

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

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ABSTRACT

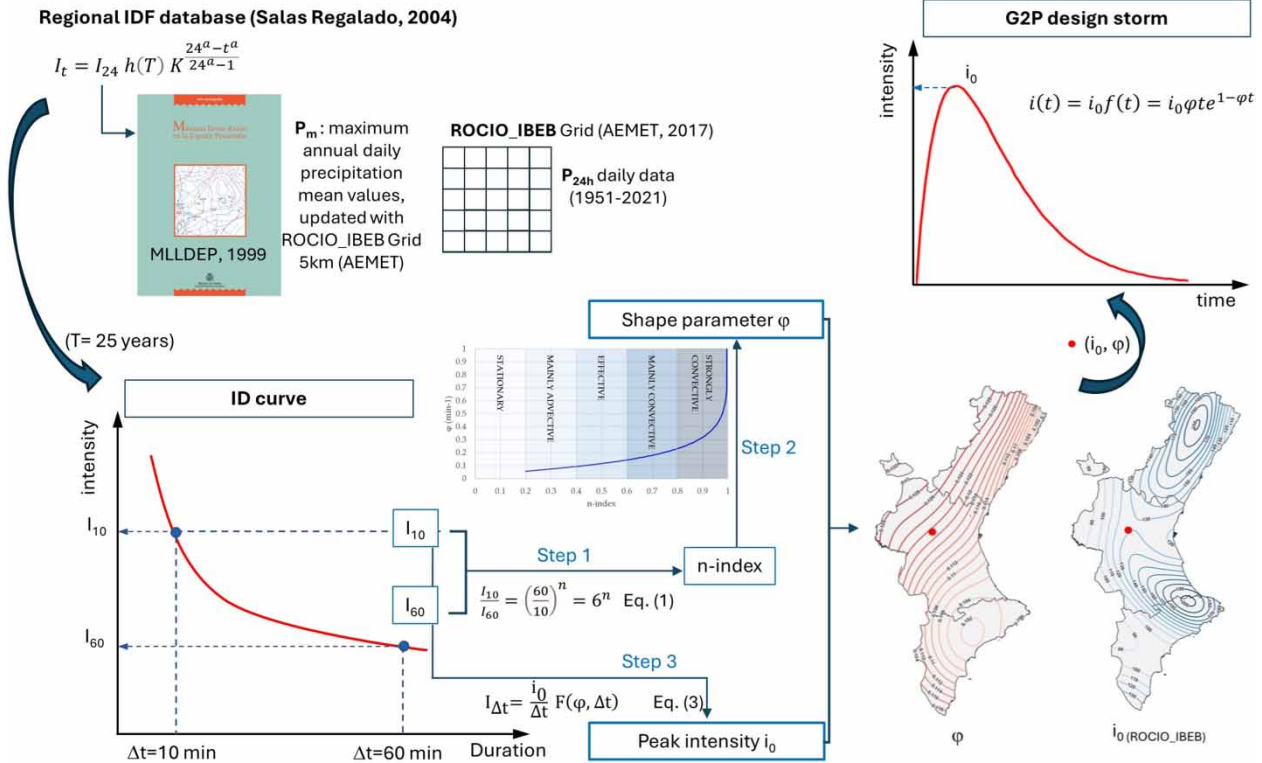
A significant amount of information on regional rainfall characteristics is available nowadays, allowing its use in hydrological applications. This article is motivated by the availability of regional studies regarding maximum daily rainfall and intensity–duration–frequency curves that can be coupled 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.

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

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:

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

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:

$$I_{\Delta t} = \frac{i_0}{\Delta t} F(\varphi, \Delta t) \quad (3)$$

where

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

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

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

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:

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

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.

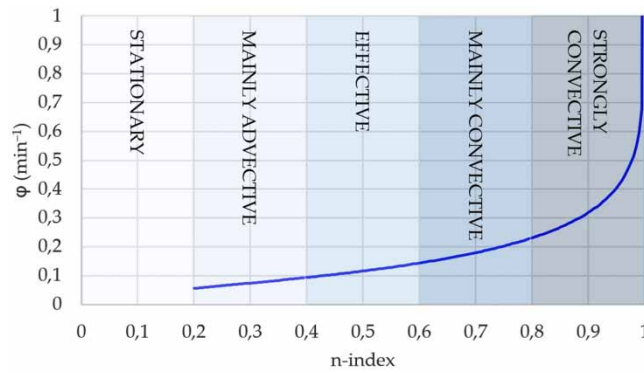


Figure 1 | Relationship between the n -index and parameter φ . Adapted from Balbastre-Soldevila *et al.* (2021).

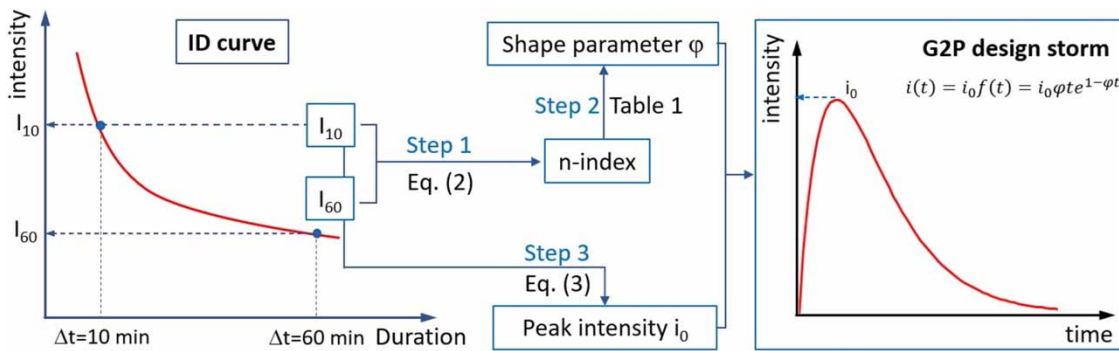


Figure 2 | Schematic summary of the proposed methodology.

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 km², 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 km² 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

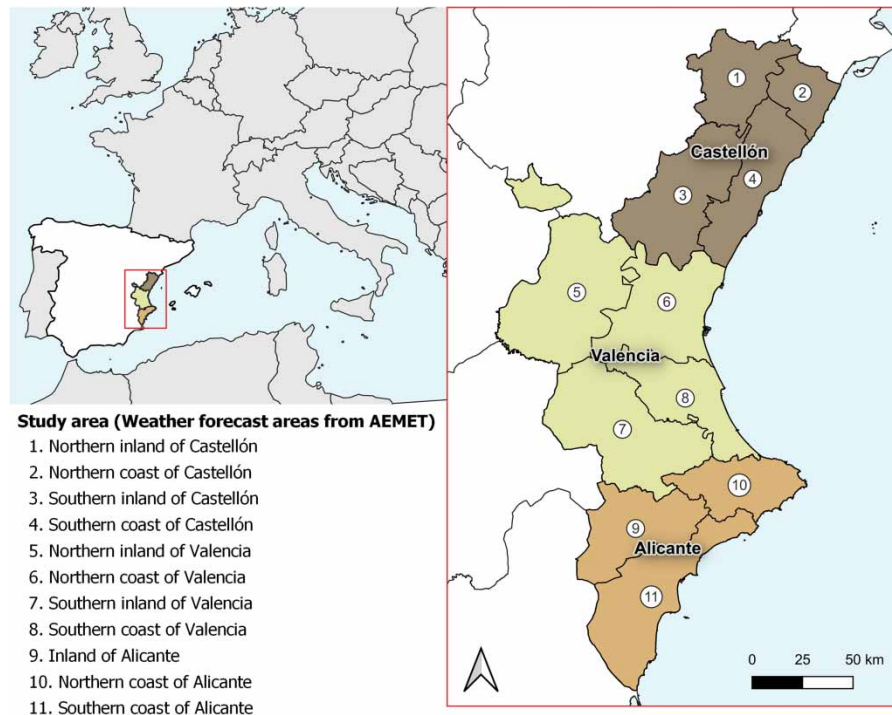


Figure 3 | Study area.

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 (\bar{I}_1) and the average annual maximum daily rainfall intensity (\bar{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 $5 \times 5 \text{ km}^2$ 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 km² for the cities of Alicante (201.3 km²), Castelló de la Plana (111.3 km²) and Valencia (134.6 km²), the obtained watershed smearing ratio for a rainfall measurement grid of 5 × 5 km² 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

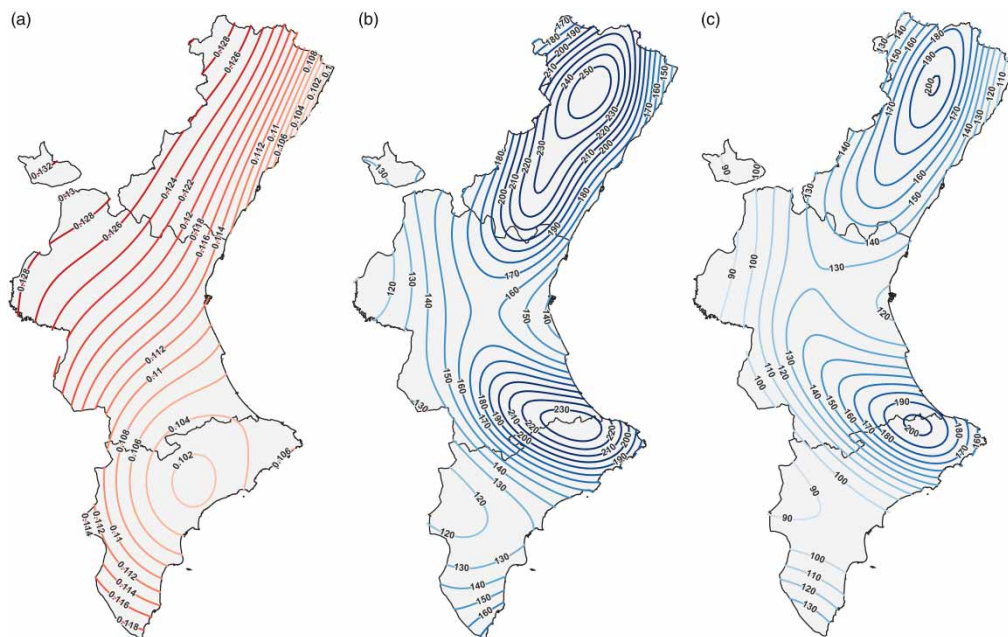


Figure 4 | Results from MLLDEP and ROCIO_IBEB datasets. (a) φ (min⁻¹) contour lines from the MLLDEP and ROCIO_IBEB datasets, (b) i_0 (mm h⁻¹) contour lines from the MLLDEP dataset, and (c) i_0 (mm h⁻¹) contour lines from the ROCIO_IBEB dataset.

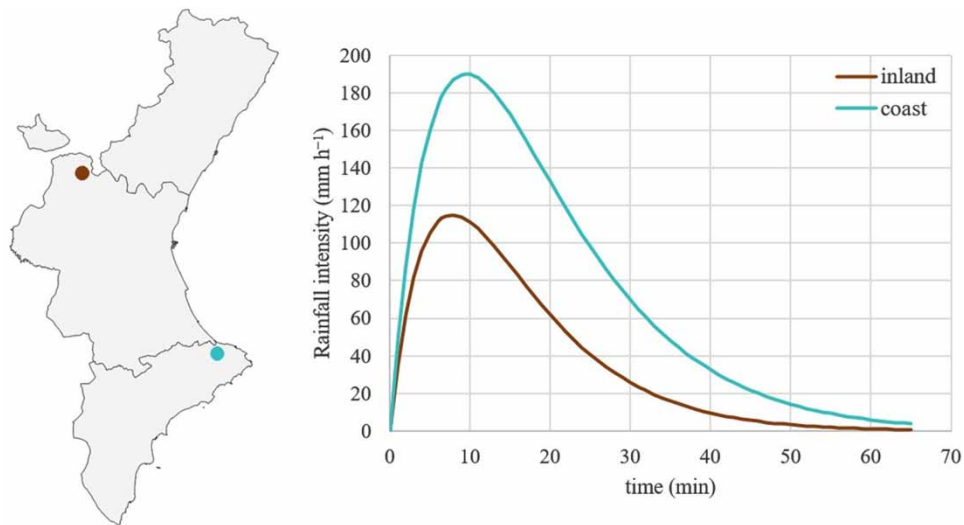


Figure 5 | G2P design storms for $T = 25$ years (comparison between inland and coastal locations).

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 $5 \times 5 \text{ km}^2$ 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.

REFERENCES

- Adamowski, K., Alila, Y. & Pilon, P. J. 1996 Regional rainfall distribution for Canada. *Atmospheric Research* **42** (1–4), 75–88. [https://doi.org/10.1016/0169-8095\(95\)00054-2](https://doi.org/10.1016/0169-8095(95)00054-2).
- AEMET 2022 Plan Nacional de Predicción y Vigilancia de Fenómenos Meteorológicos Adversos (METEOALERTA). Available from: <https://www.aemet.es/es/eltiempo/prediccion/avisos/ayuda/> (accessed 25 September 2022).
- Balbastre-Soldevila, R., García-Bartual, R. & Andrés-Doménech, I. 2019 A comparison of design storms for urban drainage system applications. *Water (Switzerland)* **11**, 4. <https://doi.org/10.3390/w11040757>.
- Balbastre-Soldevila, R., García-Bartual, R. & Andrés-Doménech, I. 2021 Estimation of the G2P design storm from a rainfall convectivity index. *Water (Switzerland)* **13**, 14. <https://doi.org/10.3390/w13141943>.
- Bharath, R. & Srinivas, V. V. 2015 Regionalization of extreme rainfall in India. *International Journal of Climatology* **35** (6), 1142–1156. <https://doi.org/10.1002/joc.4044>.
- Bruni, G., Reinoso, R., Van De Giesen, N. C., Clemens, F. H. L. R. & Ten Veldhuis, J. A. E. 2015 On the sensitivity of urban hydrodynamic modelling to rainfall spatial and temporal resolution. *Hydrology and Earth System Sciences* **19** (2), 691–709. <https://doi.org/10.5194/hess-19-691-2015>.
- Camarasa Belmonte, A. M. & Soriano, J. 2015 La intensidad de lluvia en entornos mediterráneos. Valores extremos según la escala de observación. *Boletín de La Asociación de Geógrafos Españoles* **68**, 279–300. (Rainfall intensity in Mediterranean environments: Extreme values according to the observation scale. Bulletin of the Association of Spanish Geographers, 68, 279–300). <https://doi.org/10.21138/bage.1862>.

- Cardoso, C. O., Bertol, I., Soccol, O. J. & Sampaio, C. A. D. P. 2013 Generation of intensity duration frequency curves and intensity temporal variability pattern of intense rainfall for Lages/SC. *Brazilian Archives of Biology and Technology* **57** (2), 274–283. <https://doi.org/10.1590/S1516-89132013005000014>.
- Chavan, S. R. & Srinivas, V. V. 2017 Regionalization based envelope curves for PMP estimation by Hershfield method. *International Journal of Climatology* **37** (10), 3767–3779. <https://doi.org/10.1002/joc.4951>.
- Chen, J. & Brissette, F. P. 2014 Comparison of five stochastic weather generators in simulating daily precipitation and temperature for the Loess Plateau of China. *International Journal of Climatology* **34** (10), 3089–3105. <https://doi.org/10.1002/joc.3896>.
- Cristiano, E., Ten Veldhuis, M. C. & Van De Giesen, N. 2017 Spatial and temporal variability of rainfall and their effects on hydrological response in urban areas – a review. *Hydrology and Earth System Sciences* **21** (7), 3859–3878. <https://doi.org/10.5194/hess-21-3859-2017>.
- Darwish, M. M., Fowler, H. J., Blenkinsop, S. & Tye, M. R. 2018 A regional frequency analysis of UK sub-daily extreme precipitation and assessment of their seasonality. *International Journal of Climatology* **38** (13), 4758–4776. <https://doi.org/10.1002/joc.5694>.
- Emmanouil, S., Langousis, A., Nikolopoulos, E. I. & Anagnostou, E. N. 2020 Quantitative assessment of annual maxima, peaks-over-threshold and multifractal parametric approaches in estimating intensity-duration-frequency curves from short rainfall records. *Journal of Hydrology* **589**, 125151. <https://doi.org/10.1016/j.jhydrol.2020.125151>.
- European Commission 2012 *Guidelines on Best Practice to Limit, Mitigate or Compensate Soil Sealing*. Available from: <https://circabc.europa.eu/ui/group/54d2e010-4fc4-4962-9113-1e7d574f4a46/library/ca21940a-44ea-4e0e-bb13-595c26667fc8/details> (accessed on 20 November 2022).
- 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** (1), 655–672. <https://doi.org/10.5194/hess-22-655-2018>.
- Ganguli, P. & Coulibaly, P. 2019 Assessment of future changes in intensity-duration-frequency curves for Southern Ontario using North American (NA)-CORDEX models with nonstationary methods. *Journal of Hydrology: Regional Studies* **22**, 100587. <https://doi.org/10.1016/j.ejrh.2018.12.007>.
- García-Bartual, R. & Andrés-Doménech, I. 2017 A two-parameter design storm for Mediterranean convective rainfall. *Hydrology and Earth System Sciences* **21** (5), 2377–2387. <https://doi.org/10.5194/hess-21-2377-2017>.
- Gellens, D. 2002 Combining regional approach and data extension procedure for assessing GEV distribution of extreme precipitation in Belgium. *Journal of Hydrology* **268** (1–4), 113–126. [https://doi.org/10.1016/S0022-1694\(02\)00160-9](https://doi.org/10.1016/S0022-1694(02)00160-9).
- Ghanmi, H., Bargaoui, Z. & Mallet, C. 2016 Estimation of intensity-duration-frequency relationships according to the property of scale invariance and regionalization analysis in a Mediterranean coastal area. *Journal of Hydrology* **541**, 38–49. <https://doi.org/10.1016/j.jhydrol.2016.07.002>.
- Ghiaei, F., Kankal, M., Anilan, T. & Yuksek, O. 2018 Regional intensity–duration–frequency analysis in the Eastern Black Sea Basin, Turkey, by using L-moments and regression analysis. *Theoretical and Applied Climatology* **131** (1–2), 245–257. <https://doi.org/10.1007/s00704-016-1953-0>.
- Guerreiro, S., Glenis, V., Dawson, R. & Kilsby, C. 2017 Pluvial flooding in European cities – A continental approach to urban flood modelling. *Water* **9** (4), 296. <https://doi.org/10.3390/w9040296>.
- Hailegeorgis, T. T., Thorolfsson, S. T. & Alfredsen, K. 2013 Regional frequency analysis of extreme precipitation with consideration of uncertainties to update IDF curves for the city of Trondheim. *Journal of Hydrology* **498**, 305–318. <https://doi.org/10.1016/J.JHYDROL.2013.06.019>.
- Hosseinzadehtalaei, P., Tabari, H. & Willems, P. 2018 Precipitation intensity–duration–frequency curves for central Belgium with an ensemble of EURO-CORDEX simulations, and associated uncertainties. *Atmospheric Research* **200**, 1–12. <https://doi.org/10.1016/j.atmosres.2017.09.015>.
- Hou, D., Charles, M., Luo, Y., Toth, Z., Zhu, Y., Krzysztofowicz, R., Lin, Y., Xie, P., Seo, D.-J., Pena, M. & Cui, B. 2014 Climatology-Calibrated precipitation analysis at fine scales: Statistical adjustment of stage IV toward CPC gauge-Based analysis. *Journal of Hydrometeorology* **15** (6), 2542–2557. <https://doi.org/10.1175/JHM-D-11-0140.1>.
- Llasat, M. C. 2021 Floods evolution in the mediterranean region in a context of climate and environmental change. *Geographical Research Letters* **47** (1), 13–32. <https://doi.org/10.18172/cig.4897>.
- Llasat, M. C., Marcos, R., Turco, M., Gilabert, J. & Llasat-Botija, M. 2016 Trends in flash flood events versus convective precipitation in the Mediterranean region: The case of Catalonia. *Journal of Hydrology* **541**, 24–37. <https://doi.org/10.1016/j.jhydrol.2016.05.040>.
- Madsen, H., Gregersen, I. B., Rosbjerg, D. & Arnbjerg-Nielsen, K. 2017 Regional frequency analysis of short duration rainfall extremes using gridded daily rainfall data as co-variate. *Water Science and Technology* **75** (8), 1971–1981. <https://doi.org/10.2166/wst.2017.089>.
- Martel, J.-L., Brissette, F. P., Lucas-Picher, P., Troin, M. & Arsenault, R. 2021 Climate change and rainfall intensity–duration–frequency curves: Overview of science and guidelines for adaptation. *Journal of Hydrologic Engineering* **26**, 10. [https://doi.org/10.1061/\(asce\)he.1943-5584.0002122](https://doi.org/10.1061/(asce)he.1943-5584.0002122).
- McRobie, F. H., Wang, L.-P., Onof, C. & Kenney, S. 2013 A spatial-temporal rainfall generator for urban drainage design. *Water Science and Technology* **68** (1), 240–249. <https://doi.org/10.2166/wst.2013.241>.
- Ministerio de Fomento 1999 *Máximas luvias diarias en España Peninsular* (Maximum daily rainfall in Peninsular Spain). General Directorate of Highways. Monographic series of the Ministry of Development) Madrid, Spain. https://www.transportes.gob.es/recursos_mfom/0610300.pdf (accessed 3 July 2024).

- Ministerio de Obras Públicas y Urbanismo. Gobierno de España 2016 Orden FOM/298/2016, de 15 de febrero, por la que se aprueba la norma 5.2 - IC drenaje superficial de la Instrucción de Carreteras. Boletín Oficial Del Estado, 60, de 10 de marzo, 18882–19023. (Ministry of Public Works and Urban Planning. Government of Spain. (2016). Order FOM/298/2016, of 15 February, approving standard 5.2 - IC surface drainage of the Highway Instruction. Official State Gazette, 60, of 10 March, 18882–19023) <https://doi.org/BOE-A-2012-5405>.
- Moncho, R., Belda, F. & Caselles, V. 2009 Climatic study of the exponent 'n' in IDF curves: Application for the Iberian Peninsula. *Journal of Weather & Climate of the Western Mediterranean* **6**, 3–14. <https://doi.org/10.3369/tethys.2009.6.01>.
- Monjo, R. 2016 Measure of rainfall time structure using the dimensionless n-index. *Climate Research* **67** (1), 71–86. <https://doi.org/10.3354/cr01359>.
- Monjo, R. & Martin-Vide, J. 2016 Daily precipitation concentration around the world according to several indices. *International Journal of Climatology* **36** (11), 3828–3838. <https://doi.org/10.1002/joc.4596>.
- Myhre, G., Alterskjær, K., Stjern, C. W., Hodnebrog, Ø., Marelle, L., Samset, B. H., Sillmann, J., Schaller, N., Fischer, E., Schulz, M. & Stohl, A. 2019 Frequency of extreme precipitation increases extensively with event rareness under global warming. *Scientific Reports* **9** (1), 1–10. <https://doi.org/10.1038/s41598-019-52277-4>.
- Ogden, F. L. & Julien, P. Y. 1994 Runoff model sensitivity to radar rainfall resolution. *Journal of Hydrology* **158** (1–2), 1–18. [https://doi.org/10.1016/0022-1694\(94\)90043-4](https://doi.org/10.1016/0022-1694(94)90043-4).
- Pan, F., Nagaoka, L., Wolverton, S., Atkinson, S. F., Kohler, T. A. & O'Neill, M. 2021 A constrained stochastic weather generator for daily mean air temperature and precipitation. *Atmosphere* **12** (2), 135. <https://doi.org/10.3390/atmos12020135>.
- Peleg, N., Blumensaat, F., Molnar, P., Fatichi, S. & Burlando, P. 2017 Partitioning the impacts of spatial and climatological rainfall variability in urban drainage modeling. *Hydrology and Earth System Sciences* **21** (3), 1559–1572. <https://doi.org/10.5194/hess-21-1559-2017>.
- Peral, C., Navascués, B. & Ramos-Calzado, P. 2017 Serie de precipitación diaria en rejilla con fines climáticos. Nota Técnica 24 de AEMET. (Gridded daily precipitation series for climatic purposes. AEMET Technical Note 24). <https://doi.org/10.31978/014-17-009-5>.
- Petroselli, A., De Luca, D. L., Młyński, D. & Wałęga, A. 2022 Modelling annual maximum daily rainfall with the STORAGE (STOchastic RAInfall GEnerator) model. *Hydrology Research* **53** (4), 547–561. <https://doi.org/10.2166/nh.2022.100>.
- Salas Regalado, L. d. 2004 *Regionalización de leyes IDF para el uso de modelos hidrometeorológicos de estimación de caudales*. Universidad Politécnica de Madrid. (Regionalization of IDF laws for the use of hydrometeorological models for flow estimation. Polytechnic University of Madrid).
- Salas Regalado, L. d., Carrero Díez, L. & Fernandez Yuste, J. A. 2007 MAXIN: Aplicación SIG para la estimación de valores Intensidad-Duración-Frecuencia de precipitaciones en la España peninsular. *Ingeniería Civil* **146**, 137–143. (MAXIN: GIS application for the estimation of Intensity-Duration-Frequency values of precipitation in peninsular Spain. Civil Engineering, 146, 137–143).
- Seneviratne, S. I., Nicholls, N., Easterling, D., Goodess, C. M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X., 2012 Changes in climate extremes and their impacts on the natural physical environment. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K. L., Mastrandrea, M. D., Mach, K. J., Plattner, G.-K., Allen, S. K., Tignor, M. & Midgley, P. M., eds.). A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 109–230. <https://doi.org/10.7916/d8-6nbt-s431>.
- Silva, D. F., Simonovic, S. P., Schardong, A. & Goldenfum, J. A. 2021 Assessment of non-stationary IDF curves under a changing climate: Case study of different climatic zones in Canada. *Journal of Hydrology: Regional Studies* **36** (July), 100870. <https://doi.org/10.1016/j.ejrh.2021.100870>.
- Thorndahl, S. & Andersen, C. B. 2021 CLIMACS: A method for stochastic generation of continuous climate projected point rainfall for urban drainage design. *Journal of Hydrology* **602**, August. <https://doi.org/10.1016/j.jhydrol.2021.126776>.
- Wallis, J. R., Schaefer, M. G., Barker, B. L. & Taylor, G. H. 2007 Regional precipitation-frequency analysis and spatial mapping for 24-hour and 2-hour durations for Washington State. *Hydrology and Earth System Sciences* **11** (1), 415–442. <https://doi.org/10.5194/hess-11-415-2007>.
- Waymire, E. & Gupta, V. K. 1981 The mathematical structure of rainfall representations: 1. A review of the stochastic rainfall models. *Water Resources Research*. <https://doi.org/10.1029/WR017i005p01261>.
- Waymire, E., Gupta, V. K. & Rodriguez-Iturbe, I. 1984 A spectral theory of rainfall intensity at the Meso- β Scale. *Water Resources Research* **20** (10), 1453–1465. <https://doi.org/10.1029/WR020i010p01453>.
- Westra, S., Fowler, H. J., Evans, J. P., Alexander, L. V., Berg, P., Johnson, F., Kendon, E. J., Lenderink, G. & Roberts, N. M. 2014 Future changes to the intensity and frequency of short-duration extreme rainfall. *Reviews of Geophysics* **52** (3), 522–555. <https://doi.org/10.1002/2014RG000464>.
- Yan, H., Sun, N., Chen, X. & Wigmosta, M. S. 2020 Next-generation intensity-duration-frequency curves for climate-resilient infrastructure design: Advances and opportunities. *Frontiers in Water* **2**. <https://doi.org/10.3389/frwa.2020.545051>.
- Yeo, M. H., Frei, A., Gelda, R. K. & Owens, E. M. 2020 A stochastic weather model for generating daily precipitation series at ungauged locations in the Catskill Mountain region of New York state. *International Journal of Climatology* **40** (2), 687–705. <https://doi.org/10.1002/joc.6230>.