Accuracy of Siphoning Rain Gauges

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Abstract

The dynamic calibration of a siphoning rain gauge (SR) formed the starting point of this study: for different simulated rainfall intensities the difference between measured and ‘real’ rainfall depth was studied. The siphoning time was also measured during these calibration experiments and these data showed that the mean siphoning rate is independent of the rainfall intensity. A theoretical formula was derived to determine the siphoning time for any particular rain gauge and this formula was validated with data from 3 other commercial rain gauges.

A calibration curve, depending on the siphoning rate, could be derived. This was done theoretically and the findings were confirmed by the laboratory measurements. Field measurements of SR’s can now be corrected according to these calibration curves. This correction is function of the receiving area and the siphoning rate of the device.

Comparison of the correction curves for tipping bucket rain gauges (TBR’s) and SR’s shows that the accuracy of both devices is of the same order of magnitude. The role that the resolution plays for the TBR, is played by the siphoning rate for the SR: for the SR the accuracy gets poor in case of a low siphoning rate (~ 10 ml/s), whereas TBR measurements should absolutely be corrected in case of a high resolution (< 0.2 mm).

Introduction

Rainfall measurements are important data in hydrological applications. The prediction of peak discharges and high water levels in rivers is a first important application where accurate rainfall data are indispensable. Also in urban hydrology, for data verification campaigns of combined sewer systems or for real-time-control applications, accurate rainfall data are one of the most important input data.

For these hydrology applications, most often devices are used with a high autonomy, thus devices that can register storm events for a longer period (few weeks-months) and can be read afterwards. The two types of rain gauges that answer this criterion and are most frequently used are the tipping bucket rain gauge (TBR) and the siphoning rain gauge (SR). TBR’s contain a tipping mechanism that tips when a certain rainfall depth was collected by the gauge (mostly this depth varies between 0.1 mm and 1 mm). SR’s collect usually a larger volume of water (mostly varying between 5 mm and 30 mm), that is recorded continuously and finally siphoned in the shortest possible time.

TBR’s are known for the fact that they underestimate rainfall volumes at high rainfall rates. Publications on the accuracy of SR’s are rather scarce and often they are considered to be more accurate, probably because the tipping action of the TBR, responsible for the losses, occurs much more often than the siphoning action of the SR.

In this publication SR’s are studied more closely, especially what losses can be expected during the siphoning action and how recorded data could be corrected to account for these losses.
Calibration of a Hellman-Fuess siphoning gauge

In the hydraulics laboratory of the University of Leuven a Hellman-Fuess rain gauge was subjected to a detailed series of calibration experiments. This series comprised 13 experiments, each of which 1 litre of water was poured through the gauge. For every experiment a different rainfall intensity was simulated. The tested device had a receiving area of 200cm² and siphoning took place every time a rainfall depth of 10mm had been collected. Cumulative rainfall depths were recorded continuously with a pen-writer and this cumulative depth was read after each experiment. The time necessary to siphon the collected 10mm of rainfall (siphoning time) was measured as well. During every experiment siphoning took place 4 or 5 times.

Siphoning time and siphoning rate. The SR generates losses by the fact that rainfall that is collected during siphoning is not recorded: the gauge immediately siphons this amount of water and therefore this volume gets ‘lost’. Therefore the siphoning time of this kind of gauges should be as short as possible. The relationship between siphoning time and siphoning rate can be calculated, as a function of the rainfall rate:

\[
    t_s = t_{s,0} \cdot \left[ 1 + \left( \frac{q'}{q} \right) + \left( \frac{q'}{q} \right)^2 + \left( \frac{q'}{q} \right)^3 + \ldots \right] = \frac{t_{s,0}}{1 - \left( \frac{q'}{q} \right)}
\]

with: 
- \( t_s \) = siphoning time [h]
- \( t_{s,0} \) = siphoning time when no water is collected during siphoning [h]
- \( q' \) = ‘rainfall’ rate during siphoning [ml/s]
- \( q \) = siphoning rate [ml/s]

In figure 1 siphoning times, measured for the calibration experiments are shown as a function of simulated rainfall intensity. These measurements correspond well with the values given by applying equation (1), which results in the continuous line in figure 1. The determination of \( t_{s,0} \) was done experimentally and a value of 17.5 seconds was found.
Starting from the measured siphoning times and volume losses the mean siphoning rate for every experiment can be calculated:

\[ q = \frac{V - V_{\text{rec}}}{3,600 \cdot n \cdot t_s} \] (2)

where:
- \( V \) = volume of water used for the calibration experiment [ml]
- \( V_{\text{rec}} \) = recorded volume of water during the calibration experiment [ml]
- \( n \) = number of siphoning events during the calibration experiment

The mean siphoning rates calculated in this way are represented in figure 1 as well and are found to be independent of rainfall intensity. For this particular device a value of 11.2 ml/s was found.

**Calibration relationship.** By making the comparison between measured and real rainfall volumes for all experiments, the calibration relationship for this particular rain gauge can be deduced. The relative error \( \varepsilon \) on the volume is defined as:

\[ \varepsilon = \frac{V - V_{\text{rec}}}{V_{\text{rec}}} \] (3)

This relative error can be written in function of siphoning time and rainfall intensity (figure 2):

\[ \varepsilon = \frac{t_s}{H_s} \cdot i \] (4)
By making use of the following identities for rainfall rate and siphoning rate:

\[ q' = \frac{A_f \cdot i}{36} \quad (5) \]

\[ q = \frac{A_f \cdot H_s}{36 \cdot t_{s,0}} \quad (6) \]

and by introducing the (varying) siphoning time (1), the relative error (4) can be formulated in function of siphoning rate, rainfall intensity and receiving area of the rain gauge:

\[ \varepsilon = \frac{t_{s,0}}{H_s \cdot \left(1 - \frac{q'}{q}\right)} \cdot i = \frac{t_{s,0}}{H_s \cdot \left(1 - \frac{i \cdot t_{s,0}}{H_s}\right)} \cdot i = \frac{i \cdot A_f}{(36 \cdot q - i \cdot A_f)} \quad (7) \]

with:
- \( \varepsilon \) = relative error on the volume [-]
- \( i \) = rainfall intensity [mm/h]
- \( H_s \) = rainfall depth corresponding to 1 siphoning event [mm]
- \( A_f \) = receiving area of the collection funnel of the rain gauge [cm²]
In figure 3 the results of all calibration experiments are plotted as a function of the rainfall intensity. These points match the expected error (7) very well. The dotted line represents the expected error, calculated with a constant siphoning time. For low rainfall intensities the difference between both curves is neglectable, but for high intensities (> 150 mm/h) the difference increases to 2-3 %.

Figure 3. Results of the calibration experiments.
Theoretical calculation of the siphoning time

The time it takes to empty the measuring tube can be calculated theoretically, using the geometrical characteristics of this measuring tube and the siphon (figure 4).

As soon as the level $H_t$ is reached in the tube, siphoning starts and the siphoning rate is given by:

$$q = -\frac{A_r}{36} \cdot \frac{dh}{dt} \quad (8)$$

For low Reynolds numbers ($Re \sim 10^3$ for the flow in the siphon), friction losses can be calculated using Blasius’ equation (Berlamont, 1992) (entrance losses are neglected):

$$h = J \cdot L = \left[ 0.000016 \cdot \frac{U^4}{d^5} \right] \cdot L \quad (9)$$

This equation can be used to obtain another expression of the siphoning rate:

$$q = \frac{\pi}{4} \cdot \left( \frac{h}{0.000016 \cdot L} \right)^{\frac{4}{7}} \cdot \frac{19}{d^{\frac{19}{7}}} \quad (10)$$
Finally, the siphoning time $t_{s,0}$ can be calculated after combination of equation (8) and (10):

$$t_{s,0} = \frac{\int_{0}^{19} \frac{4}{36 \cdot \pi \cdot d^7} \int_{-4}^{0} \frac{4}{36 \cdot \pi \cdot d^7} dh}{4}$$

$$t_{s,0} = \frac{7 \cdot 0.000016}{27 \cdot \pi} \cdot \frac{4}{d^7} \cdot \frac{4}{L^2} \cdot \frac{3}{H_t^2} = 0.00015 \cdot \frac{4}{d^7} \cdot \frac{4}{L^2} \cdot \frac{3}{H_t^2}$$

In table 1 theoretical siphoning times are calculated for several commercial rain gauges and the comparison is made with the siphoning times given in research papers or technical specifications of the manufacturing company. For all 4 siphoning gauges considered, the calculated siphoning times agree very well with the values given by the manufacturer.

<table>
<thead>
<tr>
<th>Table 1. Characteristics of a few commercial siphoning rain gauges and the calculated siphoning times.</th>
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<tbody>
<tr>
<td>device</td>
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<tr>
<td>H_t (mm)</td>
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<td>L (mm)</td>
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<td>D_t (mm)</td>
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<td>ts,0 (s) specifications</td>
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<td>calculated</td>
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The characteristics of the different gauges were found in: (1) Šťastný et al. (1999), (2) Hewitt (2001), (3) R.M. Young Company (1999).

The following dimensions and flow properties are used in this analysis:

- $A_t$ = area of the measuring tube [cm$^2$]
- $d$ = diameter of the siphon [mm]
- $D_t$ = diameter of the measuring tube [mm]
- $h$ = water level in measuring tube [mm]
- $H_t$ = water level in measuring tube when siphoning starts [mm]
- $J$ = energy losses per unit of length [-]
- $L$ = length of the siphon [mm]
- $U$ = mean velocity in siphon [mm/s]
Correction of recorded rainfall data

Equation (7) can be used to estimate the losses during siphoning events. For this computation siphoning rate and rainfall intensity during the siphoning are required. Siphoning rate can be determined, either by testing the particular device, either by calculating siphoning time and siphoned volume theoretically. The siphoned volume is calculated as:

$$V_s [ml] = \frac{A_f \cdot H_s}{10} = \frac{A_i \cdot H_i}{10}$$

(13)

This rate will stay reasonably constant for a particular rain gauge, when regular maintenance is executed. Determination of the rainfall intensity will be a more difficult exercise. For devices with a pen recorder or for devices that weigh the collected amount of water continuously, this intensity could be estimated by measuring the slope of the rainfall record, just before the siphoning event starts. Simply dividing the siphoned rainfall depth by the time between two siphoning events is not a good method because in most cases these time intervals will be very large and the rainfall intensity will be very variable within those long time intervals. This method would be applicable for devices with a very small siphoned volume only.

In figure 5 the underestimation is presented as a function of rainfall intensity and in function of siphoning rate. For a SR with a receiving area of 600 cm$^2$ and a siphoning rate of 15 ml/s, rainfall depth will be underestimated by approximately 12% for a rainfall intensity of 100 mm/h.

![Figure 5. Estimation of the relative error in function of rainfall intensity, receiving area and siphoning rate.](image-url)
Comparison with the accuracy of tipping bucket rain gauges.

TBR’s are the rain gauges that are most widely used in all kinds of measuring campaigns. Several researchers have studied their accuracy and many publications can be found regarding this topic (Giulliani et al., 1996; Ciaponi et al., 1993; Fankhauser, 1998). A detailed study containing calibration results of 24 TBR’s resulted in the following calibration formula (Luyckx & Berlamont, 2001):

\[
\varepsilon = \frac{\tau}{R} \cdot i = \frac{\tau}{10 \cdot V_b} \cdot i \cdot A \tag{14}
\]

where

\( \tau = \) tipping time of the tipping bucket rain gauge [h]
\( R = \) resolution of the rain gauge [mm]
\( V_b = \) volume of one of the tipping buckets [ml]

The resolution of a TBR is the rainfall depth necessary to make the bucket system tilt. Figure 6 shows that similar calibration curves are found for the TBR and the SR. The role played by the siphoning rate for the SR is played by the bucket volume for the TBR (because the tipping time was found to have a nearly constant value for all tested TBR’s (Luyckx & Berlamont, 2001)).

![Figure 6. Analogy between the calibration curves of TBR (left) and SR (right).](image-url)
The order of magnitude of the errors is equal for both types of rain gauges. Therefore, the intuitive feeling that siphoning gauges would be more accurate than tipping bucket gauges is proven wrong. Both devices have the tendency to underestimate rainfall volumes.

In figure 7 the slope $K$ of the calibration curve ($\varepsilon = K \cdot i$) is presented graphically for both types of rain gauges. For the TBR the slope is only depending on the resolution $R$, whilst for the SR it is depending on the siphoning time as well as on the siphoned rainfall depth. Increasing the receiving area of a SR (e.g. by placing a larger funnel on top of the device) will ensure a more frequent siphoning, thus the rainfall depth corresponding to 1 siphoning event decreases. The figure shows that in that case ($H_s$ decreases, $t_s$ remains the same) the slope of the calibration curve increases. This could be expected since more frequent siphoning will cause larger volume losses. Increasing the receiving area of a TBR will increase the resolution ($R$ decreases), again resulting in a higher slope of the calibration line. Hence, for both devices can be concluded that a higher resolution in the time domain generates more losses of rainfall and there will be an increasing need for an appropriate correction method.

For TBR’s a correction method was proposed (Luyckx & Berlamont, 2001) and it was advised to apply this correction method whenever a TBR with a resolution better than 0.2mm is used ($R < 0.2\text{mm}$). In order to find a similar criterion for SR’s, the 4 gauges of table 1 are presented in figure 7 (red markers). There seems to be a strong correlation between siphoning time and siphoned rainfall depth for the 4 devices considered in this study. This may seem logical, but again the example with the increased receiving area proves that this relationship can not be generalised. Indeed, an increased receiving area will have a large influence on $H_s$, but the siphoning time $t_s$ will not change since this will only depend on the siphoning system.

![Figure 7. Slope of the calibration line for both types of rain gauges (TBR and SR).](image-url)
However, Figure 7 indicates that SR’s with a siphoned rainfall depth of 5-10 mm have a calibration curve similar to TBR’s with a resolution of 0.2mm. Therefore, it is recommended to apply volume corrections for siphoning rain gauges with $H_s < 10$mm.

As far as absolute errors are concerned, they are very much depending on regional climatological conditions. When the Flemish IDF-curves (Intensity-Frequency-Duration) are considered (Vaes, 1999), figure 8 shows the expected absolute errors per rainfall event for different types of rain gauges and for 3 different return periods. In these graphs storm duration of 15 minutes is considered. For a storm with a return period of 10 years, with a total rainfall volume of 15.5mm, the absolute error for the different siphoning gauges varies between 0.16 and 0.7mm (1% - 4.5%). A tipping bucket rain gauge with $R = 0.1$mm underestimates the total volume by 1.2mm (7.7%).

**Figure 7. Expected absolute errors per storm event (Flemish IDF-curves).**

**Conclusions**

In this work errors on rainfall records, collected by a siphoning rain gauge are studied both experimentally and theoretically. The theoretical findings were confirmed by the calibration results on a Hellman-Fuess rain gauge. The results of this study can be applied in different domains:

- The calibration curve deduced for siphoning gauges can be used to correct rainfall records in order to obtain a data set with an increased accuracy. Indeed, rainfall volumes are underestimated due to the siphoning action, especially for more extreme events. These events are usually the most important ones for authorities, scientists… It is recommended to correct
the rainfall records whenever a siphoning gauge is used with a siphoned rainfall depth below 10mm.

- A formula is proposed for the siphoning time of a siphoning gauge. This time is necessary to calculate the calibration curve but could also be used by gauge manufacturers for optimising the design of their devices.
- Because the underestimation for tipping bucket rain gauges and siphoning gauges is of the same order of magnitude, both devices are considered ‘equally good’ and both types should be taken into consideration when a measuring campaign is planned.

**References**


