Simplified method to correct rainfall measurements from tipping bucket rain gauges

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Abstract

Tipping bucket rain gauges are commonly used in rainfall measurement campaigns. The main disadvantage of these devices is that they underestimate rainfall volumes at the higher rainfall intensities, due to the loss of water during the tipping action of the device.
In this paper a new method is proposed to correct recorded rainfall data, without the need for a detailed calibration test. The comparison of the calibration results of 24 gauges (6 different types) shows an interesting relationship between the rain gauge resolution (rainfall depth corresponding to 1 tip) and the slope of its calibration curve. This relationship proves that the tipping time of the tipping mechanism has nearly the same value for every tested device. Therefore the slope of the regression line can be calculated theoretically and, as a consequence, one simple calibration test is enough to determine the complete calibration curve of any tipping bucket rain gauge. This test has to be carried out anyway in order to find the exact resolution of the device.
Two monitored storm events, one moderate storm and one heavy storm, are used to study the possible influence of the correction method on calculated cumulative rainfall volumes.

Introduction

Rainfall measurements are important data in hydrology. They can be used in several kinds of applications: as input for flood forecasting models of river basins, for real time control of sewer systems, for data verification purposes...
Since the uncertainty on the input data for numerical models can be quite high (Willems and Berlamont, 1999; Willems, 2000), it is important to limit these uncertainties where possible. Rainfall measurements are one of these data where the uncertainty can be limited by a good calibration of the rain gauges. Tipping bucket rain gauges are commonly used for collecting rainfall data in urban hydrology. These devices are known for their tendency to underestimate rainfall volumes, especially for the higher rainfall intensities (Luyckx et al., 1998). These more extreme events are just the ones most important in applications concerning sewer overflows, flood forecasting…
Therefore, within the framework of several sewer modelling studies, different types of tipping bucket rain gauges, a number of 21 devices in total, were tested in the Hydraulics Laboratory of the Leuven University. Also some rain gauge calibration results from literature are used in this study. In table 1 an overview is given of all the pluviographs which are used in this study, together with their most important characteristics.

Table 1. Overview of all tested pluviographs.

type	number of pluviographs	resolution (mm)	diameter (cm)	bucket volume (ml)
A	4	0.1	16	2.01
B	12	0.1	20	3.14
C	2	0.2	22.5	7.95
D	3 (*)	0.2	35.7	20.02
E	2	0.254	20.9	8.71
F	1	0.5	20	15.71

(*) Calibration results from literature (Ciaponi et al. (1993); Giuliani et al. (1996)).

Calibration of the rain gauges

Each of the rain gauges was brought to the laboratory and was subjected to a *dynamic calibration* procedure. This means that the comparison between measured and exact volume of water, poured through the rain gauge, was made for different simulated rainfall intensities. For each device, at least 10 tests were performed where a known volume of water (mostly1 litre) was sent through the gauge and where the corresponding number of tips was recorded.

For every test the relative error ε, being $\frac{V - V_{rec}}{V_{rec}} = \frac{n^* - n}{n}$ is calculated.

Hereby is
- V = volume of water used for the test [ml]
- V_{rec} = volume of water indicated by the rain gauge [ml]
- n^* = expected amount of tips
- n = amount of tips recorded by the rain gauge

Incorporating the characteristics of the respective rain gauge, and taking into account the following identity:

$$V_{rec} = n \cdot v_b = 0.1 \cdot n \cdot R \cdot A \qquad (1)$$

this error can be rewritten as:

$$\varepsilon = \frac{V}{0.1 \cdot n \cdot R \cdot A} - 1$$

with
- v_b = volume of each tipping bucket [ml]
- R = resolution of the rain gauge [mm]
- A = receiving area of the rain gauge [cm^2]

When these errors are plotted in function of the rainfall intensity, as recorded by the pluviograph, for all devices a similar calibration curve is found, consisting of 3 regions (figure 1):

- $i_{rec} < i_{low}$. For very low intensities, the raindrops fall into the buckets with intervals larger than the tipping time of the rain gauge. This tipping time is the time interval between the start of the movement of the tipping mechanism until the passage of the central position. Therefore no water gets lost and a horizontal part in the calibration curve is found.

The rainfall intensity i_{low} can be calculated as:

$$i_{low} = \frac{10 \cdot v_d}{\tau \cdot A} \qquad (2)$$

where: i_{low} = intensity where the time interval between drops equals the tipping time [mm/h]
v_d = volume of 1 drop [ml]
τ = tipping time [h]

The drop volume v_d is depending on the design of the bottom of the funnel. When no detailed measurements are available, a drop volume of 0.075 ml can be assumed. This value gave good agreements with the experimental results (i_{low} ranging between 15 and 30 mm/h).

- $i_{low} < i_{rec} < i_{upp}$. In this region the buckets are still being filled by a discontinuous series of drops. The time interval between two drops however is smaller than the time necessary for the mechanism to tip and, as a consequence, some water gets lost during this tipping action. This loss of water becomes more important when more tips occur during a given time step. The tipping time remains constant since it is initiated by the kinetic energy of one single drop. In literature (Fankhauser, 1996) also a constant tipping time for intensities between 0 and 210 mm/h was given. Therefore the error is proportional to the amount of tips in a given time period and also proportional to the tipping time τ (constant term is neglected):

$$\varepsilon = \frac{n \cdot \tau}{\Delta T} = \frac{\tau}{R} \cdot \frac{n \cdot R}{\Delta T} = \frac{\tau}{R} \cdot i_{rec} = K \cdot i_{rec}$$

in which: ΔT = time interval in which n tips occur [h]
i_{rec} = rainfall intensity, as recorded by the rain gauge [mm/h]
K = slope of the regression curve [h/mm]

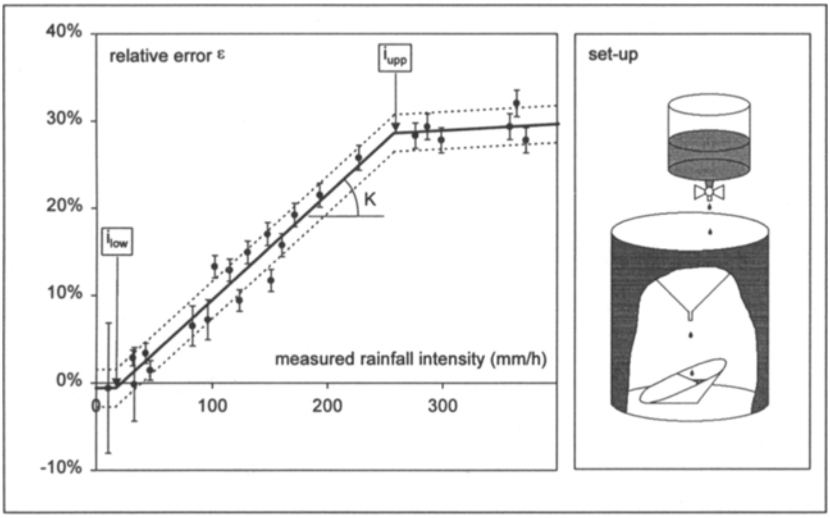

Figure 1. Example of calibration curve (type B gauge) and sketch of the experimental set-up. (positive error indicates underestimation of rainfall volume)

- $i_{rec} > i_{upp}$. For very high intensities the buckets are being filled by a continuous trickle. The tipping time decreases now for increasing intensities, since a more intense trickle makes the buckets rotate faster. A nearly horizontal line is found in the calibration curve: the extra loss due to more tips for increasing intensity is compensated by a decreased tipping time.
  Again the i_{upp}-value is depending on the device, but was in every tested case higher than 200 mm/h.

Tipping time of the different rain gauges

In figure 2 the slopes of the different regression lines are plotted in function of the gauge resolution. By means of regression analysis the following formula could be found:

$$K = \frac{\tau}{R} = \frac{1.25 \cdot 10^{-4}}{R} \quad [\text{h/mm}]$$

This means that not only for one pluviograph the tipping time remains constant (for intensities below i_{upp}), but this tipping time seems to have a quite constant value for all the tested devices:

$$\tau = 1.25 \cdot 10^{-4}\ \text{h} = 0.45\ \text{s}$$

This value of τ can be used to calculate i_{low} (equation 2).
Analysing the slope of the dynamic calibration regression line was thus an indirect way for determining the tipping time of the rain gauge. This value is found to be independent of bucket size, resolution... (figure 3). Only for the very small bucket sizes a large scatter is found: the slightest presence of dust can have a large effect on the tipping time. The larger, more robust buckets will be less sensitive to these external influences.

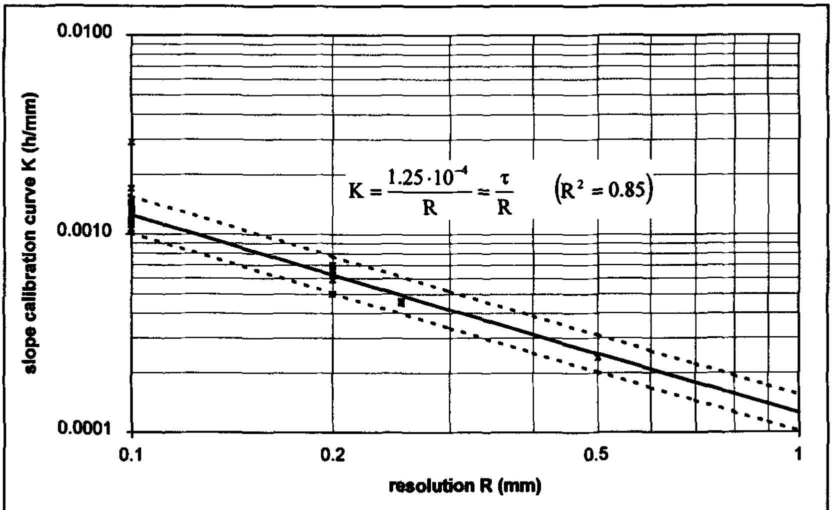

Figure 2. Influence of rain gauge resolution on the calibration curves.

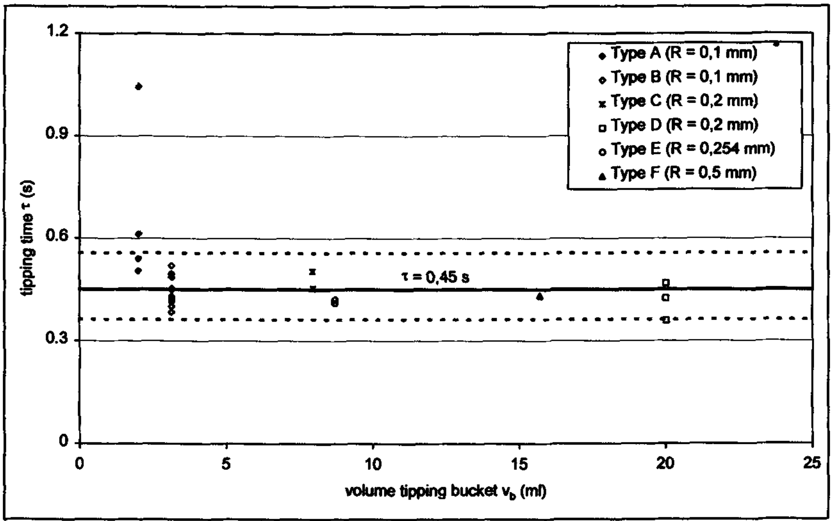

Figure 3. Influence of tipping bucket volume on the tipping time.

For the constant term of the calibration curve no correlation was found. This term is determined by the position of the screws that determine the content of the tipping buckets (thus the rainfall depth corresponding to 1 tip). A slight adjustment of this screw position changes the constant term of the calibration curve.

Practical calibration of rain gauges – correcting rain gauge data

Static calibration. Since the tipping time seems to have a quite constant value, it is possible to estimate the 'dynamic' calibration curve by just doing one single calibration test. Several authors advise this test (Fankhauser, 1998; Rauch et al., 1998), the so-called *static calibration*, since the resolution of the rain gauge does not always match the specifications given by the manufacturer. This calibration is done by pouring a known volume of water through the rain gauge at a constant, slow rate. A simulated intensity of approximately 40 mm/h can be advised. This artificial rainfall intensity can be calculated as:

$$i_{cal} = \frac{10 \cdot V}{A \cdot \Delta t_{cal}}$$

in which: i_{cal} = intensity that is used for the static calibration [mm/h]
Δt_{cal} = total time [h] of the calibration test (indicated by the gauge)

Equation (1) can be used for the static calibration:
This formula can be used in two ways. Firstly, the screws that determine how much water is needed for the tipping mechanism to 'tip' could be adjusted, so that the R-value corresponds to the resolution given by the manufacturer. This method has the disadvantage that this procedure has to be repeated until the right position is found. Secondly, the resolution found by solving equation (1) can be considered as the resolution of the rain gauge and can be used as such for the field measurements. Whichever method is used, the calibrated resolution R_{cal} of the gauge has been determined.
Because the complete calibration curve will be based on 1 single calibration experiment, this experiment should be carried out accurately. The relative error on the resolution is given by:

$$\frac{\Delta R_{cal}}{R_{cal}} = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta n}{n}\right)^2} = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + 2\cdot\left(\frac{\Delta D}{D}\right)^2 + \left(\frac{v_b \cdot \Delta n}{V}\right)^2} \qquad (3)$$

in which D is the diameter of the collecting area.

Equation (3) can be used to determine what volume of water should be used for the static calibration test, in order to get a certain accuracy for the calibrated resolution. The following assumptions are made:

ΔV = 5 ml; an absolute error of 5ml on the volume of water used for the calibration

$\frac{\Delta D}{D}$ = 1%; a relative error of 1% on the diameter of the receiving area

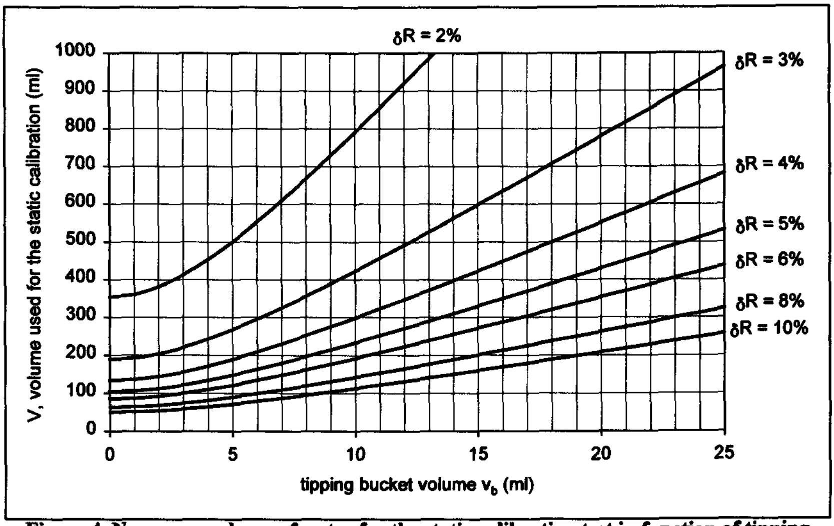

Figure 4. Necessary volume of water for the static calibration test in function of tipping bucket volume.

For bucket volumes smaller than 5ml, a calibration volume of 500ml gives sufficient accurate results (uncertainties smaller than 2%). For larger bucket sizes it is better to use larger calibration volumes.

Further correction of field measurements. With the help of this R_{cal}-value and the knowledge that the tipping time remains constant for the most important part of the calibration curve, field measurements can be corrected using the following formula, which gives the rainfall depth corresponding to 1 tip:

- $i_{rec} > i_{low}$: $h = R_{cal} + \tau \cdot (i_{rec} - i_{cal}) = R_{cal} + \tau \cdot \left(\frac{R_{cal}}{\Delta t} - i_{cal}\right)$
- $i_{rec} < i_{low}$: $h = R_{cal} + \tau \cdot (i_{low} - i_{cal})$

and in which: h = rainfall depth corresponding to 1 tip [mm]
R_{cal} = calibrated resolution of the rain gauge [mm]
Δt = time interval between two consecutive tips [h]

Unless more accurate measurements are available, these two values can be recommended:
i_{low} = equation (2), with $v_d = 0.075$ ml
τ = $1.25 \cdot 10^{-4}$ h

Uncertainty after correction. The uncertainty on the corrected data is coming from two sources: firstly there is the uncertainty on the calibrated resolution and, secondly, there is an uncertainty on the value of the tipping time. In figure 5 these confidence limits (standard deviations) are shown graphically and in table 2 the values are calculated for 3 different resolutions. The figure shows once more that an accurate static calibration is very important.

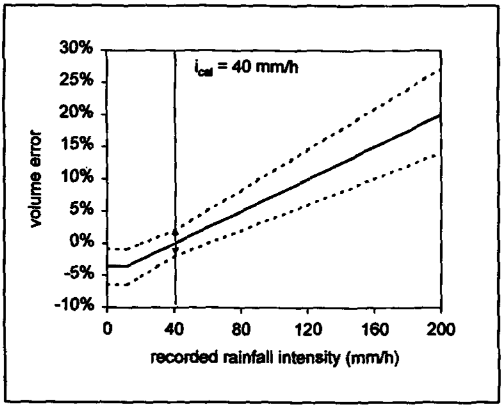

Figure 5. Confidence interval of the correction curve. (R_{cal} = 0.1mm)

Table 2. Uncertainty after correction (%).

intensity (mm/h)	resolution (mm) 0.1	0.2	0.5
20	2.6	2.3	2.1
40	2.0	2.0	2.0
60	2.5	2.3	2.1
80	3.0	2.5	2.2
100	3.4	2.7	2.3
120	3.9	3.0	2.4
140	4.3	3.2	2.5
160	4.7	3.4	2.6
180	5.1	3.7	2.7
200	5.4	3.9	2.8

Influence of correction method on rainfall volumes during monitored storm events

To study the applicability of this correction method, measurements from two single storm events, monitored by tipping bucket rain gauges, were corrected according to different correction methods. The first storm event was recorded in the catchment of Brakel (Flanders), where 3 pluviographs were used to monitor the spatial rainfall for a sewer system modelling study (Berlamont et al., 2000). Referring to table 1, one type F (P2) and two type A (P1 and P3) pluviographs were used. The second, more intense storm event was recorded in the city of Antwerp. In this case a type B pluviograph was used (P4). All the gauges were calibrated dynamically and their calibration relationships can be found in figure 6. Pluviographs P1, P3 and P4 have the same resolution (0.1mm) and the slope of their regression line is almost identical. The constant term on the other hand differs a lot (more than 20%). The resolution of pluviograph P2 is lower (0.5mm) and the slope of its regression line is therefore much milder.
To evaluate the possible impact of the rainfall correction method, for both storm events the measured rainfall data were corrected using different methods. Firstly they were corrected according to the dynamic calibration results. These values are considered to be the most accurate and are therefore used as reference values in table 3.
The first comparison that is made is with the uncorrected data. Rainfall depths are calculated with the resolution, given by the manufacturer. For two of the devices the underestimation of the cumulative rainfall depth is about 15%. Again this points at the need for an accurate static calibration of every device.

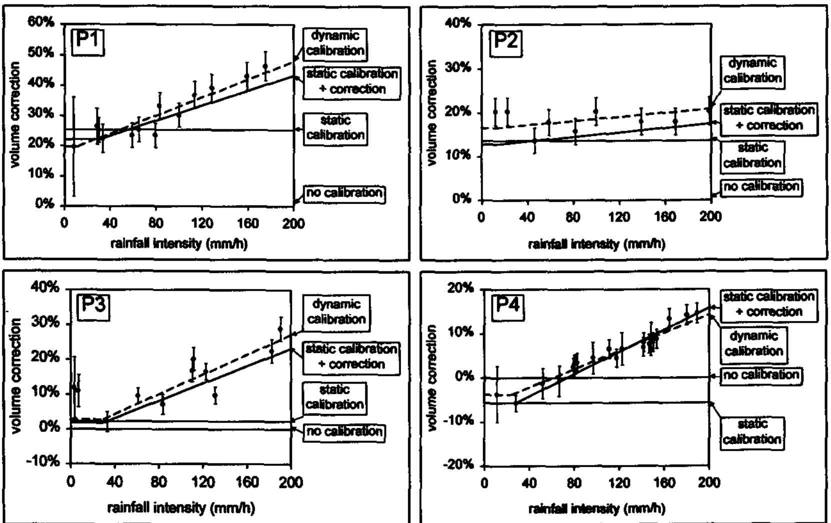

Figure 6. Different correction curves for the 4 rain gauges.

Table 3: overview of the errors made with respect to the different correction methods.

pluvio-graph (type)	dynamic calibration	no calibration		static calibration		static calibration + correction	
	rainfall depth (mm)	rainfall depth (mm)	error (%)	rainfall depth (mm)	error (%)	rainfall depth (mm)	error (%)
Storm event: Brakel (6/03/1998); i_{max} = 44 mm/h during 1 minute							
P1 (A)	31.0	25.8	**-16.7**	31.2	0.7	31.1	0.5
P2 (F)	38.0	32.5	**-14.5**	36.9	-2.9	36.8	-3.1
P3 (A)	29.4	28.6	-2.8	29.2	-0.6	29.2	-0.9
Storm event: Antwerp (11/07/1996); i_{max} = 172 mm/h during 1 minute							
P4 (B)	34.0	33.4	-1.9	31.5	**-7.4**	33.5	-1.7

Indeed, the second comparison, with statically calibrated data shows a considerably better agreement. For the low intensity storm event, which has a frequency between 5 and 10 times a year for storm duration of 15 minutes (Vaes, 1999), the agreement with the dynamically calibrated results is good. Former research indicated already that it was much more important to have an accurate static calibration, than trying to correct according to a dynamic calibration curve (Fankhauser, 1996).
For the heavy storm event however, the underestimation is still 7.4%, when the data are corrected according to the static calibration results. This event has a return period of approximately 75 years for storm duration of 15 minutes (Vaes, 1999).
When the proposed correction method is used on these heavy storm data, the agreement with the dynamically calibrated results is remarkably better.

Conclusions

A number of 21 tipping bucket rain gauges were thoroughly calibrated in the hydraulics laboratory of the university of Leuven. Analysis of these calibration data showed that the tipping time of the gauges remains constant for recorded rainfall intensities below 200mm/h. It was also shown that this tipping time has nearly the same value for all the tested devices, regardless bucket size, resolution... This constant tipping time gives the possibility to correct the measured rainfall data in a dynamic way (different correction for different rainfall intensity), without having to do a complete dynamic calibration test, which is often neglected in reality because it is too time consuming. One single, 'static' calibration experiment is sufficient to estimate the complete calibration curve. Guidelines concerning the accuracy needs for this static calibration test are given in this paper. Since the presence of insects, dust... can influence the tipping time, it is advisable to clean the device and repeat the static calibration regularly.
Measured rainfall data of two storm events were used to show the influence of the correction method. First of all, it was proven once more that it is absolutely necessary to do a static calibration test. Indeed, rain gauge resolution indicated by the manufacturer often differs a lot (not rarely more than 10%) from the calibrated one. For moderate storm events, statically calibrated measurements give good results when compared to dynamically calibrated measurements. On the other hand, in heavy storm events the underestimation of the cumulative

rainfall depth by only correcting according to a static calibration test can get large. These events are the most important ones in e.g. flood forecasting or combined sewer overflow problems. Therefore the proposed correction method can be a useful and easy-to-use tool to avoid underestimation of rainfall volumes in these heavy storm conditions. Especially since wind effects, and a strong wind often coincides with heavy storm events, tend to underestimate rainfall volumes (Braak, 1945), it is necessary to measure the rainfall volumes that are collected by the rain gauge, as accurate as possible.

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