Climate change impacts in the design of drainage systems: case study of Portugal

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Climate change impacts in the design of drainage systems – A case study for Portugal

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Abstract

This study aims to assess the necessity of updating the Intensity-Duration-Frequency (*IDF*) curves used in Portugal to design building storm-water drainage systems. A comparative analysis of the design was performed for the three pre-defined rainfall regions in Portugal using the *IDF* curves currently in use and estimated for future decades. Data for recent and future climate conditions simulated by a global/regional climate model chain (ECHAM5/MPI-OM1/COSMO-CLM) are used to estimate possible changes of rainfall extremes and its implications for the drainage systems. The methodology includes the disaggregation of precipitation up to sub-hourly scales, the robust development of *IDF* curves and the correction of model bias. Obtained results indicate that projected changes are largest for the plains in Southern Portugal (5 – 33%) than for mountainous regions (3 – 9%) and that these trends are consistent with projected changes in the long term 95th-percentile of the daily precipitation throughout the 21st century. We conclude for the need to review the current precipitation regime classification and change the new drainage systems towards larger dimensions to mitigate the projected changes in extreme precipitation.

ASCE Subject Headings: Climate change, Hydraulic design, Drainage systems, Precipitation, Portugal

Author keywords: IDF curves; Climate change; Drainage systems design; Extreme precipitation.

Introduction

The recent IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC 2012) have recently provided evidence that the intensity of extreme precipitation may increase even in areas where total precipitation decreases (Diodato et al. 2011; IPCC 2012). This implies shorter return periods for extreme rainfall. In particular, the changes in the water cycle are likely change the frequency and intensity of floods and droughts for many parts of the world (IPCC 2012); hence, the knowledge of the regime of heavy precipitation in regional terms both under recent and future climate conditions is critical (Beijo et al. 2005; IPCC 2012).

From the engineering point of view, empirical approaches are used to link extremes of precipitation with physical structures. The Intensity-Duration-Frequency (*IDF*) curves represent key information for the design of urban and building storm-water drainage systems, as they provide maximum precipitation intensity related to a given length and a given return period (Brandão et al. 2001). The *IDF* curves are mathematically described by the power law behaviour dependence of the precipitation intensity (I) of the duration (t),

$$I = a \times t^b \quad (1)$$

where a and b are the *IDF* parameters. In Portugal, the designers of building storm-water drainage systems work according to the Portuguese law (DR 1995), which stipulates the *IDF* curves developed by Matos and Silva (1986). However, long-term trends in rainfall intensities and the projected climate change in terms of the water cycle fosters the assessment of the impact of extreme precipitation in the current and future design of building storm-water drainage systems and the possible update of *IDF* curves (e.g. Fowler and Kilsby 2003 and Vasiljevic et al. 2012). Recently, the impact of climate change on *IDF* curves have been assessed in several studies performed for the U.S. and Canada (Mailhot et al. 2007; Peck et al. 2012; Zhu et al. 2012; Das et al. 2013; Zhu 2013; Zhu et al. 2013). However, these studies did not assess the possible consequences of such changes to the design of building storm-water drainage systems as the one conducted in northern Europe, for the sewer system of Fredrikstad, Norway by Nie et al. (2009).

Global circulation models (GCM) and regional climate models (RCM) are important tools to study the impact of climate change on meteorological, chemical, hydrological and hydraulic processes. Given pre-defined scenarios of the world development, these models provide projections of different meteorological variables for possible future conditions of the climate system (Meehl et al. 2007; Taylor et al. 2012). The GCMs used for these climate projections have typically resolutions of 100-300 km, which is typically too low for direct use of model output in regional studies. Downscaling techniques, using RCMs, statistical downscaling or a combination of both have been used to obtain results at a finer spatial and temporal time scale (e.g. Maraun et al. 2010). Furthermore, model biases towards the real climate conditions must be adequately assessed, interpreted and corrected before applications can be performed.

In the specific case of urban building drainage systems, the design requires knowledge of rainfall depth intensity values over short periods of time (between minutes to hours). On this assumption, it is necessary to use appropriate methodology capable of performing the disaggregation of daily precipitation depth in sub-daily and sub-hourly precipitation (e.g., Pui et al. 2012). A possible approach is the method of the fragments, introduced by Svanidze in the 1960s (Svanidze 1964, Svanidze 1980), as it is a commonly used method in the precipitation disaggregation (Sharif and Burn, 2007;

Arganis-Juárez et al. 2008) used to obtain the disaggregation coefficients presented in Brandão et al. (2001), which is an official publication of the national Directorate of Services of Water Resources with the results of the analysis of extreme precipitation in Continental Portugal.

Several studies have assessed the impact of climate change on the design of drainage systems, using model simulations/climate scenarios, with converging results in different parts of the world towards increased precipitation intensity and the potential under-designing of drainage systems (e.g. Nie et al 2009; Rosenberg et al. 2010; He et al. 2011; Rosenzweig et al. 2007). Some of these studies have provided evidence that the design of building storm-water drainage systems may be inadequate or at least under designed for future climate conditions.

The purpose of this study is the assessment of possible changes in the *IDF* curves and consequent designing of building storm-water drainage systems as a result of changes in the distribution of extreme values of precipitation intensity due to the projected climate change for Continental Portugal. Section 2 deals with description of the data and the methodology used in this study. Results are presented and discussed in section 3. Finally, section 4 is devoted to the conclusions.

Material and Methods

Database / Data analysis

In this work, the characterization of intense precipitation was substantiated with three distinct databases. The first database consist of hourly precipitation time series obtained from the database of the *Sistema Nacional de Informação e Recursos Hídricos* [National System of Water Information and Resources] (SNIRH) for previously selected weather stations, with the purpose of being representative of the three rainfall areas defined in Matos and Silva (1986), (Fig. 1) and present in the Portuguese Regulation-decree n.º 23/95 of August 23 (DR 1995). The selection criteria were based on longevity and quality the historical series of hourly precipitation values (Table 1). Time series cover between 8.2 (Castelo Melhor) and 12 (Covilhã) consecutive years, which corresponds to 72 000 and 93 000 records, and have less than 5% of missing values, excepting for stations located in mountainous rainfall region C (Covilhã and Pega) but even so, with the 2nd and 3rd largest number of observed values (92 860 and 84 430 records).

With the aim to characterize the spatial distribution of extreme daily precipitation over Continental Portugal, a second database of observed daily rainfall used in this study: The most recent 8.0 version of the E-OBS gridded dataset (0.25 degree regular lat-lon grid), released in April 2013 by ECA&D (http://www.ecad.eu) project (Haylock et al. 2008).

Finally, the third database consists of precipitation data simulated by the COSMO-CLM [COnsortium for Small-scale MOdelling and Climate Limited-area Modelling Community] (Rockel et al. 2008) regional climate model (RCM). The simulations are run with ECHAM5/MPI-OM1 boundary conditions for recent climate conditions (20C, 1961 – 2000) and for two SRES scenarios (Nakicenovic et al. 2000), A1B and B1 (2000 – 2100). The resolutions of the rainfall data is roughly 18 km (0.165° latitude) and 6-hourly. For this study, data for the spatial sub-domain defined between 36.6º N – 42.4° N and 6.2° W – 9.8° W is considered as it encompasses Portugal and the nearby areas. The COSMO-CLM model has demonstrated its capacity to model the weather and climate conditions, particularly temperature and precipitation, in different regions of Europe. Furthermore, it has been used in several climate change studies analysing changes of precipitation over Europe (e.g., Haslinger et al. 2012; Kotlarski et al. 2012) and specifically in Portugal (Costa et al. 2012).

Precipitation indices suggested by the joint project Commission for Climatology/Climate Variability and Predictability (CLIVAR)/Joint WMO/IOC Technical Commission for Oceanography and Marine Meteorology Expert Team on Climate Change Detection and Indices (Frich et al. 2002; Karl et al. 1999; Peterson 2005) are used to study climate change scenarios for precipitation extremes in Portugal (cf. also Costa et al. 2012).

Aggregation and disaggregation of precipitation

The precipitation datasets described in the previous section are not available on time scales adequate for this study. Consequently, it was necessary to use methods of aggregation and disaggregation of precipitation, in order to have data of maximum precipitation for the duration of 5 min, 10 min, 15 min, 30 min, 1 h, 2 h, 6 h, 12 h, 24 h and 48 h. The aggregation process consisted on the use of precipitation depth values obtained for smaller sampling durations to calculate precipitation depth values for higher durations. For example, having hourly precipitation depth, it is rather easy to obtain precipitation depth for 2, 6, 12, 24 and 48 h, simply by summing hourly values that integrate the desired duration. This procedure was adopted for both databases (observed and simulated), for higher durations than the sample ones. The disaggregation of COSMO-CLM daily data to sub-daily data, namely, 1, 2, 6 and 12 h, was performed using the method of fragments or coefficients of disaggregation of the maximum precipitation values. Fragments (w_i) are the fraction of daily precipitation that occurred at a given hour of the day (h_i),

$$w_i = \frac{h_i}{\sum_{i=1}^{24} h_i} \quad (2)$$

Consequently, the sum of the coefficients (w_i) for the 24 hours of the day is equal to the unit. Then, to estimate the precipitation depth in each hour of the day (h_i'), the corresponding fragment (w_i) is multiplied by the daily precipitation depth (d),

$$h_i' = w_i \times d \quad (3)$$

This disaggregation procedure assures that the hourly precipitation estimation (h_i') does not change the total daily precipitation. The disaggregation fragments for 1, 2, 6 and 12 hours were estimated from the hourly observed data by using the Equation (2). Fragments for each duration were computed and sorted in descending order, revealing that the arithmetic averages computed for 50, 100 and 200 highest values were very similar, and were adopted as the values of the coefficients of disaggregation, w_i. This disaggregation procedure assures that the adopted fragments allow an adequate estimation of the maximum precipitation depth for each duration while retaining consistency with the observed data. The adopted coefficients of disaggregation w_i were then applied to daily simulated data by the COSMO-CLM model using Equation (3) to estimate maximum precipitation depth for 1, 2, 6 and 12 hours for each cell of the model grid. This procedure was applied for to the recent and the future periods. The inexistence of observed precipitation data for sub-hourly sampling time compel the disaggregation precipitation process for these temporal scales to rely on the fragments obtained from the relationship between hourly and sub-hourly precipitation proposed for Portugal by Brandão et al. (2001). These disaggregation coefficients are in good agreement with those proposed in the Guide to Hydrological Practices of the World Meteorological Organization and studies performed by the Portuguese Meteorological Institute.

Intensity-Duration-Frequency Curves

The development of *IDF* curves that consider future climate conditions is critical for the adequate design of building storm-water drainage systems, as it would allow mitigating a possible change in the frequency and intensity of floods, and thus reducing the damage associated with them. The methodology followed to develop the *IDF* curves is equivalent to the estimation of the a and b parameters (Equation (1)), which includes the: (i) computation of maximum precipitation intensity time series for each of ten durations (5, 10, 15 and 30 min and 1, 2, 6, 12, 24 and 48 h); (ii) fitting of the Gumbel distribution function to those time series, which mean estimate the location (μ) and scale (σ) parameters in each case (cf. Coles 2001); (iii) estimation of precipitation intensity for each duration and eight different return periods (2, 5, 10, 20, 50, 100, 500 and 1000 years) using Gumbel inverse distribution function; (iv) representation of the precipitation intensity (mm/h) as a function of precipitation duration (min) in a log-log plot to estimate the slope and intercept regression parameters. This last procedure corresponds to linearization of the Intensity-Duration-Frequency curves (Equation (1)),

$$\log(I) = \log(a) + b \times \log(t) \quad (4)$$

which led to the estimation of the (a and b) *IDF* parameters with a statistical significance level of 5%. The quality of the linear regression fit is also assessed by the coefficient of determination (R^2), the *F-statistic* ($p - value$) and the error variance.

The adopted methodology is similar to that described in Brandão et al. (2001). The major differences reside, on the one hand, on the way of adjusting the Gumbel law to the data (likelihood estimation, using *evfit* function of MATLAB) and assessing the quality of the fitting, made in this case with the Quantile-Quantile plots and Kolmogorov-Smirnov test ($KStest$) and the use of robust regression method (RR) to estimate the *IDF* parameters a and b. Major difference of RR in relation to the ordinary least square method (OLS) used in Brandão et al. (2001) lies in the attribution of weights to the observed points, as higher as the corresponding regression residual. A deeper description of the RR method as well as the comparison with OLS may be found in Holland et al. (1977), Huber (1981) and Street et al. (1988).

Many different methods can be used to derive *IDF* curves, from the usual univariate empirical analysis of the intensity of rainfalls at fixed time intervals, to bivariate frequency analysis using the copula method (Ariff et al. 2012), partial duration series (Ben-Zvi 2009; Kingumbi and Mailhot 2010), multifractal approaches (Garcia-Marin et al. 2013; Veneziano et al. 2013), ensemble empirical mode decomposition and scaling properties (Bougadis and Adamowski 2006; Kuo et al. 2013). Several studies comparing methodologies have been conducted but generally all methods seem to be able to produce accurate *IDF* estimates (Mohymont et al. 2004; Veneziano et al. 2007; Dame et al. 2008). The type I extreme value, (EVI or Gumbel) distribution has been used successfully in many recent rainfall intensity studies in Europe (Llasat 2001; Bara et al. 2010; Olsson et al. 2012), Asia (Ariff et al. 2012; Ben-Zvi 2009; Ahammed and Hewa 2012), Africa (Kuo et al. 2013; Mohymont et al. 2004) and America (Lumbroso et al 2011; Pizarro et al. 2012). EVI is currently the recommended distribution function for use in Canada and the best choice for the estimation of *IDF* curves under changing climate conditions (Das et al. 2013). Other distribution functions such as the general extreme value type II (EVII or Fréchet) have also been used, e.g. to estimate the *IDF* curves using short-record satellite data in Ghana (Endreny and Imbeah 2009).

The estimation of the *IDF* curves was performed for precipitation simulated by the ECHAM5/MPI-OM1 / COSMO-CLM model chain for the grid cells including the location of the six weather stations (cf. Table 1). With this aim, time series for 30 years period 1971 – 2000 for the C20 scenario, corresponding to the recent past weather conditions, and for two future climate scenarios SRES A1B and B1, regarding the periods 2011 – 2040, 2041 – 2070 and 2071 – 2100, were considered. In general, climate models are not capable of accurately reproduce the observed precipitation. Several methods can be used to correct this bias, ranging from the more traditional methods to the Delta Change approach, in order to include projected future changes in some key precipitation statistics (Olsson et al. 2012; Pereira et al. 2013). The procedure adopted here to correct the model bias is conditioned by just knowing the final values of the *IDF* parameters proposed in Matos and Silva (1986) and consisted of matching the values of the parameters obtained by the robust regression method for C20 (a_{C20} and b_{C20}) with the values (a_{MS} and b_{MS}) proposed by Matos and Silva (1986) which are the *IDF* parameters adopted by the Portuguese law (DR 1995). The correction factor of parameter a (Δa) results from the difference between the logarithm of parameter a_{C20} associated to scenario C20 and the logarithm of parameter a_{MS} from Matos and Silva (1986),

$$\Delta a = \log_{10} a_{C20} - \log_{10} a_{MS} \qquad (5)$$

In turn, the corrective factor of parameter b (Δb) results from the ratio between parameter b_{C20} associated to scenario C20 and parameter b_{MS} resulting from Matos and Silva's (1986) study,

$$\Delta b = \frac{b_{C20}}{b_{MS}}. \qquad (6)$$

Afterwards, these same correction factors were applied to parameters a_{A1B} and b_{A1B} obtained for scenario A1B, proceeding as follows:

$$a_{A1B\ corr} = 10^{(\log_{10} a_{A1B} - \Delta a)} \tag{7}$$

and

$$b_{A1B\ corr} = \frac{b_{A1B}}{\Delta b} \tag{8}$$

which allowed obtaining corrected versions of parameters a and b. The same procedure was applied to intermediate results obtained for scenario B1.

The two-sample Kolmogorov-Smirnov test is used to compare the distributions of the precipitation depth intensity simulated for future (I_{future}) and recent climate conditions (I_{past}). The null hypothesis is that I_{future} and I_{past} are from the same continuous distribution, while the alternative hypothesis is that they belong to different continuous distributions. In both cases, the *IDF* curves ($I = a \times t^b$) are used to generate I values for different duration times, by resorting to parameters estimated for future periods/scenarios after correcting climate model bias and proposed by Matos and Silva (1986), respectively.

Design of the urban building drainage system

The main goal of this study focuses on the comparison between the design of building drainage systems, based on the *IDF* curves proposed in Matos and Silva (1986) and the design based on *IDF* curves estimated for different periods of future scenarios for the three rainfall regions (A, B and C, in Fig. 1). For quantitative comparison purpose and sake of simplicity, specific residential roof drainage gutter and rainwater pipe were considered as examples of building storm-water drainage systems to be designed. The flows were calculated with the rational method equation,

$$Q = C.I.A \tag{9}$$

where, the contribution area (A) of the gutter is 100.14 m^2, whereas the area of the devices that reach the rainwater pipe is 155.69 m^2, the flow coefficient (C) used for building coverings is equal to the unit while the precipitation intensity (I) was calculated according to the Equation (1) for a duration (t) of 5 minutes and a return period (T) of 10 years. Parameters a and b used in the calculation of the precipitation intensity follow the *IDF* curves established in the Regulation-decree n.º 23/95 (DR 1995), and those obtained for precipitation data simulated for future scenarios A1B and B1, after correction of the climate model bias.

The gutter defined for conducting the storm water has a rectangular shape, with a base (B) of 20 cm and inclination (i) of 0.5%. It was dimensioned so that the height of the water depth (h) therein does not exceed 7/10 of the total height of the gutter. The Manning-Strickler's formula, Equation (10), was used with a roughness coefficient (K) of 90 $m^{1/3}/s$, corresponding to metal plate. The hydraulic radius (R) and the area occupied by the fluid (A_f), in the case of rectangular sections, are determined by the Equation (11) and Equation (12), respectively:

$$Q = K \times A_f \times R^{2/3} \times i^{1/2} \tag{10}$$

$$R = \frac{B \times h}{(B + 2h)} \tag{11}$$

$$A_f = B \times h \tag{12}$$

The residential rainwater pipe was designed using the Manning-Strickler formula (10) for full section, roughness (K) of 120 $m^{1/3}/s$ corresponding to polyvinyl chloride (PVC) and inclination (i) of 2%. The hydraulic radius (R), in the case of a filled circular section, is given by Equation (13), where D_i is the internal diameter of the piping.

$$R = \frac{D_i}{4} \quad (13)$$

Results and discussion

Before focussing in the *IDF* curves in three precipitation regions, we analyse the precipitation distribution and projected changes for Continental Portugal. With this aim, the long term (1961 – 2000) average of the annual maximum daily precipitation depth was computed based on the ECAD precipitation dataset (Fig. 2). The obtained spatial pattern is dominated by a region of very large values (>60 mm), located over NW Portugal. This pattern is quite different from the three rainfall areas configuration proposed by Matos and Silva (1986) and adopted by the Portuguese legislator (Fig. 1).

Then, to assess potential future changes on extreme precipitation regime, four extreme precipitation indices were computed using the precipitation dataset simulated by COSMO-CLM for each of the 30-year periods for the C20, B1 and A1B scenarios, namely: the total precipitation depth (*PRCTOT*); the long-term 95th percentile (*PRC95p*); the ratio between *RR95pTOT* and *PRCTOT* (*R95T*); and, the total precipitation depth falling in days with daily precipitation amounts greater than the corresponding *PRC95p* (*RR95pTOT*). The computations were performed taking only into account wet days defined has days with precipitation depth above or equal to 1.0 mm.

Results obtained for simulated recent–past climate conditions (C20 scenario, 1971 – 2000) over continental Portugal (Fig. 1) reveals high spatial variability in the total precipitation depth, with values ranging between 11×10^4 mm in the NW part of the country and 1×10^4 mm, in the remaining area of the country (Fig. 3(a)) resembling the configuration of the average annual maximum daily precipitation depth (Fig. 2). This spatial pattern is also very similar to the long term 95th percentile of the daily precipitation depth (Fig. 3(b)), with highest values (as higher as 80 mm) located over the NW quarter of country and in the southernmost region (of about 60 mm) and much lower values (smaller than 45 mm) elsewhere.

The spatial distribution of *RR95pTOT* and *R95T* also helps to understand the regime of extreme precipitation in Portugal. The spatial pattern of *RR95pTOT* (Fig. 3(c)) is very similar to the *PRCTOT* but, as expected, with much lower values. This means that precipitation amount falling in the days of extreme precipitation assume higher values in the same regions where total precipitation depth is greater. The *R95T*, which is a fraction (%) of total precipitation depth falling during extreme rainfall days, present a pattern characterized by highest values (of about 30%) in the southern part of the country and (of about 23%) on NW part of the country and along the Tagus river basin (Fig. 3(d)).

Differences between the *PRC95p* (Δ*PRC95p*) obtained for each of the 30-year period of the future climate change SRES scenarios (B1 and A1B) and for the recent–past climate conditions (C20 scenario) are displayed in Fig. 4. For the B1 scenario, positive differences of 7 to 10 mm may be expected in the NW region with smaller magnitudes elsewhere for the 2011-2040 period (Fig. 4(a)). The pattern for the following period (2041 – 2070, Fig. 4(b)) is characterized by generally smaller values (< 5 mm) while for the last 30-year period (2071 – 2100, Fig. 4(c)), resembles the 2011-2040 pattern except in the southernmost area, where a decrease (of about -5 mm) in $PRC95p$ should be expected. This is a clear indication that natural variability on longer time scales may be superimposed on the long-term trends of precipitation associated with climate change. For the A1B scenario and 2011 – 2040 period (Fig. 4(d)), a modest increase of the $PRC95p$ is revealed in all territory, except in small and sparse regions in NW part of the country. For latter periods (Fig. 4(e) and Fig. 4(f)), the pattern of the $\Delta PRC95p$ has the same but amplified spatial configuration with values as high as +10 to 15 mm in the NW region, over the Tagus river basin and southern part of the country for the 2071 – 2100 period.

Next, time series for the six weather stations are analysed. Given the ten temporal durations, three 30-year periods (2011 – 2040, 2041 – 2070, and 2071 – 2100) for each of the two future scenarios (A1B and B1) and one period for the recent past climate conditions, a total of 420 time series is considered. The visual inspection of the Quantile-Quantile plots and the value of the Kolmogorov-Smirnov statistical test (and corresponding $p - value$) confirm the goodness of fit of the Gumbel distribution function to all these time series. The probability density function for each scenario suggests that the return period for a given amount of precipitation intensity decreases for the three periods of the future scenarios vis-à-vis the period observed (not shown).

Values of the *IDF* parameters *a* and *b* used here were obtained by linear regression, for durations times between 5 min and 30 min and return periods of 2, 5, 10, 20, 50 and 100 years. The quality of the regression was confirmed by the values of the coefficient of determination (R^2), *F-statistic* and by the estimated error variance. The R^2 represents faction of the variance of the dependent variable (in this case, the precipitation intensity) by the linear model using the independent variable (in this case the duration). In all cases the values of R^2 were always higher than 0.99, which means that more than 99%

of the variance of intensity of precipitation can be explained by the variance of the duration. The values of the *F-statistic* are used to assess the tests of nullity of parameters for a given level of significance and it is reasonable to assume that the linear regression equation fits the data well because of the high value of the *F-statistic* and the $p - values$ tends to zero for a significance level of 5%. Finally, the extremely small value of the estimated error variance obtained in all cases supports the idea that the regression line provides a good fit to the data.

The linear regression models based on the minimization of the squared error are based on a number of assumptions which are not always verified, e.g. the non-normality of the residuals, the existence of an asymmetric distribution of errors and outliers. This fosters the use of the RR method in this study, which constitutes an alternative approach that aims to be more robust and resistant than the OLS. Table 2 allows assessing changes in the design of a residential gutter and rainwater pipe, as a consequence of variations recorded in the *IDF* curves, as a result of the changes in the distribution of the maximum precipitation values due to climate change. The determination of the design flow was performed on the basis of the values of precipitation intensities estimated from the *IDF* curves for all time periods and both scenarios (after bias correction) and *IDF* curves currently used in designing building drainage systems in Portugal, developed by Matos and Silva (1986) and embraced by the Portuguese legislation (DR 1995).

Overall, there is a clear tendency to increase the size of gutters and rainwater pipes compared to the current dimensions defined in the Portuguese legislation (Table 2). However, changes are not uniform: For region A, the estimated increases in the height of the gutter for scenario A1B, range from 6% (2041 – 2070) to 11% (2071 – 2100) in the station of Ponte da Barca, to 30% (2011 – 2040) to 39% (2071 – 2100) in São Manços. For region B, the estimated increase may vary from 11% (2041 – 2070) to 39%

(2071 – 2100) for Castelo Melhor and scenario A1B and from 12% (2041 – 2070) to 28% (2071 – 2100) for scenario B1. In the station of Pinelo, the design of the gutter varies from -7% (2011 – 2040) and 18% (2071 – 2100) for scenario A1B, whereas, for scenario B1, it varies from 3% (2011 – 2040 and 2041 – 2070) and 10% (2071 – 2100).

In order to obtain an average value representative for the mid-21st century, averages were built for each station over the three time periods, thus sampling decadal variability. This results for example on an estimated average increase of 39% in São Manços and 9% for Ponte da Barca for the A1B scenario (both Region A). For region B, changes are larger for Castelo Melhor (20%) than for Pinelo (5%) for both scenarios. On the contrary, little differences are found for region C: ranges are 3% to 16% for scenario A1B and from 3% to 9% for scenario B1 in the station of Covilhã, whereas for the station of Pega, it ranges from 4% to 16% and from 3% to 6%, respectively. Furthermore, averages were built over both stations in each region and both scenarios to obtain values representative per region considering scenario uncertainty. Averaged increase in Gutter dimension is likely to be higher in Region A (21%) than in region B (12%) and in region C (7%).

The projected changes in the rainwater pipe size are essentially proportional to the gutter (Table 2). Therefore, a detailed presentation of the results is omitted. The main results are: (*i*) averaged changes in the rainwater pipe diameter increases from 4% in region C, to 7% in region B and 11% in region A; (*ii*) different behaviour in region A is characterized by higher changes in the weather stations located in the southern (São Manços) than in the northern part (Ponte da Barca) and, in region B, at lower (Castelo Melhor) than at higher altitude (Pinelo); (*iii*) higher homogeneity in the expected changes in mountainous region C and (*iv*) changes are typically smaller than for the gutter.

In general terms, the estimated changes are projected to be largest at the end of the 21st century and under the conditions of scenario A1B scenario. In region C, there is a clear increasing trend in the changes (increases) in the size of these building storm-water drainage systems when the results for the three consecutive 30-year periods are analysed, independently of the scenario considered. However, this behaviour is not always observed in other regions where may even be expected decreasing trends (as in São Manços, located in region A, for the conditions of scenario B1), probably associated with natural variability on longer time scales. The temporal evolution of patterns of the 95th percentile, allow the interpretation of the results obtained for the expected changes in the dimensions of the rainwater collecting organs. In the case of the A1B SRES scenario, the expected changes in the size of the gutter and rainwater pipe along the three 30-year periods are characterized by increasing long-term trends in the Pinelo, Pega and Covilhã stations; for São Manços and Castelo Melhor, changes of similar magnitude are found for 2011 – 2040 and 2041 – 2070, which are enhanced for 2071 – 2100; For Ponte da Barca, a relative decrease is detected in the latter period at least for the B1 scenario (Table 2). As mentioned above, part of these relative changes between periods may be associated with multi-decadal natural climate variability and not with a long-term climate trend. These projected changes are consistent with the trends in the changes of *PRC95p* as discussed for the A1B scenario (Fig. 3).

Finally, it is important to underline that projected changes in the size of the building storm-water drainage systems are statistical significant at the 99% level in all cases except in the 6 cases (17%) identified by a dagger in Table 2 and for the station of Pega in the first 30-year period of the A1B scenario. It is important to underline that projected changes in all cases of rainfall region A are statistical significant (99%) and that statistical significance is higher in the end of the XXI century.

Conclusions

This study aimed at discussing the current status of the *IDF* curves adopted by the Portuguese Law and investigate the possible influence of projected changes in extreme precipitation in the current designing of building storm-water drainage systems. Patterns of spatial distribution of annual maximum daily rainfall and extreme precipitation indices, obtained from both observed and simulated data for recent past conditions, exhibit considerable variability and suggest the necessity to revise the results of Matos and Silva (1986) included in the legislation (DR 1995), which divide Continental Portugal in three homogeneous rainfall regions. This is the case even assuming the long-term stationarity of current precipitation regime.

The developed methodology to assess the impacts of projected climate change is well grounded in literature and ensures the robustness and statistical significance of the results. The comparison of the design carried out with the *IDF* curves outlined for future scenarios with the curves obtained by Portuguese law allowed estimating an average increase of the gutter section and the rainwater pipe that is higher for region A (21% and 11%, respectively) than for region B (13% and 7%) and region C (7% and 4%). Regarding the uncertainty for the three regions, estimated as the range between the two stations, estimates were similar for region C, with maximum increases of 16% for the gutter and 9% for the rainwater pipe. For region B, the estimates for gutter design varies between 18% and 39% and, for the rainwater pipe range between 10% and 21%. For region A, estimates are larger for southern Portugal (São Manços) – of 40% for the gutter and 20% for the rainwater pipe – than for Northern Portugal (Ponte da Barca), with 20% and 11% for the gutter and rainwater pipe, respectively. In spite of these uncertainties, the sign of the trends are very consistent between regions and stations.

These tendencies are in line with the projected long-term changes of the 95th percentile (*PRC95p*) and other extreme precipitation indices for under future climate conditions which exhibit similar spatial patterns to the annual maximum daily rainfall. These results, together with the spatial distribution of rainfall and extreme precipitation indices seem to reinforce the suggested need to evaluate the precipitation regime classification performed in Matos and Silva (1986).

Most cases studies discussed above (cf. Tab. 2) identified statistically significant differences between the dimensions of the building storm-water drainage systems estimated for recent and future climate conditions. This is also the case for the near-future period of 2011 – 2041 and for the entire rainfall region A, which covers by far the largest part of the mainland area.

In summary, the impact of projected climate change should be reflected in the overall increase in the design of drainage storm-water drainage systems based on *IDF* curves as defined in Portuguese law for all scenarios and future periods analysed. Projected changes are typically larger and increasingly statistical significant for the end of the 21st century, and the magnitude of the changes is larger for the scenario A1B than for scenario B1. Current laws and regulations relating to the design and management of hydraulic works may become out of date in the short term, given the increase in the frequency and intensity of extreme precipitation events. Therefore, the design of new building storm-water drainage systems for Continental Portugal should be modified to larger dimensions to mitigate the projected changes in extreme precipitation

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Tables

Table 1 – Weather stations used in this study. Characterization includes the code, name, abbreviation, altitude (H), geographical coordinates (latitude, longitude), cover period (P) and percentage of hourly precipitation missing values (MV).

Code	Name	Altitude (m)	Latitude (º N)	Longitude (º W)
03G/02C	Ponte da Barca, PB	39	41.80	-8.42
23K/01UG	São Manços, SM	190	38.46	-7.75
07O/05UG	Castelo Melhor, CM	286	41.01	-7.06
04R/02G	Pinelo, PI	607	41.63	-6.55
12L/03G	Covilhã, CO	719	40.28	-7.51
11O/01G	Pega, PE	770	40.43	-7.14

Code	Name	Alt (m)	Lat (º N)	Lon (º W)	P	MV (%)
03G/02C	Ponte da Barca, PB	39	41.80	-8.42	01/2003-09/2012	4.9
23K/01UG	São Manços, SM	190	38.46	-7.75	02/2001-03/2012	1.1
07O/05UG	Castelo Melhor, CM	286	41.01	-7.06	10/2001-12/2009	0.0
04R/02G	Pinelo, PI	607	41.63	-6.55	02/2003-01/2012	3.8
12L/03G	Covilhã, CO	719	40.28	-7.51	05/1998-05/2010	11.8
11O/01G	Pega, PE	770	40.43	-7.14	10/2001-03/2012	8.6

Table 2 – Projected changes in the dimension of the drainage systems. Height of the Gutter (H) and diameter of the rainwater Pipe (D) designed for weather stations located in the three pre-defined rainfall regions, using the precipitation intensity estimated by Portuguese law (DR 1995) and with data simulated by COSMO-CLM, for three periods of thirty years of the two future scenarios (A1B and B1) as well as the relative differences between these dimensions (ΔH and ΔD). Projected changes are statistical significant at 99% level except for the cases identified by superscript lowercase letter ([a]). Arithmetic averages of ΔH and ΔD for each weather station ($\overline{\Delta H}_w$ and $\overline{\Delta D}_w$) and region and scenario ($\overline{\Delta H}_s$ and $\overline{\Delta D}_s$) are also shown. The former values are calculated over different periods to obtain an average value representative for the mid-21st century, thus sampling decadal variability. The latter are derived to obtain values representative for each region considering scenario uncertainty.

Region	Station	Scenario	Period	Gutter H (cm)	Gutter ΔH (%)	Gutter $\overline{\Delta H}_s$ (%)	Gutter $\overline{\Delta H}_w$ (%)	Rainwater pipe D (cm)	Rainwater pipe ΔD (%)	Rainwater pipe $\overline{\Delta D}_s$ (%)	Rainwater pipe $\overline{\Delta D}_w$ (%)
Region A	Ponte da Barca	DR nº23/95		4.51				96.60			
		A1B	2011-2040	4.92	9%			101.48	5%		
			2041-2070	4.79	6%	9%		99.94	3%	5%	
			2071-2100	5.01	11%			102.57	6%		
		B1	2011-2040	5.28	17%			105.50	9%		
			2041-2070	5.39	20%	17%		106.81	11%	9%	
			2071-2100	5.14	14%			103.90	8%		
	São Manços	DRnº23/95		4.51			21%	96.60			11%
		A1B	2011-2040	5.84	30%			111.67	16%		
			2041-2070	5.91	31%	33%		112.38	16%	17%	
			2071-2100	6.26	39%			116.00	20%		
		B1	2011-2040	6.17	37%			115.06	19%		
			2041-2070	5.61	24%	26%		109.13	13%	14%	
			2071-2100	5.28	17%			105.57	9%		
Region B	Castelo Melhor	DRnº23/95		3.89				88.80			
		A1B	2011-2040	4.50	16%			96.52	9%		
			2041-2070	4.33	11%	22%		94.34	6%	12%	
			2071-2100	5.41	39%			107.04	21%		
		B1	2011-2040	4.47	15%			96.18	8%		
			2041-2070	4.36	12%	18%		94.76	7%	10%	
			2071-2100	4.99	28%			102.31	15%		
	Pinelo	DRnº23/95		3.89			12%	88.80			7%
		A1B	2011-2040	3.63	-7%			85.34	-4%		
			2041-2070[a]	3.91	1%	4%		89.01	0%	2%	
			2071-2100	4.57	18%			97.38	10%		
		B1	2011-2040[a]	4.01	3%			90.38	2%		
			2041-2070[a]	4.00	3%	5%		90.26	2%	3%	
			2071-2100	4.27	10%			93.74	6%		
Region C	Covilhã	DRnº23/95		5.09				103.44			
		A1B	2011-2040[a]	5.25	3%			105.22	2%		
			2041-2070	5.37	5%	8%		106.58	3%	4%	
			2071-2100	5.89	16%			112.09	8%		
		B1	2011-2040	5.38	6%			106.68	3%		
			2041-2070	5.53	9%	6%		108.32	5%	3%	
			2071-2100[a]	5.24	3%			105.03	2%		
	Pega	DRnº23/95		5.09			7%	103.44			4%
		A1B	2011-2040[b]	5.29	4%			105.64	2%		
			2041-2070	5.45	7%	9%		107.48	4%	5%	
			2071-2100	5.93	16%			112.53	9%		
		B1	2011-2040[a]	5.24	3%			105.09	2%		
			2041-2070	5.39	6%	5%		106.76	3%	3%	
			2071-2100	5.38	6%			106.63	3%		

[a] change is not statistically significant (p-values>0.05).
[b] change is statistically significant at 95% level

Figures

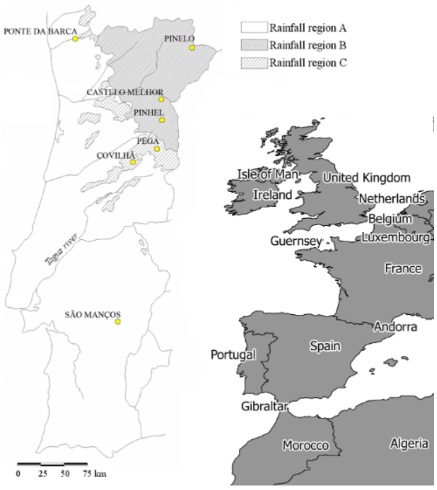

Figure 1 – Rainfall regions defined in the Portuguese Law (DR 1995), including the geographical location of the weather stations used in this study (left panel) and the geographical location of Continental Portugal in Western Europe (right panel).

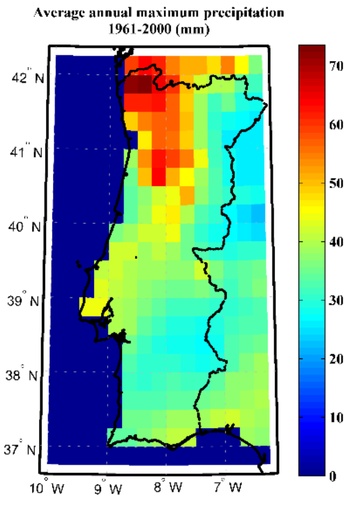

Figure 2 – The long-term (1961-2000) arithmetic average of the annual maximum daily precipitation. Values were evaluated with ECAD precipitation dataset (E-OBS v8.0, 0.25 degree regular lat-lon grid) over Continental Portugal.

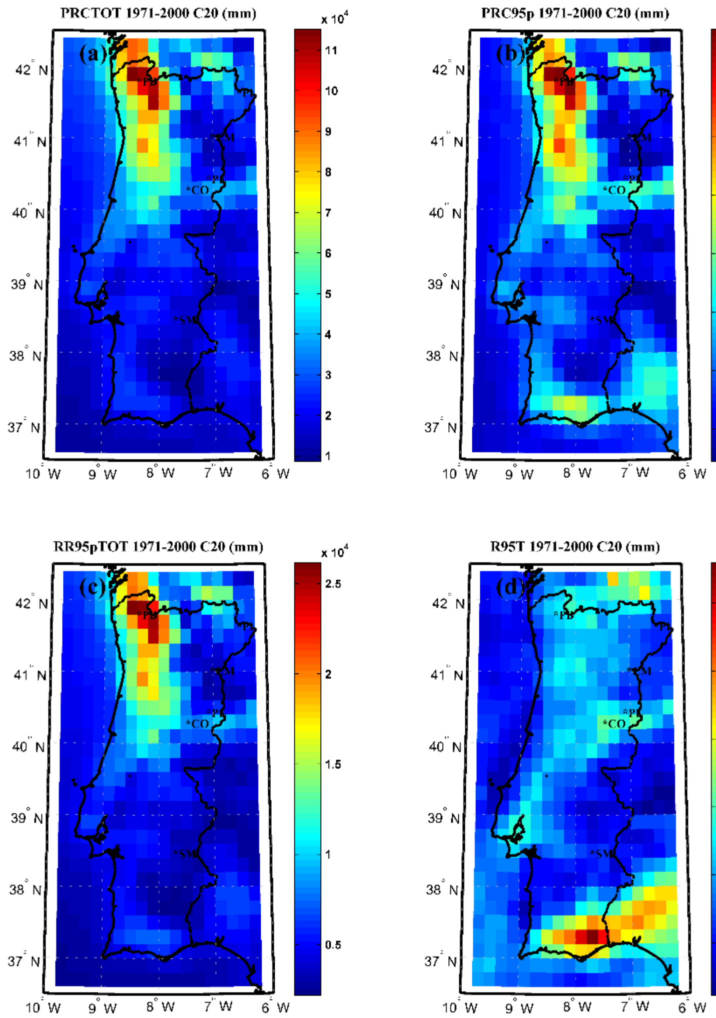

Figure 3 – Extreme Precipitation indices for Continental Portugal. Values of the (a) long-term 95th percentile (*PRC95p*), (b) total precipitation (*PRCTOT*), (c) total precipitation falling in days with daily precipitation amounts greater than the corresponding *PRC95p* (*RR95pTOT*) and (d) the ratio between *RR95pTOT* and *PRCPTOT* (*R95T*) evaluated for daily precipitation simulated by the COSMO-CLM model, for recent–past climate conditions (C20 scenario, 1971 – 2000).

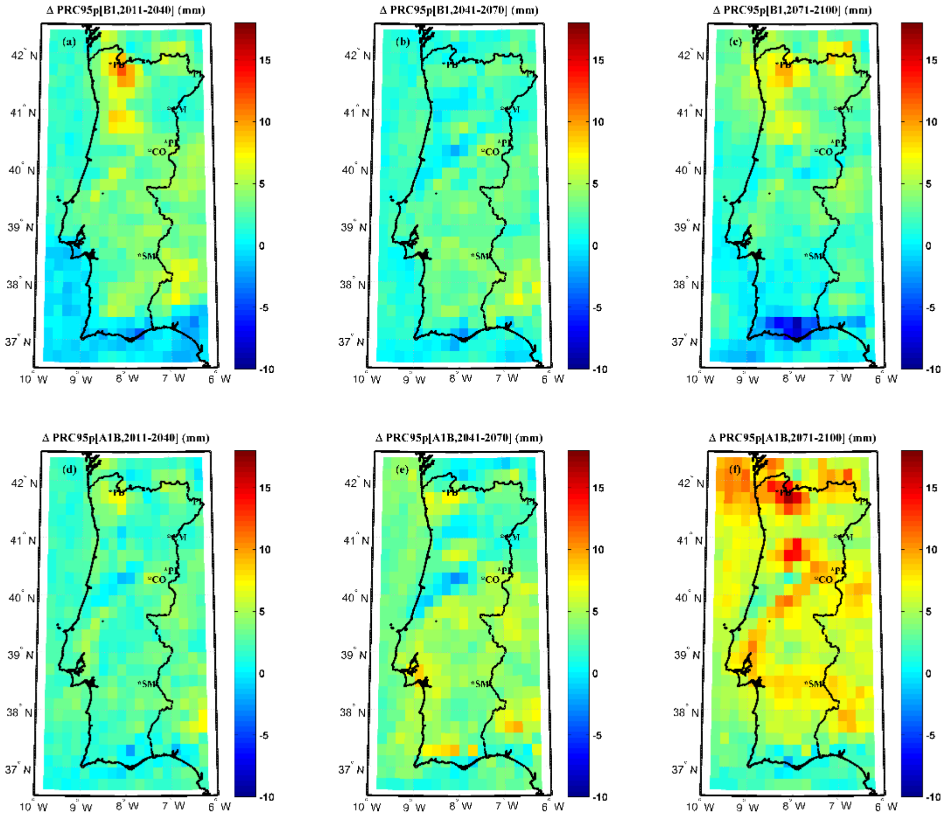

Figure 4 – Trends in long-term 95th percentile *PRC95p* over continental Portugal. Differences between of the long-term 95th percentile (Δ*PRC95p*) evaluated for future climate conditions under the B1 (top panel) and A1B (bottom panel) SRES scenarios and three 30-year periods 2011 – 2040 (left panels), 2041 – 2070 (middle panels) and 2071 – 2100 (right panels) in relation to recent–past climate conditions (C20 scenario, 1971 – 2000).