6 right), being the optimal at a 70km 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 (Figure P4 - 6 - left).

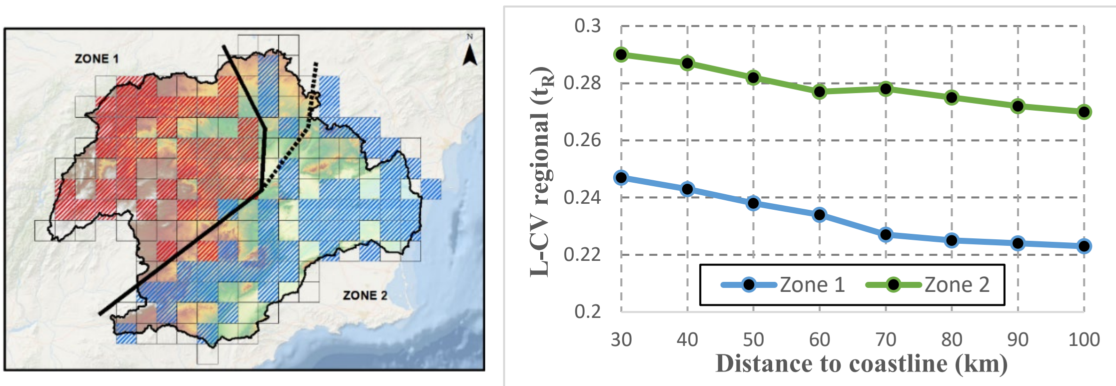


Figure P4 - 6 - Left: regions with a 70 km distance threshold to the coastline before considering the northern area (dashed line) and after (continuous line); and right: variation of the regional L-CV with the distance to the coastline.

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.

5.5.2. 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 Figure P4 - 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 default, obtaining a systematic quantile underestimation for both zones (left panel in Figure P4 - 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 (SOND).

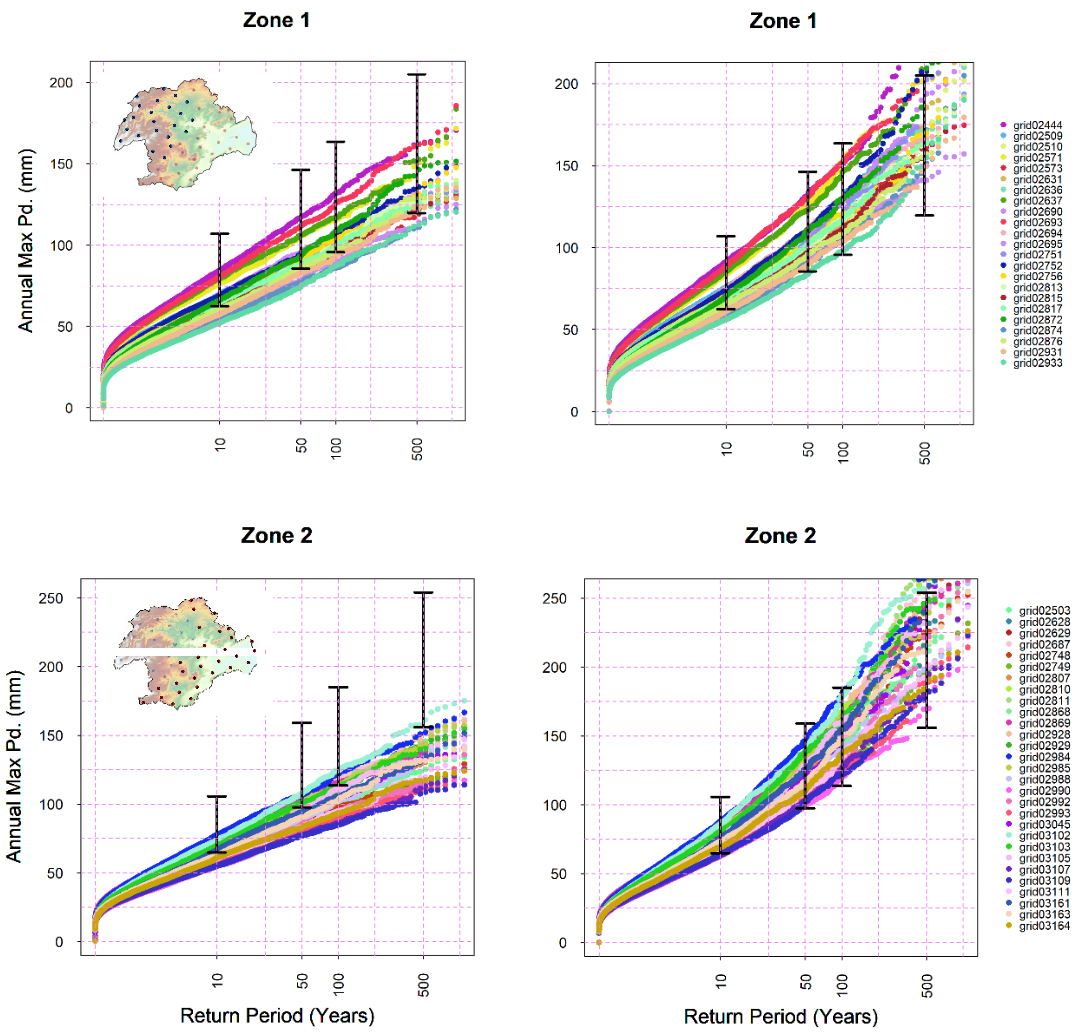


Figure P4 - 7 - WG Calibration: Plotting Positions of simulated precipitation data series before calibrating the shape parameter ξ (left) and after (right) for both regions.

Estimated shape parameters ξ for each zone and each period of time are represented in Table P4 - 1.

Table P4 - 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

5.5.3. Storm selection, and 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. Figure P4 - 8 shows an example of a disaggregated storm.

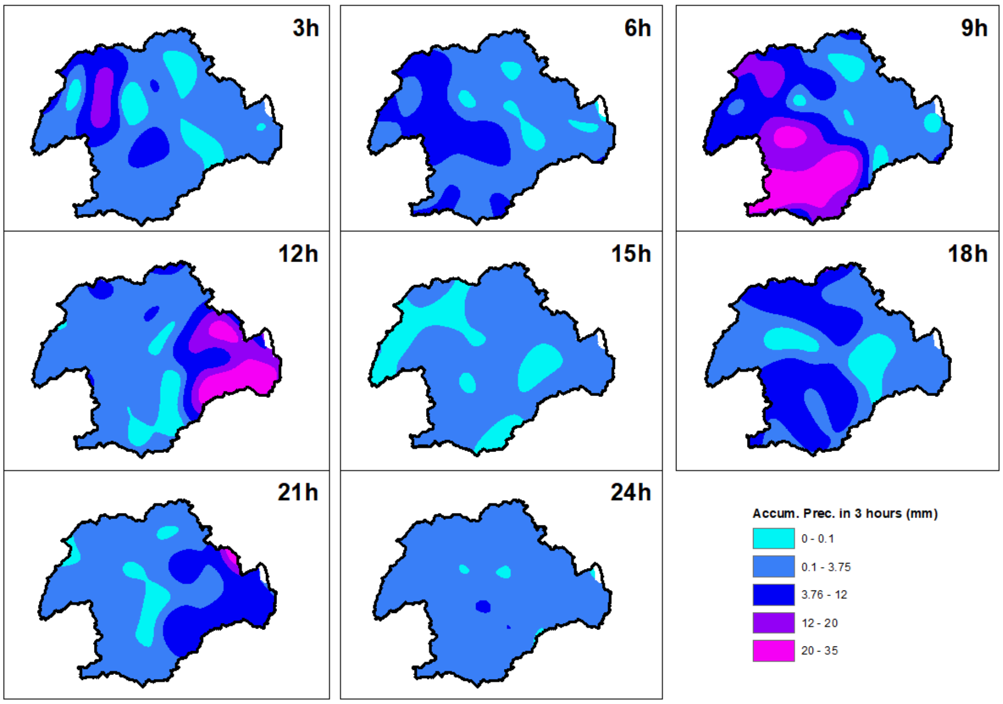


Figure P4 - 8 - Hourly spatial distribution of rainfall every 3h for disaggregated storm n #384.

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 Figure P4 - 9.

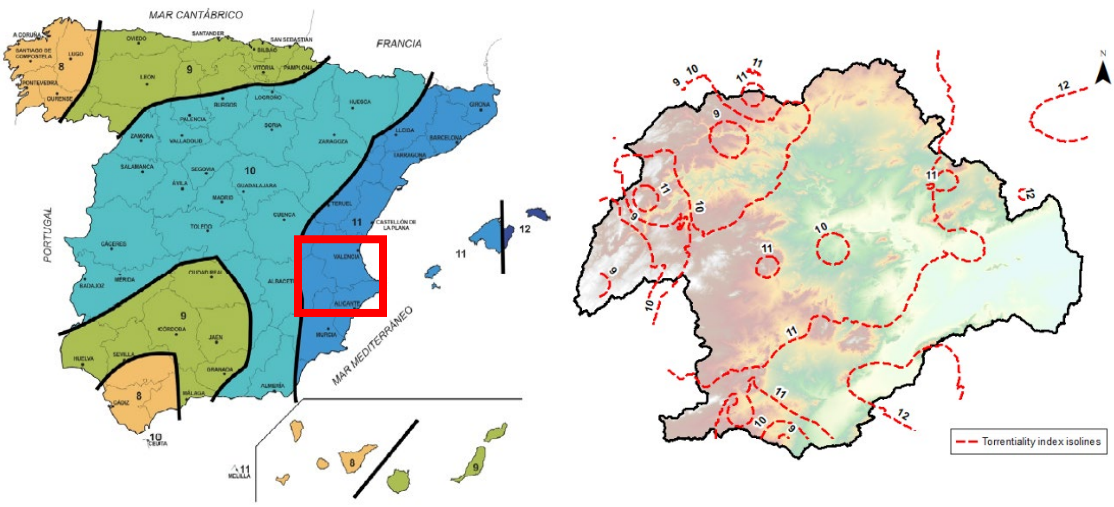


Figure P4 - 9 - Rainfall validation - Left: Torrentiality index map according to Standard 5.2. IC, Superficial Drainage, Order FOM/298/2016. Right: Torrentiality index isolines estimated from the synthetic storms.

5.5.4. Implementation of a fully-distributed HM

For computational reasons and following hydromorphological criteria, the Segura basin was divided into five models (Figure 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).

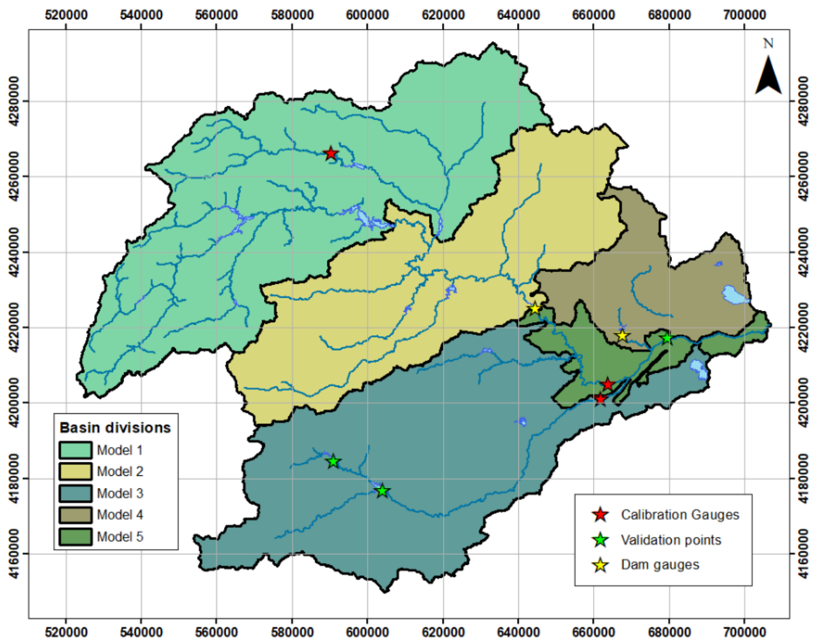


Figure P4 - 10 - Hydrological model basin subdivisions and points of interest.

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.

Table P4 - 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

5.5.5. 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 Figure P4 - 11 Figure 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.

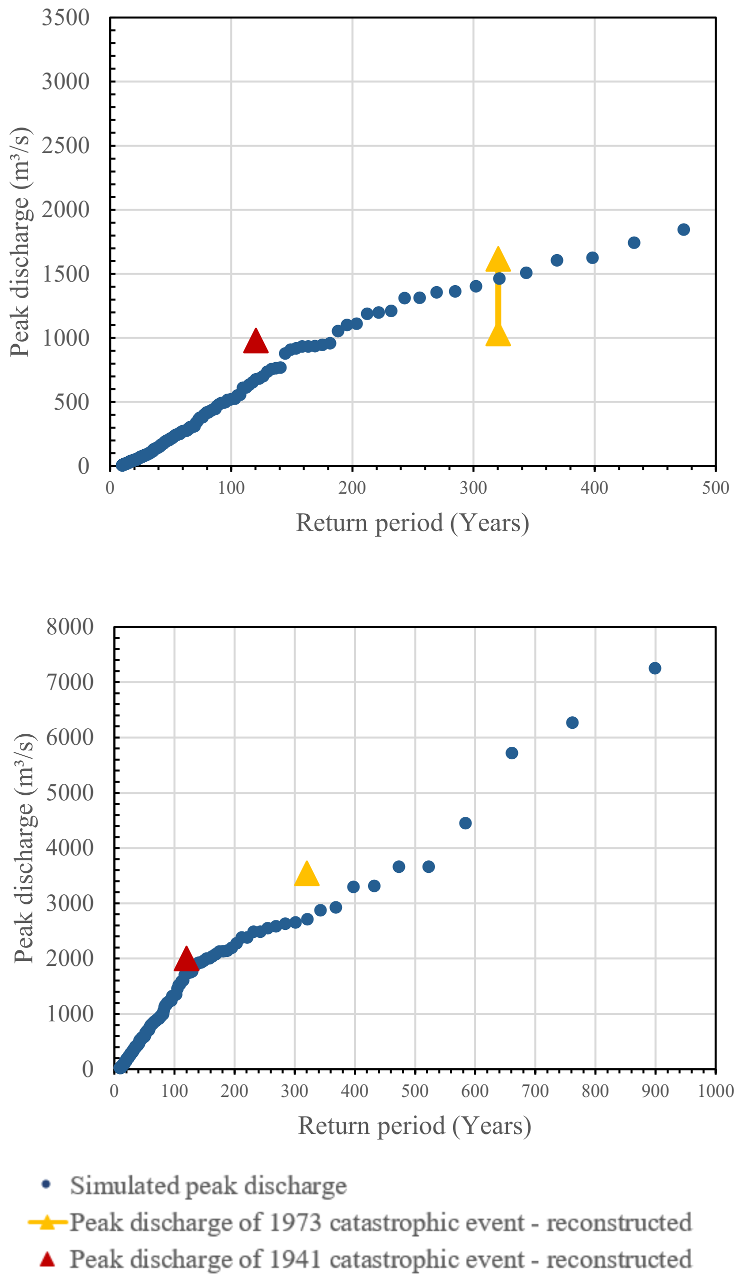


Figure P4 - 12 - Comparison between simulated quantiles in the natural regime and probability assignment to non-systematic events (upper plot: Valdeinfierno reservoir; lower plot: Puentes reservoir). Common censoring threshold represented by a triangle in and the plotting position of the lower bound of the maximum flood represented by an arrow.

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). Figure P4 - 12 shows the plotting positions of the systematic data reconstructed at the Orihuela gauging station, completed with the data from Murcia (1912 to 1993) and the perception threshold of historical floods (Frances et al., 1994) in Murcia. This latest 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 m³/s which is equivalent to a return period of only 21.8 years.

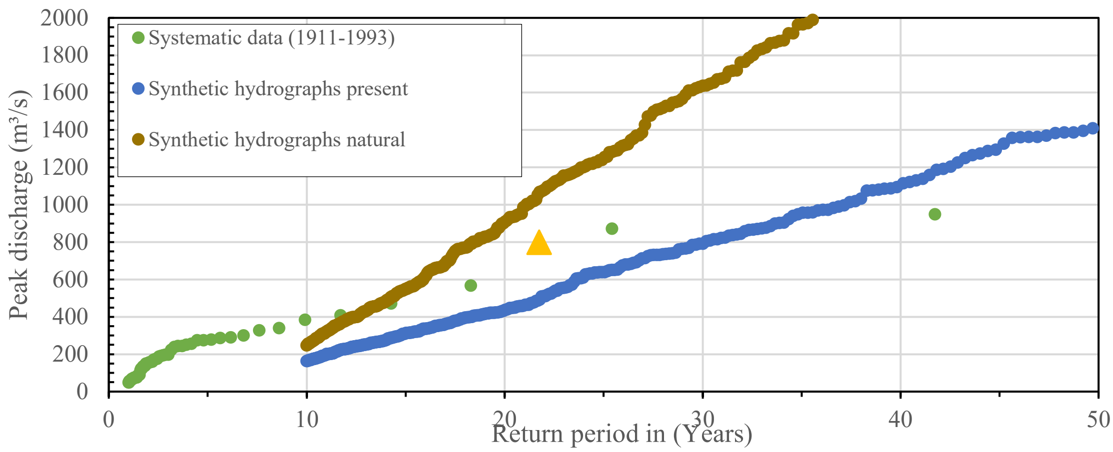


Figure P4 - 13 - Plotting positions of the simulated discharges in Orihuela (natural and present conditions), systematic data and the perception threshold of historical floods in Murcia.

5.6. Discussion

5.6.1. On the added value of expanding information from regional models.

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 (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-2s 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 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.

Figure P4 - 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.

5.6.2. 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 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 Figure 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.

5.6.3. 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 (Figure P4 - 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 (Figure P4 - 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 Figure P4 - 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).

5.7. 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 km2), 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 > 50yrs), 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)

Declaration of Competing Interest

The authors have no conflict of interest to declare.

Acknowledgements

This work was supported by the Spanish Ministry of Science and Innovation through the research projects TETISCHANGE (RTI2018-093717-B-100) and TETISPREDICT (PID2022-141631OB-I00). Funding for the Open Access charge has been provided by Universitat Politècnica de València.

6. On the Use of Weather Generators for the Estimation of Low-Frequency Floods Under a Changing Climate.

Carles Beneyto[a], José Ángel Aranda[a], and Félix Francés[a]*

[a] *Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Camino de Vera s/n, E-46022 Valencia, Spain*

* Correspondence: jaranda@upv.es; Tel.: +34-963-877-000 (ext. 76152)

Beneyto, C., Ángel, J., Francés, F.. *On the Use of Weather Generators for the Estimation of Low-Frequency Floods Under a Changing Climate. 2024, 16, 1059*

This is the author version of the paper published in the scientific journal Water (Switzerland) in 2024.

6.1. Abstract

The present work presents a methodology based on the use of stochastic weather generators (WG) for the estimation of high return period floods under climate change scenarios. Applying the proposed methodology in a case study: Rambla de la Viuda (Spain), satisfactory results have been obtained through the regionalization of the bias-corrected EUROCORDEX climate projections and the integration of this information into the parameterization of the WG. The generated synthetic data series fed a fully-distributed hydrological model to obtain the future flood quantiles. The results obtained show a clear increase in the precipitation extreme quantiles for the two analyzed projections, although slightly reducing the annual amount of precipitation. In terms of temperatures, results point to clear increases in maximum and minimum temperatures for both projections (up to 3.6ºC), these increases being greater for the long-term projection, where the heat waves intensify importantly in both magnitude and frequency. All this translate into substantial shifts in the river flows regimes, increasing the frequency and magnitude of extreme flood events although presenting, in general, lower flows during the year.

Keywords: weather generator; climate change; quantile; regional study of maximum annual daily precipitation.

6.2. Introduction

Ensuring accurate estimation of high return period flood quantiles is paramount for appropriately dimensioning infrastructure and establishing effective flood warning systems (Kidson and Richards, 2005; Lisø et al., 2017). Despite the emergence of novel methodologies for estimating these quantiles in recent years, the prevailing estimates still harbor substantial uncertainties. The limited temporal length of available time series data and the sparse deployment of rain gauges and monitoring stations stand out as primary sources of uncertainty, presenting formidable challenges within Flood Frequency Analysis

(FFA). This challenge is particularly accentuated in arid and semi-arid regions (Metzger et al., 2020), often poorly monitored.

Rapid advancements in computing capabilities have paved the way for the widespread adoption of Synthetic Continuous Simulation (SCS) within the scientific community: a hybrid methodology blending statistical and deterministic techniques for FFA studies. Leveraging a stochastic Weather Generator (WG) in tandem with a Hydrological Model (HM), SCS facilitates the generation of synthetic data series spanning a wide range of hydrometeorological variables. However, to ensure the robust performance of WGs, it is necessary to feed them with adequate input information, particularly when modeling extreme events (Soltani and Hoogenboom, 2003). Nevertheless, the duration of current observational records, typically limited to around 100 years at most, proves insufficient for optimal WG performance. Consequently, addressing this data deficiency necessitates the incorporation of additional flood information (Merz and Blöschl, 2009, 2008). This may encompass non-systematic data sources, including historical and palaeoflood records, as demonstrated by Benito et al. (2020), regional maximum precipitation studies, as exemplified by Evin et al. (2018) or a blend of both approaches, as showcased by Beneyto et al. (2020).

Furthermore, climate studies predict an increase in the frequency and magnitude of extreme events (e.g., (Alfieri et al., 2017; Paprotny and Morales-Nápoles, 2017)), which combined with the global socioeconomic development will lead to an increase in flood losses resulting from extreme precipitation events in the near future (IPCC, 2022). All this further highlights the need to develop methodologies that reduce the uncertainty in the flood estimates, especially those associated with low probability of occurrence. Generally, most of the studies currently carried out to estimate future flood quantiles are broadly based on the use of the available products from the Global Circulation Models (GCM), downscaling the outputs of these to finer scales and obtaining the flow series through a HM (e.g., (Roudier et al., 2016; Soriano et al., 2020; Yin et al., 2018)). Downscaling methods to obtain observed small-scale variables and from

GCMs can be based on the use of either RCM, analogue methods (circulation typing), regression analysis, or neural network methods (Jain, 2014). However, downscaled data present large biases that need to be corrected. Over the past decades, various bias-correction methods have been proposed. Main examples include delta change (Gleick, 1986; Hay et al., 2000), direct statistical downscaling (Hay and Clark, 2003; Maraun et al., 2010), quantile mapping (QM) (Pierce et al., 2015), Nested Bias Correction or its multivariate counterpart Multivariate Bias Correction (Mehrotra and Sharma, 2016). More extensive review of bias-correction methods can be found in Themeßl et al. (2011) and Maraun (2016).

Although it is true that to properly capture extreme convective precipitation episodes a sub-daily modeling time step is required for most applications (Beranová et al., 2018), and that climate model outputs are now increasingly available at sub-daily time steps, a very limited number of studies have looked at the bias correction of sub-daily climate model outputs (Faghih et al., 2022) and the focus has been on correcting sub-daily annual maximum values (e.g., (Requena et al., 2021)). Instead, daily climate projections of 30 years in length are usually used in climate change studies that, although according to the "World Meteorological Organization", are of sufficient length to smooth out the variations from one year to the next (WMO, 2017), in the opinion of the authors of this work, they are insufficient for the adequate estimation of extreme flood quantiles. Although 30-years data series could be enough for specific studies and some meteorological variables, flood quantile estimation requires longer datasets, especially if we are focused on adequately modeling extreme events, which they could be achieved with an effectively parametrized WG.

In this context and following the steps of the previous works of Beneyto et al. (2023a, 2023b, 2020), this study presents a new methodology that integrates different sources of information generated from hydrometeorological models fed with the amount of information necessary to achieve an adequate characterization of the main variables that must be considered in the FFA under climate change scenarios of only 30 years in length.

6.3. Case study

6.3.1. Study area.

The methodology outlined in this study was implemented and evaluated in the setting of the Rambla de la Viuda (Castellón), a typical Mediterranean ephemeral river located in eastern Spain (Figure P5 - 1). Stretching over a distance of 36 kilometers and covering a drainage area of 1513 square kilometers, this river originates from the junction of the Montlleó River and the Rambla Carbonera, eventually joining the Millars River near its endpoint at the Mediterranean Sea.

Annual precipitation averages approximately 550 mm, showcasing significant variability throughout the year. Consequently, the river sustains flow for an average of 31 days annually, often persisting for as briefly as 2 or 3 days, and is correlated with cumulative rainfall surpassing 70 mm. (Camarasa and Segura, 2001).

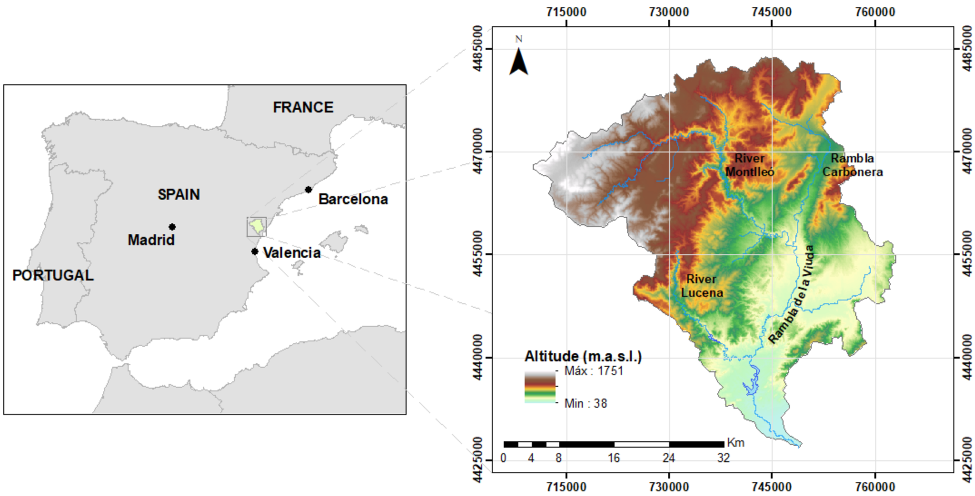


Figure P5 - 1 - Study Area.

6.3.2. Hydrometeorological information

Meteorological data were obtained from different sources. Observed daily precipitation and maximum and minimum temperatures were obtained from the Spain02-v5 dataset (Herrera et al., 2019; Kotlarski et al., 2017). A total of 20 pluviometers and thermometers covering the basin with daily records from 1951 to 2015 (66 years) were selected (Figure P5 - 2).

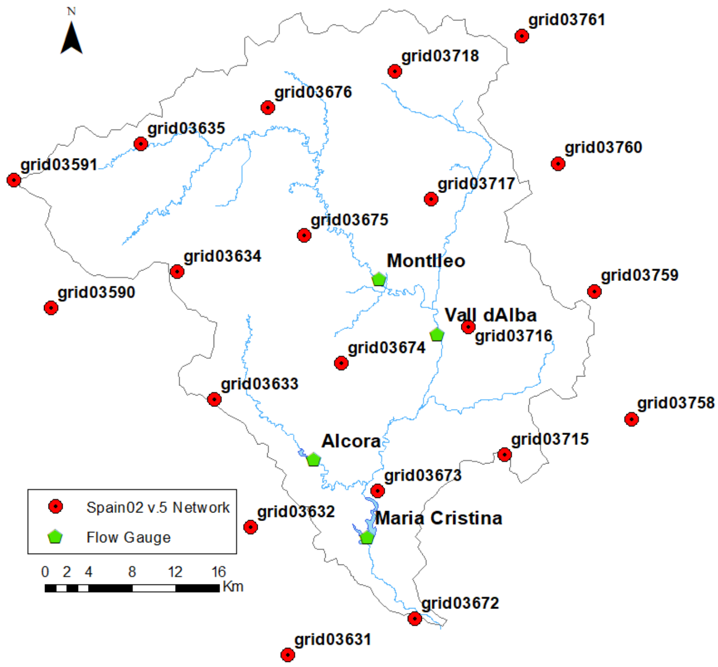


Figure P5 - 2 - Hydrometeorological information.

Climate projections were obtained from the "Coordinated Regional Downscaling Experiment for Europe" experiment (EURO-CORDEX) (https://www.euro-cordex.net/). A total of 12 different combinations of Global Circulation Models (GCM) and Regional Circulation Models (RCM) were used in this study (Table P5 - 1), including daily precipitation, minimum, and maximum temperature with a spatial resolution of 0.11°. These data included a control period (1971–2000), a medium-term projection (2035–2064), and a long-term projection (2065-2094). The projections used in this study correspond to the Radioactive Concentration Pathways (RCP) 8.5, which represents a scenario with continuous emissions of CO2 throughout the 21st century (Meinshausen et al., 2011). Additionally, temperature data (bias corrected) were used to create time series of Potential Evapotranspiration (ET0), which were estimated with the Hargreaves-Samani equation (Hargreaves and Samani, 1985).

Table P5 - 1 - EUROCORDEX models.

Model	GCM	RCM	Institute
1	MPI-M-MPI-ESM-LR	COSMO-crCLIM-v1-1	CLMcom-ETH
2	CNRM-CERFACS-CNRM-CM5	CCLM4-8-17	CLMcom
3	CNRM-CERFACS-CNRM-CM5	RACMO22E	KNMI
4	ICHEC-EC-EARTH	COSMO-crCLIM-v1-1	CLMcom-ETH
5	ICHEC-EC-EARTH	RACMO22E	KNMI
6	IPSL-IPSL-CM5A-MR	RACMO22E	KNMI
7	MOHC-HadGEM2-ES	CCLM4-8-17	CLMcom
8	MOHC-HadGEM2-ES	RACMO22E	KNMI
9	MPI-M-MPI-ESM-LR	CCLM4-8-17	CLMcom
10	MPI-M-MPI-ESM-LR	KNMI-RACMO22E	KNMI
11	MPI-M-MPI-ESM-LR	REMO2009	MPI-CSC
12	NCC-NorESM1-M	COSMO-crCLIM-v1-1	CLMcom-ETH

Lastly, discharge data for the HM implementation were obtained from the Júcar River basin Water Authority (CHJ) through its Automatic System of Hydrological information (SAIH): two gauges located at Vall d'Alba and Montlleó Rivers; and two stations located in Alcora and Maria Cristina reservoirs, where the flows were estimated from the balance between the reservoir levels and their releases.

6.4. Methodology

Following in the footsteps of a previous work by Beneyto et al., (2020), the proposed methodology encompasses undertaking the following procedures: (1) correct the bias of climate models; (2) perform (if not available) a regional study of maximum daily precipitation of the bias-corrected climate models (both for control period and for the projections); (3) implement a stochastic multi-site WG incorporating the information from the ad hoc regional studies and generate very long series (i.e., 5000 years) of precipitation and temperatures; and (4) implement a fully-distributed HM and feed it with the outputs from the WG to generate series of synthetic discharges. Figure P5 - 3 shows an outline of the proposed methodology, the steps of which are developed in the following sections.

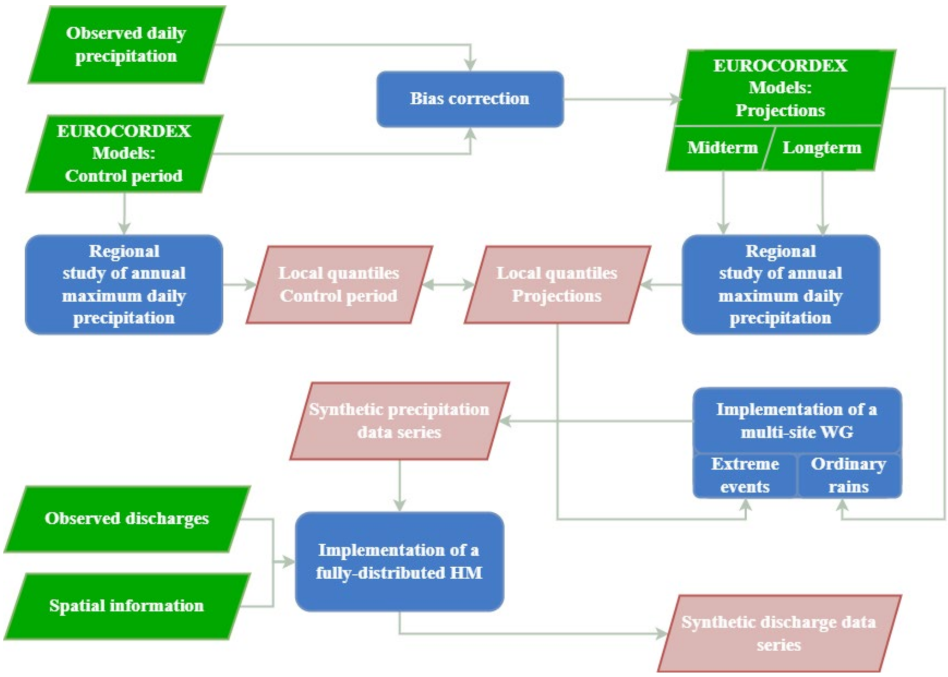


Figure P5 - 3 - Workflow chart of the proposed methodology.

6.4.1. Bias correction of climate series.

The temperature and precipitation time series of the 12 climate models were bias corrected relative to the observed climate data (Spain02 dataset). The bias correction was based on the non-parametric statistical transformation of empirical quantiles or "quantile mapping" (Gudmundsson et al., 2012) and was implemented for each season of the year separately (December-February, March-May, June-August, and September November). The bias correction procedure applied in this study also considered the adaptation of the frequency of wet/dry days proposed by Themeßl et al. (2012). Bias correction functions established in the control period were applied to future climate projections assuming stationary biases.

6.4.2. Regional study of maximum daily precipitation

The second phase of the methodology, if not available, entails conducting a comprehensive regional study of maximum daily precipitation, encompassing both historical control period data and projections previously bias-corrected. This in-depth analysis aims to expand the available information and capture a holistic understanding of precipitation patterns across the region. The insights gleaned from this study serve as crucial inputs for the effective implementation of the WG, which is explained in the following subsection. A comparison of regionalization methods to improve in-situ estimates of daily precipitation can be found in Haruna et al. (2022).

In our study, the regional analysis followed the methodology developed by Hosking and Wallis (1997, 1993), employing the Index Variable method (Dalrymple, 1960) alongside linear moments. As recommended by the authors, a Discordance and Homogeneity test based on L-moments was conducted to identify homogeneous regions, resulting in the identification of a single homogeneous region.

Finally, once the homogeneous regions were identified and following the premises of the Index Variable, the probability function that best fit (i.e., Generalized Pareto Distribution) was selected according to the criterion developed by Akaike (1977) and the local quantiles were deregionalized for each of the models and grids of the basin.

6.4.3. Weather generator: GWEX

The WG employed in this study was GWEX (Evin et al., 2018), a multi-site stochastic model designed specifically to accurately model extreme events. Noteworthy among its many features is the incorporation of the Extended Generalized Pareto Distribution (E-GPD) function, as described by Papastathopoulos and Tawn (2013). This distribution is essentially derived by raising the Generalized Pareto Distribution to a power k>0. This unique characteristic enhances the WG's capability to effectively simulate extreme weather phenomena, which is particularly relevant for the objectives outlined in this study.

$$F(x;\lambda) = \left[1 - \left(1 + \frac{\xi x}{\sigma}\right)_+^{-1/\xi}\right]^{\kappa}, \qquad x > 0 \tag{1}$$

The parameter vector λ= (k, σ, ξ) comprises the parameters controlling various aspects of the distribution. Specifically, k governs the shape of the lower tail, σ represents the scale parameter, and ξ regulates the decay rate of the upper tail, as described by Naveau (2016). In a similar way to the proposed methodology in Beneyto et al. (2020), the value of this latter parameter was adjusted for each model with the regional X_{100}, thus reducing the uncertainty in the estimates as demonstrated in Beneyto et al. (2023b, 2023a).

6.4.4. Ecohydrological model: TETIS

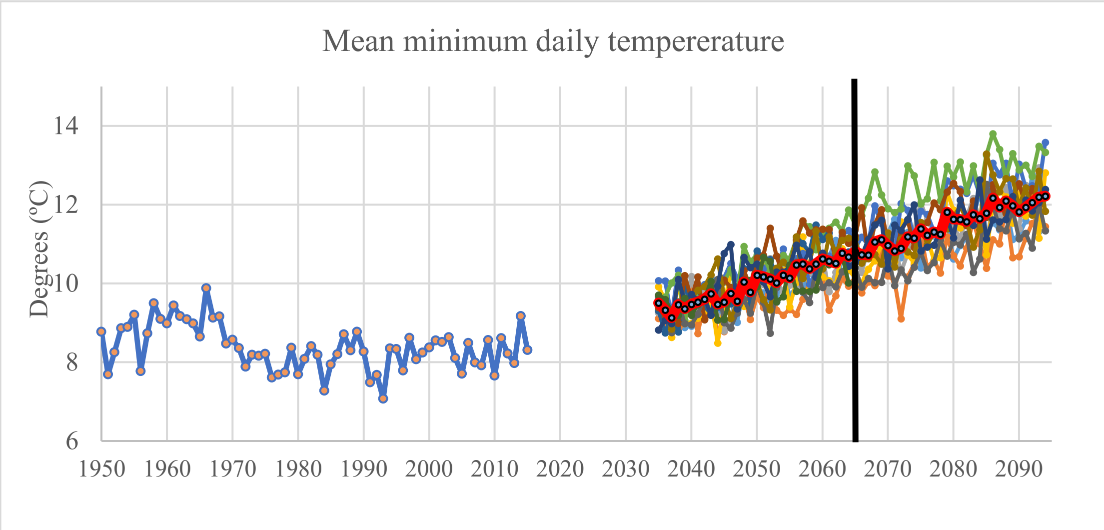
The fully-distributed ecohydrological model TETIS was used (Francés et al., 2007; Vélez et al., 2007). This model had already been implemented in a previous work by Beneyto et al. (2020). In this study, slight modifications to the correction factors were made, which improved the results in terms of Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) both in calibration and in temporal, spatial and spatio-temporal validation. For more information regarding the model implementation refer to Beneyto et al. (2020).

6.5. Results

6.5.1. Temperatures

Although the analysis of the temperatures is not within the main objectives of the present study, it is evident that the potential change in the temperature trends resulting from the effects of the climate change will lead to alterations to the discharge regimes. This is, temperature has a clear impact on the initial conditions of the basin: apart from higher evapotranspiration, higher temperatures would potentially increase the soil aridity, resulting in higher volumes of infiltration at the initial moments of the storm, thus, supposedly resulting in lower initial flows.

Figure P5 - 4 below shows the comparison of the mean daily maximum and minimum temperatures of the observations and the 12 GCM-RCM combinations for both the mid-term and the long-term projection. It is worth mentioning that, in the case of the temperatures, the analysis has been carried out comparing purely the data from the observations and from the climate projections (bias corrected). This is, the use of a WG was considered not necessary for this analysis given that the length of the data series weas enough to capture the trend and the potential variations.



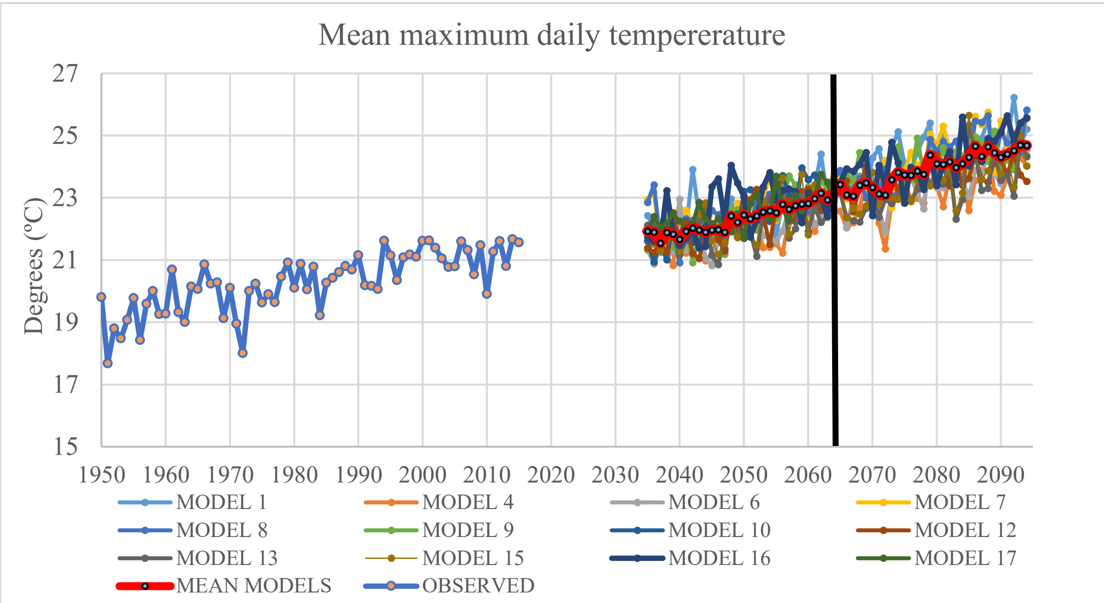


Figure P5 - 4 - Mean minimum (top) and maximum (bottom) daily temperature of the observations and the 12 climate projections (black line denotes the separation between mid-term and long-term projections)

From this figure, it can be appreciated a clear increasing trend for both maximum and minimum temperatures for all projections. This increase ranges from 1.9ºC for the mid-term projection to 3.4ºC for the long-term projection in the case of minimum temperature and from 2.0ºC to 3.6ºC respectively in the case of the maximum temperature. If we look at the monthly variations (Table P5 - 2), it can be observed that, for both variables, the greater increases occur over the summer months whereas the lower increases take place during the winter months.

Table P5 - 2 - Average monthly increase in maximum and minimum temperatures for mid-term and long-term projections.

ΔT (ºC)	Minimum temperature		Maximum temperature	
	Mid-term	**Long-term**	**Mid-term**	**Long-term**
January	2.43	2.55	2.25	2.25
February	1.90	1.93	2.17	1.98
March	2.41	2.61	2.27	2.56
April	2.39	2.98	2.76	3.55
May	1.34	2.61	1.51	3.08
June	3.02	5.32	3.34	6.04
July	2.04	5.04	1.80	5.11
August	1.06	4.26	1.35	4.73
September	0.41	3.19	0.34	3.18
October	1.47	3.68	1.43	3.67
November	2.71	4.28	2.73	4.18
December	1.67	2.59	1.56	2.40

Finally, an analysis of the percentage of the days with temperatures under- or over certain thresholds was conducted. Results of this analysis are shown in Figure P5 - 5 below.

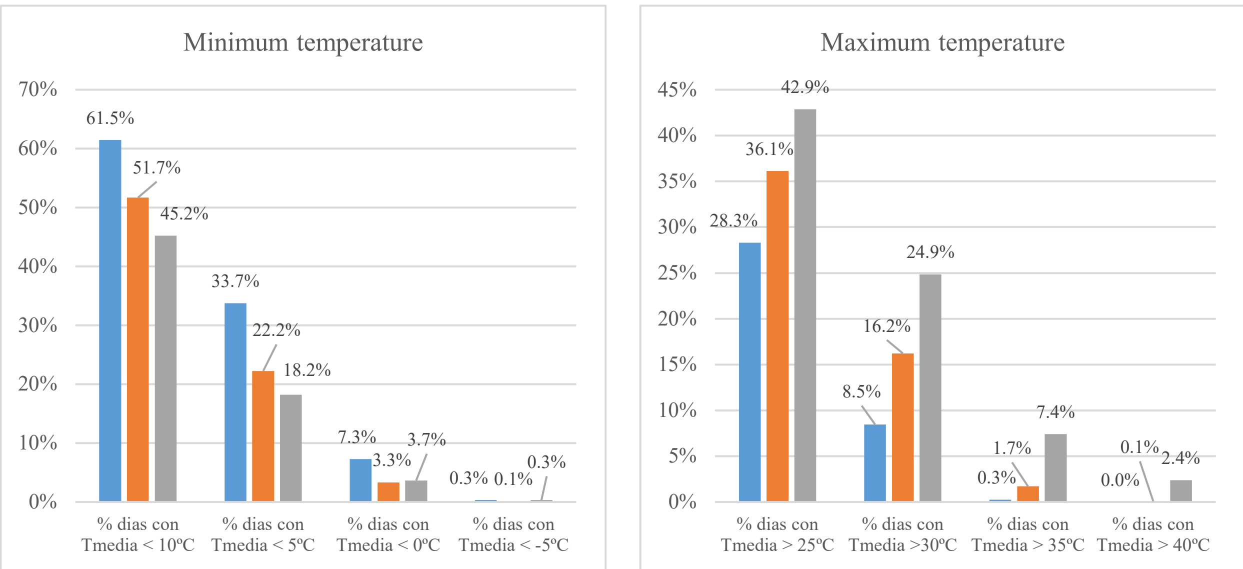


Figure P5 - 5 - Variation in the number of days with extreme mean daily temperatures.

In the case of the minimum temperature, the percentage of days with mean minimum temperature lower than 10ºC, 5ºC, 0ºC, and -5ºC was analyzed, observing a clear decrease in the number of cold days compared to the observations and more pronounced in the case of the long-term projection. Similarly, in the case of the maximum temperature, the percentage of days with mean maximum temperature higher than 25ºC, 30ºC, 35ºC, and 40ºC was examined, spotting and important increase in the number of warm days and, again, being this increase more remarked in the case of the long-term projection.

6.5.2. Precipitation

Results in terms de precipitation are shown in Figure P5 - 6, where the boxplots of the estimated precipitation quantiles (standardized with homologous quantiles in control period) from the generated 5000 years for both the mid-term projection and the long-term projection are represented for one of the grids of the basin (i.e., grid 03759). Similarly to what occurs with the rest of the grids, low return period quantiles experience small differences with their corresponding quantiles in control period. Future quantiles tend to increase systematically with the return period, being this increase more evident in case of the long-term projection. Additionally, the uncertainty of these estimations broadens with the quantile (wider boxplots).

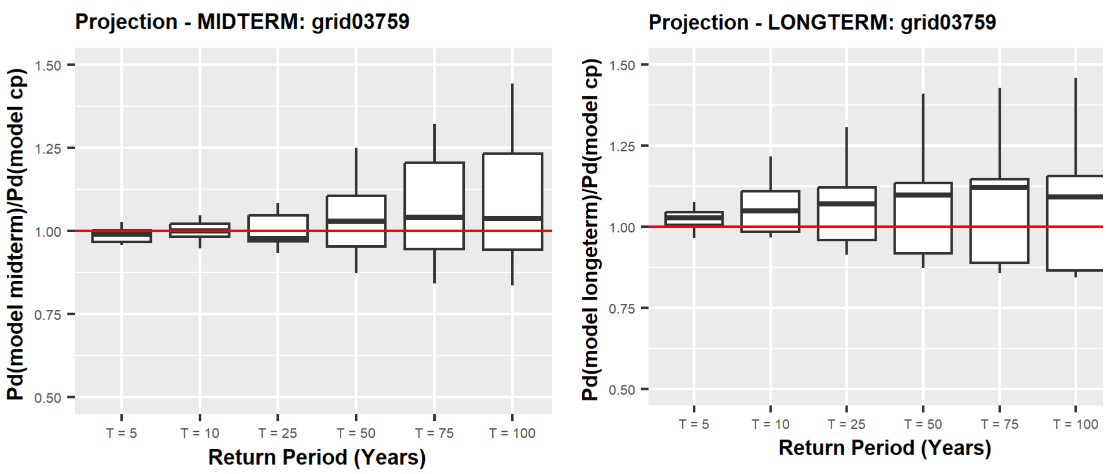


Figure P5 - 6 - Standardized precipitation quantiles in grid03759 for both mid-term projection (left) and long-term projection (right)

Considering the mean quantile of all grids and all models (in control period, mid-term projection and long-term projection), we could obtain the expected differences in the future quantiles (Δ%), which applied to the observed quantiles results in the estimated future precipitation quantiles (Table P5 - 3).

Table P5 - 3 - Estimated future precipitation quantiles (mean of all models and all grids)

T (years)	Observations	Mid-term projection		Long-term projection	
	X_T	Δ%	X_T	Δ%	X_T
5	80	4.3%	83	12.8%	90
10	99	6.0%	105	16.7%	116
25	125	8.4%	136	18.6%	148
50	145	11.5%	162	19.3%	173
75	158	13.5%	179	19.7%	189
100	167	14.4%	191	19.4%	199

These increases in the precipitation quantiles range between 4.3% for a return period of 5 years in the mid-term projection to 19.7% for a return period of 100 years in the long-term projection. While it is clear that the increase is proportional to the return period in the case of the mid-term projection, for the long-term projection this increase seems to be quite stable for all return periods except for a return period of 5 years.

6.5.3. Discharges

The 25 WG implementations (i.e., observations, 12 mid-term projections, and 12 long-term projections) fed the fully-distributed HM TETIS obtaining the discharges shown in Figure P5 - 7 represented by their plotting positions.

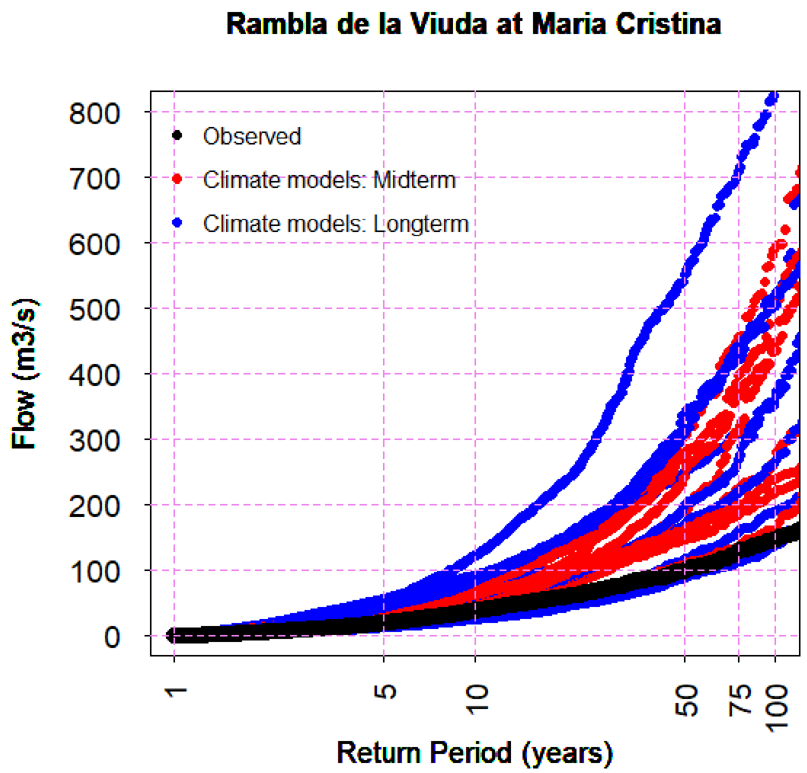


Figure P5 - 7 - Plotting positions of the observed daily discharges and the simulated discharges from the climate models (both for the mid-term and for the long-term projection) at Maria Cristina reservoir.

As expected with the results obtained for the precipitation, the plotting positions of the generated discharges are clearly higher to those observed for both the mid-term and the long-term projection. Notwithstanding, it is also clear the uncertainty surrounding these estimates depending on the model, presenting flood quantiles that range from 180 m3/s to 810 m3/s for a return period of 100 years, for example. Despite variations across scenarios, an increase is evident in all cases, Table P5 - 4 presents the estimated percentage increase in flood quantiles at Maria Cristina reservoir, calculated as the difference between those obtained during the control period and those projected by each model. Additionally, the table includes the anticipated future flood quantile, derived by applying this percentage increase to the observed quantiles.

Table P5 - 4 - Estimated future flood quantiles at Maria Cristina (catchment area: 1447 m^2)

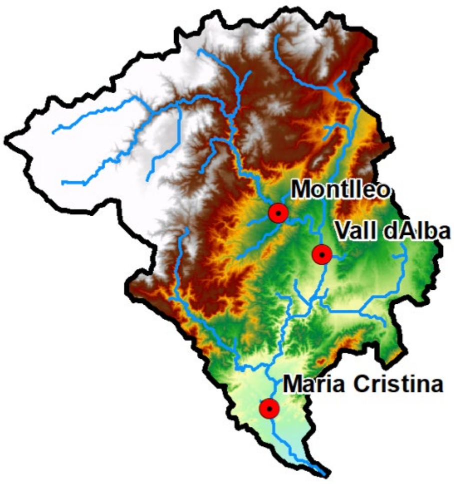
T (years)	**Climate projections (m^3/s)**

	Observed (m³/s)	Δ%	Mid-term	Δ%	Long-term
5	20	12%	22	8%	21
10	38	12%	43	16%	44
25	68	22%	83	33%	91
50	101	38%	140	54%	155
75	130	48%	192	56%	202
100	147	53%	225	58%	232

The increase is systematic for all quantiles and for both projections, ranging from 8-12% for low return periods to 53-58% for high return periods, where increases in flood quantiles are more pronounced. Finally, and exploiting the benefits of using a fully-distributed HM, the same analysis was conducted for additional two flow gauges located at Vall d'Alba (906 km2) and Montlleó (501 km^2) (Table P5 - 5). Results in both flow gauges presented increases for all flood quantiles, however, it can be observed that, compared to Maria Cristina, this increases are higher in Vall d'Alba (ranging from 10% to 80%) and specially in Montlleó (ranging from 5% to 145%). This is, future flood quantiles appear to experiment higher increases as the catchment is smaller.

Table P5 - 5 - Estimated future flood quantiles at Vall d'Alba and Montlleó (catchment areas: 906 km^2 and 501 km^2 respectively)

Vall d'Alba					
T (years)	Observed (m³/s)	Climate projections (m³/s)			
		Δ%	Mid-term	Δ%	Long-term
5	12	11%	14	10%	13
10	22	13%	24	33%	29
25	39	21%	47	64%	64
50	56	41%	79	88%	105
75	69	49%	103	86%	130
100	80	50%	121	80%	145
Montlleó					
T (years)	Observed (m³/s)	Climate projections (m³/s)			
		Δ%	Mid-term	Δ%	Long-term
5	4	3%	4	5%	4
10	6	7%	6	42%	8
25	11	27%	14	111%	23
50	17	57%	27	137%	40
75	21	73%	37	145%	52
100	28	77%	49	130%	64



6.6. Discussion

SCS, a widely embraced hybrid methodology for flood quantile estimations, addresses the limitations of purely statistical or deterministic approaches in estimating flood quantiles. By effectively characterizing the initial conditions of a basin and adequately representing the spatio-temporal distribution of precipitation, SCS offers significant advantages in flood estimation. Despite these advancements, uncertainty persists in estimating low-frequency flood quantiles.

The primary source of this uncertainty stems from the length of existing hydrometeorological series and the sparse distribution of monitoring stations, particularly pronounced in arid and semi-arid regions. The scarcity of data poses a formidable challenge in accurately estimating flood quantiles. While longer input data sets could potentially mitigate uncertainty, this remedy relies solely on the passage of time for data accumulation.

Addressing the challenges of uncertainty in flood quantile estimation requires concerted efforts in data collection and analysis. Strategies to enhance monitoring networks and extend data collection periods can contribute to reducing uncertainty. Additionally, advancements in modeling techniques and the integration of remote sensing data can provide valuable insights into hydrological processes, aiding in more accurate flood quantile estimation. Despite the inherent challenges, ongoing research and technological innovations hold promise for improving the reliability of flood quantile estimates and enhancing our ability to manage flood risks effectively. Additionally, climate patterns are no longer as we used to know them, they are rapidly changing as a consequence of the effects of the climate change. Practically all available research point to alterations in the rivers flow regimes resulting from the changes in the temperature and precipitation patterns. This adds even more uncertainty in the estimation of future flood quantiles, and certainly a challenge to be faced for a correct sizing of infrastructures and for protecting those areas now vulnerable of being affected by floods.

Numerous studies can be found in the literature assessing the impacts of climate change on hydrology and water resources in many regions. They all start from the same source of information: GCMs. These are the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations (Hartmann, 2016). Notwithstanding, these models inevitably simulate large biases in temperature, precipitation, and humidity at regional scales and at individual grid points (Flato et al., 2013; Randall et al., 2013) and their resolution is too coarse for undertaking reliable flood studies at a local scale. Downscaling methods to obtain observed small- scale variables and from GCMs can be based on the use of either RCM, analogue methods (circulation typing), regression analysis, or neural network methods (Jain, 2014).

Many projects are now under way offering a wide range of climatic data, mostly based on combinations of GCMs and RCMs, such as the EUROCORDEX project, the data of which have been used in the present study. These climate projections include a 66-year control period for correcting the potential biases and 95 years of future projections. Although 95 years could be a reasonable data length for certain studies implying specific climatic variables, under these authors opinion, it is not enough for the case of the precipitation, specifically if we are focusing on estimating extreme events. WGs, however, fed by these climate projections, can generate long data series in multiple realizations, reducing the uncertainty of future quantile estimations. Nevertheless, it has been demonstrated that WGs need robust information to perform adequately (Beneyto et al., 2023a, 2023b, 2020). Incorporating additional sources of information or improving model implementation can lead to considerable improvements in the reliability of flood quantile estimates.

The present work tries to contribute in this sense, establishing a new methodology for the estimation of extreme floods in climate change scenarios through the use of WGs. Similarly as in Beneyto et al., (2023a, 2023b, 2020), we perform an ad hoc regional study of annual maximum daily precipitation the results of which are incorporated in the WG parametrization for better reproduction of the precipitation quantiles in both the present and the future climate.

The results obtained applying this methodology in terms of temperatures show a substantial increase in relation to current observations for both the medium-term projection (35-64) and the long-term projection (65-94), with the increase being considerably greater for the long-term projection, with mean maximum temperature values of up to 6ºC higher for the month of June. These results follow the same line as the results obtained by other authors such us Wuebblles et al. (2017) or Zubaidi et al. (2019), predicting warmer summers and milder winters. Furthermore, as can be seen in Figure P5 - 5, the number of days with mean maximum temperature above 35ºC and 40ºC increases considerably, which means that the number of heat waves will intensify in the future, as other studies already highlighted (e.g., (Guerreiro et al., 2018; Lhotka et al., 2018)). Similarly, the mean minimum temperature also increases in both projections, although slightly less pronounced than in the case of the maximum temperature. Furthermore, the percentage of intense cold days reduces systematically for all analyzed temperatures in the case of the medium-term projection, although it increases again for the long-term projection when looking at mean temperature below 0ºC and -5ºC, which means that cold waves could intensify in the future, even though this increase could also be caused by the models' variability.

When we look at the precipitation, results obtained show a substantial increase for all quantiles, both in the medium-term projection (35-64) and in the long-term projection (65-94) with respect to the control period regional quantiles. Despite the higher variability between the models with the return period evidenced by the width of the boxplots in Figure P5 - 6, the upward trend is clear for all of them, being more pronounced for the highest return period quantiles, where the increases in the precipitation quantiles reach 15% to 20%. Again, these results align with studies from other authors (e.g., Prein et al., 2017; Wasko et al., 2021; Willems and Vrac, 2011), that predict an increase in the magnitude and frequency of extreme precipitation episodes as a consequence of climate change.

This increase in the magnitude and frequency of precipitation events is logically transferred to discharges, with these increasing significantly for all quantiles and, once again, more evidently for low frequency quantiles. This increase in flows, however, is slightly compensated due to the decrease in the average annual precipitation and the increase in temperatures, which translates into greater evapotranspiration and lower humidity in the basin prior to storm episodes. Even so, although there is a high variability between climate models, all of them predict increases in the peak discharges, which means that flood events will be more frequent and more extreme in the future.

Finally, it is worth noting the presence of the "dog-leg" effect in the flood plotting positions, as demonstrated in Figure P5 - 7 of the simulations. This distinctive phenomenon, originally described by Potter (Potter, 1958), is particularly evident in Mediterranean Rivers in the region and can be accurately reproduced using a TCEV distribution, as proposed by Francés (Francés, 1998).

The escalating magnitude of extreme precipitation events underscores the imperative to urgently address and prepare for potential amplification in the scale of future river floods. As climate change continues to influence weather patterns, the heightened intensity of precipitation poses an increased risk of severe flooding. To effectively mitigate and adapt to these evolving challenges, proactive measures must be implemented. This involves not only bolstering infrastructure resilience to withstand higher water levels but also instituting comprehensive flood risk management strategies. Emphasizing the importance of early warning systems, community preparedness, and sustainable land-use practices becomes paramount. Additionally, fostering international collaboration for data sharing, research, and the development of adaptive policies can play a crucial role in building a collective defense against the escalating threat of more substantial river floods. In this context, a holistic and proactive approach is essential to navigate the complex dynamics of climate-induced changes and their impact on the hydrological cycle, ensuring the safety and resilience of communities in the face of future flood events.

6.7. Conclusions

SCS approach is becoming increasingly popular as a strategy to augment the constrained hydrometeorological records currently available. However, its efficacy is heavily dependent on the availability of comprehensive observational data, which, in practice, often lacks the necessary temporal depth. This limitation can result in substantial underestimations or overestimations of flood quantiles, especially when focusing on accurately modeling extreme events. This uncertainty becomes even higher when climate change scenarios are incorporated into de study, adding the uncertainty of the GCMs realizations and the downscaling techniques into the equation. Biases are usually corrected with procedures such as delta method, direct statistical or quantile mapping, by comparing the projections in control period with the observations and translating the changes into de future projections. These practices certainly mitigate the uncertainty of future projections, and they could be sufficient for specific types of variables and studies. However, when it comes to the estimation of future flood quantiles, precipitation data from the projections (i.e., usually 30 years) is not long enough for their correct estimation, being necessary the use of WG adequately parametrized for extending this data series.

The methodology presented in Beneyto et al. (2020) demonstrated that integrating additional information into the WG implementation considerably reduced the uncertainty of high return period flood quantile estimates. Furthermore, this was quantified under different information scenarios in Beneyto et al. (2023a) and in Beneyto et al. (2023b). The presented methodology applied in the case study of Rambla de la Viuda draws from the premises of these studies to estimate extreme floods under climate change scenarios. In this case, the information obtained from the regionalization of the climate projections is integrated in the WG, obtaining satisfactory results.

The results obtained from the EUROCORDEX project projections for an RCP8.5 emissions scenario in the study area analyzed show a clear increase in maximum and minimum temperatures, with more frequent and severe hot waves, which will result in increasing evapotranspiration rates. Precipitation quantiles experience similar increases as temperatures, although the average annual precipitation is seen slightly reduced. This will probably translate into a reduction in the average annual flow of rivers, combined with increasingly frequent episodes of large floods, as numerous studies already remark. These results demonstrate the robustness of the presented methodology, being able to obtain satisfactory results at any point of the study area.

Accurate estimation of flood quantiles under climate change scenarios is of paramount importance for informed decision-making and effective water resource management. As climate patterns evolve, the frequency and intensity of extreme weather events, including floods, are anticipated to undergo significant changes. Adequate estimation of flood quantiles is crucial for assessing and mitigating the associated risks, particularly in the context of shifting precipitation patterns and altered hydrological regimes. Precise quantification enables the identification of vulnerable areas, informs the design of resilient infrastructure, and aids in the formulation of adaptive strategies. Moreover, reliable estimates are indispensable for developing robust floodplain management plans and optimizing resource allocation for flood prevention and response efforts. Inaccuracies in flood quantile estimation may lead to either underpreparedness or unnecessary investments, emphasizing the critical role of precise assessments in enhancing resilience to the challenges posed by climate change-induced variations in flood magnitudes and frequencies.

Declaration of Competing Interest

The authors have no conflict of interest to declare.

Acknowledgements

This work was supported by the Spanish Ministry of Science and Innovation through the research projects TETISCHANGE (RTI2018-093717-B-100) and TETISPREDICT (PID2022-141631OB-I00).

7. General discussion of the results

In this section, a synthesis of the outcomes from the five research papers is presented.

Traditional FFA have historically resulted in flood estimates presenting high uncertainty, especially those associated with low-frequency (Hosking y Wallis, 1993). The main reason behind this is that available discharge and precipitation records are still far from being sufficiently robust for an adequate estimation of extreme events with a high return period. Beyond the paradigm of the Design Storm approach, with its inherent limitations (i.e., initial conditions of the catchment and spatio-temporal distribution of the storm), CSS approach using a WG and a fully-distributed HM seems to be becoming one of the potential candidates to deal with this challenge and its use is rapidly increasing over recent years (Lamb et al., 2016). The possibility of extending the records beyond the available ones using a WG reduces the uncertainty of the calculated flood quantiles. Yet, the quality of the precipitation input data series (length, spatial density, reliability, and completeness) is critical to obtain reliable results and, therefore, extra tools and additional information must be integrated to complement their current short length and improve the performance of the WG. Results from the first manuscript: “New approach to estimate extreme flooding using continuous synthetic simulation supported by regional precipitation and non-systematic flood data”, showed, in terms of precipitation, how introducing the information from a regional study of annual maximum precipitation in the WG parameterization improved the accuracy in the reproduction of the estimated quantiles. This was more evident for those quantiles associated with high return periods, which were the ones most underestimated when the WG was fed only with the information from the available observations for its parameterization. Figure 8 below shows the plotting positions of the simulated precipitation when the WG was only implemented with the available observations (represented in blue in Figure 8), and when the shape parameter ξ of the marginal cdf was calibrated with the information of the regional study (represented in red in Figure 8).

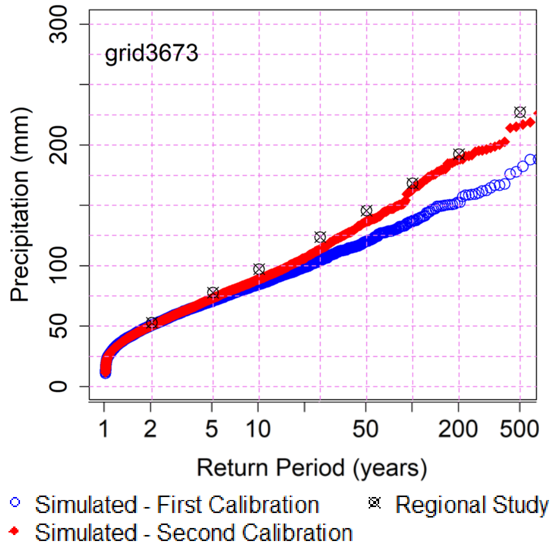


Figure 8 - Results of WG calibration in one representative grid points.

Thanks to the use of a fully-distributed HM, it was possible to validate the resulting discharges in different points. Specifically, at two locations where information beyond the systematic records was available: at Rambla de la Viuda river close to the Maria Cristina dam; and at Montlleó river (a tributary watercourse of the former). Figure 9 shows the plotting positions of the simulated discharges satisfactorily validated with the historical and palaeoflood information at both sites, represented by a triangle (common censoring threshold) and by an arrow in Figure 9 (where the data length includes the systematic and non-systematic periods).

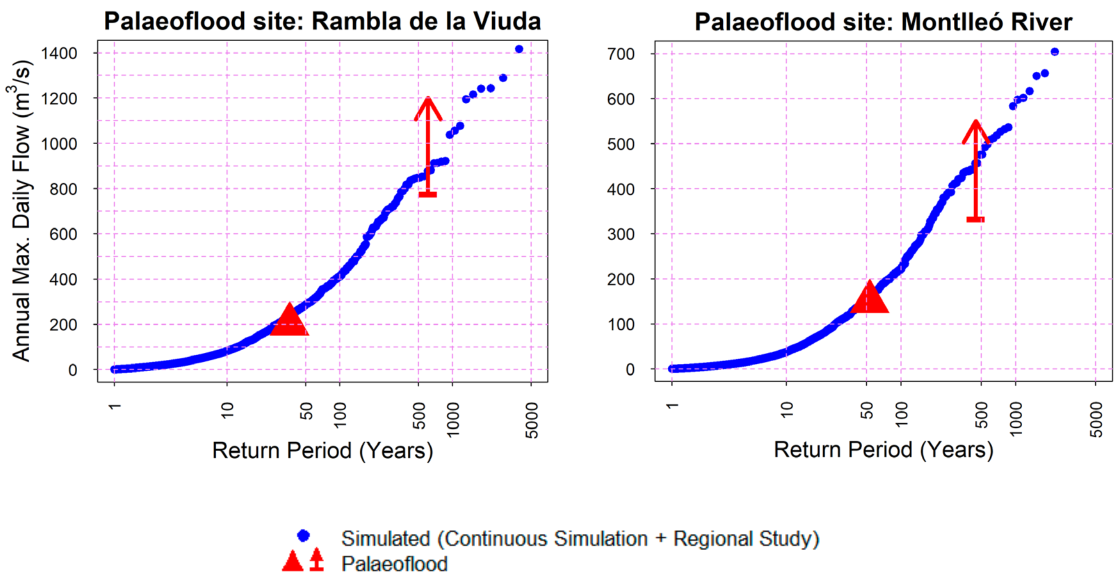


Figure 9 - Plotting positions of 10,000 simulated annual maximum daily flows and palaeoflood information used for validation at Rambla de la Viuda and Montlleó River.

These results clearly reduced the uncertainty of the quantile estimates. In this first manuscript, however, the analysis of the reduction of the uncertainty associated with the flood quantile estimates was not in the scope, but it served, however, as the motivation to undertake further analyses to quantify this uncertainty, both in terms of precipitation and flood quantiles. The second manuscript, "Exploring the uncertainty of Weather Generators' extreme estimates in different practical available information scenarios", demonstrated thought a Monte Carlo analysis how important is to incorporate additional information in the model calibration when the input data is limited. Furthermore, it was concluded that calibrating the WG with the regional X_T provided better results than using the population ξ, which represents a clear advantage since the latter is limited to those studies where the WG and the regional study of annual maximum daily precipitation share the same distribution function (Figure 10).

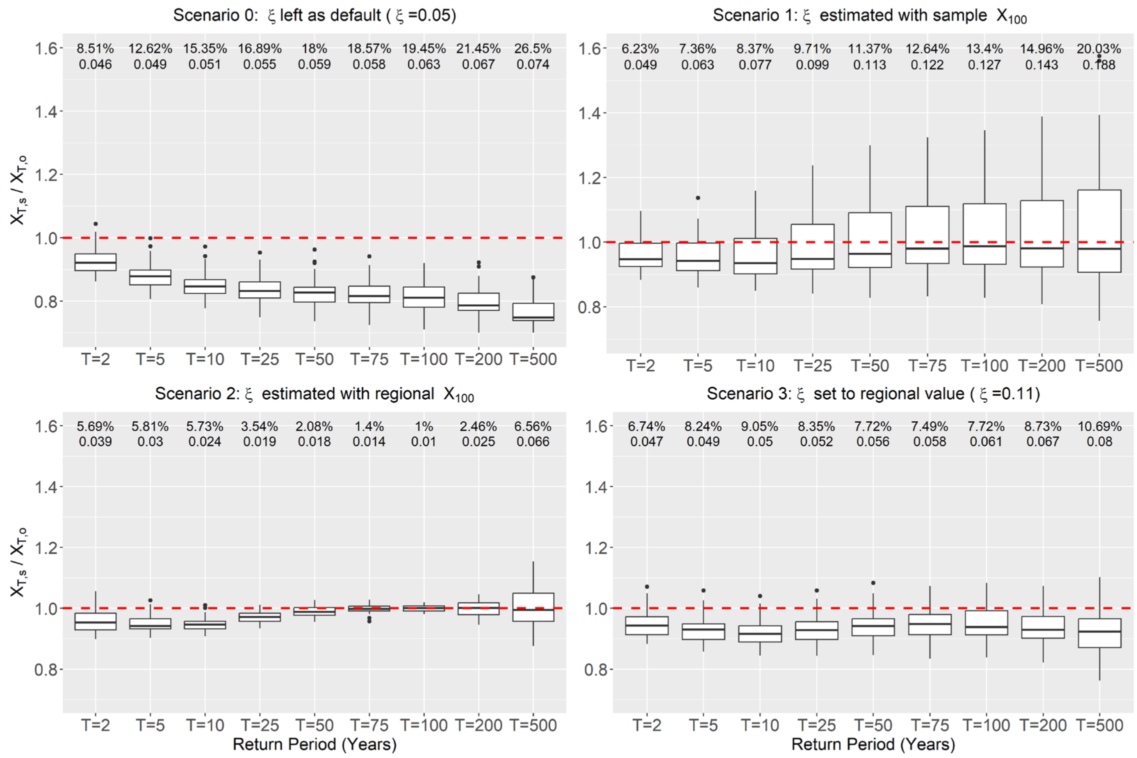


Figure 10 - Boxplots of the estimated quantiles (standardized with the population quantiles) for the four information scenarios. Both the RRMSE (expressed in %) and the CV are shown on top of each boxplot for each T

Moreover, climate extremality was proven to be a key factor in the uncertainty of the quantile estimations, which evidences the special need to integrate additional information in the WG calibration process in arid and semi-arid climates, where most of the annual rainfall is concentrated in short extreme episodes. Lastly, no significant reduction in the uncertainty of the estimations was found when analyzing different sample lengths compared to the reduction obtained when incorporating additional information, which means that integrating a regional study of annual maximum daily precipitation provide more information than having an input data series thirty or sixty years longer.

The third manuscript, "Sample uncertainty analysis of daily flood quantiles using a weather generator", is an extension of the second one, analyzing this time the uncertainty in terms of flood quantiles and under different precipitation regimes, climate extremality, and basin hydrological characteristics. The findings of this study highlight the significant influence of the precipitation regime on the estimated flood quantile uncertainty. While it appears that the basin size (Figure 11 - left) and the hydrological characteristics of the basin(Figure 11 - middle) do not substantially impact on flood quantiles' uncertainty, it has been found that uncertainty clearly increases with the aridity of the climate (Figure 11 - right).

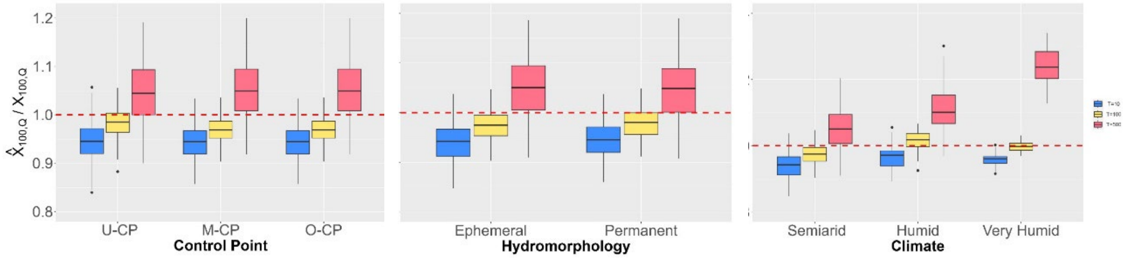
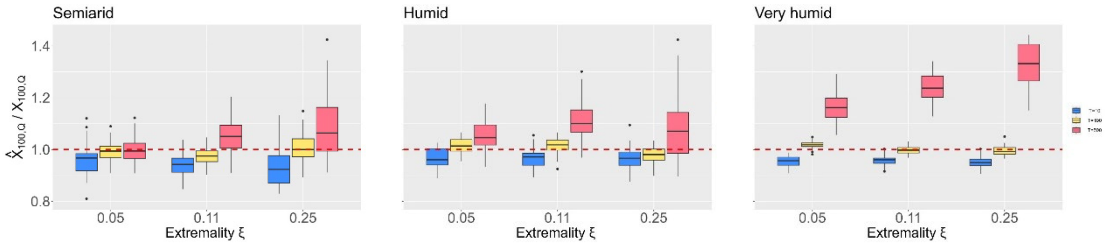


Figure 11 - Boxplots of flood quantile estimates for return periods of 10, 100, and 500 years, considering: a semi-arid climate, medium extremality (ξ=0.11), and an ephemeral regime in the three CPs (left); in two different hydrological basin characteristics (middle); and in the three analyzed climates (right)

Finally, flood quantiles presented higher uncertainty than their precipitation quantile counterparts (Figure 12), indicating that the HM does not act as a balance component in the SCS approach as it was expected. General findings of this research reveal that low-frequency flood quantile estimates by SCS are still far from presenting adequate levels of uncertainty for flood studies if additional information is not integrated in the WG implementation. Integrating a regional $X_{T,P}$ (with a relatively high reliability) in the WG model calibration clearly reduces the uncertainty of flood quantile estimates independently the climate, the extremality, the drainage area and, the hydrological characteristics of the basin (i.e., in a broad range of hydro-climatic conditions). This uncertainty reduction is greater for flood quantiles with return periods near the regional precipitation quantile used $X_{T,P}$.



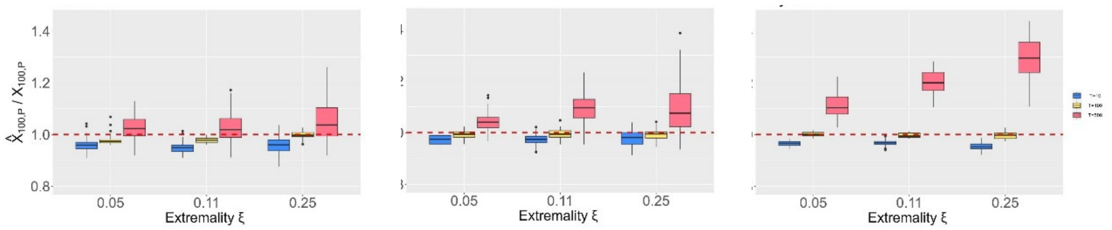


Figure 12 - Boxplots of flood quantile estimates (upper plots) and precipitation quantile estimates (lower plots) for an ephemeral river for return periods of 10, 100, and 500 years in the three analyzed climates and climate extremality.

Before incorporating the effects of the climate change in the methodology, the current methodology, improved with all the knowledge acquired and presented in the second and third manuscript, was implemented in a case study, Segura River Basin. The research paper: "Expanding Information for Flood Frequency Analysis Using a Weather Generator: Application in a Spanish Mediterranean Catchment" is the outcome of this study. In this case, the temporal resolution was required to be sub-daily, thus, a disaggregation procedure was integrated to reduce the temporal scale of the daily precipitation time series generated by the WG. Given the extension of the study catchment (ca. 15,000 km^2), the regional quantiles (from an *ad hoc* regional study) were grouped in different ranges to validate the WG implementation in the two homogeneous regions obtained (Figure 13). The calculated quantile ranges were very similar for both regions for low and medium quantiles, only appreciating a significant difference for high quantiles, being Region 2 (coast) where the values were higher (i.e., more extreme).

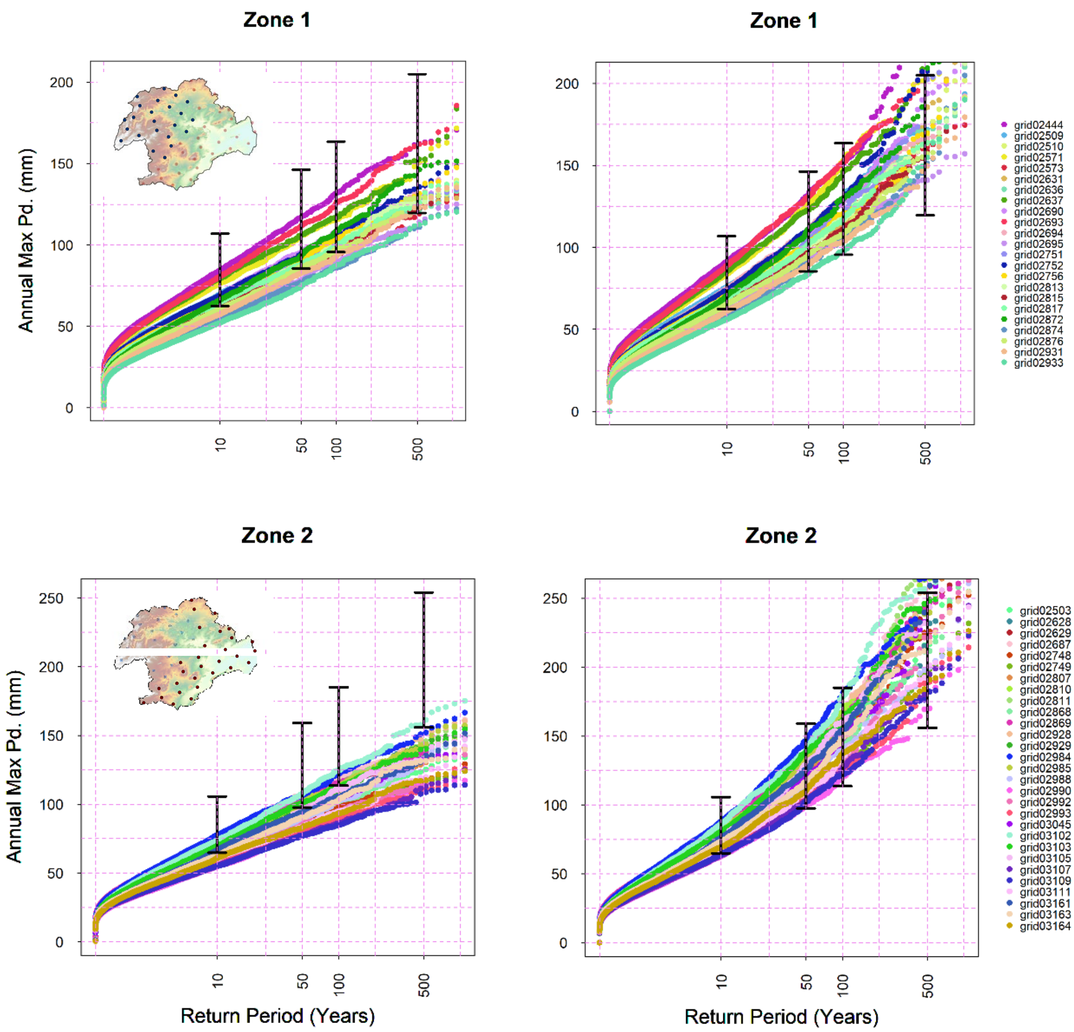


Figure 13 - WG Calibration: Plotting Positions of simulated precipitation data series before calibrating the shape parameter ξ (left) and after (right) for both regions.

Figure 13 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.

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 Extended Generalized Pareto Distribution.

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: Valdeinfierno and Puentes reservoir inlets on the Guadalentin river and at the gauging station located in Orihuela on the 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. In Figure 14 it can be seen that the plotting positions of the generated discharges are coherent with the assignment of probability to the reconstructed historical floods.

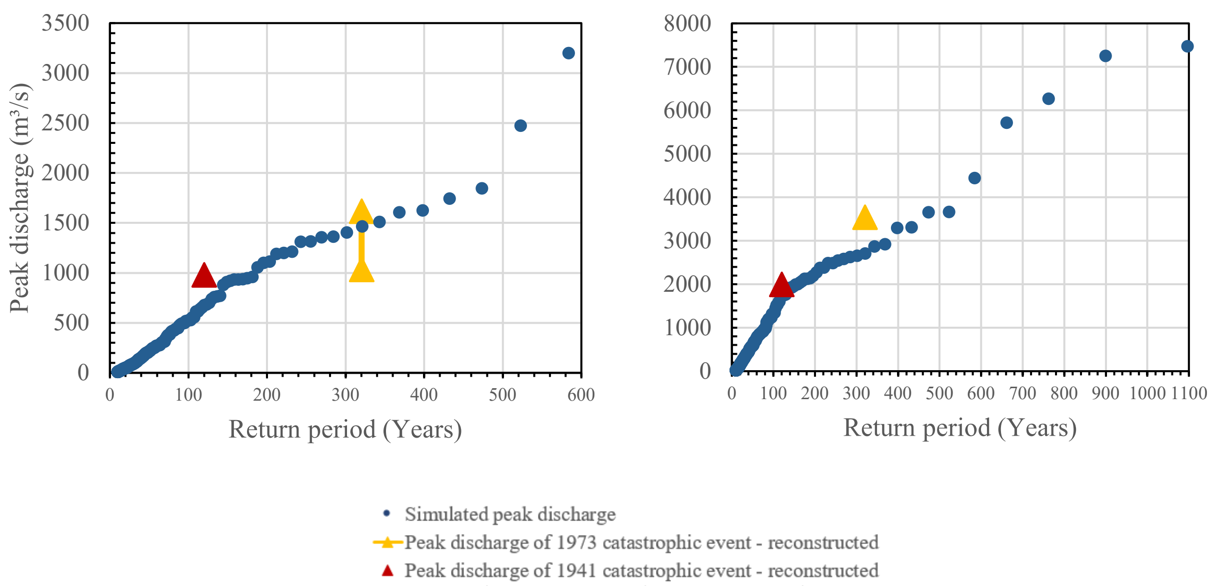


Figure 14 - Comparison between simulated quantiles in the natural regime and probability assignment to non-systematic events (left: Valdeinfierno reservoir; right: Puentes reservoir).

In the case of the Segura River in Orihuela, it was necessary to compare both with the natural regime, and with the current regime. Figure 15 shows the plotting positions of the systematic data reconstructed at the Orihuela gauging station, completed with the data from Murcia (1912 to 1993) and the perception threshold of historical floods in Murcia. This latest calculated with the four registered extraordinary events presenting a flow greater than 800 m^3/s in Murcia for the historical period 1825-1911, which is equivalent to a return period of 21.8 years.

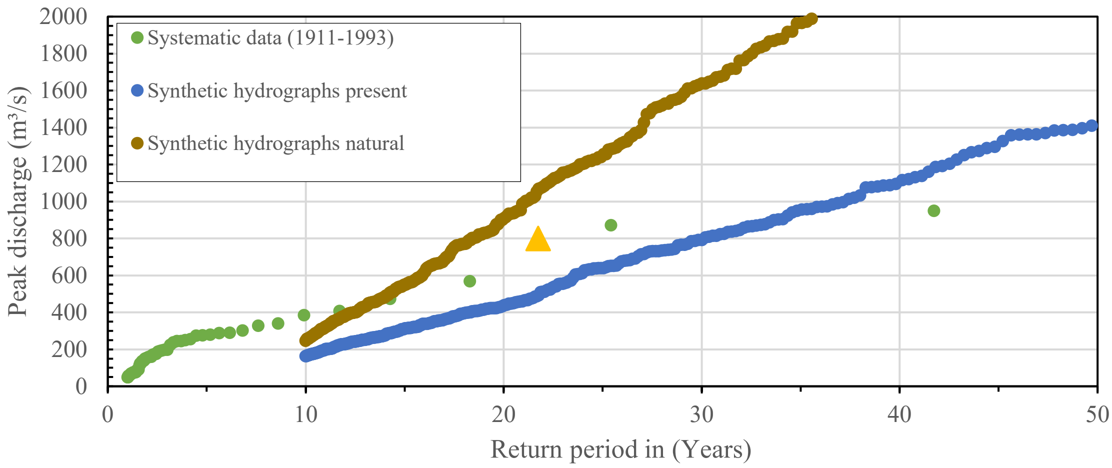


Figure 15 - Plotting positions of the simulated discharges in Orihuela (natural and present conditions), systematic data and the perception threshold of historical floods in Murcia.

Integrating both systematic and non-systematic (historical and palaeoflood records) information, allow 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.

Lastly, the fifth research paper: "On the Use of Weather Generators for the Estimation of Low-Frequency Floods Under a Changing Climate", presents a methodology to estimate future precipitation and flood quantiles under the global change scenarios. The proposed methodology was applied in la Rambla de la Viuda study area, obtaining systematic increases in terms of precipitation quantiles (Table 3). These increases in the precipitation quantiles range between 4.3% for a return period of 5 years in the mid-term projection to 19.7% for a return period of 100 years in the long-term projection.

Table 3 - Estimated future precipitation quantiles (mean of all models and all grids)

T (years)	Observations	Mid-term projection		Long-term projection	
	X_T	Δ%	X_T	Δ%	X_T
5	80	4.3%	83	12.8%	90
10	99	6.0%	105	16.7%	116
25	125	8.4%	136	18.6%	148
50	145	11.5%	162	19.3%	173
75	158	13.5%	179	19.7%	189
100	167	14.4%	191	19.4%	199

As expected with the results obtained for the precipitation, the plotting positions of the generated discharges are clearly higher to those of the observed for both the mid-term and the long-term projection (Figure 16).

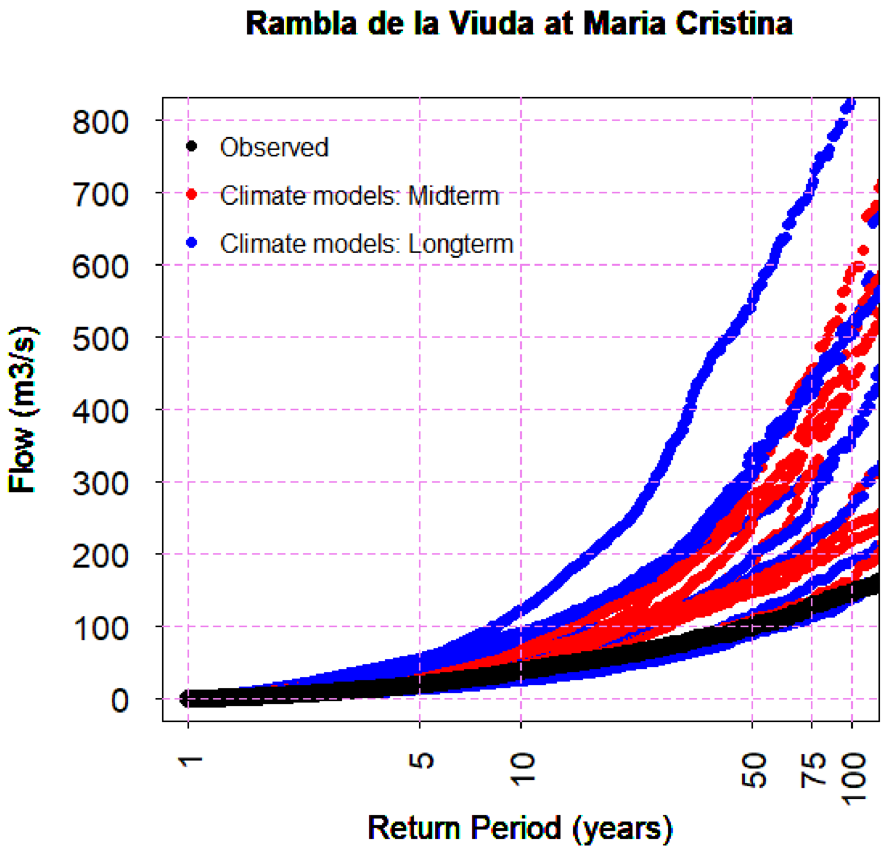


Figure 16 - Plotting positions of the observed daily discharges and the simulated discharges from the climate models (both for the mid-term and for the long-term projection) at Maria Cristina reservoir.

Notwithstanding, it is clear the uncertainty surrounding these estimates depending on the model, presenting flood quantiles that range from 180 m3/s to 810 m3/s for a return period of 100 years, for example. Nevertheless, the increase is clear in all cases, Table 4 shows the estimated percentage increase in the flood quantiles (calculated as the difference between the obtained in the control period and the obtained in the projection of each model) and the expected future flood quantile (obtained by applying this percentage to the observed quantiles) at Maria Cristina reservoir.

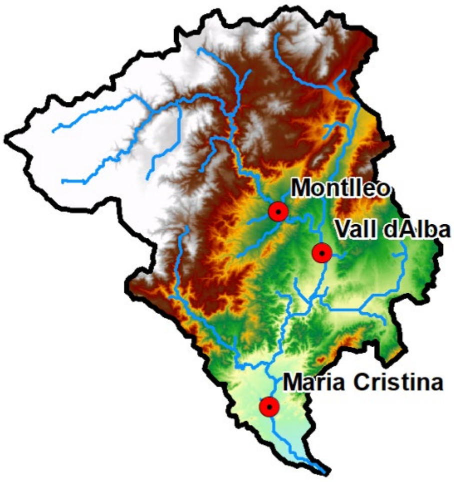
Table 4 - Estimated future flood quantiles at Maria Cristina (catchment area: 1447 m^2)

T (years)	Observed (m^3/s)	Climate projections (m^3/s)			
		Δ%	Mid-term	Δ%	Long-term
5	20	12%	22	8%	21
10	38	12%	43	16%	44
25	68	22%	83	33%	91
50	101	38%	140	54%	155
75	130	48%	192	56%	202
100	147	53%	225	58%	232

The increase is systematic for all quantiles and for both projections, ranging from 8-12% for low return periods to 53-58% for high return periods, where increases in flood quantiles are more pronounced. Finally, and exploiting the benefits of using a fully-distributed HM, the same analysis was conducted for additional two flow gauges located at Vall d'Alba (906 km^2) and Montlleó (501 km^2) (Table 5). Results in both flow gauges presented increases for all flood quantiles, however, it can be observed that, compared to Maria Cristina, these increases are higher in Vall d'Alba (ranging from 10% to 80%) and specially in Montlleó (ranging from 5% to 145%). This is, future flood quantiles will experiment higher increases as the catchment is smaller.

Table 5 - Estimated future flood quantiles at Vall d'Alba and Montlleó (catchment areas: 906 km² and 501 km² respectively)

Vall d'Alba					
T (years)	**Observed (m³/s)**	**Climate projections (m³/s)**			
		Δ%	**Mid-term**	Δ%	**Long-term**
5	12	11%	14	10%	13
10	22	13%	24	33%	29
25	39	21%	47	64%	64
50	56	41%	79	88%	105
75	69	49%	103	86%	130
100	80	50%	121	80%	145
Montlleó					
T (years)	**Observed (m³/s)**	**Climate projections (m³/s)**			
		Δ%	**Mid-term**	Δ%	**Long-term**
5	4	3%	4	5%	4
10	6	7%	6	42%	8
25	11	27%	14	111%	23
50	17	57%	27	137%	40
75	21	73%	37	145%	52
100	28	77%	49	130%	64

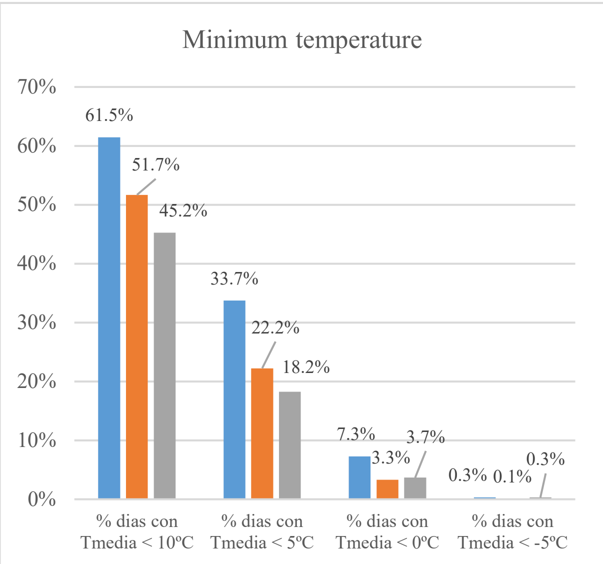


Furthermore, although the analysis of the temperatures was not within the main objectives of this study, it is evident that the potential change in the temperature trends resulting from the effects of the climate change will lead to alterations to the discharge regimes. This is, temperature has a clear impact on the initial conditions of the basin: apart from the higher evapotranspiration, higher temperatures would result in higher volumes of infiltration at the initial moments of the storm, thus, supposedly resulting in lower initial flows. A clear increasing trend for both maximum and minimum temperatures for all projections was observed. This increase ranges from 1.9ºC for the mid-term projection to 3.4C for the long-term projection in the case of minimum temperature and from 2.0C to 3.6C respectively in the case of the maximum temperature. If we look at the monthly variations (Table 6), it can be observed that, for both variables, the greater increases occur over the summer months whereas the lower increases take place during the winter months, being this more evident in the case of the long-term projection.

Table 6 - Average monthly increase in maximum and minimum temperatures for mid-term and long-term projections.

ΔT (ºC)	Minimum temperature		Maximum temperature	
	Mid-term	Long-term	Mid-term	Long-term
January	2.43	2.55	2.25	2.25
February	1.90	1.93	2.17	1.98
March	2.41	2.61	2.27	2.56
April	2.39	2.98	2.76	3.55
May	1.34	2.61	1.51	3.08
June	3.02	5.32	3.34	6.04
July	2.04	5.04	1.80	5.11
August	1.06	4.26	1.35	4.73
September	0.41	3.19	0.34	3.18
October	1.47	3.68	1.43	3.67
November	2.71	4.28	2.73	4.18
December	1.67	2.59	1.56	2.40

Additionally, an analysis of the percentage of the days with temperatures under- or over certain thresholds was conducted. In the case of the minimum temperature, the percentage of days with mean minimum temperature lower than 10C, 5C, 0C, and -5C was analyzed, observing a clear decrease in the number of days compared to the observations and more pronounced in the case of the long-term projection. Similarly, in the case of the maximum temperature, the percentage of days with mean maximum temperature higher than 25C, 30C, 35C, and 40C was examined, spotting and important increase in the number of days and, again, being this increase more remarked in the case of the long-term projection (Figure 17).



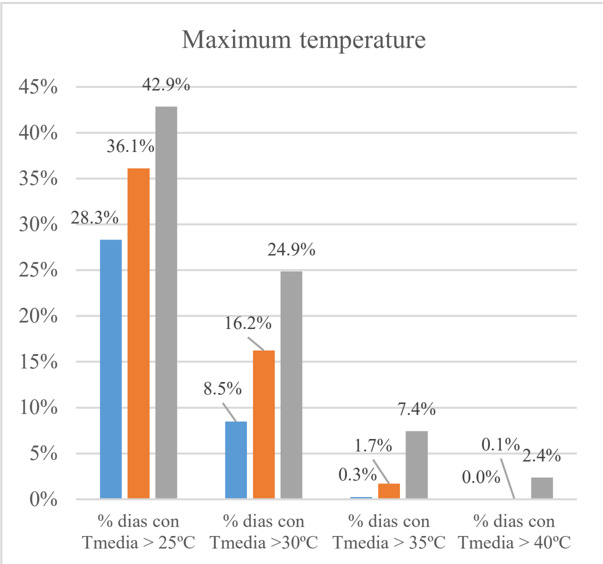


Figure 17 - Variation in the number of days with extreme mean daily temperatures.

Finally, non-stationarity in hydrological time series presents a significant challenge, characterized by temporal variations in the statistical properties of hydrological variables over time. This phenomenon, often attributed to climate change, land use changes, and other anthropogenic influences, undermines the assumption of stationarity commonly employed in traditional hydrological analyses. Non-stationarity manifests in various forms, including shifts in mean values, alterations in variability, and changes in the frequency and intensity of extreme events. These fluctuations pose considerable implications for water resource management, flood risk assessment, and infrastructure design, as historical data may no longer accurately represent future hydrological conditions. Addressing non-stationarity requires innovative approaches that account for temporal variability and incorporate adaptive strategies to mitigate its impacts effectively. Many authors have addressed this aspect (e. g., Pedretti and Irannezhad, 2019; She et al., 2015; Westra and Sisson, 2011), concluding that rare events are changing its frequency of occurrence per year with temperature, along with the extremes changing more clearly with temperature. Different approaches are rapidly emerging focusing on this (De Luca and Galasso, 2018; Rashid et al., 2016; Wasko et al., 2021; O'Shea et al., 2023). Although this has not been contemplated in the present study for extension reasons, further research must be done in this direction. Embracing non-stationarity as a fundamental aspect of hydrological systems appears to be converting in essential for fostering resilience and sustainability in water management practices amidst evolving environmental conditions.

8. Conclusions

The objective of this research thesis is to formulate a novel methodology that integrates diverse information sources derived from hydrometeorological models, operating at an appropriate spatiotemporal scale. This approach aims to effectively characterize key variables relevant to the FFA within the context of climate change scenarios. The ultimate aim is to minimize uncertainty in the estimation of low-frequency quantiles.

This thesis comprises a compendium of research papers, encompassing five scientific papers already published.

The final proposed methodology has been shaped step by step through: the development of a methodology to estimate extreme flooding in current climate at daily scale; the uncertainty analysis of both precipitation and flood quantile estimates generated with a WG under different practical scenarios of available information, different precipitation regimes, climate extremality, and basin hydrological characteristics; the development of a methodology to estimate extreme flooding in current climate at sub-daily scale; and finally through the development of a methodology to estimate extreme flooding at daily scale under the effects of climate change. All these methodologies and studies have been tested in different case studies (i.e., Rambla de la Viuda, Segura River Basin, and synthetic study areas), and gathered in the five research manuscripts.

In this chapter, the conclusions drawn from the various manuscripts comprising this thesis are outlined. This chapter is subdivided into four distinct sections. In the first point, the conclusions about the robustness and validity of the proposed methodology are presented. The second point details the main conclusions of the methodology application in the case study. The third point summarizes the main conclusions reached in this study, and the last point presents some potential future research lines.

8.1. A holistic methodological approach to estimate extreme flood frequency under a changing climate.

The methodology presented is an improvement of the CSS model. Apart from the benefits of this approach already discussed (i.e., initial conditions of the catchment and spatio-temporal distribution of the storm), we propose the integration of additional information to deal with the estimation bias on the flood quantile resulting from the short length of the existing hydrometeorological data series. Results from the application of this methodology for current climate in the Rambla de la Viuda study area, which can be found in the first manuscript (Chapter 2), show a clear reduction of the uncertainty of the flood quantile estimates, which remarks the importance of incorporating additional information in the model calibration when the input data is limited has been demonstrated.

This uncertainty reduction was quantified in the Monte Carlo analysis undertook for a synthetic population under different information scenarios (Chapter 3 and Chapter 4) in which, moreover, it was found that calibrating the WG with the regional X_T provided better results than using the population ξ, which represents a clear advantage since the latter is limited to those studies where the WG and the regional study of annual maximum daily precipitation share the same distribution function. Additionally, it was concluded that the basin size, the climate extremality, and the hydrological characteristics of the basin do not substantially impact on flood quantiles' uncertainty. However, uncertainty clearly increased with the aridity of the climate and flood quantiles presented higher uncertainty than their precipitation quantile counterparts, indicating that the HM does not act as a balance component in the CSS approach as it was expected.

In the fourth manuscript (Chapter 5), an additional component was integrated into the methodology, reducing the temporal scale of the model outputs to sub-daily scale (i.e., 60 min). This upgraded methodology, which was applied in the Segura River basin case study, incorporated a temporal disaggregation procedure to disaggregate a set of representative storms from the generated daily precipitation data series with the WG from daily to hourly temporal resolution. The satisfactory results obtained reinforced the previous conclusions, confirming that there is no need for long input data series: combining different sources of available flood data (systematic and non-systematic) allows for the validation of the results of the FFA. Additionally, it was proven that there is no need for high computational requirements: giving the hybrid nature of the proposed solution, it is possible to handle the temporal resolution of models (daily and sub-daily).

In the last research paper (Chapter 6), a new methodology for the estimation of extreme floods in climate change scenarios using WGs is presented. Following in the footsteps of the previous methodologies and with the knowledge acquired from them, an *ad hoc* regional study of annual maximum daily precipitation is performed. In this case, the results of this study are incorporated in the WG parametrization in both the control period and in the future projections, thus, obtaining the climate change signal that is applied to the observations.

As in the first research paper, this approach was implemented in the Rambla de la Viuda case study, obtaining more reliable quantile estimates and highlighting the need to not only rely just in the outputs from the GCMs for an adequate characterization of future extreme flood quantiles.

8.2. Future flood quantile projections

The findings derived from the EUROCORDEX project projections under the RCP8.5 emissions scenario within the studied region point to a discernible and concerning trajectory in the climate dynamics. Both maximum and minimum temperatures showcase a clear upward trend, accompanied by a rise in the frequency and severity of heatwaves. These shifts in temperature patterns carry far-reaching consequences for the environment and communities.

In tandem, precipitation quantiles exhibit a corresponding increase, mirroring the temperature trends. However, the parallel reduction in average annual precipitation in the case studies (i.e., Mediterranean regions), raises concerns about water resource availability. The potential implications extend beyond a simple reduction in average annual river flow; they encompass a complex interplay of factors that can impact ecosystems, agriculture, and human settlements.

The anticipated surge in large flood events adds another layer of concern, as it aligns with an emerging trend observed in various studies. The increased frequency of intense rainfall events, combined with a potential decrease in the river's capacity to manage these inputs due to reduced average annual flow, could lead to more frequent and severe flooding incidents. Such events pose a substantial risk to infrastructure, agricultural productivity, and, more critically, the safety and well-being of communities residing in flood-prone areas.

On the other hand, higher temperatures will imply higher rates of evapotranspiration. This will translate in drier catchment conditions and more infiltration capacity at the beginning of storms, which could partially compensate the increase in the precipitation extremality. This will be deeply studied in future research, but the hints obtained in this direction, again, remarks the need for continuous simulation approaches as the presented in this thesis.

8.3. Final remarks

Extreme flood studies (i.e., dealing with very high return periods) are frequently required, for example, for the design of key infrastructures or for the elaboration of flood risk maps. These demand a tremendous amount of hydrometeorological information for an accurate estimation of flood quantiles. Unfortunately, this amount of information is not available within the current hydrometeorological observations, meaning that additional information or procedures must be integrated for a proper characterization of high return period flood quantiles. The proposed methodology in this thesis presents an extension of the CSS approach. It combines the use of a WG for expanding the current precipitation records with the integration of a regional study of annual maximum precipitation in the WG implementation to improve the upper-tail fit of the marginal cdf, thus, better reproducing extremes + palaeofloods. This methodology, valid for both current climate and future climate under the effects of climate change, has been implemented in two real case studies: Rambla de la Viuda (current and future climate at daily temporal resolution) and Segura River

Basin (current climate at sub-daily resolution), obtaining satisfactory results, which demonstrates the validity of the approach.

Finally, this methodology, thanks to the use of fully-distributed HM, can be implemented in any region regardless of its size or its climate; however, the more remarked climate variability, the greater the need to add extra sources of information due to their erratic hydrology. Furthermore, this approach 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.

8.4. Future research

Further to the results obtained in this research thesis, future research lines have been constantly coming up, which will be continued by this author in the years to come. The following lines correspond to compelling aspects that would enhance a thorough investigation into the topic of this study.

- Firstly, a WG benchmarking project is being set up by our research group and led by this author. This project, which will require the participation of many WG developers across the world, aims to compare how much uncertainty present the quantile estimates of different WG with different conceptualizations and complexities, and under different types of climates and precipitation regimes.
- In the same line, with the constant computational advances, WG are rapidly evolving and new software are appearing, addressing past issues, incorporating new conceptualizations, and reducing the temporal resolution of the generated data series. A constant literature review of all these must be maintained, and why not, develop an own source new one.
- Climate projections are continuously evolving as a result of the advances in scientific knowledge and, again, with the expansion of computer memory and processing capacities. These, together with the previous point, opens up new possibilities. Specifically, and

considering the precipitation regime of the Mediterranean area, it would be interesting to upgrade the proposed methodology, being this able of returning flood discharges at sub-daily scale.

- Rather than just focusing on the right tail of the distribution function, the analysis of the future lower return period quantiles for water resources management could be an interesting research line.
- Another potential line of investigation is to apply the methodology backwards, aiming to better integrate the palaeoflood and historical information.
- Other Bias Correction methods such as Nested Bias Correction (NBC, or its multivariate counterpart, MBC) and how these affect in the flood quantiles estimations should be another focus of attention in further research.
- Evidences of non-stationary time series are commencing to emerge. Evolve the proposed methodology towards a non-stationary framework for evaluating the impacts of climate change and human activities on hydrological extremes seems to a be mandatory path.
- Precipitation data, as the primary source of information for undertaking flood studies, are where lie most of the uncertainty of the flood quantile estimation. Many different sources of information (e.g., ERA5, ERA5-land, Spain02, Iberia, GSMaP, CHIRPS, etc.) have appeared over the last years, which will be interesting to analyze and compare, also assessing their influence in terms of the resulting discharges.
- In methodological terms, although the approach presented in this research thesis has demonstrated to be valid and satisfactory results can be obtained, it is true that it requires certain specific expertise in handling a wide range of different existing WGs and HMs, which is the main reason why authorities and practitioners opt for using traditional methodologies for FFA, mainly based on the Design Storm, and are reluctant to incorporate these new approaches. Additionally, these methodologies are not easy to understand for end users, which usually

do not possess the technical understanding or skills. Further research in this sense should be aimed to try to reduce the complexity in the implementation of this types of methodologies, making them more intuitive and user-friendly, also conveying to the pertinent authorities the clear message about the importance of incorporating these types of approaches for flood studies.

9. ANNEXES

A.1 References

- Acharya, S.C., Nathan, R., Wang, Q.J., Su, C.H., 2022. Temporal disaggregation of daily rainfall measurements using regional reanalysis for hydrological applications. Journal of Hydrology 610, 127867. https://doi.org/10.1016/J.JHYDROL.2022.127867
- Ahn, K.H., 2020. Coupled annual and daily multivariate and multisite stochastic weather generator to preserve low- and high-frequency variability to assess climate vulnerability. Journal of Hydrology 581, 124443.
- Ailliot, P., Boutigny, M., Koutroulis, E., Malisovas, A., Monbet, V., 2020. Stochastic weather generator for the design and reliability evaluation of desalination systems with Renewable Energy Sources. Renewable Energy 158, 541-553.
- Akaike, H., 1977. On Entropy Maximization Principle. Krishnaiah, P.R., Ed., Applications of Statistics.
- Alfieri, L., Bisselink, B., Dottori, F., Naumann, G., de Roo, A., Salamon, P., Wyser, K., Feyen, L., 2017. Global projections of river flood risk in a warmer world. Earth's Future 5, 171-182.
- Ali, M., Khan, S.J., Aslam, I., Khan, Z., 2011. Simulation of the impacts of land-use change on surface runoff of Lai Nullah Basin in Islamabad, Pakistan. Landscape and Urban Planning 102, 271-279. https://doi.org/10.1016/J.LANDURBPLAN.2011.05.006
- Allahbakhshian-Farsani, P., Vafakhah, M., Khosravi-Farsani, H., Hertig, E., 2020. Regional Flood Frequency Analysis Through Some Machine Learning Models in Semi-arid Regions. Water Resources Management 34, 2887-2909. https://doi.org/10.1007/s11269-020-02589-2
- Bafitlhile, T.M., Li, Z., 2019. Applicability of ε-Support Vector Machine and artificial neural network for flood forecasting in humid, semi-humid and semi-arid basins in China. Water (Switzerland) 11. https://doi.org/10.3390/w11010085

- Baker, V.R., 1987. Paleoflood hydrology and extraordinary flood events. Journal of Hydrology 96, 79-99. https://doi.org/10.1016/0022-1694(87)90145-4
- Balbás, J.A., 1892. El libro de la provincia de castellon.
- Ballesteros-Cánovas, J.A., Sanchez-Silva, M., Bodoque, J.M., Díez-Herrero, A., 2013. An Integrated Approach to Flood Risk Management: A Case Study of Navaluenga (Central Spain). Water Resources Management 27, 3051-3069. https://doi.org/10.1007/s11269-013-0332-1
- Bárdossy, A., Das, T., 2008. Influence of rainfall observation network on model calibration and application. Hydrology and Earth System Sciences 12, 77-89. https://doi.org/10.5194/hess-12-77-2008
- Beltrán Manrique, E., 1958. Almazora el Mijares. Narración Histórica. Hijos de F. Armengot.
- Beneyto, C., Ángel, J., Francés, F., 2023. Exploring the uncertainty of Weather Generators' extreme estimates in different practical available information scenarios. Hydrological Sciences Journal 000, 1-10. https://doi.org/10.1080/02626667.2023.2208754
- Beneyto, C., Aranda, J.Á., Benito, G., Francés, F., 2020. New approach to estimate extreme flooding using continuous synthetic simulation supported by regional precipitation and non-systematic flood data. Water (Switzerland) 12, 1-16. https://doi.org/10.3390/w12113174
- Beneyto, C., Vignes, G., Aranda, J.Á., Francés, F., 2023d. Sample Uncertainty Analysis of Daily Flood Quantiles Using a. Water (Switzerland) 15.
- Benito, G., Rico, M., Sánchez-Moya, Y., Sopeña, A., Thorndycraft, V.R., Barriendos, M., 2010. The impact of late Holocene climatic variability and land use change on the flood hydrology of the Guadalentín River, southeast Spain. Global and Planetary Change 70, 53-63. https://doi.org/10.1016/j.gloplacha.2009.11.007
- Benito, G., Sanchez-Moya, Y., Medialdea, A., Barriendos, M., Calle, M., Rico, M., Sopeña, A., Machado, M.J., 2020. Extreme Floods in Small Mediterranean

Catchments: Long-Term Response to Climate Variability and Change. Water 12, 1008.

- Benito, G., Thorndycraft, V.R., 2005. Palaeoflood hydrology and its role in applied hydrological sciences. Journal of Hydrology 313, 3-15. https://doi.org/https://doi.org/10.1016/j.jhydrol.2005.02.002
- BOE, 2021. Boletón Oficial del Estado. Boletín Oficial del Estado.
- Botero, B.A., Francés, F., 2010. Estimation of high return period flood quantiles using additional non-systematic information with upper bounded statistical models. Hydrology and Earth System Sciences 14, 2617-2628. https://doi.org/10.5194/hess-14-2617-2010
- Boughton, W., Droop, O., 2003. Continuous simulation for design flood estimation—a review. Environmental Modelling & Software 18, 309-318. https://doi.org/https://doi.org/10.1016/S1364-8152(03)00004-5
- Breinl, K., Di Baldassarre, G., 2019. Space-time disaggregation of precipitation and temperature across different climates and spatial scales. Journal of Hydrology: Regional Studies 21, 126-146. https://doi.org/10.1016/j.ejrh.2018.12.002
- Breinl, K., Di Baldassarre, G., Girons Lopez, M., Hagenlocher, M., Vico, G., Rutgersson, A., 2017. Can weather generation capture precipitation patterns across different climates, spatial scales and under data scarcity? Scientific Reports 7, 1-12.
- Brocca, L., Liersch, S., Melone, F., Moramarco, T., Volk, M., 2013. Application of a model-based rainfall-runoff database as efficient tool for flood risk management. Hydrology and Earth System Sciences 17, 3159-3169. https://doi.org/10.5194/hess-17-3159-2013
- Bussi, G., Francés, F., Horel, E., López-Tarazón, J. A., & Batalla, R. J. 2014. Modelling the impact of climate change on sediment yield in a highly erodible Mediterranean catchment. Journal of Soils and Sediments, 14, 1921-1937.
- Butts, M.B., Payne, J.T., Kristensen, M., Madsen, H., 2004. An evaluation of the impact of model structure on hydrological modelling uncertainty for

streamflow simulation. Journal of Hydrology 298, 242-266. https://doi.org/10.1016/j.jhydrol.2004.03.042

- Camarasa Belmonte, A.M., Segura Beltrán, F., 2001. Flood events in Mediterranean ephemeral streams (ramblas) in Valencia region, Spain. Catena 45, 229-249. https://doi.org/10.1016/S0341-8162(01)00146-1
- Cameron, D.S., Beven, K.J., Tawn, J., Blazkova, S., Naden, P., 1999. Flood frequency estimation by continuous simulation for a gauged upland catchment (with uncertainty). Journal of Hydrology 219, 169-187. https://doi.org/10.1016/S0022-1694(99)00057-8
- Cardoso Pereira, S., Marta-Almeida, M., Carvalho, A.C., Rocha, A., 2020. Extreme precipitation events under climate change in the Iberian Peninsula. International Journal of Climatology 40, 1255-1278. https://doi.org/10.1002/joc.6269
- Caron, A., Leconte, R., Brissette, F., 2009. An Improved Stochastic Weather Generator for Hydrological Impact Studies. Canadian Water Resources Journal 33, 233-256.
- Cavanaugh, N.R., Gershunov, A., Panorska, A.K., Kozubowski, T.J., 2015. On the Probability Distribution of Daily Precipitation Extremes. Geophysical Research Letters 42, 1560-1567. https://doi.org/10.1002/2015GL063238.Received
- CEDEX, 1994. Mapa de Caudales Máximos. Memoria Técnica. Madrid (España).
- CEDEX, 2023. Guía metodológica para la elaboración de estudios hidrológicos de avenidas para presas.
- Chen, J., Brissette, F.P., Leconte, R., 2010. A daily stochastic weather generator for preserving low-frequency of climate variability. Journal of Hydrology 388, 480-490.
- Chen, J., Brissette, F.P., Leconte, R., 2011. Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. Journal of Hydrology 401, 190-202.

- Chen, X., 2019. Understanding future safety of dams in a changing climate. Bulletin of the American Meteorological Society 100, 1395-1404.
- Chow, V. Te, Maidment, D.R., Mays, L.W., 1998. Applied Hydrology. McGraw-Hill, New York.
- CHS, 2015. Plan Hidrológico de la Cuenca del Segura. 2015-2021. Confederación Hidrográfica del Segura, Ministerio de Medioambiente, Madrid 226 pp.
- Chun, K.P., Wheater, H.S., Onof, C., 2013. Comparaison des projections de sécheresse utilisant deux générateurs de données météorologiques du Royaume-Uni. Hydrological Sciences Journal 58, 295-309. https://doi.org/10.1080/02626667.2012.754544
- Cohn, T.A., England, J.F., Berenbrock, C.E., Mason, R.R., Stedinger, J.R., Lamontagne, J.R., 2013. A generalized Grubbs-Beck test statistic for detecting multiple potentially influential low outliers in flood series. Water Resources Research 49, 5047-5058. https://doi.org/10.1002/wrcr.20392
- Cowpertwait, P., Ocio, D., Collazos, G., De Cos, O., Stocker, C., 2013. Regionalised spatiotemporal rainfall and temperature models for flood studies in the Basque Country, Spain. Hydrology and Earth System Sciences 17, 479-494. https://doi.org/10.5194/hess-17-479-2013
- Cowpertwait, P.S.P., 1998. A Poisson-cluster model of rainfall: High-order moments and extreme values. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 454, 885-898.
- Cunnane, C., 1978. Unbiased plotting positions—a review. Journal of Hydrology 37, 205-222.
- Dai, A., Zhao, T., Chen, J., 2018. Climate Change and Drought: a Precipitation and Evaporation Perspective. Current Climate Change Reports 4, 301-312. https://doi.org/10.1007/s40641-018-0101-6
- Dai, C., Qin, X.S., 2019. Assessment of the effectiveness of a multi-site stochastic weather generator on hydrological modelling in the Red Deer River

watershed, Canada. Hydrological Sciences Journal 64, 1616-1628. https://doi.org/10.1080/02626667.2019.1661416

- Dalrymple, T., 1960. Flood-Frequency Analyses. Manual of Hydrology Part 3. Flood-flow techniques. Usgpo 1543-A, 80.
- De Luca, D.L., Galasso, L., 2018. Stationary and Non-Stationary Frameworks for Extreme Rainfall Time Series in Southern Italy. Water 2018, Vol. 10, Page 1477 10, 1477. https://doi.org/10.3390/W10101477
- De Martonne, E., 1926. L'indice d'aridité. Bulletin de l'Association de géographes 9, 3-5.
- De Wrachien, D., Mambretti, S., Schultz, B., 2011. Flood management and risk assessment in flood-prone areas: Measures and solutions. Irrigation and Drainage 60, 229-240. https://doi.org/10.1002/ird.557
- Diez-Sierra, J., Navas, S., Del Jesus, M., 2023. NEOPRENE v1.0.1: A Python library for generating spatial rainfall based on the Neyman-Scott process. Geoscientific Model Development 16, 5035-5048. https://doi.org/10.5194/gmd-16-5035-2023
- Dore, M.H.I., 2005. Climate change and changes in global precipitation patterns: What do we know? Environment International. https://doi.org/10.1016/j.envint.2005.03.004
- Dunne, T., Black, R.D., 1970. Partial Area Contributions to Storm Runoff in a Small New, England Watershed. Water Resources Research 6, 1296-1311.
- Eagleson, P.S., 1972. Dynamics Flood Frequency. Water Resources Research 8, 878--898.
- Ehret, U., Zehe, E., Wulfmeyer, V., Warrach-Sagi, K., Liebert, J., 2012. "Should we apply bias correction to global and regional climate model data?" Hydrology and Earth System Sciences 16, 3391-3404. https://doi.org/10.5194/hess-16-3391-2012
- Emmanuel, I., Payrastre, O., Andrieu, H., Zuber, F., 2017. A method for assessing the influence of rainfall spatial variability on hydrograph modeling.

First case study in the Cevennes Region, southern France. Journal of Hydrology 555, 314-322. https://doi.org/10.1016/j.jhydrol.2017.10.011

- England Jr., J.F., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas Jr, W.O., Veilleux, A.G., Kiang, J.E., Mason Jr, R.R., 2019. Guidelines for determining flood flow frequency—Bulletin 17C, Techniques and Methods. Reston, VA. https://doi.org/10.3133/tm4B5
- Evin, G., Favre, A.C., 2012. Further developments of a transient Poisson-cluster model for rainfall. Stochastic Environmental Research and Risk Assessment 27, 831-847. https://doi.org/10.1007/s00477-012-0612-y
- Evin, G., Favre, A.C., Hingray, B., 2018. Stochastic generation of multi-site daily precipitation focusing on extreme events. Hydrology and Earth System Sciences 22, 655-672. https://doi.org/10.5194/hess-22-655-2018
- Faramarzi, M., Abbaspour, K.C., Ashraf Vaghefi, S., Farzaneh, M.R., Zehnder, A.J.B., Srinivasan, R., Yang, H., 2013. Modeling impacts of climate change on freshwater availability in Africa. Journal of Hydrology 480, 85-101. https://doi.org/10.1016/j.jhydrol.2012.12.016
- Fathzadeh, A., Jaydari, A., Taghizadeh-Mehrjardi, R., 2017. Comparison of different methods for reconstruction of instantaneous peak flow data. Intelligent Automation and Soft Computing 23, 41-49.
- Ferrer Polo, F.J., López Ardiles, L., 1994. Análisis estadístico de las series anuales de máximas lluvias diarias en España. Revista Digital del Cedex.
- Fatichi, S., Ivanov, V.Y., Caporali, E., 2013. Assessment of a stochastic downscaling methodology in generating an ensemble of hourly future climate time series. Climate Dynamics.
- Ficchì, A., Perrin, C., Andréassian, V., 2016. Impact of temporal resolution of inputs on hydrological model performance: An analysis based on 2400 flood events. Journal of Hydrology 538, 454-470. https://doi.org/10.1016/J.JHYDROL.2016.04.016
- Filipova, V., Lawrence, D., Skaugen, T., 2019. A stochastic event-based approach for flood estimation in catchments with mixed rainfall and

snowmelt flood regimes. Natural Hazards and Earth System Science 19, 1-18.

- Flato, G., Marotzke, J., Abiodun, B., Braconnot, P., Chou, S.C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., Rummukainen, M., Abiodun, B., Braconnot, P., Chou, S.C., Collins, W., Cox, P., Driouech, F., Emori, S., Eyring, V., Forest, C., Gleckler, P., Guilyardi, E., Jakob, C., Kattsov, V., Reason, C., Mmukainen, M.R., 2013. Evaluation of climate models. Climate Change 2013 the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/CBO9781107415324.020
- Fogués, F., 1931. Las inundaciones de la Ribera. Anales del Centro de Cultura Valenciana.
- Fontana Tarrats, J.M., 1978. Historia del clima en el litoral mediterráneo: Reino de Valencia más Provincia de Murcia.
- Fortesa, J., Latron, J., García-Comendador, J., Tomàs-Burguera, M., Company, J., Calsamiglia, A., Estrany, J., 2020. Multiple Temporal Scales Assessment in the Hydrological Response of Small Mediterranean-Climate Catchments. Water 2020, Vol. 12, Page 299 12, 299. https://doi.org/10.3390/W12010299
- Foster, H.A., 1924. Theoretical frequency curves and the application to engineering problems 142-173.
- Francés, F., 1995. Utilización de la información historica en el análisis regional de las avenidas.
- Francés, F., 1998. Using the TCEV distribution function with systematic and non-systematic data in a regional flood frequency analysis. Stochastic Hydrology and Hydraulics 12, 267-283. https://doi.org/10.1007/s004770050021
- Frances, F., Salas, J.D., Boes, D.C., 1994. Flood frequency analysis with systematic and historical or paleoflood data based on the two-parameter

general extreme value models. Water Resources Research 30, 1653-1664. https://doi.org/10.1029/94WR00154

- Francés, F., Vélez, J.I., Vélez, J.J., 2007. Split-parameter structure for the automatic calibration of distributed hydrological models. Journal of Hydrology 332, 226-240. https://doi.org/10.1016/j.jhydrol.2006.06.032
- Fuller, W., 1914. Flood flows. Transactions of the American Society of Civil Engineers 77, 564-617.
- Furrer, E.M., Katz, R.W., 2008. Improving the simulation of extreme precipitation events by stochastic weather generators. Water Resources Research 44, 1-13. https://doi.org/10.1029/2008WR007316
- Gabellani, S., Boni, G., Ferraris, L., von Hardenberg, J., Provenzale, A., 2007. Propagation of uncertainty from rainfall to runoff: A case study with a stochastic rainfall generator. Advances in Water Resources 30, 2061-2071. https://doi.org/10.1016/j.advwatres.2006.11.015
- Gaume, E., 2018. Flood frequency analysis: The Bayesian choice. Wiley Interdisciplinary Reviews: Water 5, e1290. https://doi.org/10.1002/WAT2.1290
- Gil-Guirado, S., Pérez-Morales, A., Pino, D., Peña, J.C., Martínez, F.L., 2022. Flood impact on the Spanish Mediterranean coast since 1960 based on the prevailing synoptic patterns. Science of the Total Environment 807. https://doi.org/10.1016/J.SCITOTENV.2021.150777
- Gleick, P.H., 1986. Methods for evaluating the regional hydrologic impacts of global climatic changes. Journal of Hydrology 88, 97-116. https://doi.org/10.1016/0022-1694(86)90199-X
- Grimaldi, S., Nardi, F., Piscopia, R., Petroselli, A., Apollonio, C., 2020. Continuous hydrologic modelling for design simulation in small and ungauged basins : A step forward and some tests for its practical use. Journal of Hydrology 125664. https://doi.org/10.1016/j.jhydrol.2020.125664

- Grimaldi, S., Volpi, E., Langousis, A., Michael Papalexiou, S., De Luca, D.L., Piscopia, R., Nerantzaki, S.D., Papacharalampous, G., Petroselli, A., 2022. Continuous hydrologic modelling for small and ungauged basins: A comparison of eight rainfall models for sub-daily runoff simulations. Journal of Hydrology 610. https://doi.org/10.1016/j.jhydrol.2022.127866
- Gringorten, I., 1963. A Plotting Rule for Extreme Probability Paper. Journal of Geophysical Reserach 68, 813-814.
- Gudmundsson, L., Bremnes, J.B., Haugen, J.E., Engen-Skaugen, T., 2012. Technical Note: Downscaling RCM precipitation to the station scale using statistical transformations – A comparison of methods. Hydrology and Earth System Sciences 16, 3383-3390. https://doi.org/10.5194/hess-16-3383-2012
- Guerreiro, S.B., Dawson, R.J., Kilsby, C., Lewis, E., Ford, A., 2018. Future heat-waves, droughts and floods in 571 European cities. Environmental Research Letters 13. https://doi.org/10.1088/1748-9326/aaaad3
- Guhathakurta, P., Sreejith, O.P., Menon, P.A., 2011. Impact of climate change on extreme rainfall events and flood risk in India. Journal of Earth System Science 120, 359-373. https://doi.org/10.1007/s12040-011-0082-5
- Haktanir, T., Horlacher, H.B., 1993. Evaluation of various distributions for flood frequency analysis. Hydrological Sciences Journal 38, 15-32. https://doi.org/10.1080/02626669309492637
- Hall, J., Solomatine, D., 2008. A framework for uncertainty analysis in flood risk management decisions. International Journal of River Basin Management 6, 85-98. https://doi.org/10.1080/15715124.2008.9635339
- Hargreaves, G., Samani, Z., 1985. Reference Crop Evapotranspiration from Temperature. Applied Engineering in Agriculture 1, 96-99. https://doi.org/10.13031/2013.26773
- Hartmann, D.L., 2016. Global Climate Models, in: Global Physical Climatology. Elsevier, pp. 325-360. https://doi.org/10.1016/b978-0-12-328531-7.00011-6

- Haruna, A., Blanchet, J., Favre, A.C., 2022. Performance-based comparison of regionalization methods to improve the at-site estimates of daily precipitation. Hydrology and Earth System Sciences 26, 2797-2811. https://doi.org/10.5194/HESS-26-2797-2022
- Hay, L.E., Clark, M.P., 2003. Use of statistically and dynamically downscaled atmospheric model output for hydrologic simulations in three mountainous basins in the western United States. Journal of Hydrology 282, 56-75. https://doi.org/10.1016/S0022-1694(03)00252-X
- Hay, L.E., Wilby, R.L., Leavesley, G.H., 2000. A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. Journal of the American Water Resources Association 36, 387-397. https://doi.org/10.1111/j.1752-1688.2000.tb04276.x
- Herrera, S., Fernández, J., Gutiérrez, J.M., 2016. Update of the Spain02 gridded observational dataset for EURO-CORDEX evaluation: Assessing the effect of the interpolation methodology. International Journal of Climatology 36, 900-908. https://doi.org/10.1002/joc.4391
- Herrera, S., Kotlarski, S., Soares, P.M.M., Cardoso, R.M., Jaczewski, A., Gutiérrez, J.M., Maraun, D., 2019. Uncertainty in gridded precipitation products: Influence of station density, interpolation method and grid resolution. International Journal of Climatology 39, 3717-3729. https://doi.org/10.1002/joc.5878
- Hine, D., Hall, J.W., 2010. Information gap analysis of flood model uncertainties and regional frequency analysis. Water Resources Research 46. https://doi.org/10.1029/2008wr007620
- Hongwei, Z., Xuehua, Z., Bao'an, Z., 2009. Application of Developed Grid-GA Distributed Hydrologic Model in Semi-Humid and Semi-Arid Basin. Transactions of Tianjin University 15, 70-74. https://doi.org/10.1007/s12209
- Höök, M., Tang, X., 2013. Depletion of fossil fuels and anthropogenic climate change—A review. Energy Policy 52, 797-809. https://doi.org/10.1016/J.ENPOL.2012.10.046

- Hosking, J.. R.M., Wallis, J.R., 1993. Some Statistics Useful in Regional Frequency Analys. Water Resources Research 29, 271-281.
- Hosking, J.R.M., Wallis, J.R., 1997. Regional Frequency Analysis: An approach based on L-moments, Cambridge University Press, New York.
- Houghton-Carr, H., 1999. Restatement and application of the Flood Studies Report rainfall-runoff method. Volume 4 of the Flood Estimation Handbook. Institute of Hydrology, Oxfordshire.
- Huang, Y., Zhang, K., Bárdossy, A., 2019. Sensitivity of hydrological models to temporal and spatial resolutions of rainfall data. Hydrology and Earth System Sciences 23. https://doi.org/10.5194/hess-23-2647-2019
- Hundecha, Y., Pahlow, M., Schumann, A., 2009. Modeling of daily precipitation at multiple locations using a mixture of distributions to characterize the extremes. Water Resources Research 45.
- IPCC, 2022. IPCC AR6 WGII Sixth Assessment Report.
- Jain, S., 2014. Downscaling Methods in Climate Change Studies. Nihroorkee.Gov.in 1-18.
- Jonkman, S.N., 2005. Global perspectives on loss of human life caused by floods. Natural Hazards 34, 151-175. https://doi.org/10.1007/s11069-004-8891-3
- Khazaei, M.R., Hasirchian, M., Zahabiyoun, B., 2021. An improved daily weather generator for the assessment of regional climate change impacts. Theoretical and Applied Climatology 146, 475-487.
- Kidson, R., Richards, K.S., 2005. Flood frequency analysis: Assumptions and alternatives. Progress in Physical Geography 29, 392-410. https://doi.org/10.1191/0309133305pp454ra
- Kim, D., Cho, H., Onof, C., Choi, M., 2017. Let-It-Rain: a web application for stochastic point rainfall generation at ungaged basins and its applicability in runoff and flood modeling. Stochastic Environmental Research and Risk Assessment 31, 1023-1043. https://doi.org/10.1007/s00477-016-1234-6

- Kossieris, P., Koutsoyiannis, D., Onof, C., Tyralis, H., Efstratiadis, A., 2012. HyetosR: An R package for temporal stochastic simulation of rainfall at fine time scales. European Geosciences Union General Assembly 14, 11788.
- Kotlarski, S., Szabó, P., Herrera, S., Räty, O., Keuler, K., Soares, P.M., Cardoso, R.M., Bosshard, T., Pagé, C., Boberg, F., Gutiérrez, J.M., Isotta, F.A., Jaczewski, A., Kreienkamp, F., Liniger, M.A., Lussana, C., Pianko-Kluczyńska, K., 2017. Observational uncertainty and regional climate model evaluation: A pan-European perspective. International Journal of Climatology 3730-3749.
- Koutsoyiannis, D., Onof, C., Wheater, H.S., 2003. Multivariate rainfall disaggregation at a fine timescale. Water Resources Research 39, 1173. https://doi.org/10.1029/2002WR001600
- Kundzewicz, Z.W., Kanae, S., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L.M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G.R., Kron, W., Benito, G., Honda, Y., Takahashi, K., Sherstyukov, B., 2014. Le risque d'inondation et les perspectives de changement climatique mondial et régional. Hydrological Sciences Journal 59, 1-28. https://doi.org/10.1080/02626667.2013.857411
- Lamb, R., Faulkner, D., Wass, P., Cameron, D., 2016. Have applications of continuous rainfall-runoff simulation realized the vision for process-based flood frequency analysis? Hydrological Processes 30, 2463-2481. https://doi.org/10.1002/hyp.10882
- Lhotka, O., Kyselý, J., Farda, A., 2018. Climate change scenarios of heat waves in Central Europe and their uncertainties. Theoretical and Applied Climatology 131, 1043-1054. https://doi.org/10.1007/s00704-016-2031-3
- Li, X., Babovic, V., 2019. Multi-site multivariate downscaling of global climate model outputs: an integrated framework combining quantile mapping, stochastic weather generator and Empirical Copula approaches. Climate Dynamics 52, 5775-5799.
- Li, Z., Shi, X., 2019. Stochastic generation of daily precipitation considering diverse model complexity and climates. Theoretical and Applied Climatology 137, 839-853.

- Linsley, R.., Kohler, M.., Paulhus, J.L.., 1968. Applied hydrology. Journal of Hydrology 6, 224-225. https://doi.org/10.1016/0022-1694(68)90169-8
- Lisø, K.R., Kvande, T., Time, B., 2017. Climate Adaptation Framework for Moisture-resilient Buildings in Norway. Energy Procedia 132, 628-633. https://doi.org/10.1016/j.egypro.2017.09.698
- Llasat, M.C., Puigcerver, M., 1990. Cold air pools over Europe. Meteorology and atmospheric physics 42, 171-177.
- Loarie, S.R., Duffy, P.B., Hamilton, H., Asner, G.P., Field, C.B., Ackerly, D.D., 2009. The velocity of climate change. Nature 462, 1052-1055. https://doi.org/10.1038/nature08649
- López-Martínez, F., Gil-Guirado, S., Pérez-Morales, A., 2017. Who can you trust? Implications of institutional vulnerability in flood exposure along the Spanish Mediterranean coast. Environmental Science and Policy 76, 29-39. https://doi.org/10.1016/J.ENVSCI.2017.06.004
- Lu, Y., Qin, X.S., 2014. Multisite rainfall downscaling and disaggregation in a tropical urban area. Journal of Hydrology 509, 55-65. https://doi.org/10.1016/J.JHYDROL.2013.11.027
- Machado, M.J., Benito, G., Barriendos, M., Rodrigo, F.S., 2011. 500 Years of rainfall variability and extreme hydrological events in southeastern Spain drylands. Journal of Arid Environments 75, 1244-1253. https://doi.org/10.1016/j.jaridenv.2011.02.002
- Machado, M.J., Medialdea, A., Calle, M., Rico, M.T., Sánchez-Moya, Y., Sopeña, A., Benito, G., 2017. Historical palaeohydrology and landscape resilience of a Mediterranean rambla (Castellón, NE Spain): Floods and people. Quaternary Science Reviews 171, 182-198. https://doi.org/10.1016/j.quascirev.2017.07.014
- Mackay, N.G., Chandler, R.E., Onof, C., Wheater, H.S., 2001. Disaggregation of spatial rainfall fields for hydroloigcal modelling Disaggregation of spatial

rainfall fields for hydrological modelling. Hydrology and Earth System Sciences 5, 165-173.

- Maraun, D., 2016. Bias Correcting Climate Change Simulations - a Critical Review. Current Climate Change Reports 2, 211-220. https://doi.org/10.1007/s40641-016-0050-x
- Maraun, D., Wetterhall, F., Ireson, A.M., Chandler, R.E., Kendon, E.J., Widmann, M., Brienen, S., Rust, H.W., Sauter, T., Themel, M., Venema, V.K.C., Chun, K.P., Goodess, C.M., Jones, R.G., Onof, C., Vrac, M., Thiele-Eich, I., 2010. Precipitation downscaling under climate change: Recent developments to bridge the gap between dynamical models and the end user. Reviews of Geophysics 48, 1-34. https://doi.org/10.1029/2009RG000314
- Marco, J.B., 1995. Hydrometeorological and Hydraulic Factors and Problems Related to Floods in Arid Regions of Spain.
- Mateu, J.F., 1974. La Rambla de la Viuda. Clima e Hidrología. Cuadernos de Geografia.
- Mehrotra, R., Sharma, A., 2016. A multivariate quantile-matching bias correction approach with auto- and cross-dependence across multiple time scales: implications for downscaling. Journal of Climate 29, 3519–3539. https://doi.org/10.1175/JCLI-D-15-0356.1
- Mehrotra, R., Westra, S., Sharma, A., Srikanthan, R., 2012. Continuous rainfall simulation: 2. A regionalized daily rainfall generation approach. Water Resources Research 48. https://doi.org/10.1029/2011WR010490
- Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J., Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M., van Vuuren, D.P.P., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change 109, 213-241. https://doi.org/10.1007/S10584-011-0156-Z/TABLES/5
- Merz, R., Blöschl, G., 2008. Flood frequency hydrology: 1. Temporal, spatial, and causal expansion of information. Water Resources Research 44.

- Merz, R., Blöschl, G., 2008a. Flood frequency hydrology: 1. Temporal, spatial, and causal expansion of information. Water Resources Research 44. https://doi.org/10.1029/2007wr006744
- Merz, R., Blöschl, G., 2008b. Flood frequency hydrology: 1. Temporal, spatial, and causal expansion of information. Water Resources Research 44. https://doi.org/10.1029/2007wr006744
- Metzger, A., Marra, F., Smith, J.A., Morin, E., 2020. Flood frequency estimation and uncertainty in arid/semi-arid regions. Journal of Hydrology 590, 125254. https://doi.org/10.1016/j.jhydrol.2020.125254
- Mezghani, A., Hingray, B., 2009. A combined downscaling-disaggregation weather generator for stochastic generation of multisite hourly weather variables over complex terrain: Development and multi-scale validation for the Upper Rhone River basin. Journal of Hydrology 377, 245-260. https://doi.org/10.1016/J.JHYDROL.2009.08.033
- Millán, M.M., 2014. Extreme hydrometeorological events and climate change predictions in Europe. Journal of Hydrology 518, 206-224. https://doi.org/10.1016/J.JHYDROL.2013.12.041
- Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Climate change: Stationarity is dead: Whither water management? Science 319, 573-574. https://doi.org/10.1126/science.1151915
- Ministerio de Fomento, 2019. Drenaje superficial. Norma 5.2-IC de la Instrucción de carreteras. MINISTERIO DE FOMENTO.
- Ministerio de Fomento. Dirección General de, C., 1999. Máximas lluvias diarias en España Peninsular.
- Ministerio de Medio Ambiente y Medio Rural y Marino, 2011. Guía metodológica para el desarrollo del sistema nacional de cartografía de zonas inundables.
- Miró, J.J., Estrela, M.J., Olcina-Cantos, J., Martin-Vide, J., 2021. Future projection of precipitation changes in the júcar and segura river basins

(Iberian peninsula) by CMIP5 GCMs local downscaling. Atmosphere 12, 879. https://doi.org/10.3390/atmos12070879

- Moges, E., Demissie, Y., Larsen, L., Yassin, F., 2021. Review: Sources of hydrological model uncertainties and advances in their analysis. Water (Switzerland) 13, 1-23. https://doi.org/10.3390/w13010028
- Moulin, L., Gaume, E., Obled, C., 2009. Uncertainties on mean areal precipitation: Assessment and impact on streamflow simulations. Hydrology and Earth System Sciences 13, 99-114. https://doi.org/10.5194/hess-13-99-2009
- Nash, J.E., Sutcliffe, J. V, 1970. River flow forecasting through conceptual models part I — A discussion of principles. Journal of Hydrology 10, 282-290. https://doi.org/https://doi.org/10.1016/0022-1694(70)90255-6
- Naveau, P., 2016. Modeling jointly low, moderate, and heavy rainfall intensities without a threshold selection. Water Resources Research 52, 2753-2769.
- Núñez Mora, J.Á., 2019. Análisis Meteorológico Y Climático Temporal De Precipitaciones Torrenciales Septiembre De 2019 En La Comunidad Valenciana.
- O'Shea, D., Nathan, R., Sharma, A., Wasko, C., 2023. Improved Extreme Rainfall Frequency Analysis Using a Two-Step Kappa Approach. Water Resources Research 59. https://doi.org/10.1029/2021WR031854
- Ortega, J.A., Razola, L., Garzón, G., 2014. Recent human impacts and change in dynamics and morphology of ephemeral rivers. Natural Hazards and Earth System Sciences 14, 713-730. https://doi.org/10.5194/nhess-14-713-2014
- Panagos, P., Van Liedekerke, M., Jones, A., Montanarella, L., 2012. European Soil Data Centre: Response to European policy support and public data requirements. Land Use Policy 29, 329-338. https://doi.org/10.1016/J.LANDUSEPOL.2011.07.003

- Papalexiou, S.M., 2018. Unified theory for stochastic modelling of hydroclimatic processes: Preserving marginal distributions, correlation structures, and intermittency. Advances in Water Resources 115, 234-252.
- Papalexiou, S.M., 2022. Rainfall Generation Revisited: Introducing CoSMoS-2s and Advancing Copula-Based Intermittent Time Series Modeling. Water Resources Research 58, 1-33. https://doi.org/10.1029/2021wr031641
- Papalexiou, S.M., Markonis, Y., Lombardo, F., AghaKouchak, A., Foufoula-Georgiou, E., 2018. Precise Temporal Disaggregation Preserving Marginals and Correlations (DiPMaC) for Stationary and Nonstationary Processes. Water Resources Research 54, 7435-7458.
- Papastathopoulos, I., Tawn, J.A., 2013. Extended generalised Pareto models for tail estimation. Journal of Statistical Planning and Inference 143, 131-143. https://doi.org/10.1016/j.jspi.2012.07.001
- Paprotny, D., Morales-Nápoles, O., 2017. Estimating extreme river discharges in Europe through a Bayesian network. Hydrology and Earth System Sciences 21, 2615-2636.
- Pathiraja, S., Westra, S., Sharma, A., 2012. Why continuous simulation? the role of antecedent moisture in design flood estimation. Water Resources Research 48, 1-15. https://doi.org/10.1029/2011WR010997
- Pedretti, D., Irannezhad, M., 2019. Non-stationary peaks-over-threshold analysis of extreme precipitation events in Finland, 1961–2016. International Journal of Climatology 39, 1128–1143. https://doi.org/10.1002/JOC.5867
- Peleg, N., Blumensaat, F., Molnar, P., Fatichi, S., Burlando, P., 2017. Partitioning the impacts of spatial and climatological rainfall variability in urban drainage modeling. Hydrol. Earth Syst. Sci 21, 1559-1572. https://doi.org/10.5194/hess-21-1559-2017
- Pierce, D.W., Cayan, D.R., Maurer, E.P., Abatzoglou, J.T., Hegewisch, K.C., 2015. Improved bias correction techniques for hydrological simulations of climate change. Journal of Hydrometeorology 16, 2421-2442. https://doi.org/10.1175/JHM-D-14-0236.1

- Pilgrim, D.H., Chapman, T.G., Doran, D.G., 1988. Problèmes de la mise au point de modèles pluie-écoulement dans les régions arides et semi-arides. Hydrological Sciences Journal 33, 379-400. https://doi.org/10.1080/02626668809491261
- Pluntke, T., Pavlik, D., Bernhofer, C., 2014. Reducing uncertainty in hydrological modelling in a data sparse region. Environmental Earth Sciences 72, 4801-4816. https://doi.org/10.1007/s12665-014-3252-3
- Potter, W.D., 1958. Upper and lower frequency curves for peak rates of runoff. Eos, Transactions American Geophysical Union 39, 100–105. https://doi.org/10.1029/TR039i001p00100
- Prein, A.F., Rasmussen, R.M., Ikeda, K., Liu, C., Clark, M.P., Holland, G.J., 2017. The future intensification of hourly precipitation extremes. Nature Climate Change 7, 48-52. https://doi.org/10.1038/nclimate3168
- Pui, A., Sharma, A., Mehrotra, R., Sivakumar, B., Jeremiah, E., 2012. A comparison of alternatives for daily to sub-daily rainfall disaggregation. Journal of Hydrology 470-471, 138-157. https://doi.org/10.1016/j.jhydrol.2012.08.041
- Rajagopalan, B., Lall, U., 1999. A k-nearest-neighbor simulator for daily precipitation and other weather variables. Water Resources Research 35, 3089-3101.
- Rajczak, J., Pall, P., Schär, C., 2013. Projections of extreme precipitation events in regional climate simulations for Europe and the Alpine Region. Journal of Geophysical Research: Atmospheres 118, 3610-3626. https://doi.org/10.1002/jgrd.50297
- Randall, D., Richard A. Wood, Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R.J., Sumi, A., Taylor, K., 2013. Chapter 8: Climate Models and Their Evaluation Coordinating Lead Authors: David Randall (USA), Richard A. Wood (UK) Lead [WWW Document]. IPCC WG1 Fourth Assessment Report. URL https://www.researchgate.net/publication/233421523_Climate_Models_and_Their_Evaluation (accessed 12.2.23).

- Rashid, M.M., Beecham, S., Chowdhury, R.K., 2016. Statistical downscaling of rainfall: a non-stationary and multi-resolution approach. Theoretical and Applied Climatology 124, 919–933. https://doi.org/10.1007/s00704-015-1465-3
- Richardson, C.W., 1981. Stochastic modelling of daily precipitation, temperature and solar radiation. Water Resources Research 17, 182-190.
- Richardson, C.W., Wright, D.A., 1984. WGEN: A model for generating daily weather variables. U.S. Department of Agriculture Research and Service, ARS 8, 235.
- Rigo, T., Berenguer, M., del Carmen Llasat, M., 2019. An improved analysis of mesoscale convective systems in the western Mediterranean using weather radar. Atmospheric Research 227, 147-156. https://doi.org/10.1016/j.atmosres.2019.05.001
- Rodriguez-Iturbe, I., Cox, D.R., Isham, V., 1987. SOME MODELS FOR RAINFALL BASED ON STOCHASTIC POINT PROCESSES. Proceedings of The Royal Society of London, Series A: Mathematical and Physical Sciences 410, 269-288. https://doi.org/10.1098/rspa.1987.0039
- Roudier, P., Andersson, J.C.M., Donnelly, C., Feyen, L., Greuell, W., Ludwig, F., 2016. Projections of future floods and hydrological droughts in Europe under a +2C global warming. Climatic Change 135, 341-355. https://doi.org/10.1007/s10584-015-1570-4
- Salazar-Galán, S., García-Bartual, R., Salinas, J.L., Francés, F., 2021. A process-based flood frequency analysis within a trivariate statistical framework. Application to a semi-arid Mediterranean case study. Journal of Hydrology 603. https://doi.org/10.1016/j.jhydrol.2021.127081
- Sánchez Adell, J., Montins, O., Sánchez Almela, F., 1993. E.(1993): Elenco de fechas para la historia urbana de Castellón de la Plana.
- Sangal, B.P., 1983. Practical Method of Estimating Peak Flow. Journal of Hydraulic Engineering 109, 549-563. https://doi.org/10.1061/(ASCE)0733-9429(1983)109:4(549)

- Segura, F.S., Camarasa, A., 1996. Balances hídricos de crecidas em ramblas mediterráneas: Pérdidas hídricas, in: Marzol, M. V, Dorta, P., Valladares, P. (Eds.), Clima y Agua: La Gestión de Un Recurso Climático. La Laguna University, Tenerife, pp. 235-245.
- Sharafati, A., Pezeshki, E., 2020. A strategy to assess the uncertainty of a climate change impact on extreme hydrological events in the semi-arid Dehbar catchment in Iran. Theoretical and Applied Climatology 139, 389-402.
- Sharif, M., Burn, D.H., 2006. Simulating climate change scenarios using an improved K-nearest neighbor model. Journal of Hydrology 325, 179-196.
- She, D., Shao, Q., Xia, J., Taylor, J.A., Zhang, Y., Zhang, L., Zhang, X., Zou, L., 2015. Investigating the variation and non-stationarity in precipitation extremes based on the concept of event-based extreme precipitation. Journal of Hydrology 530, 785–798. https://doi.org/10.1016/J.JHYDROL.2015.10.029
- Simon J. Mason, Waylen, P.R., Mimmack, G.M., Rajaratnam, B., Harrison, J.M., 1999. CHANGES IN EXTREME RAINFALL EVENTS IN SOUTH AFRICA. Climatic Change 41, 249-257.
- Simón, J.L., Pérez-Cueva, A.J., Calvo-Cases, A., 2013. Tectonic beheading of fluvial valleys in the Maestrat grabens (eastern Spain): Insights into slip rates of Pleistocene extensional faults. Tectonophysics 593, 73-84. https://doi.org/https://doi.org/10.1016/j.tecto.2013.02.026
- Singh, A., Singh, V.P., AR, B., 2018. Computation of probable maximum precipitation and its uncertainty. International Journal of Hydrology 2, 504-514. https://doi.org/10.15406/ijh.2018.02.00118
- Smith, A., Sampson, C., Bates, P., 2015. Regional flood frequency analysis at the global scale. Water Resources Research 51, 539-553. https://doi.org/10.1002/2014WR015814
- Sohoulande Djebou, D.C., Singh, V.P., 2016. Impact of climate change on precipitation patterns: a comparative approach. International Journal of Climatology 36, 3588-3606. https://doi.org/10.1002/joc.4578

- Solomon, S., Plattner, G.K., Knutti, R., Friedlingstein, P., 2009. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences of the United States of America 106, 1704-1709. https://doi.org/10.1073/pnas.0812721106
- Soltani, A., Hoogenboom, G., 2003. Minimum data requirements for parameter estimation of stochastic weather generators. Climate Research 25, 109-119. https://doi.org/10.3354/cr025109
- Soriano, E., Mediero, L., Garijo, C., 2020. Quantification of Expected Changes in Peak Flow Quantiles in Climate Change by Combining Continuous Hydrological Modelling with the Modified Curve Number Method. Water Resources Management 34, 4381-4397. https://doi.org/10.1007/s11269-020-02670-w
- Stedinger, J.R., Baker, V.R., 1987. Surface water hydrology: Historical and paleoflood information. Reviews of Geophysics 25, 119-124. https://doi.org/10.1029/RG025i002p00119
- Stedinger, J.R., Cohn, T.A., 1986. Flood Frequency Analysis With Historical and Paleoflood Information. Water Resources Research 22, 785-793. https://doi.org/10.1029/WR022i005p00785
- Stedinger, J.R., Griffis, V.W., 2008. Flood Frequency Analysis in the United States: Time to Update. Journal of Hydrologic Engineering 13, 199-204. https://doi.org/doi:10.1061/(ASCE)1084-0699(2008)13:4(199)
- Sun, X., Mein, R.G., Keenan, T.D., Elliott, J.F., 2000. Flood estimation using radar and raingauge data. Journal of Hydrology 239, 4-18. https://doi.org/10.1016/S0022-1694(00)00350-4
- Tabari, H., 2020. Climate change impact on flood and extreme precipitation increases with water availability. Scientific Reports 10, 1-10. https://doi.org/10.1038/s41598-020-70816-2
- Tague, C., Grant, G.E., 2009. Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions. Water Resources Research 45, 1-12. https://doi.org/10.1029/2008WR007179

- Tegegne, G., Kim, Y.O., Seo, S.B., Kim, Y., 2019. Hydrological modelling uncertainty analysis for different flow quantiles: a case study in two hydro-geographically different watersheds. Hydrological Sciences Journal 64, 473-489. https://doi.org/10.1080/02626667.2019.1587562

- Témez, J.R., 1987. Cálculo hidrometeorológico de Caudales Máximos en Pequeñas Cuencas Naturales. Dirección General de Carreteras. MOPU.
- Themeßl, M.J., Gobiet, A., Heinrich, G., 2012. Empirical-statistical downscaling and error correction of regional climate models and its impact on the climate change signal. Climatic Change 112, 449-468. https://doi.org/10.1007/s10584-011-0224-4
- Tóth, B., Weynants, M., Pásztor, L., Hengl, T., 2017. 3D soil hydraulic database of Europe at 250 m resolution. Hydrological Processes 31, 2662-2666. https://doi.org/10.1002/HYP.11203
- Trenberth, K.E., 2011. Changes in precipitation with climate change. Climate Research 47, 123-138. https://doi.org/10.3354/cr00953
- UNDRR, 2015. United Nations Office for Disaster Risk Reduction GAR2015 — Global Assessment Report on Disaster Risk Reduction.
- United States Environmental Protection Agency, 2005. Causes of Climate Change | Climate Change Science | US EPA [WWW Document]. URL https://19january2017snapshot.epa.gov/climate-change-science/causes-climate-change_.html (accessed 12.8.23).

- Vélez, J.J., Botero, A., 2011. Estimation of the time of concentration and the lag time at san Luis creek basin, Manizales. DYNA (Colombia) 78, 58-71.

- Vélez, J.J., López Unzu, F., Puricelli, M., Francés, F., 2007. Parameter extrapolation to ungauged basins with a hydrological distributed model in a regional framework. Hydrology and Earth System Sciences Discussions 4, 909-956. https://doi.org/10.5194/hessd-4-909-2007

- Verdin, A., Rajagopalan, B., Kleiber, W., Katz, R.W., 2015. Coupled stochastic weather generation using spatial and generalized linear models. Stochastic

Environmental Research and Risk Assessment 29, 347-356. https://doi.org/10.1007/s00477-014-0911-6

- Vesely, F.M., Paleari, L., Movedi, E., Bellocchi, G., Confalonieri, R., 2019. Quantifying Uncertainty Due to Stochastic Weather Generators in Climate Change Impact Studies. Scientific Reports 9, 1-8.
- Wasko, C., Nathan, R., Stein, L., O'Shea, D., 2021. Evidence of shorter more extreme rainfalls and increased flood variability under climate change. Journal of Hydrology 603, 126994. https://doi.org/10.1016/j.jhydrol.2021.126994
- Westra, S., Sisson, S.A., 2011. Detection of non-stationarity in precipitation extremes using a max-stable process model. Journal of Hydrology 406, 119–128. https://doi.org/10.1016/J.JHYDROL.2011.06.014
- Wilks, D.S., 1998. Multisite generalization of a daily stochastic precipitation generation model. Journal of Hydrology 210, 178-191.
- Wilks, D.S., 2009. A gridded multisite weather generator and synchronization to observed weather data. Water Resources Research. https://doi.org/10.1029/2009WR007902
- Wilks, D.S., Wilby, R.L., 1999. The weather generation game: a review of stochastic weather models. Progress in Physical Geography 23, 329-357.
- Willems, P., Vrac, M., 2011. Statistical precipitation downscaling for small-scale hydrological impact investigations of climate change. Journal of Hydrology 402, 193-205. https://doi.org/10.1016/j.jhydrol.2011.02.030
- Willner, S.N., Otto, C., Levermann, A., 2018. Global economic response to river floods. Nature Climate Change 8, 594-598. https://doi.org/10.1038/s41558-018-0173-2
- Winter, B., Schneeberger, K., Dung, N. V., Huttenlau, M., Achleitner, S., Stötter, J., Merz, B., Vorogushyn, S., 2019. A continuous modelling approach for design flood estimation on sub-daily time scale. Hydrological Sciences Journal 64, 539-554. https://doi.org/10.1080/02626667.2019.1593419
- WMO, 2011. Guide to Climatological Practices, Naturaweb.Net.

- WMO, 2017. Guidelines on the Calculation of Climate Normals. WMO-No. 1203 29.
- Wuebbles, D.J., Fahey, D.W., Hibbard, K.A., De Angelo, B., Doherty, S., Hayhoe, K., Horton, R., Kossin, J.P., Taylor, P.C., Waple, A.M., Weaver, C.P., 2017. Executive summary. In: Climate Science Special Report: Fourth National Climate Assessment. Facial Plastic Surgery. https://doi.org/10.1055/s-2000-12579
- Yin, J., Guo, S., He, S., Guo, J., Hong, X., Liu, Z., 2018. A copula-based analysis of projected climate changes to bivariate flood quantiles. Journal of Hydrology 566, 23-42. https://doi.org/10.1016/j.jhydrol.2018.08.053
- Zaman, M.A., Rahman, A., Haddad, K., 2012. Regional flood frequency analysis in arid regions: A case study for Australia. Journal of Hydrology 475, 74-83. https://doi.org/https://doi.org/10.1016/j.jhydrol.2012.08.054
- Zhang, X., Zwiers, F.W., Li, G., Wan, H., Cannon, A.J., 2017. Complexity in estimating past and future extreme short-duration rainfall. Nature Geoscience 2017 10:4 10, 255-259. https://doi.org/10.1038/ngeo2911
- Zubaidi, S.L., Kot, P., Hashim, K., Alkhaddar, R., Abdellatif, M., Muhsin, Y.R., 2019. Using LARS-WG model for prediction of temperature in Columbia City, USA. IOP Conference Series: Materials Science and Engineering 584. https://doi.org/10.1088/1757-899X/584/1/012026