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The impact of tipping-bucket raingauge measurement errors on design rainfall for urban-scale applications

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Abstract:

The tipping-bucket rain gauge is known to underestimate rainfall at high intensities because of the rain water amount that is lost during the tipping movement of the bucket. The related biases are known as systematic mechanical errors and, since their effect increases with rain intensity, have a significant influence on the derived statistics of rainfall extremes. A correction procedure for rain intensity data sets is proposed in this paper based on the dynamic calibration of the gauge at both fine and coarse resolution, either in direct form or after proper downscaling of the available figures. The effect of systematic mechanical errors on the assessment of design rainfall for urban-scale applications is quantified based on two rain-rate data sets recorded at very different resolutions in time. A random cascade downscaling algorithm is used for the processing of coarse-resolution data so that correction can be applied at suitable time scales. The resulting depth–duration–frequency curves obtained from the original and corrected data sets are used to quantify the impact of uncorrected rain-intensity measurements on design rainfall and the related statistical parameters. Copyright © 2005 John Wiley & Sons, Ltd.

INTRODUCTION

Efficient storm water control in the urban environment is generally obtained by proper dimensioning of the drainage system (including pipes, culverts, storage tanks, etc.) according to a suitable design rainfall event with a specified non-exceedance probability F. In the usual design practice this is also expressed by means of the related return period $T = 1/(1 - F)$. Since the risk associated with system failures is relatively low, values of T in the range 10–20 years are generally accepted, although in specific situations (where the vulnerability of the urban context is high or the structure in hand is important) design rainfall can be determined by assuming a higher return period, in the order of 100–200 years.

The design rainfall can be assumed either to have constant intensity in time or a hyetograph can be produced based on some suitable hypotheses about rainfall variability in time, e.g. assuming that for each sub-event duration at least one rainfall component exists with the specified return period (Keifer and Chu, 1957). The analogous assumption of having uniform intensity in space within the catchment basin results in overestimation of the area-averaged rainfall, and suitable area reduction factors (ARFs) are used in order to take statistically into account the effect of rainfall variability in space (WMO, 1983). In principle, since rainfall exhibits significant space–time variability and the response of the urban catchment depends strongly on the actual pattern of rain intensities within the basin as well, a design storm should be defined. However, the definition of the return period of a space–time rainfall event is not straightforward, and different rainfall patterns can, in principle, produce the same flow output in a basin, showing in this sense the same return period with non-uniqueness problems, etc.

Accurate prediction of design rainfall, whichever of the above simplifying assumptions is employed, is usually obtained by determining the depth–duration–frequency (DDF) curves of station precipitation based

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on the available data records. The DDF or intensity–duration–frequency (IDF) curves are indeed one of the most commonly used statistical tool in designing drainage systems aimed at storm water control in urban-scale applications. According to Koutsoyiannis *et al*. (1998), the establishment of this tool dates back in the early 1930s (Bernard, 1932), and various methods have been proposed in different countries, reflecting the different climatic characteristics.

In traditional engineering practice, derivation of the DDF curves is mostly performed by employing heuristic procedures based on qualitative assumptions on the inner structure of space–time rainfall, and mainly obtained by fitting an underlying probability distribution of rainfall extremes and interpolating the quantile predictions of extreme rainfall data for specified durations. The traditional mathematical framework for derivation of the DDF curves is formalized quite comprehensively in the paper by Koutsoyiannis *et al*. (1998), where a general relationship is proposed (actually in terms of rainfall intensities, i.e. for the IDF curves, the duration d being the multiplicative factor relating the two variables) in the form

$$I(d, T) = \frac{a(T)}{b(d)} \tag{1}$$

where $a(T)$ is a suitable function of the return period T, and $b(d)$ is expressed in terms of the rainfall duration d as

$$b(d) = (d + \theta)^{\eta} \tag{2}$$

with $\theta \geq 0$ and $0 < \eta < 1$ some suitable parameters derived from the exercise of fitting the available data. The function $a(T)$ is completely determined in a theoretically consistent manner from the probability distribution function of the maximum rainfall intensity and, if a Gumbel (EV1) distribution is successfully fitted to the sample data set, has the form (see Koutsoyiannis *et al*. (1998) for further details):

$$a(T) = \lambda\{\psi - \ln[-\ln(1 - 1/T)]\} \tag{3}$$

with λ and ψ are the scale and location parameters of the Gumbel cumulative distribution function (Kottegoda and Rosso, 1997).

In the last decade, a scientifically sound theoretical framework for the DDF curves based on the scale invariance properties of extreme storm probabilities was also developed (Burlando and Rosso, 1996; Menabde *et al*., 1999), the same approach also recently being applied to the derivation of the ARF (De Michele *et al*., 2001). However, since the common practice in urban design mostly relies on traditional methods, this paper only concentrates on the latter methods, the main concept and results of the work being not significantly affected by the background theories assumed to justify the procedure adopted (which is, incidentally, very similar in the two cases, yielding analogous results in practical terms).

Based on such considerations, the bias induced on design rainfall by systematic mechanical errors of tipping-bucket rain gauges is estimated in the following with reference to the common form of the DDF curves expressed in terms of the rainfall depth h as

$$h(d, T) = a(T)\, d^{\nu} \tag{4}$$

which is derived from Equation (1) after posing $\theta = 0$, as typical and verified for the specific site analysed, and $\nu = 1 - \eta$.

This is obtained here according to the following steps. In the second section, the source and relevance of systematic mechanical errors is recalled and the calibration parameters for the rain gauges investigated are derived. The third section deals with the procedure of direct data correction, based on the hypothesis that rain records are available at a sufficiently fine resolution scale, in the order of 1 to 5 min, as for the case study presented. Since this is very rarely the case in practical applications, the fourth section describes a possible procedure for correction of coarse-resolution rain records based on suitable downscaling algorithms, and a more typical case study is presented. The penultimate section, before conclusions are drawn, reports the results of the corrections applied in the two case studies investigated. The impact of the errors is demonstrated by comparison of the original and corrected time series, and expressed in terms of the most common statistics used for design rainfall estimation, i.e. in terms of the derived DDF curves and the assessment of the related return periods.

RAIN-GAUGE MEASUREMENT ERRORS

Design rainfall is obtained by processing historic rain-intensity data sets, recorded at a suitable measurement station located within or in the vicinity of the basin investigated. Correct estimation of the return period of a given rain event is, therefore, based on the prolonged and accurate measurement of rain data.

The measurement of rain intensity is, however, affected by a number of errors, due to both catching and counting inaccuracies, related to both the positioning and mechanics/electronics of the instrument employed. Most of the errors due to the catching problem have a limited influence on rain-intensity figures, but are important for rain accumulation measurements at the daily, monthly or longer time scales. These are commonly categorized as wind-induced, wetting, splashing, and evaporation errors, all of them occurring within or at the top of the water collector implemented to convey rainfall from a standardized orifice into the measuring device. The error always results in this case in some underestimation of the total amount of rainfall. A wide literature exists about the assessment and correction of catching-type errors, mainly concerned with climatologic studies and light to moderate (or solid) precipitation (e.g. Sevruk, 1982; Sevruk and Hamon, 1984; Legates and Willmott, 1990).

On the other hand, mechanical errors due to the inherent characteristics of the counting device, although less important in terms of accumulated rainfall, have a strong influence on the measurement of the rain intensity, with an increasing impact as the rain rate increases. In particular, the measurement of rain intensity is traditionally performed by means of tipping-bucket rain gauges, the most popular and widespread type of rain gauge actually employed worldwide. This is known to underestimate rainfall at higher intensities because of the rainwater amount that is lost during the tipping movement of the bucket. The related biases are known as systematic mechanical errors and result in the overestimation of rainfall at lower intensities and underestimation at the higher rain rates. Though this inherent shortcoming can be easily remedied by dynamic calibration (see later in this section), the usual operational practice in hydro-meteorological services and instrument manufacturing companies relies on single-point calibration, based on the assumption that dynamic calibration has little influence on the total recorded rainfall depth (Fankhauser, 1997).

In a recent paper, the bias introduced by systematic mechanical errors of tipping-bucket rain gauges in the estimation of return periods and other statistics of rainfall extremes was quantified in very general terms by La Barbera *et al.* (2002) and Molini *et al.* (2001), based on the error figures obtained after laboratory tests over a wide set of operational rain gauges from the network of the Liguria region of Italy. An equivalent sample size was also defined as a simple index that can be easily employed by practitioner engineers to measure the influence of systematic mechanical errors on common hydrological practice and the derived hydraulic engineering design.

Water losses that are observed during the tipping movement of the bucket can be explained as follows (Marsalek, 1981). Consider the tipping movement (see Figure 1) as starting at that instant in time when the bucket is completely filled in with its nominal volume of water. Initiation of the movement of the two paired compartments is subject to inertial forces, and completion of the bucket tipping around its rotation axis requires a certain amount of time. During such a time window the incoming rain intensity continues to supply water through the funnel. The amount of water received by the rotating bucket during half its tipping movement, i.e. during rotation until the compartment being emptied does not receive any more water from the receiver, is lost in the measurement process.

The bias, estimated on average at about 10–15% for rain rates higher than 200 mm h^{-1}, is strongly specific to the single rain gauge, depending on the manufacturer, the date of production and the type of wear (as a

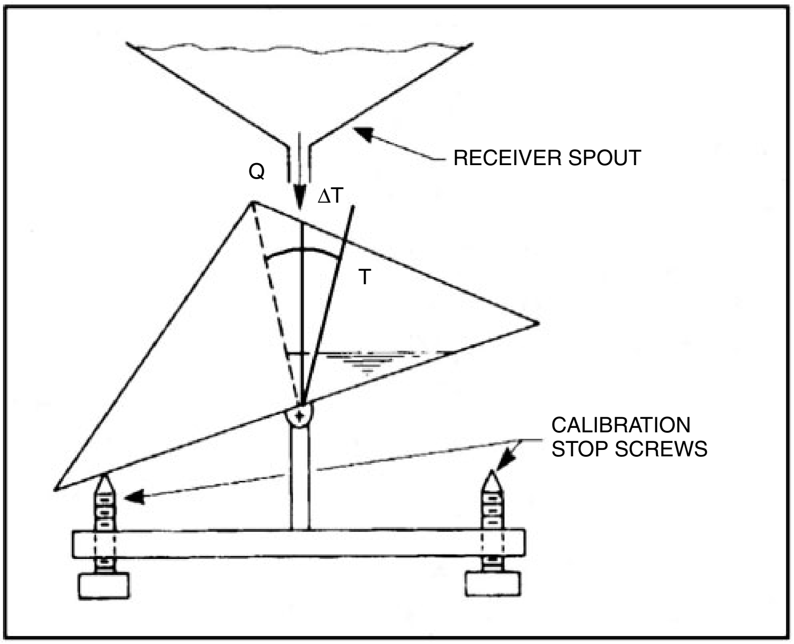

Figure 1. The tipping-bucket mechanism (after Marsalek (1981))

function of the existing environmental conditions) (Becchi, 1970; Marsalek, 1981; Adami and Da Deppo, 1986).

The relevance of such losses, affecting each single tipping of the bucket, increases with rainfall intensity and is a function of the total time ΔT requested for the bucket to complete its rotation. According to Marsalek (1981), the relationship between the recorded I_r and actual I_a intensities as a function of ΔT is given by:

$$\frac{I_r}{I_a} = \frac{h_n}{h_n + I_a \Delta T} \tag{5}$$

where h_n is the nominal rainfall depth increment per one tip. Note that $I_r/I_a = 1$ only in the case of $\Delta T = 0$ and that ΔT is a function of rainfall intensity.

The relationship presented by Marsalek (1981: figure 1) between ΔT and I_a shows significant durations of the bucket movement ranging between 0·3 and 0·6 s for the instruments analysed. However, the uncertainty involved in the measurement of the time of tipping (due to the very slow initiation of the bucket rotation) made the comparison of experimental and theoretical calibration curves difficult in that author's work. Sophisticated measurement of ΔT allows better success in comparing the experimental calibration curve with its theoretical expression.

However, direct estimation of the calibration curve is far more reliable than its theoretical derivation, as it does not involve sophisticated measurements of very short intervals in time as a function of varying rain rates. A simple hydraulic apparatus can be used for this, which allows high-precision measurements and reliable dynamic calibration of tipping-bucket rain gauges (e.g. Calder and Kidd, 1978; Marsalek, 1981; Niemczynowicz, 1986; Pagliara and Viti, 1994; Lombardo and Stagi, 1998). The objective is that of providing the gauge receiver with a constant rain rate at a number of calibration points in the (I_a, I_r) space. This is achieved by connecting a constant-water-level tank with the receiver by interposition of a nozzle with specified diameter. By modifying the water head over the orifice and the nozzle diameter, constant flows can be generated at various flow rates as desired (see Humphrey *et al.*, 1997; Lanza and Stagi, 2002).

Calibration curves reflecting the so-called dynamic calibration of the gauge can be expressed by means of a power law formulation as

$$I_\mathrm{a} = \alpha I_\mathrm{r}^{\beta} \tag{6}$$

where I_a and I_r are again the actual and recorded rain intensities, and α and β are the calibration parameters. The associated relative measurement error e can be defined as:

$$e = \frac{I_\mathrm{r}}{I_\mathrm{r} - I_\mathrm{a}} \times 100 \tag{7}$$

so that $e < 0$ indicates underestimation rather than overestimation ($e > 0$) of the actual rain rates.

As an example, we report here the results of the dynamic calibration exercise performed on the two rain gauges that will be used in the following sections to demonstrate the impact of measuring errors on the estimation of design rainfall in the case of urban-scale applications. These are the high-resolution rain gauge station of the University of Genoa and the two used on successive time spans at the Meteorological Observatory 'Andrea Bianchi' of Chiavari, located about 40 km east of Genoa along the coastline, and operating since 1883. In all cases the rain gauge in use was accurately calibrated in the laboratory using the automatic qualification module for rain-intensity measurement instruments developed by Lanza and Stagi (2002), and the estimated calibration parameters α and β for the three gauges are reported in Table I. The respective calibration curves are depicted in Figure 2.

For a study of the variability of the calibration parameters over a set of tipping-bucket rain gauges from various manufacturers, see the laboratory survey reported in Lombardo and Stagi (1998).

The two parameters α and β are therefore sufficient to characterize the mechanical behaviour of the instruments at hand, and to allow correction of the recorded data sets in order to increase their accuracy.

Table I. Calibration parameters α and β for the three gauges analysed

Station	Rain gauge	α	β
DIAM, University of Genoa	CAE (1990–2002)	0·7948	1·0632
Observatory Andrea Bianchi of Chiavari	SIAP (1961–89)	0·7582	1·0699
	SILIMET (1990–2000)	0·7579	1·0513

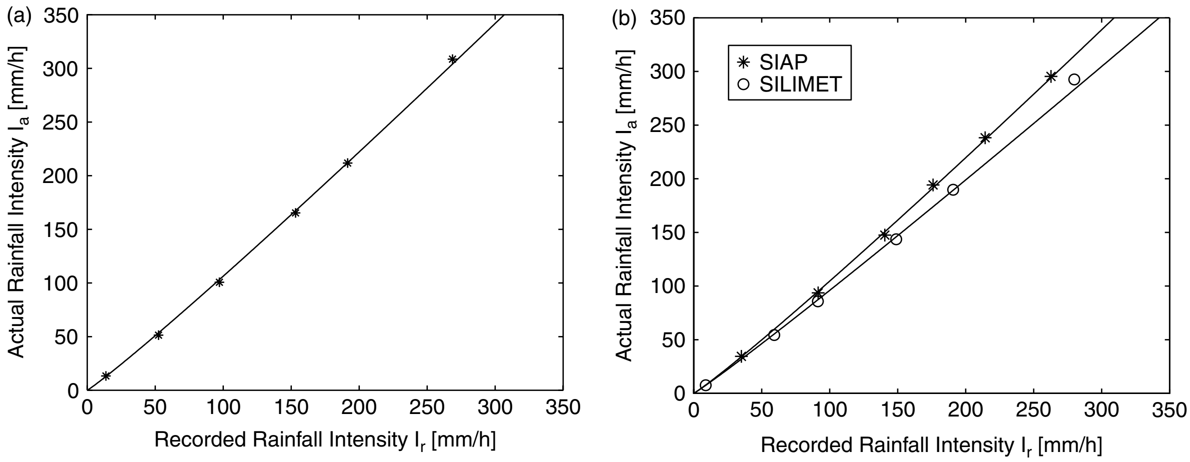

Figure 2. Calibration curves for the tipping-bucket rain gauge of DIAM—University of Genoa (a) and the two gauges employed at the Meteorological Observatory "Andrea Bianchi" of Chiavari (b)

The need for correcting rain intensity data sets measured by non-calibrated rain gauges was demonstrated by La Barbera *et al.* (2002) with reference to the bias induced on the most common statistics of rainfall extremes in both local and regional studies. In particular, the uncertainty deriving from uncorrected data sets was quantified in terms of the so-called 'equivalent sample size', a simple index able to measure the deriving influence of the errors for design purposes. This is defined, with reference to the yearly maxima on a specified duration, as

$$n_{\mathrm{EQ}} = \frac{n}{[1 + \varphi/(\mathrm{cv}\ k_{\varepsilon/2})]^2} \tag{8}$$

where n is the actual sample size (i.e. the number of years of observation), $k_{\varepsilon/2}$ a specified quantile such that $1 - F_{\mathrm{U}}(k_{\varepsilon/2}) = \varepsilon/2$ (with F_{U} the standard Gaussian cumulative function and ε the confidence level assumed in the statistical analysis), cv is the coefficient of variation and φ a suitable function of the error as obtained from dynamic calibration (see La Barbera *et al.* (2002: 9)). The values of n and n_{EQ} for the two data sets analysed in this paper and with $\varepsilon = 0{\cdot}10$ are reported in Table II.

Since mechanical errors affect the higher rain rates that are usually recorded at very short intervals in time (even within events totalling low to average rain volumes), recovering of rain records by means of suitable correction is only possible at very fine resolution in time. Unfortunately, most of the historical information is stored in the form of accumulated rainfall values over intervals of 30 to 60 min at best, and the details of the rain process at finer time scales are irremediably lost. In those cases correction can be performed based on suitable downscaling of the recorded figures at least down to resolution in the order of 5 min, where the rain rate is higher and significant biases arise. Obviously, correction would result in a statistical sense, and no deterministic assessment can be performed of the actual impact of the error on design values.

In the following sections the correction procedure is applied to both fine-resolution (direct data correction) and coarse-resolution (correction after downscaling) data sets, and the effect of the correction is estimated in terms of design rainfall for urban-scale applications.

DIRECT DATA CORRECTION

Where the rain series is available at fine resolution in time (e.g. in the order of 1 to 10 min), direct correction is possible by simply modifying recorded values at each single time step. Correction is obtained using Equation (6), with the actual intensity now being the unknown variable. The specific correction parameters α and β must first be available for the instrument at hand, as derived from suitable dynamic calibration of the gauge. The calibration exercise should be repeated periodically, since the performances of the instrument change with time and wear, so that at least yearly checking would be desirable.

Most of the above conditions are fulfilled in the case of the meteorological station operating since 1990 at the Environmental Engineering Department of the University of Genoa. Rain data are sampled every 1 min by a traditional tipping-bucket rain gauge and recorded with the same resolution. The high-resolution data set used in this work is publicly available online from the University of Genoa at http://www.diam.unige.it.

Table II. Actual (n) and equivalent (n_{EQ}) sample size for the two rain series analysed. The value of n_{EQ} for the DIAM time series refers to $T = 50$ years, and the equivalent sample size for the Chiavari series refers to $T = 200$ years

Rain series	n	n_{EQ}
University of Genoa (1990–2003)	13	11
Meteorological Observatory of Chiavari (1961–89)[a]	39	28

[a] The equivalent sample size was estimated based on the characteristics of the SIAP instrument.

Although the overall length of the rain records is limited in this case, thus reducing the significance of the statistics derived, we believe it is worth including those data in the analysis reported here so as to describe the procedure fully in the case of direct data correction. Note that, based on the commonly available rain intensity data sets, direct correction is hardly possible in real-world applications. Moreover, since the return periods in urban design are commonly in the range of 10 to 20 years, we believe that limiting the analysis at a maximum return period $T = 50$ years for the Genoa data set will sufficiently overcome this problem, at least for the objectives in hand.

Based on such considerations, direct correction was performed over the entire data set using the parameters derived from the dynamic calibration exercise performed previously. Statistics of the corrections applied are reported in Table III, and in Figure 3 the fitting of the Gumbel cumulative distribution function on the original data is presented.

CORRECTION AFTER DOWNSCALING

The most common resolution for historic rain records of sufficient length to allow suitable statistical analysis is the hourly scale. This is also the case for the data set obtained from the Meteorological Observatory 'Andrea Bianchi' of Chiavari over the period 1961–2000. The high-resolution pattern of rain intensity in time is, therefore, unknown, and correction cannot be applied directly. Figure 4 present the fitting of the Gumbel cumulative distribution function to the original data.

Indeed, the apparent rainfall intensity decreases with increasing aggregation of the rain depth increments in time, so that correction would be applied on artificially lower rain-rate figures that do not correspond to the original rain rates actually recorded by the instrument. On the contrary, the error affects the originally recorded rain rates; thus, higher values than those resulting from aggregation at the hourly scale, and direct correction of such information, would inevitably result in large underestimation of the biases involved.

Reconstruction of the original variability at sub-hourly scales is, therefore, required, at least down to a resolution in the order of 1 to 5 min, since at lower scales sampling errors may also become relevant. Appropriate downscaling methodologies allow this exercise to be performed in a statistical sense, i.e. by generating a set of possible scenarios of the inner rainfall structure that are compatible with the recorded pattern at the coarser (hourly) scale. Once small-scale data are available for each of the scenarios generated, direct correction is possible and data are re-aggregated at the original resolution in order to allow comparison with the original data set. Ensemble statistics for the whole set of corrected time series may finally provide the required parameters and their dispersion characteristics.

The downscaling procedure used in this work is a multiplicative random cascade of branching number two with exact conservation of mass. A detailed description of the method and its theoretical background is provided, for example, by Güntner *et al.* (2001), Menabde *et al.* (1997) and Olsson (1998). The cascade process essentially repeatedly divides the available space into smaller regions, in each step redistributing some associated quantity according to rules specified by the so-called cascade generator. The generator specifies

Table III. Statistics of the corrections applied to the high-resolution rain series (for the 4 min time aggregation) of DIAM, University of Genoa. Underestimation occurs for figures above the single-point calibration value (50 mm h^{-1}), whereas overestimation derives from lower figures

	Max value (mm h^{-1})	Mean value (mm h^{-1})	Standard deviation (mm h^{-1})
Underestimation ($e > 0$)	27	2·6	12·75
Overestimation ($e < 0$)	1	0·3	10·85

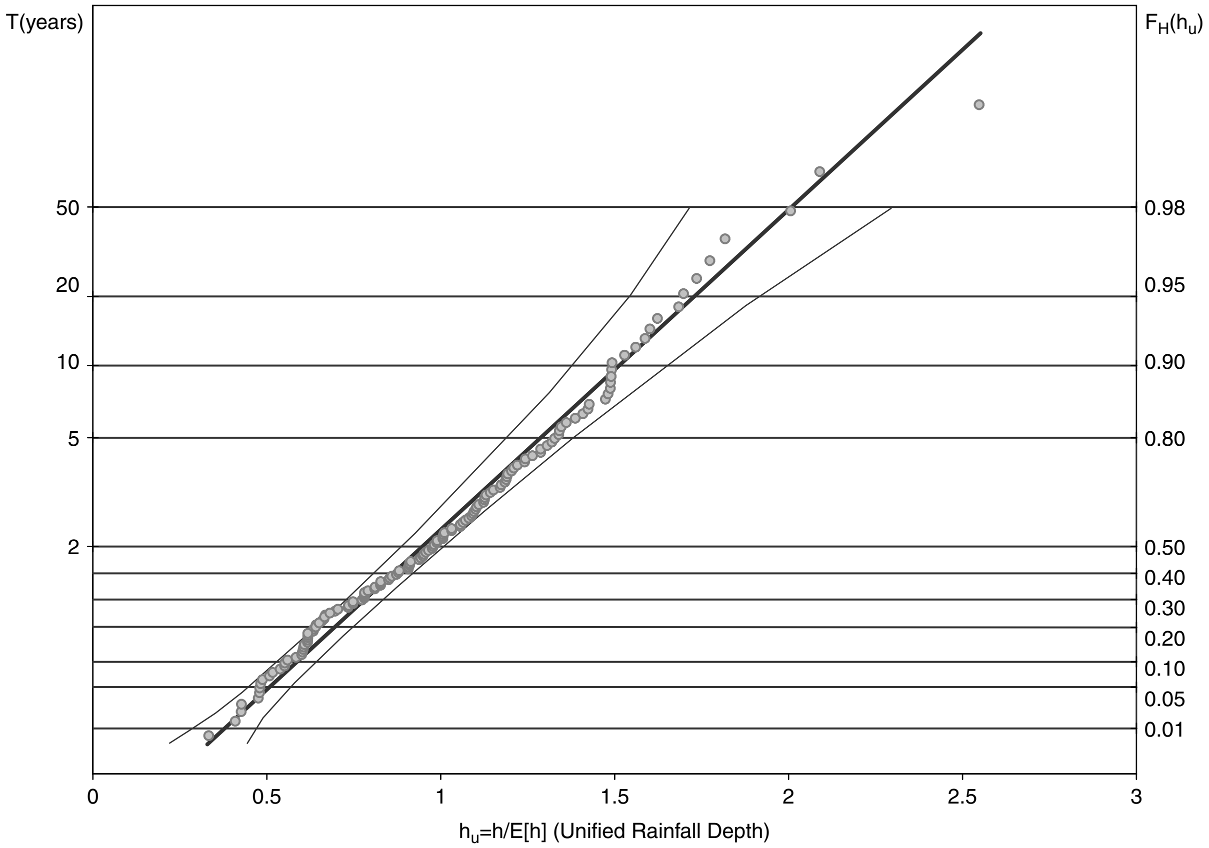

Figure 3. Fitting of the Gumbel distribution of rainfall extremes for the rain series of DIAM, University of Genoa

the multiplicative weights W_1 and W_2 associated with each single branching, e.g. in the form

$$W_1, W_2 = \begin{cases} 0 \text{ and } 1 & \text{with probability} \quad P(0|1) \\ 1 \text{ and } 0 & \text{with probability} \quad P(1|0) \\ W_{x|x} \text{ and } 1 - W_{x|x} & \text{with probability} \quad P(x|x) \end{cases} \tag{9}$$

where $0 < W_{x|x} < 1$ and $P(0/1) + P(1/0) + P(x|x) = 1$ (Güntner *et al.*, 2001).

The multiplicative weights W_1 and W_2 are estimated for each single time step of any generic level of the cascade based on a series of rain records that must be available at high resolution. In the case study presented here, reference data are obtained from the rain series of DIAM, Genoa, used in the previous section, covering the period 1990–2001 with time resolution of 1 min. The station is assumed to be suitable to act as a reference station based on the substantial climatic similarity with the historic site of Chiavari, being 40 km distant along the coastline.

The same division into position classes as in Olsson (1998) is employed, i.e. (1) box preceded by a dry box (with volume $V = 0$) and succeeded by a wet box ($V > 0$) (starting box); (2) box preceded and succeeded by wet boxes (enclosed box); (3) box preceded by a wet box and succeeded by a dry box (ending box); and (4) box preceded and succeeded by dry boxes (isolated box). In Figure 5 the overall cumulative distribution of the weights derived from the high-resolution data set is reported for the aggregation scales involved and the four position classes above.

The Chiavari hourly data series, therefore, was processed for downscaling throughout the cascade until a final resolution of 4 min was obtained, using a Monte Carlo simulation framework where several scenarios are

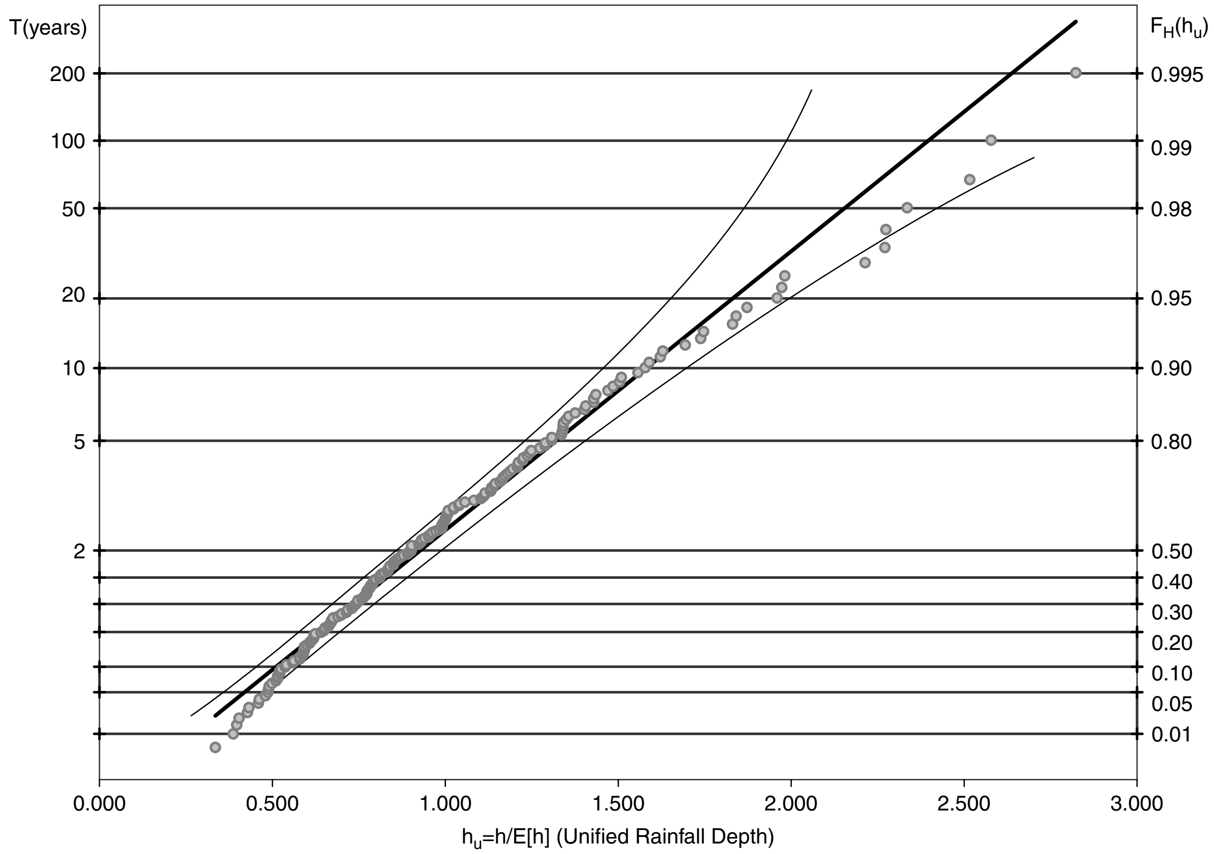

Figure 4. Fitting of the Gumbel distribution of rainfall extremes for the Chiavari rain series

produced using the same statistical parameters. One thousand realizations were generated for this particular case study, and the synthetic figures mentioned in the following always refer to the average over the whole ensemble of high-resolution rain series produced. Direct correction was, therefore, performed over each single realization of the entire data set using the parameters derived from the dynamic calibration exercise already performed. The results are discussed in the following section, together with those obtained from direct calibration in the case of the DIAM data set.

THE IMPACT ON DESIGN RAINFALL ESTIMATES

Under the Gumbel hypothesis, DDF curves have been obtained for both the original and corrected data sets of the two case studies examined, in the form:

$$h(d, T) = a(T) \cdot d^{\nu} \tag{10}$$

where h indicates rainfall depth and d the duration, with $a(T)$ and ν some suitable parameters to be obtained from experimental data.

In the case of direct correction performed over high-resolution data sets, the procedure is deterministic and, therefore, the statistics derived from original and corrected rain records can be easily compared. In Figure 6 the DDF curves for the DIAM station are reported, with return periods from 2 to 50 years. Higher

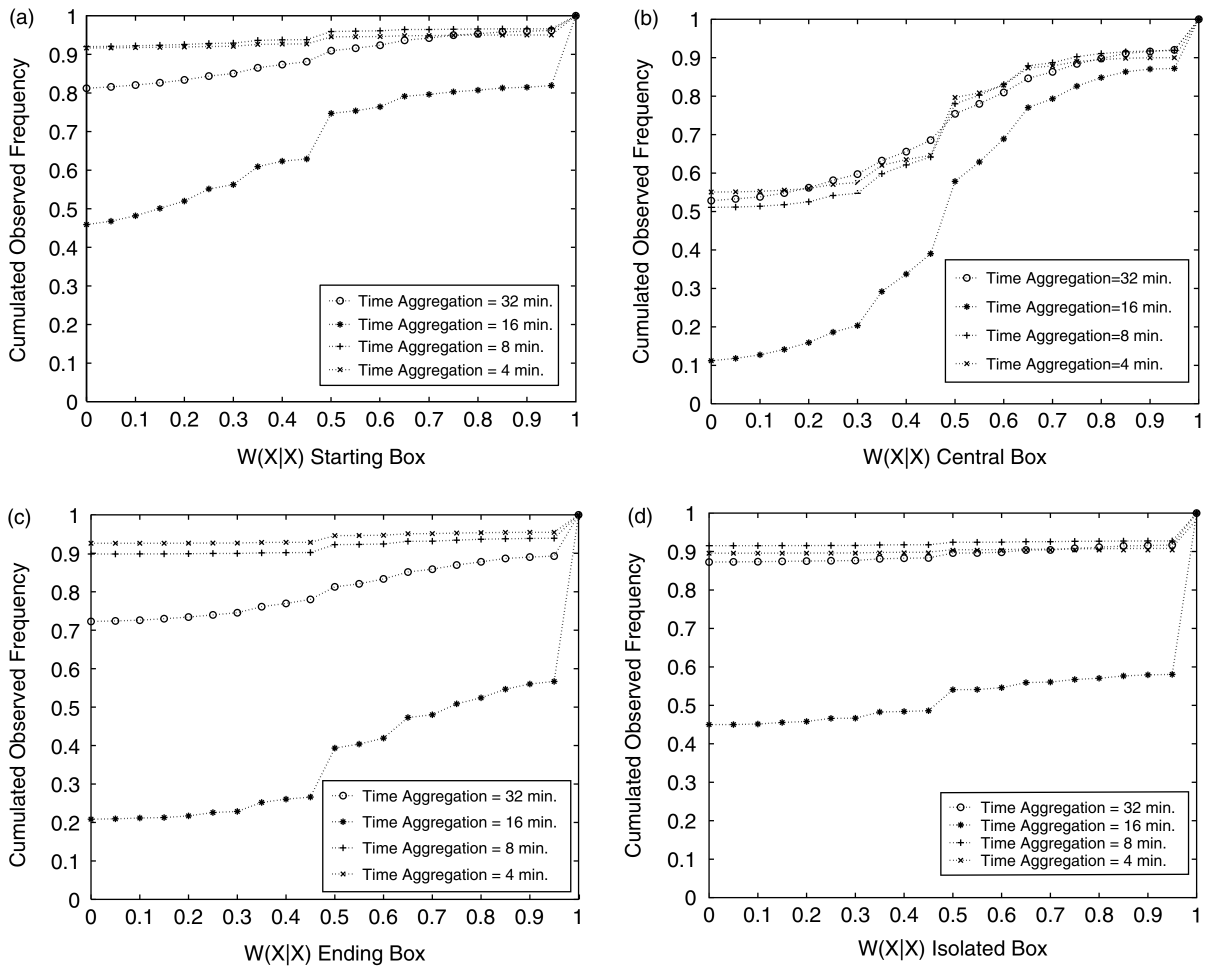

Figure 5. Cumulative distribution of the downscaling parameters for the reference high-resolution DIAM rain series for the aggregation scales involved and for starting (a), central (b), ending (c) and isolated (d) boxes

return periods are not shown because of this limitation deriving from the short time period of the available observations (about 10 years). In each graph the curves based on the original and corrected data are reported so as to facilitate comparison between design rainfall estimates in the two cases. Obviously, results can be read from different viewpoints, and the representation used in Figure 6 allows an easy assessment of the ratio between original and corrected design rainfall for any duration of the rain event and for a given choice of the associated return period. The same information is synthesized in Figure 7, where the actual 'gain' obtained after direct correction is applied is expressed as a function of duration for all the return periods analysed.

It can be noted that the gain decreases with increasing duration, since the relative weight of low-intensity components of the rain event (where correction is not significant) increases. On the contrary, the gain obviously increases for any fixed duration with increasing return periods, since the error increasingly affects the higher intensities. Negative gains may appear towards longer durations and for short return periods, due to the fact that correction inversely affects the rain intensity figures when these are lower than the single-point calibration value usually provided by the rain-gauge manufacturers on all instruments (these are calibrated at a rain rate of around 30–50 mm h^{-1}).

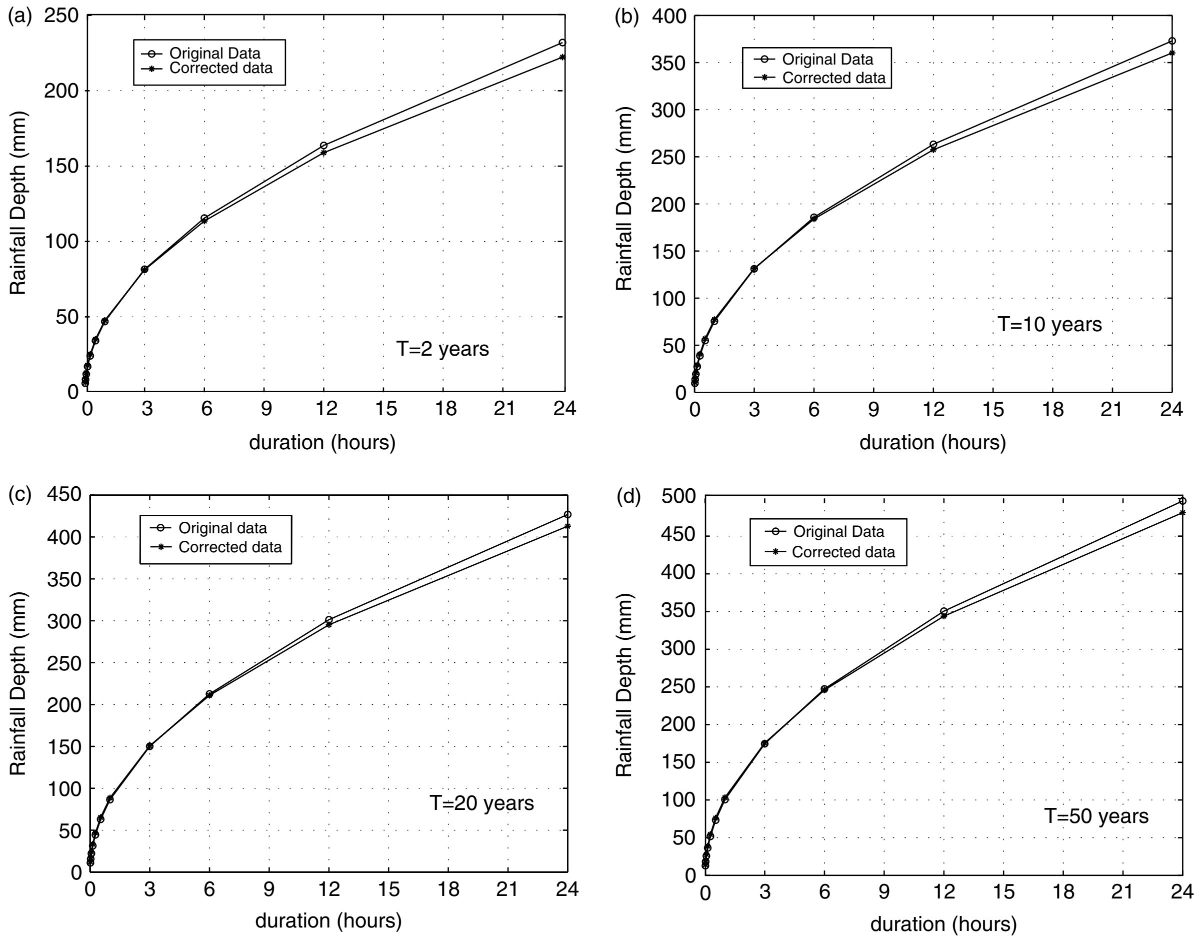

Figure 6. Original and corrected DDF curves for the DIAM station for return periods of (a) $T = 2$, (b) $T = 10$, (c) $T = 20$ and (d) $T = 50$ years

Conversely, data can be interpreted as a measure of the error induced on the assessment of the return period for rainfall events with a given magnitude and duration. This is synthetically provided in the representation shown in Figure 8, where the ratio between the return periods estimated on corrected and original data is plotted against the event duration, for a set of reference return periods calculated on the original data.

Again, the ratio increases with decreasing duration and with increasing reference return period. A measure of the overall effect of systematic mechanical errors of tipping-bucket rain gauges on the assessment of design rainfall can, therefore, be derived from such a representation: the induced bias can be quantified as an error of 65% on the assessment of the return period of design rainfall for duration 1 h when the return period is in the order of 50 years.

As for the high-resolution Chiavari time series, obtained after downscaling as an ensemble of possible realizations, the parameters of the above DDF curves have been evaluated for each single realization, therefore allowing interpretation only in statistical terms. An average curve and a measure of dispersion can easily be provided to describe the results. In Figure 9, the original DDF curve and the ensemble of the corrected curves derived from 500 realizations of the possible rain intensity pattern at a sub-hourly scale are represented on the same graph, together with the average corrected curve. The information is now provided for return periods from 2 to 200 years, since the original hourly records cover a longer period of time in this case.

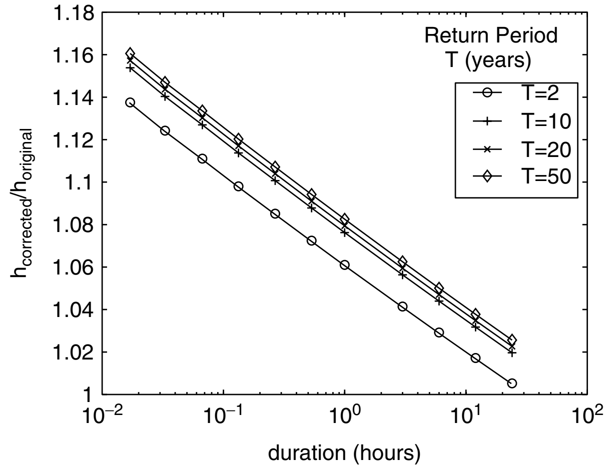

Figure 7. Synthetic representation of the 'gain' obtained after direct correction on the high-resolution data set from the DIAM station

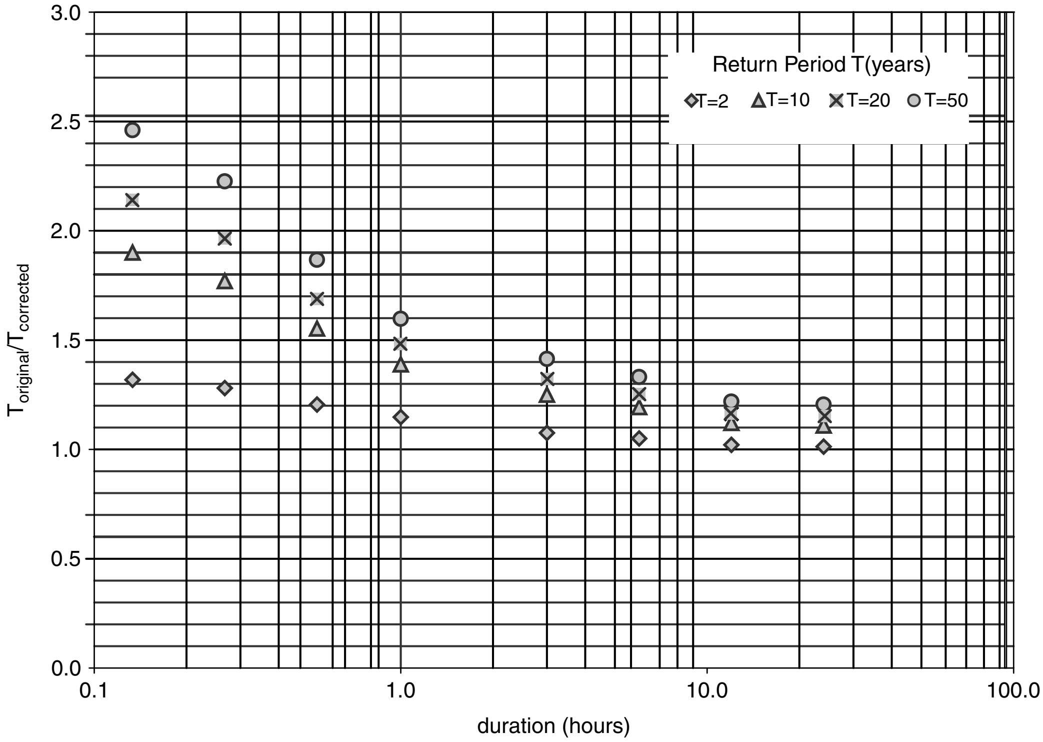

Figure 8. The influence of systematic mechanical errors on the assessment of the return period for the DIAM station

Also in this case, the results can be read from different viewpoints and the representation used in Figure 9 is synthesised in Figure 10, where the actual 'gain' obtained after statistical correction is applied is expressed as a function of duration for all the return periods analysed. The figures reported in this graph refer to the average corrected curve.

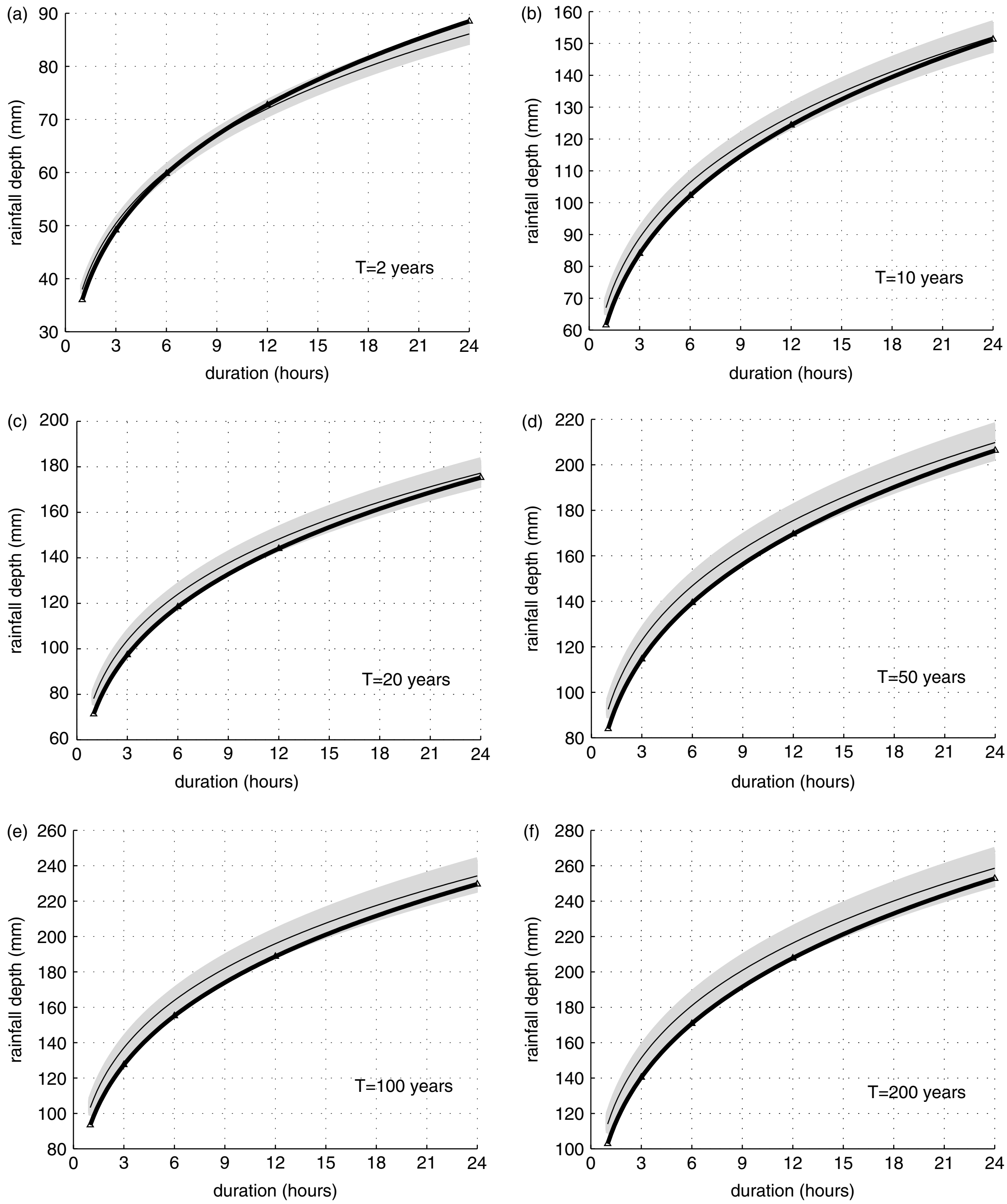

Figure 9. Original (bold) and ensemble of corrected DDF curves for the Chiavari station at various return periods from $T = 2$ to $T = 200$ years. The thin line indicates the average corrected curve

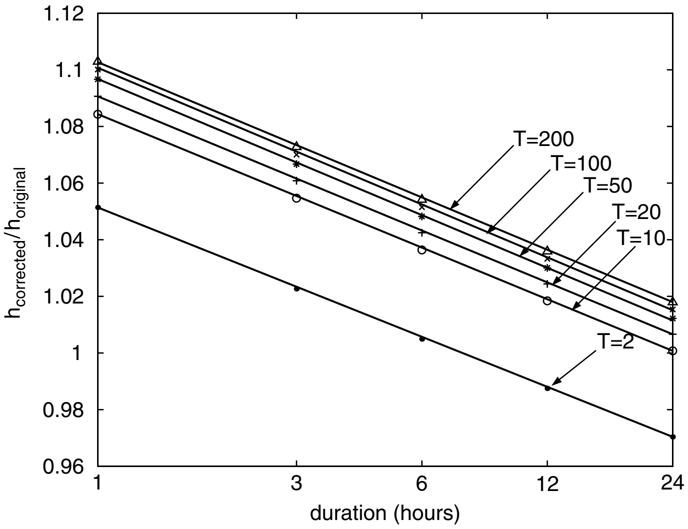

Figure 10. Synthetic representation of the 'gain' obtained after correction of the high-resolution realizations obtained from downscaling hourly records from the Chiavari station

Again, data can be interpreted as a measure of the error induced on the assessment of the return period of rainfall events with a given magnitude and duration. This is synthetically provided in the representation shown in Figure 11, where the ratio between the return periods estimated on corrected and original data is plotted against the event duration, for a set of reference return periods calculated on the original data. The figures reported in this graph refer to the average corrected curve.

CONCLUSIONS

The bias induced by systematic mechanical errors of tipping-bucket rain gauges is usually neglected in hydrological practice, based on the assumption that it has little influence on the total recorded rainfall depth. We have demonstrated that, since the error increases with rainfall intensity, the assumption is not acceptable for the assessment of design rainfall in urban-scale applications. In this case, indeed, the high resolution required for the monitoring of rainfall intensities (due to the very short response time of urban catchment basins) amplifies the influence of mechanical errors on the derived statistics of rainfall extremes, with a bias that can be quantified as an underestimation of about 60 to 100% on the assessment of the return period of design rainfall for duration 1 h and return periods from 20 to 200 years.

The above figures were estimated in this paper both by direct correction of the available high-resolution rain records and after suitable downscaling of a coarser data set. In the first case, correction is deterministic and does not require any sophisticated algorithm. Therefore, when original records with a resolution of at least 5 min are available, the use of uncorrected data seems unjustified in practical urban design applications. Dynamic calibration is indeed easily attainable, and rain-gauge manufacturers are progressively producing self-calibrating instruments to overcome the problem and provide more accurate rain-intensity measurements.

In the more common case, where the original data set is available at coarser resolution scales, typically in the order of 1 hour in most meteorological stations, correction of systematic mechanical errors involves the implementation of some suitable downscaling algorithm in order to apply direct correction on rain data described at proper resolution in time. The multiplicative cascade process is one suitable candidate for this, with the possible methodology and related results being presented in this paper. However, whatever the algorithm selected, correction is applied in this case on a set of possible scenarios of the unknown small-scale

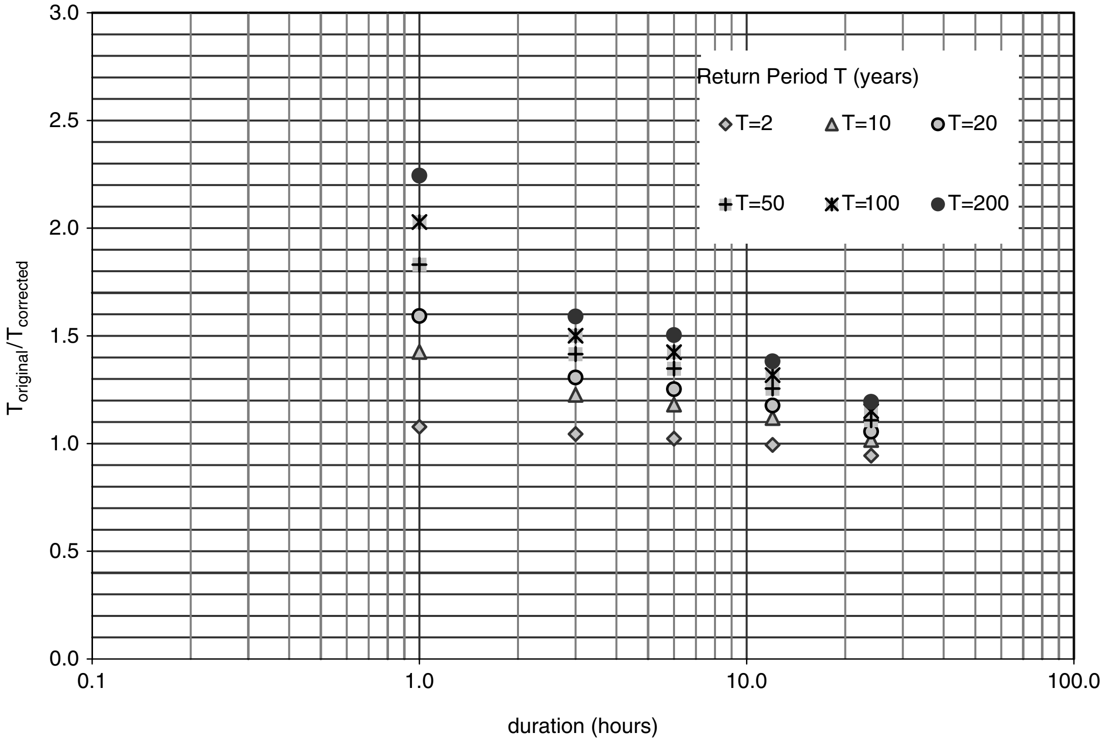

Figure 11. The influence of systematic mechanical errors on the assessment of the return period for the Chiavari station

pattern of rain intensity over time. The results are, therefore, available only in the form of statistical estimates, and a suitable measure of dispersion must be provided in order to qualify such information better.

The structure of the downscaling model may actually influence the results obtained in terms of statistics of the corrected data. In this regard, a comparison of different algorithms would, therefore, be desirable, although it is quite reasonable that the resulting correction on the statistical parameters will be basically determined by the imposed variance of the inner-scale process. The choice of the most suitable algorithm for downscaling is, however, beyond the objective of this paper, whose principal aim and result is to show that the amount of correction required in the case of urban-scale applications is far from being negligible, with relevant practical impacts on the management and design of urban drainage systems.

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REFERENCES

Adami A, Da Deppo L. 1986. On the systematic errors of tipping bucket recording rain gauges. In *Proceedings of International Workshop on the Correction of Precipitation Measurements*, Zurich, Switzerland, 1–3 April 1985.

Becchi I. 1970. *On the possibility of improving rain measurements: calibration of tipping-bucket rain gauges*. Technical report for CNR grant no. 69.01919, University of Genoa (in Italian).

Bernard MM. 1932. Formulas for rainfall intensities of long durations. *Transactions of the American Society of Civil Engineers* **96**: 592–624.

Burlando P, Rosso R. 1996. Scaling and multiscaling models of depth–duration–frequency curves for storm precipitation. *Journal of Hydrology* **187**: 45–64.

Calder IR, Kidd CHR. 1978. A note on the dynamic calibration of tipping-bucket gauges. *Journal of Hydrology* **39**: 383–386.

De Michele C, Kottegoda NT, Rosso R. 2001. The derivation of areal reduction factor of storm rainfall from its scaling properties. *Water Resources Research* **37**: 3247–3252.

Fankhauser R. 1997. Measurement properties of tipping bucket rain gauges and their influence on urban runoff simulation. *Water Science and Technology* **36**(8–9): 7–12.

Güntner A, Olsson J, Calver A, Gannon B. 2001. Cascade-based disaggregation of continuous rainfall time series: the influence of climate. *Hydrology and Earth System Sciences* **5**: 145–164.

Humphrey MD, Istok JD, Lee JY, Hevesi JA, Flint AL. 1997. A new method for automated calibration of tipping-bucket rain gauges. *Journal of Atmospheric and Oceanic Technology* **14**: 1513–1519.

Keifer CJ, Chu HH. 1957. Synthetic storm pattern for drainage design. *Journal of the Hydraulics Division, ASCE* **83**(HY4): 1–25.

Kottegoda NT, Rosso R. 1997. *Statistics, Probability and Reliability for Civil and Environmental Engineering*. McGraw-Hill: New York.

Koutsoyiannis D, Kozonis D, Manetas A. 1998. A mathematical framework for studying rainfall intensity–duration–frequency relationships. *Journal of Hydrology* **206**: 118–135.

La Barbera P, Lanza LG, Stagi L. 2002. Tipping bucket mechanical errors and their influence on rainfall statistics and extremes. *Water Science and Technology* **45**(2): 1–9.

Lanza L, Stagi L. 2002. *Quality standards for rain intensity measurements*. WMO Commission on Instruments and Observing Methods—Report No. 75—WMO/TD-No.1123, P2(4). Published on CD-ROM.

Legates DR, Willmott CJ. 1990. Mean seasonal and spatial variability in gauge-corrected, global precipitation. *International Journal of Climatology* **10**: 111–127.

Lombardo F, Stagi L. 1998. Testing and dynamic calibration of rain gauges aimed at the assessment of errors for intense rainfall. In *Proceedings of XXVI Conference on Hydraulics and Hydraulic Structures*, CUECM (ed.), Catania; 85–96 (in Italian).

Marsalek J. 1981. Calibration of the tipping bucket raingage. *Journal of Hydrology* **53**: 343–354.

Menabde M, Harris D, Seed A, Austin G, Stow D. 1997. Multiscaling properties of rainfall and bounded random cascades. *Water Resources Research* **33**(12): 2823–2830.

Menabde M, Seed A, Pegram G. 1999. A simple scaling model for extreme rainfall. *Water Resources Research* **35**(1): 335–339.

Molini A, La Barbera P, Lanza LG, Stagi L. 2001. Rainfall intermittency and the sampling error of tipping-bucket rain gauges. *Physics and Chemistry of the Earth* **26**(10–12): 737–742.

Niemczynowicz J. 1986. The dynamic calibration of tipping-bucket raingauges. *Nordic Hydrology* **17**: 203–214.

Olsson J. 1998. Evaluation of a cascade model for temporal rainfall disaggregation. *Hydrology and Earth System Sciences* **2**: 19–30.

Pagliara S, Viti C. 1994. Dynamic calibration of a tipping-bucket rain gauge sensor. *Bollettino Geofisico* **2**: 63–69 (in Italian).

Sevruk B. 1982. *Methods of correction for systematic error in point precipitation measurement for operational use*. Operational Hydrology Report No. 21, WMO Report No. 589.

Sevruk B, Hamon WR. 1984. *International comparison of national precipitation gauges with a reference pit gauge*. Instruments and Observing Methods Report No. 17, WMO.

WMO. 1983. *Guide to Hydrological Practices*, vol. II, *Analysis, Forecasting and Other Applications*, 4th ed. WMO no. 168. World Meteorological Organization: Geneva, Switzerland.

