Uncertainty Analysis in the Evaluation of the DDF Curves Parameters in Climate Change Scenarios

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Abstract

On the global scale, there is a robust observational evidence that, over the last decades, the frequency and intensity of extreme events significantly changed, even if regional and local studies have highlighted complex and non-uniform spatial patterns. Climate change can cause increased rainfall intensities which leads to an additional impact on drainage systems, due to the alteration of magnitude and frequency of peak flows over their service life. For this reason, the design criteria of urban drainage infrastructures need to be revised and updated, in order to take into account the possible variations of extreme rainfall. In particular, the Depth-Duration-Frequency (DDF) curves, widely used in engineering to assess the return periods of rainfall events, require an adjustment for climate change.

The main purpose of this study is to provide a methodology to assess the DDF curves parameters in climate change scenarios, once the evidence of a statistically significant trend in extreme rainfall was verified. Specifically, a Bayesian procedure has been applied for two cases of study located in the Sicily (Southern Italy), in order to incorporate the effects of extreme rainfall variations on the definition of DDF curve for a future climate condition and to evaluate the uncertainty related to such projection. The climate projection has been compared with a baseline scenario representative of current climate conditions. Finally, the implications of the uncertainty related to the DDF parameters estimation on the design of real detention tanks were analyzed, thus providing an evaluation of their hydraulic performance under the assumption of climate change. Results showed that the assessment of DDF parameters from historical extreme rainfall series could not be adequate to provide reliable estimations of future

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design storm. Therefore, the occurring climate change cannot be neglected in the design procedure based on extreme rainfall estimation.

Keywords: extreme rainfall trend; uncertainty analysis; climate change scenarios; detention tank design.

1. Introduction

The increase of global surface temperature will be likely to produce changes in atmospheric moisture and, as a consequence, to intensify the hydrological cycle [1-3]. Trends of extreme rainfall depth and frequency are one of the evidence of the climate change occurring and have been thoroughly analyzed in several studies at different spatial and temporal scales [4-6].

Due to their considerable social, economic and environmental consequences, the assessment of future variations in extreme rainfall and their implications on hydraulic structures became a critical issue. The Directive 2007/60/EC on the assessment and management of flood risks invites Member States to take into account long term developments, including climate change in the flood risk management cycle addressed in this Directive [7].

The DDF curves are widely used in engineering applications in order to evaluate the extreme rainfall depth for a specified return period and duration. Therefore, reliable estimations of the DDF curves parameters are required for the optimal design of hydraulic infrastructures. Different procedures have been developed and applied to integrate the effects of climate change in DDF relationships [8-11]. The assessment of future variations of extreme rainfall is affected by an high level of uncertainty, related to location, rainfall duration and return period [12]. Nevertheless, neglecting the effects of climate change on extreme rainfall could lead to underestimation or overestimation of design storms. Thus, accurate and reliable techniques for future projections of the DDF curve parameters under climate change are required, not only to quantify the magnitude of extreme rainfall variations, but also to provide a measure of the uncertainty related to their estimation.

The aim of this study is the application of a Bayesian procedure to integrate the effects of extreme rainfall trends on the evaluation of the DDF curve parameters and to provide an assessment of the uncertainty linked to the parameters appraisal. With this purpose, a trend analysis has been previously carried out applying the non-parametric Mann-Kendall test to the historical series recorded in the rain gauges located in the study areas. Once the presence of a statistically significant trend has been detected, a Bayesian procedure has been applied to account for the above-mentioned trend of the DDF curve assessment in a future climate scenario. The output of the proposed procedure has been used to quantify the implications of extreme rainfall changes on the hydraulic performance of two real detention tanks located in Sicily (Southern Italy), specifically in Ciminna and Caltagirone.

2. Case of study and dataset

In this study, the annual maxima rainfall series recorded in the rain gauges of Ciminna and Caltagirone have been analyzed. These rain gauges are located in the Northern and Southern part of Sicily respectively. Sicily is an island of approximately 25,700 km² in Southern Italy, characterized by a Mediterranean climate with mild winters and hot and generally dry summers. Figure 1a and 1b show the location of the two selected rain gauges and the mean annual precipitation over the studied areas. Specifically, in the area around Ciminna and Caltagirone the mean annual precipitation is about 530 mm and 720 mm respectively. For this study, the available historical annual maxima rainfall series of duration $d$ equal to 1, 3, 6, 12 and 24 hours for the 1950-2008 period were elaborated and provided by Osservatorio delle Acque - Regione Siciliana (OA-RS). As regards to the Ciminna rain gauge, mean annual maxima rainfall for $d$ equal to 1, 3, 6, 12 and 24 hours are 23.0 mm, 32.1 mm, 40.6 mm, 50.8 mm and 62.2 mm respectively. For Caltagirone rain gauge these values are equal to 26.3 mm, 33.0 mm, 39.9 mm, 48.4 mm and 59.4 mm.
3. Methodology

3.1. Description of the procedure

The procedure developed in the present work is illustrated by the flow chart in Figure 2. Firstly, a pre-analysis was carried out in order to verify the presence of a trend in annual maxima rainfall series over the areas of study. The detection of statistically significant trends makes the updating of the DDF curves necessary in order to obtain more reliable appraisal of extreme rainfall for design purposes. Conversely, in absence of trend, the update of the DDF curves parameters is not performed, even if it cannot be excluded that in the future a trend of annual maxima rainfall will occur.

For trend detection, the non-parametric test of Mann-Kendall has been used [13, 14]. The magnitude of statistically significant trends has been evaluated as follows [15]:

![Flowchart of the proposed procedure](image-url)
where $x_l$ is the $l$-th observation.

Once the pre-analysis detected a statistically significant rainfall trend in the analyzed area, a Bayesian procedure has been performed to account for the trend in the DDF curve assessment. The DDF relationship for the return period $T$ often takes the form of a power law relationship [16]:

$$ h(d)_T = a_T \cdot d^{n_T} $$  

(2)

where $h(d)_T$ is the rainfall depth at the specified return period $T$, duration $d$ and $a_T$ and $n_T$ are parameters. Under the assumption of scale invariance, $h(d)_T$ can be expressed as follows:

$$ h(d)_T = E[H_{160}^1 w_T \cdot d^{n_T}] $$  

(3)

where $E[H_{160}^1]$ is the mean annual maximum rainfall depth for the reference duration (1 hour) and $w_T$ is the $T^{th}$ quantile of the annual maximum storm depth normalized by its mean for any duration in the range of the existence of a scaling behavior (also referred as the growth factor). The product $E[H_{160}^1] w_T$ is the parameter $a_T$ in Equation (2). Even if the above-mentioned procedure for the DDF definition is frequently used, the DDF parameters estimation could be affected by a degree of uncertainty due to the dataset length, to the presence of a trend or to other sources of inhomogeneity.

The Bayesian procedure proposed in this study has been aimed at assessing the uncertainty linked to the $a_T$ parameter of the DDF curve in the presence of an annual maxima rainfall trend. This procedure estimates the $a_T$ parameter linked to several continuous sub-datasets with different ending years and lengths. Starting from a minimum of 15 years, the length of each sub-dataset is increased by one, up to a maximum of 35 years. This choice has been based on the evidence that an intensification of the hydrological cycle occurred in the last 30–35 years, probably due to the upward temperature trend affecting Europe [17, 18]. The evidence of a statistically significant increase in mean annual rainfall over the last 30 years in Sicily [19] further supports this assumption. Finally, the purpose of this study is the assessment of implications of climate change on the design of detention tanks; thus, referring to long-term trends (greater than 50–100 years) seems to be inadequate, because of the design return periods of these systems that usually range between 30-50 years.

The procedure provided, as output, numerous series of the $a_T$ parameter, one for each ending year of the processed sub-datasets. With the purpose to evaluate the 95th, 50th, and 5th percentiles of each $a_T$ series, the likelihood function value $L_i$ has been assessed for each $i$-th element (ending year of the sub-dataset), as follows:

$$ L_i = \frac{1}{\sqrt{2\pi \sigma^2}} \exp \left( \frac{(a_i - \bar{a}_T)^2}{2\sigma^2} \right) $$  

(4)

where $\sigma^2$ is the variance of the error, $a_i$ is the $i$-th element and $\bar{a}_T$ is the median of the $a_T$ series. After that, for each $a_T$ series, the 95th, 50th, and 5th percentiles have been picked from the related cumulative distribution function (CDF). Once the percentiles series have been obtained, the linear regressions have been performed considering the last 30 years of the dataset, in order to define a mathematical law of the $a_T$ variability in time. The 95th and 5th percentile regression laws represent the upper and lower uncertainty bands linked to the estimation of the $a_T$ parameter. Thus, the width of these bands provides a quantification of the uncertainty related to the $a_T$ appraisal.

At last, following the temporal analogues approach, a climate scenario has been generated under the assumption that the rainfall changes detected by the trend analysis will proceed in the future with the same pattern. Therefore, the previously defined regressions are used to extrapolate the $a_T$ parameter values for a projection to 2050.
3.2. Detention tank sizing

Detention tanks collect and store rainwater during a rainfall event, then release it at constant rates to the downstream drainage system, thus reducing the peak flow. In order to determine the size of a detention tank, a simple method only based on annual maxima precipitation can be used. This method provides the volume of the detection tank as a function of the DDF curve parameters $a_T$ and $n_T$ and the effluent flow rate $Q_o$. Under the assumption of constant $Q_o$, the tank volume $W$ can be obtained as follows:

$$W = V_i - V_o = A \cdot \varphi \cdot a_T \cdot \theta^{n_T - 1} - Q_o \cdot \theta$$

(5)

where $V_i$ is the inflow rainfall volume (m$^3$) in the detention tank, $V_o$ is the outflow from the detention tank (m$^3$), $A$ is the catchment surface (ha), $\varphi$ is the runoff coefficient and $\theta$ is the rainfall duration (hours). The maximum volume in the tank is reached when the rainfall duration is equal to the critical duration $\theta_w$ calculated as follows:

$$\theta_w = \left( \frac{Q_o}{A \cdot \varphi \cdot a_T \cdot n_T} \right)^\frac{1}{n_T - 1}$$

(6)

Consequently, the detention tank volume can be obtained by the expression:

$$W = A \cdot \varphi \cdot a_T \cdot \left( \frac{Q_o}{A \cdot \varphi \cdot a_T \cdot n_T} \right)^{n_T - 1} - Q_o \cdot \left( \frac{Q_o}{A \cdot \varphi \cdot a_T \cdot n_T} \right)^{1/(n_T - 1)}$$

(7)

In the context of climate change, due to the extreme rainfall variations, the capacity of existing detention tanks may be overestimated/underestimated. For this reason, in the design of new detention tanks, the analysis of the performance of these systems in future climate scenarios should be included. In this study, the capacity of two real detention tanks located in Sicily has been calculated, in order to verify if these systems, designed for current climate conditions, will be able to ensure the reduction of the peak flow also in future scenarios.

4. Results and discussion

4.1. Trend analysis results

A trend analysis has been carried out for the annual maxima rainfall recorded in the Ciminna and Caltagirone rain gauges. Trends have been considered statistically significant for significance level at least equal to 0.1. In Table 1 the level of significance $\alpha$, the magnitudes $\beta$ (mm/year) and the $p$-values have been reported for each duration and rain gauge.

<table>
<thead>
<tr>
<th>Rain gauge</th>
<th>Duration</th>
<th>Trend/ $\alpha$</th>
<th>$\beta$ (mm/year)</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ciminna</td>
<td>1 hour</td>
<td>$+/\alpha = 0.1$</td>
<td>0.21</td>
<td>~0</td>
</tr>
<tr>
<td></td>
<td>3 hours</td>
<td>$+/\alpha = 0.05$</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>6 hours</td>
<td>no trend ($\alpha &lt; 0.1$)</td>
<td>0.10</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>12 hours</td>
<td>no trend ($\alpha &lt; 0.1$)</td>
<td>0.18</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>24 hours</td>
<td>no trend ($\alpha &lt; 0.1$)</td>
<td>0.31</td>
<td>0.46</td>
</tr>
<tr>
<td>Caltagirone</td>
<td>1 hour</td>
<td>$-/\alpha = 0.01$</td>
<td>-0.16</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>3 hours</td>
<td>$-/\alpha = 0.01$</td>
<td>-0.21</td>
<td>-0.23</td>
</tr>
<tr>
<td></td>
<td>6 hours</td>
<td>no trend ($\alpha &lt; 0.1$)</td>
<td>-0.12</td>
<td>-0.12</td>
</tr>
<tr>
<td></td>
<td>12 hours</td>
<td>no trend ($\alpha &lt; 0.1$)</td>
<td>-0.12</td>
<td>-0.06</td>
</tr>
<tr>
<td></td>
<td>24 hours</td>
<td>no trend ($\alpha &lt; 0.1$)</td>
<td>-0.06</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

In Table 1, the symbol “+” and “-” indicates a positive and a negative trend respectively.
Annual maxima rainfall for \( d \) equal to 1 and 3 hours recorded in Ciminna rain gauge are affected by a positive trend. For the Caltagirone rain gauge, annual maxima rainfall for \( d \) equal to 1, 3 and 6 hours are affected by a statistically significant decrease.

4.2. DDF curves parameters estimation

Once the pre-analysis detected a statistically significant trend in the analyzed areas, a Bayesian procedure was performed to account for the above-mentioned trend in the assessment of the DDF curve parameters. For the DDF curve definition, the Generalized Extreme Value (GEV) distribution has been adopted to estimate \( h(d) \) \((\text{Equation (2)})\). GEV parameters have been estimated using the l-moments \([20]\) for a return period equal to 30 years. According to the proposed procedure, several continuous sub-datasets with different ending years and lengths have been sampled, and the \( a_T \) parameter of the related DDF curve has been estimated. Namely, the value of the \( a_T \) parameter has been calculated for the subdataset including the years from 1950-1964 (15 years), then the effect of adding one by one new data has been investigated, up to a maximum length of 35 years. Moreover, the subdataset starting year was increased one by one in order to analyze the effect of less recent data on the estimation of the \( a_T \) parameter. In summary, this sampling procedure provides an increasing number of \( a_T \) from one value (related to the 1964) to a maximum of 21 values (linked to the years from 1984 to 2008), as shown in Figure 3. This approach allowed to include in the procedure as much data as possible, considering subdataset length ranging from 15 to 35 years.

Subsequently, the likelihood function value \( L_i \) has been evaluated for each \( i \)-th element of each \( a_T \) series, and the related 95th, 50th, and 5th percentiles have been obtained from the CDF of \( L_i \). Specifically, for each year, starting from 1964 to 2008, three \( a_T \) values have been obtained as the 95th, 50th, and 5th percentiles of the \( a_T \) series. In Figure 4 the 95th, 50th, and 5th percentiles of the \( a_T \) parameter and the related linear regressions (obtained considering the last 30 years) are reported for Ciminna and Caltagirone rain gauges. As regards to Ciminna rain gauge (Figure 4a), the linear regression of the \( a_T \) percentiles series shows an increasing trend. Namely, the 50th percentile showed a 50.0% increase. A downward trend has been detected for the \( a_T \) percentiles values related to the Caltagirone rain gauge data (Figure 4b); in particular the 50th percentile showed a 60.0% decrease.
4.3. DDF curves in future short-term scenarios

The 95th and 5th percentiles linear regressions identify the upper and lower limits of the uncertainty band linked to the $a_T$ appraisal respectively and the width of the uncertainty bands provides information about the reliability of the future projection. Following the temporal analogues approach, the linear regressions have been used to generate climate scenarios by supposing that the rainfall changes detected by the trend analysis will proceed in the future with the same pattern, assuming a linear trend. Therefore, the $a_T$ parameters of the DDF curves have been estimated for the Ciminna and Caltagirone rain gauge for a future short-term projection to 2050. In every scenario, $n_f$ has not been changed and has been set equal to the value obtained for current conditions (0.28 for Ciminna and 0.25 for Caltagirone). In Figure 5 the DDF curves for current climate conditions and for the 2050 scenario are showed.

![DDF curves](image)

Table 2. Critical duration $\theta_w$ and detention tank volume $W$ for each rain gauge and scenarios

<table>
<thead>
<tr>
<th>Rain gauge</th>
<th>Scenario</th>
<th>Percentile</th>
<th>$\theta_w$ [min]</th>
<th>$W$ [m³]</th>
<th>Rain gauge</th>
<th>Scenario</th>
<th>Percentile</th>
<th>$\theta_w$ [min]</th>
<th>$W$ [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ciminna</td>
<td>current conditions</td>
<td>-</td>
<td>32.4</td>
<td>28.3</td>
<td>Caltagirone</td>
<td>current conditions</td>
<td>-</td>
<td>34.8</td>
<td>30.4</td>
</tr>
<tr>
<td></td>
<td>2050 scenario</td>
<td>95th</td>
<td>60.3</td>
<td>52.6</td>
<td></td>
<td>2050 scenario</td>
<td>95th</td>
<td>19.6</td>
<td>17.1</td>
</tr>
<tr>
<td></td>
<td>2050 scenario</td>
<td>50th</td>
<td>57.4</td>
<td>50.0</td>
<td></td>
<td>2050 scenario</td>
<td>50th</td>
<td>10.5</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>2050 scenario</td>
<td>5th</td>
<td>53.5</td>
<td>46.7</td>
<td></td>
<td>2050 scenario</td>
<td>5th</td>
<td>6.3</td>
<td>5.5</td>
</tr>
</tbody>
</table>

4.4. Detention tank sizing results

In the present study, the capacity of a detention tank in Ciminna and Caltagirone has been calculated for the current climate conditions and for the 2050 scenario. It has been assumed that the detention tank collects the rainwater from an impervious area of 1 ha and the $Q_o$ has been set equal to 0.02 m³/s. Table 2 shows the obtained critical duration $\theta_w$ and the detention tank volume $W$. 

![DDF curves](image)
As regards to Ciminna, for current climate conditions a detention tank of 28.3 m³ is required. In the 2050 scenario, due to the increase of annual maximum precipitation for $d=1$ hour and, consequently, the increase of $a_T$, this capacity will not be adequate. Indeed, $W$ will need to be increased by the 57% ($W=50.0$ m³). The $W$ calculated for the 95th and the 5th percentiles scenarios identify the uncertainty related to the above-mentioned appraisal. On the other hand, the $W$ obtained for current climate conditions in Caltagirone (30.4 m³) will result to be overestimated if the downward trend of annual maximum rainfall will proceed in time. In the 2050 scenario, a capacity of about 9 m³ will be likely to be enough to reduce the peak flow.

5. Conclusion

In this study, a Bayesian procedure has been proposed for the assessment of the DDF curve $a_T$ parameter in future climate scenarios and the estimation of the related uncertainty. A preliminary trend analysis has been performed to detect the statistically significant variations of annual maxima rainfall in the areas of study, Ciminna and Caltagirone (Southern Italy). This analysis highlighted the presence of an increasing trend in Ciminna and a decreasing trend in Caltagirone. By mean of the Bayesian procedure, the $a_T$ parameter of the DDF curves has been estimated for the current climate conditions and for the future projection to 2050. The procedure allowed to evaluate the uncertainty related to the above-mentioned estimations. The $a_T$ parameters values have been used as input to calculate the capacity of two real detention tanks by means of a simple method based on the DDF curve parameters. As regard to Ciminna rain gauge, the volume of the detention tank obtained for current conditions resulted to be underestimated if compared to the capacity required in the 2050 scenario. On the contrary, due to the downward trend of annual maximum rainfall, the volume of the detention tank for Caltagirone under current climate conditions is overestimated if compared to the capacity required for the future projection to 2050. Results pointed out that climate change effects on rainfall variability can no longer be neglected in design criteria of hydraulic structures based on extreme rainfall estimations. Therefore, in order to account for climate change in the design procedures, methodologies aimed at providing reliable future evaluations of the design storm need to be developed and applied.

References


