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Design storm parameterisation for urban drainage studies derived from regional rainfall datasets: A case study in the Spanish Mediterranean region

Rosario Balbastre-Soldevila*, Ignacio Andrés-Doménech and Rafael García-Bartual

Instituto Universitario de Investigación de Ingeniería del Agua y Medio Ambiente (IIAMA), Universitat Politècnica de València, Camí de Vera s/n, 46022 Valencia, Spain

*Corresponding author. E-mail: robalsol@cam.upv.es

RB-S, 0000-0002-1034-8612; IA-D, 0000-0003-4237-4863; RG-B, 0000-0002-1811-8264

ABSTRACT

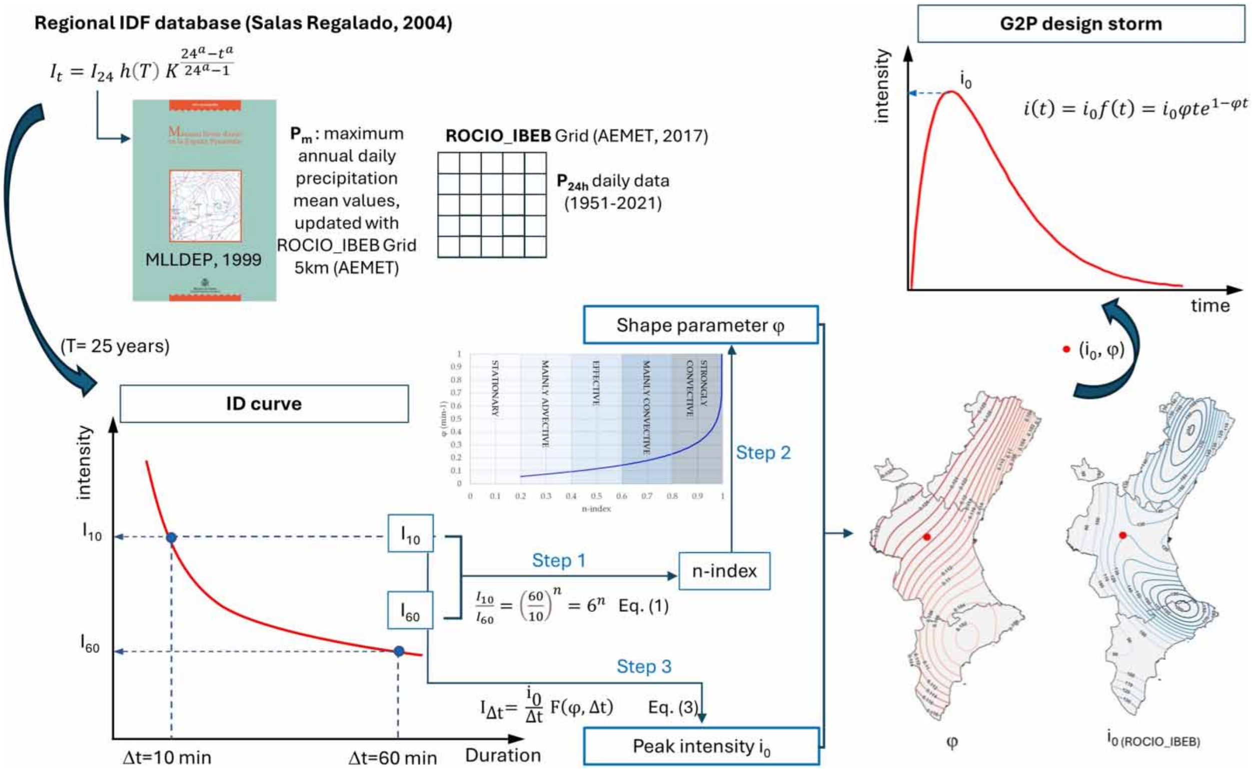
A significant amount of information on regional rainfall characteristics is available nowadays, allowing its use in hydrological applications. This article is motivated by the availability of regional studies regarding maximum daily rainfall and intensity–duration–frequency curves that can be coupled with the design storm concept for urban hydrology studies. This is accomplished through a convenient index describing temporal variability of rainfall. More precisely, a methodology for regionalising the two parameters (i_0, φ) of the two-parameter gamma design storm (G2P) is developed herein. A three-step methodology is proposed for obtaining the two parameters (i_0, φ) for a given location. The results obtained in a case study show coherence with previous studies concerning maximum rainfall statistics.

Key words: design storm, IDF curves, parameterisation methodology, regional rainfall information, urban drainage design

HIGHLIGHTS

- Three-step methodology for regionalising the G2P design storm (DS) parameters is performed.
- Parameterisation is based on regional studies from official high-resolution interpolated gridded datasets in Spain.
- The methodology led to representative DS for a given return period, is extensible to similar climate areas, and allows assessing the impact of climate change on urban drainage studies by switching the input information, if available.

GRAPHICAL ABSTRACT



INTRODUCTION

Urban hydrology and, in particular, urban drainage modelling are becoming increasingly demanding disciplines as our cities change the way they deal with rainfall events. Rapid and often uncontrolled urbanisation has led to more cities becoming more impervious in recent decades (European Commission 2012). In addition, the scientific community agrees on the increasing probability of climate scenarios where rainfall can become more intense (Seneviratne *et al.* 2012; Westra *et al.* 2014; Myhre *et al.* 2019). The combination of both problems poses a serious challenge to our cities in dealing with hydrological episodes with the greatest impact (Guerreiro *et al.* 2017).

Many practical applications of urban drainage system modelling involve as main inputs fine resolution historical rainfall records or even synthetic series generated through stochastic models (Chen & Brissette 2014; Hou *et al.* 2014; Peleg *et al.* 2017; Evin *et al.* 2018; Yeo *et al.* 2020; Pan *et al.* 2021). High-resolution data may be necessary in terms of not only time but also space, given the influence of the hydrological response on the spatiotemporal evolution of a storm within an urban catchment. Given this context, some stochastic rainfall generators that consider spatial rainfall variability and/or climate variability have been developed for urban hydrology modelling (McRobie *et al.* 2013; Thorndahl & Andersen 2021; Petroselli *et al.* 2022). These methods are cutting-edge regarding hydrological modelling and, specifically, urban drainage modelling.

However, the well-known design storm concept, as well as traditional intensity–duration–frequency (IDF) curves, continue to play a prominent role in many engineering applications, especially in areas where earlier methods cannot be developed because high-resolution rainfall data are scarce or even not available (Emmanouil *et al.* 2020). Many procedures to define design storms can be found in the literature. The different methodologies can be grouped into two categories (Balbastre-Soldevila *et al.* 2019). The first category includes design storms directly obtained from IDF curves and consistent with the rainfall intensity values derived from them (for instance, the alternating block design storm). The second category refers to theoretical storms for which the temporal pattern follows other criteria and does not depend solely on the information given by IDF curves. Within the second category, García-Bartual & Andrés-Doménech (2017) developed the two-parameter gamma function design storm (G2P). The G2P design storm involves only two parameters (Equation (1)). The first, i_0 (mm h^{-1}), is a scale parameter representing the peak rainfall intensity of the design storm; the second, φ (min^{-1}), is a shape parameter which determines the time pattern of the storm, $i(t)$, through a dimensionless gamma function $f(t)$, where t is the time in minutes.

$$i(t) = i_0 f(t) = i_0 \varphi t e^{1-\varphi t} \tag{1}$$

The G2P design storm fits well-observed rainfall data in Valencia, Spain (García-Bartual & Andrés-Doménech 2017) as its definition includes a temporal pattern inferred from empirical patterns identified in high-resolution historical rainfall data, which is an advantage above other design storms. This temporal pattern is an early-peaking storm with a steep rise until the maximum intensity is reached, followed by a gradual rainfall intensity decay until the storm ends. This means that the G2P design storm parameters represent a typical time pattern for intense storm events in extreme Mediterranean hydrologic regimes, which are mainly characterised by the occurrence of convective storms. This is a clear advantage against other design storms, such as the widely employed alternating block method, which does not preserve the rainfall intensity patterns in statistical terms (Balbastre-Soldevila *et al.* 2019). Moreover, if high-resolution historical rainfall data are not available, it is also possible to obtain the G2P design storm parameters from simpler information such as IDF curves.

Given the promising practical applicability of the G2P design storm, further research (Balbastre-Soldevila *et al.* 2021) was conducted that linked the shape parameter φ with the rainfall convectivity n-index (Monjo 2016; Monjo & Martin-Vide 2016). The n-index describes the temporal intra-event structure of a rainfall event with a dimensionless index (Equation (2)) associated with the ratio between two maximum intensities for two selected durations within the storm. In this case, intensities I_{10} and I_{60} for durations of 10 and 60 min are given as follows:

$$\frac{I_{10}}{I_{60}} = \left(\frac{60}{10}\right)^n = 6^n \tag{2}$$

A classification of storms based on n-index values according to this definition was proposed (Moncho *et al.* 2009): stationary or highly predominantly advective ($0 < n < 0.2$), predominantly advective ($0.2 \leq n < 0.4$), effective ($0.4 \leq n < 0.6$), predominantly convective ($0.6 \leq n < 0.8$), and highly predominantly convective ($0.8 \leq n \leq 1$). Therefore, physical meaning is then linked to the φ parameter through the n–φ relationship.

The analytical relationship between φ and the n-index allows, in practice, the estimation of φ from a set of IDF curves and thus provides a useful basis for easy-to-handle rainfall inputs in the context of regional urban drainage studies. Both maximum rainfall statistics and regional convectivity descriptors are frequently described on a regional basis. In fact, many regional studies for IDF characterisation can be found in the literature, mainly focusing on defining homogeneous regions regarding the statistical properties of rainfall descriptors and/or IDF parameters (Adamowski *et al.* 1996; Gellens 2002; Wallis *et al.* 2007; Cardoso *et al.* 2013; Hailegeorgis *et al.* 2013; Ghanmi *et al.* 2016; Madsen *et al.* 2017; Ghiaei *et al.* 2018; Hosseinzadehtalaei *et al.* 2018). The compactness and versatility of the G2P design storm make it particularly attractive in the context of practical urban hydrology applications on a regional scale, especially when there is a lack of high-resolution rainfall data available. Therefore, this research explores the feasibility of developing a methodology for regionalisation of the two parameters (i_0, φ) of the G2P design storm based on regional studies regarding maximum daily rainfall and IDF curves.

Many studies that estimate the impacts of climate change introduce the regional component in the analysis of expected spatial and temporal variations for climatic or hydrological variables (Hailegeorgis *et al.* 2013; Bharath & Srinivas 2015; Chavan & Srinivas 2017; Darwish *et al.* 2018). Due to the effects of climate change on extreme precipitation regimes, updated IDF curves are being adopted in many regions around the world (Hosseinzadehtalaei *et al.* 2018; Ganguli & Coulibaly 2019; Silva *et al.* 2021). This research explores the possibilities of extending such a concept to urban drainage applications through G2P design storm analytical parameterisation. For such a purpose, this methodology poses the possibility of deriving a design storm based on IDF curves. Consequently, any update regarding the IDF curves and related databases can automatically yield updated design storms with the proposed methodology. This study presents a novelty in the state of the art because there are many regional studies available in the literature in terms of hydrological variables such as maximum daily precipitation or maximum intensities according to different time intervals, but not in terms of a design storm.

Given this background, the objective of this research is to develop a methodology for regionalising the two parameters of the G2P design storm.

This approach sets the basis for evaluating rainfall inputs for urban drainage applications on a regional scale. To address these objectives, the study considers the region of Valencia, on Spain's Mediterranean coast, where these convective episodes are frequent and boosted by the influence of the orographic profiles and the proximity to the sea (Camarasa Belmonte & Soriano 2015). Therefore, new hydrological insights for the region are obtained, since the research provides a compact and robust methodology to obtain a G2P design storm throughout the region in a systematic and homogeneous way.

This article is organised as follows: the Methodology section describes the methodology used in this research; the Study Area and Data presents the study area and data used in this study; the results of the regionalised design storm parameters are presented in Results section; the Discussion section discusses the results; and, finally, the Conclusions section presents the conclusions of the research.

METHODOLOGY

The proposed methodology for estimating parameters φ and i_0 through a simple, straightforward method consists of a three-step procedure, which is described in this section. The main prior requirement is the availability of an intensity–duration curve for a given return period and for the geographical site of interest.

The first step consists of the estimation of the convectivity index (n) from the selected intensity–duration curve. Rainfall intensities for representative durations of 10 and 60 min are chosen to obtain the n-index value from Equation (2).

Next, the analytical relationship between the n-index and the shape parameter φ originally derived in Balbastre-Soldevila *et al.* (2021) can be used to estimate φ. Within this previous research, the maximum rainfall intensity for a given duration was determined as follows:

$$\mathrm{I}_{\Delta t} = \frac{i_0}{\Delta t} F(\varphi,\ \Delta t) \tag{3}$$

where

$$F(\varphi,\ \Delta t) = e^{1-\varphi\frac{\Delta t}{e^{\varphi\,\Delta t}-1}}\left[\left(\frac{\Delta t}{e^{\varphi\,\Delta t}-1}+\frac{1}{\varphi}\right) - e^{-\varphi\Delta t}\left(\frac{\Delta t}{e^{\varphi\,\Delta t}-1}+\Delta t+\frac{1}{\varphi}\right)\right] \tag{4}$$

Setting Equation (3) for $\Delta t = 10$ min and $\Delta t = 60$ min, the ratio between both intensities is given by:

$$\frac{I_{10}}{I_{60}} = \frac{60}{10}\frac{F(\varphi,\,10)}{F(\varphi,\,60)} \tag{5}$$

Finally, combining Equation (5) with Equation (2) yields the practical relationship between the n-index and the shape parameter, φ, of the G2P design storm:

$$n = 1 + 0.558\,\ln\frac{F(\varphi,\,10)}{F(\varphi,\,60)} \tag{6}$$

Given an n-index value, the associated shape parameter, φ, of the G2P design storm is obtained by solving Equation (6). The complete development of the former procedure was presented by Balbastre-Soldevila *et al.* (2021). Figure 1 shows the relationship between both parameters.

Higher values of φ are associated with stronger convectivity, i.e., higher I_{10}/I_{60} ratios. Typical design values of the parameter lie in the interval [0.08; 0.31] (García-Bartual & Andrés-Doménech 2017).

Finally, the third step of the methodology is the estimation of the remaining parameter of the G2P design storm. The peak intensity, i_0, can be solved through Equation (3) using either $\Delta t = 10$ min or $\Delta t = 60$ min, yielding the same numerical result. Figure 2 summarises the proposed methodology to obtain the G2P design storm parameters.

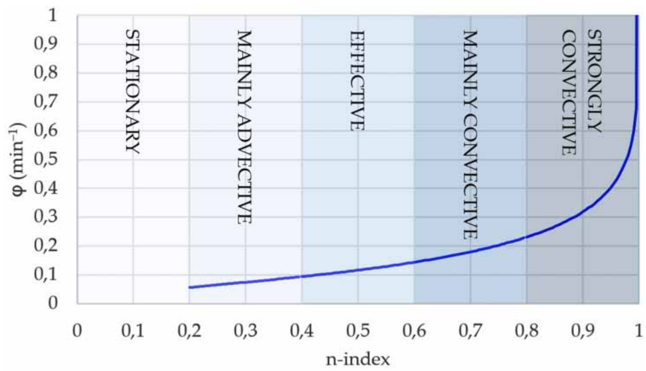


Figure 1 | Relationship between the *n*-index and parameter φ. Adapted from Balbastre-Soldevila *et al.* (2021).

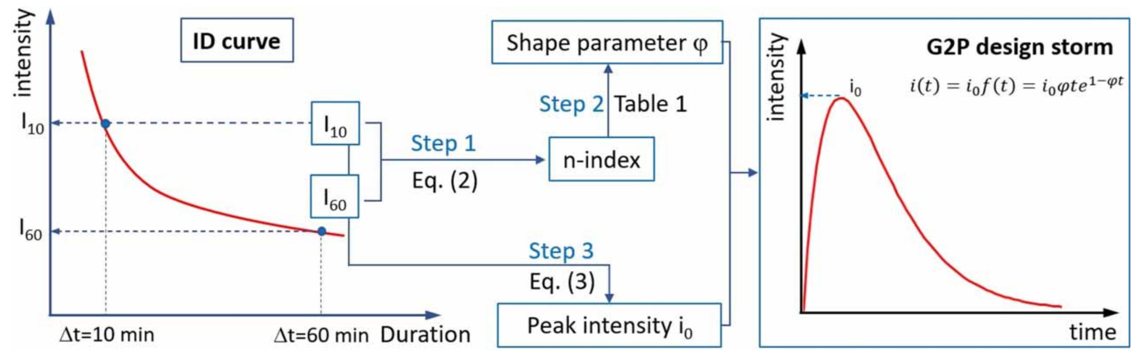


Figure 2 | Schematic summary of the proposed methodology.

STUDY AREA AND DATA

The proposed methodology was applied to the Valencian Region in Eastern Spain. The numbers in Figure 3 show the weather forecast areas of Castellón, Valencia, and Alicante provinces, established by the Meteorological State Agency of Spain (AEMET) in its warning system of adverse weather events (AEMET 2022). These areas distinguish between the inland and coastal areas of the aforementioned provinces. A previous study covering the same location (Camarasa Belmonte & Soriano 2015) highlighted the main factors influencing the probability of the generation of convective cells, in particular, the distance from the seacoast and the topography. According to the classification proposed by Waymire & Gupta (1981) and Waymire *et al.* (1984), such convective cells are characterised by a spatial extension of around 10 km^2, durations of 1 h or less, and rainfall intensities over 100 mm h^{-1}. The proximity to the sea enables a constant supply of humidity, while the increase in altitude causes an orographic shadow effect that forces unstable air flows to rise, triggering precipitation.

A regular 5×5 km^2 set of gridded points has been established within the study area. For each point that defines the grid, the required precipitation data are extracted from regional databases, described hereinafter, to estimate the parameters i_0 and φ of the G2P design storm.

I_{10} and I_{60} intensities for a given return period are needed at each of the defined points of the study area. In this particular application, the regional IDF database proposed by Salas Regalado (2004) was used. According to this database, the rainfall intensity for a given duration is expressed through Equation (7):

$$I_t = I_{24}\, h(T)\, K^{\frac{24^a - t^a}{24^a - 1}} \tag{7}$$

where I_t is the mean rainfall intensity for a given duration t, I_{24} is the expected annual maximum daily rainfall intensity (mm h^{-1}) for a given return period, and *h(T)* is a function involving the return period *T*, which is defined for the Mediterranean region

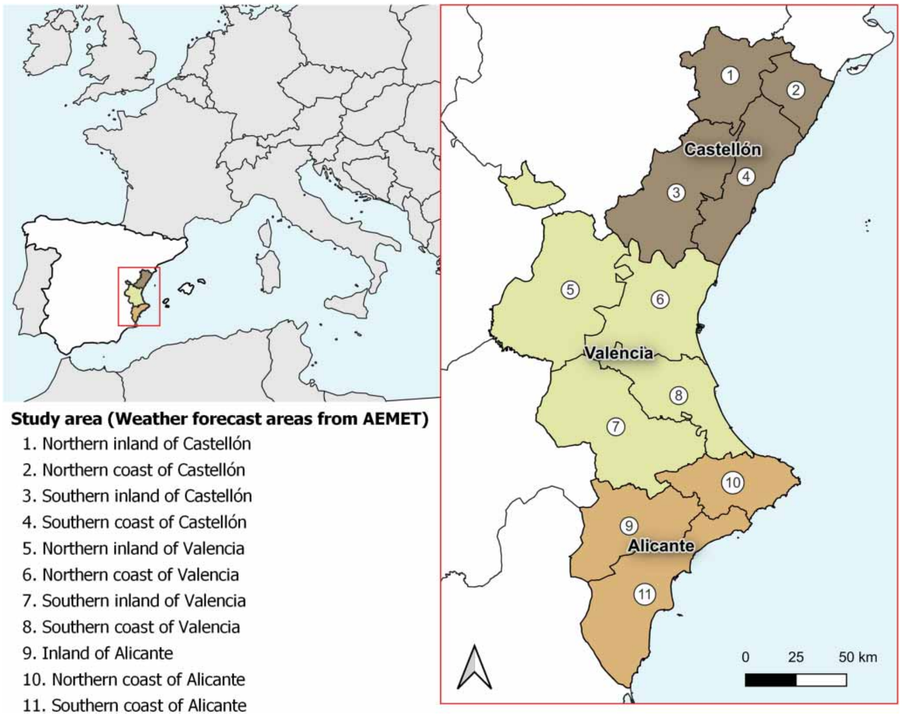


Figure 3 | Study area.

on the Iberian Peninsula as follows for durations of 1 h or less (Salas Regalado *et al.* 2007):

$$h(T) = -0.0004 \times (\ln(T))^2 + 0.0092 \times \ln(T) + 1.004 \quad (8)$$

where K is the ratio between the average annual maximum 1 h rainfall intensity ($\overline{I_1}$) and the average annual maximum daily rainfall intensity ($\overline{I_{24}}$). These K values are available for the Iberian Peninsula, after a regionalisation supported by a Geographical Information System (GIS) software (Salas Regalado 2004). a is the regionalised parameter available from the mentioned GIS (Salas Regalado 2004).

To obtain I_{24}, maximum daily rainfall values for a given return period are required. These values have been extracted from previous regionalisation studies extended to the Iberian Peninsula, in particular the work by Spain's Ministry of Transport, Mobility and Urban Agenda (Ministerio de Fomento 1999), updated with an observational grid with optimal interpolation for Spanish Iberia and the Balearic Islands (ROCIO_IBEB 5 km) developed by AEMET (Peral *et al.* 2017). The latter dataset consists of a regular 5×5 km^2 resolution gridded observational dataset for daily precipitation interpolated from more than 3,000 meteorological stations in mainland Spain and the Balearic Islands belonging to AEMET that covers the period from 1951 to 2021. AEMET used statistical interpolation analysis to generate the accumulated precipitation fields at a daily scale. According to the authors, this linear estimation method handles irregular distributions of observations well and minimises interpolation error with a correct formulation of the error statistics of the estimates from which it is based to create the analysed field (Peral *et al.* 2017).

The grid resolution has been set considering the spatial extent of the previously described convective cells in the study area and the effect that spatial variability has on the hydrological response in urban catchments. There are non-dimensional parameters in the literature that make it possible to analyse the correlation between the catchment and the storm characteristics, such as the watershed smearing ratio (Ogden & Julien 1994) and the runoff sampling number (Bruni *et al.* 2015). In the current study, the watershed smearing ratio has been obtained to set the grid resolution. When infiltration is negligible, as is the case in urban catchments, there may be significant hydrological modelling errors if the watershed smearing ratio, defined as the ratio of rainfall measurement length-to-basin length, is higher than 0.4 (Cristiano *et al.* 2017). In such cases, downscaling techniques should be applied to avoid this source of errors. According to this watershed smearing the ratio's reference value and considering an average urban catchment area of 149 km^2 for the cities of Alicante (201.3 km^2), Castelló de la Plana (111.3 km^2) and Valencia (134.6 km^2), the obtained watershed smearing ratio for a rainfall measurement grid of 5×5 km^2 is 0.17.

RESULTS

Following the proposed procedure explained in the Methodology section, the G2P design storm parameters (i_0, φ) for $T = 25$ years were estimated at the selected geographical gridded points. This return period was selected as it is the reference value for urban hydrology designs in the Valencia Region. Based on these parameters, interpolation by ordinary kriging was performed using SAGA GIS software. The resulting contour line maps for each parameter were built to present the results graphically and aid in extracting conclusions. Figure 4 includes the results obtained from the MLLDEP and ROCIO_IBEB datasets.

The shape parameter, φ, exhibits spatial variation, although this is not significant (Figure 4(a)). This parameter is shown to be constant for a given location, no matter the dataset/period considered in the analysis. This fact is clearly related to the nature of the shape parameter, which in essence represents the shape of the G2P design storm and, thus, is inherently linked to the changes in the internal structure of the rainfall intensities over time during the life of the associated convective cell producing the storm. As such, the value of the shape parameter is expected to be determined by the physical dynamics involved in the convective cell's internal structure, i.e., the growing, maturing, and decaying phases described in Moncho *et al.* (2009) and García-Bartual & Andrés-Doménech (2017). Concerning the scale parameter, i_0 (mm h^{-1}), the results from the MLLDEP dataset (Figure 4(b)) and ROCIO_IBEB dataset (Figure 4(c)) show a similar spatial distribution pattern in line with the observed rainfall behaviour in the study area, although the MLLDEP dataset provides greater i_0 values than the ROCIO_IBEB dataset. According to these results, G2P design storms derived for the inland areas depicted in Figure 3 would be more convective than those derived for the areas closer to the coast, although with a lower peak intensity, meaning that G2P design storms for coastal areas assume a higher intensity and volume than for inland areas. To illustrate this, Figure 5 shows two design storms obtained for two representative points of each area (inland vs. coastal areas). The G2P design storm parameters have been extracted from Figure 4(a)) and Figure 4(c)), as they contain the most up-to-date annual maximum rainfall value information. The representative point of the inland areas is among the highest values of the φ parameter and the lowest of the i_0 parameter. In contrast, the representative point of the coastal areas is one of the lowest values of the φ parameter, while the i_0 parameter is among the highest values. These results show a clearly noticeable difference in magnitude. The

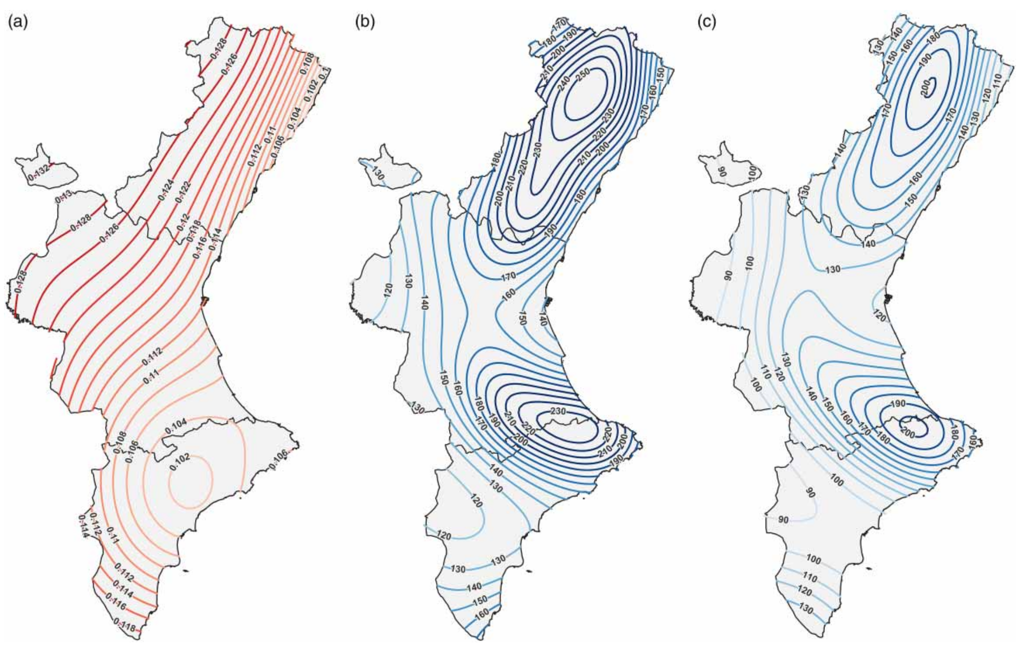


Figure 4 | Results from MLLDEP and ROCIO_IBEB datasets. (a) φ (min^{-1}) contour lines from the MLLDEP and ROCIO_IBEB datasets, (b) i_0 (mm h^{-1}) contour lines from the MLLDEP dataset, and (c) i_0 (mm h^{-1}) contour lines from the ROCIO_IBEB dataset.

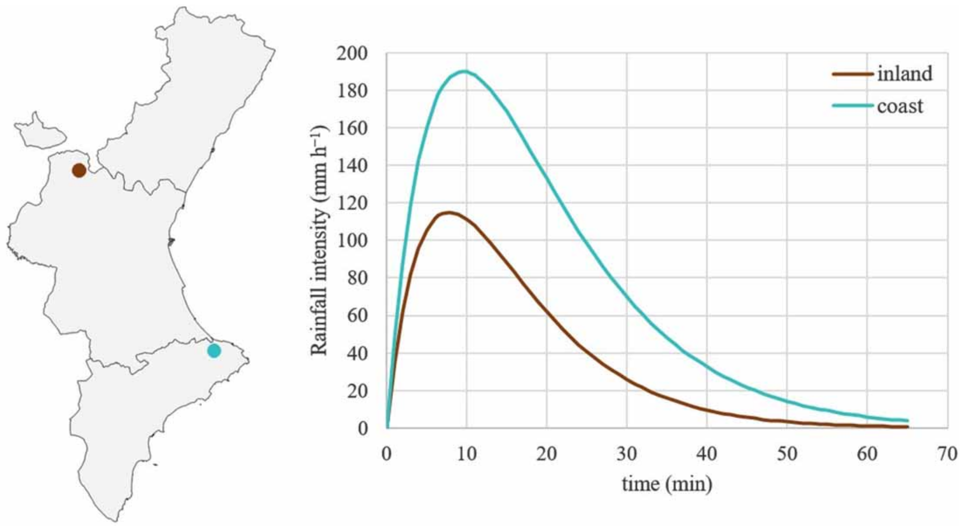


Figure 5 | G2P design storms for $T = 25$ years (comparison between inland and coastal locations).

volume of the inland G2P design storm is 50% lower than the volume obtained for the coastal point, despite its peak time value occurring 18% earlier and, strictly, the storm being a more convective event. This result might seem counterintuitive, but, as explained earlier, the whole storm pattern is mainly determined by the peak parameter, which is much more intense for the coastal location than the inland point. Table 1 summarises the G2P design storm values of each area's representative points.

DISCUSSION

The results suggest that the methodology is a practical tool for developing G2P design storms from regional datasets. It is important to note that the resolution of the grid is a key aspect to consider beforehand. The grid resolution must suit the spatial scale of the studied area. Thus, for urban drainage purposes, datasets are required with a high resolution in time and space. In this research, a 5×5 km^2 resolution grid was available from which to derive the G2P design storm parameters regionally from mean annual maximum daily rainfall values covering the 1951–2021 period.

The main limitation of the methodology is given by the region-specific scope of the G2P design storm itself. This synthetic storm reproduces the convective behaviour of observed historical storms in the Mediterranean coast of the Iberian Peninsula (García-Bartual & Andrés-Doménech 2017). However, its simple formulation through the scale and shape parameters presents strong advantages to reproduce convective episodes, which are becoming more frequent within larger areas in the whole country, even in larger areas of the Mediterranean basin (Llasat *et al.* 2016; Llasat 2021). Thus, this constraint could become a future research line to analyse if the methodology could be extended to other regions and overcome the region-specific scope, by checking the G2P fitting to other geographical areas. In particular, it is a known fact that there are many regions all over the world where maximum rainfall intensities derive mostly from convective episodes, especially along the mid-latitudes. In such cases, we should expect exciting possibilities to explore the application of G2P design storm methodology successfully.

Table 1 | Values of G2P design storm parameters and volume (inland vs. coastal points)

	Inland point	**Coastal point**
i_0 (mm h^{-1})	115.00	190.00
φ (min^{-1})	0.128	0.105
N	0.5454	0.4518
Volume, V (mm)	39.80	80.16
Peak time, t_p (min)	7.75	9.50

One of the main advantages of the G2P design storm is its versatility because it is possible to obtain the parameters based on the available information in each case. Comparison of the i_0 values obtained from the two databases (MLLDEP vs. updated values from the ROCIO_IBEB grid) yields a significant decrease in mean maximum rainfall intensities in the last 30 years. Values from the ROCIO_IBEB dataset are around 30–40 mm h^{-1} less than the values from the MLLDEP dataset. This fact gives a first indication of a possible trend due to the impact of climate change in the study area. This methodology makes it possible to obtain IDF curve projections under climate change scenarios, which is an important issue nowadays, as research in this area proves (Yan *et al.* 2020; Martel *et al.* 2021). For such purposes, regional databases information should be required for climate change scenarios, including uncertainty assessments.

CONCLUSIONS

Databases of regionalised information describing the main precipitation features over a region (i.e., IDF curves and maximum daily rainfall) allow estimation of G2P design storm parameters through a simple procedure developed within this research. Therefore, for any geographical point inside the analysed region, building an analytical representative design storm for a given return period for use in urban drainage studies applications is feasible.

The proposed methodological framework allows for a simple adaptation from available databases to assess design storm rainfall features based on the G2P formulation. In future, more up-to-date databases could be easily employed in the same manner for regional urban hydrology studies. For example, the Centre for Hydrographic Studies in Spain (CEH) is now updating two technical guidance documents for Spain with updated maximum daily rainfall maps and also the IDF curves set in Standard 5.2-IC of the Superficial Drainage of the Highway Instruction (Ministerio de Obras Públicas y Urbanismo. Gobierno de España 2016). This updated information can be used to apply the methodology and obtain updated design storms.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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