Correction of tipping-bucket data.

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Date: January 24th, 2014

INTRODUCTION

It is a well-known fact that tipping-bucket rain gauges (TBR) tend to underestimate rain at high rainfall rates. In this text, we will present to best method to correct for the loss of rain due to the finite time required for a bucket to tip. The TBR was invented in 1662 by Sir Christopher Wren.

SOURCES OF ERRORS

There are many sources of errors that would cause rain measurement by a tipping bucket rain gauge (TBR) to differ from the corrected value. We list some of these errors here that may impact computed high rainfall rates:

1. Mechanical error due to the finite time taken by a bucket to tip
2. Reduced catchment efficiency due to winds
3. Error due to small funnel size
4. Error due to partially clogged funnel
5. Siting problems

Here are some problems that may affect rain measured at any rainfall rates:

6. Evaporation losses
7. Wetting problem
8. Wind pumping
9. Drop size distribution
10. Defective instrument
11. Calibration error
12. Random errors
13. Clock error
14. Non-recorded tips, due to electrical problem or other problems
15. Early tipping due to vibration
16. Splashing out error
17. Splashing in error
18. Error due to debris on the funnel
19. Data extraction error

Some sources of error will only affect slightly the computed rainfall rates, but will cause some random errors in the measurements. Calibration procedures are not perfect. Ideally, the flow rate of injected water should be perfectly constant and water should be injected uniformly on all sides of the funnel.

In this document, we will only examine the first source of errors.

MECHANICAL ERROR DUE TO TIPPING TIME

The principle of the TBR is fairly simple: 2 buckets are exposed alternatively to collect rain. The tip occurs when a predefined amount of rain is contained in the bucket. Most of the manufacturers recommend doing a one point calibration at a rain rate that varies from one manufacturer to the next, usually in the range between 10 mm/hr to 100 mm/hr.

What the calibration does is to reduce to amount of rain collected to cause a tip in order to compensate for the water that will continue to fall into the full bucket during tipping. For example, if a TBR has a resolution of 0.2 mm and that at 50 mm/hr, 2% of the rain falls into the full bucket during tipping, this is compensated by reducing by 2% the water collected before tipping. In this case a tip would occur when water equivalent to 0.196 mm of rain has been accumulated into the bucket. Another 0.004 mm would be accumulated during tipping, for a total of 0.2 mm.

The problem is that time required to do a tip is constant within a small margin of error, but the extra water collected in the full bucket depends upon the rain rate. At a higher rate, more water will accumulate in the bucket during tipping leading to a systematic underestimation error that grows with the rain rate. At a lower rain rate, less water will be collected during tipping time, leading to a systematic overestimation error.

It is possible to derive a correction equation that will use 2 parameters to correct that mechanical error. The first parameter, C_f, is the ratio of actual rain required to start tipping to the desired rain resolution. In our example, C_f would be worth 0.196/0.200 = 0.98. The second parameter, T_{100}, is equivalent to the time during which the second bucket is collecting 100% of the rain falling during tipping. That value is always smaller than the actual tipping time (T_{tip}). Due to the fact that the bucket starts with a null rotational speed and ends its course at maximum speed, we expect that T_{100} would be worth more than half the tipping time. The resulting equation providing the corrected rain rate (R_{corr}) as a function of measured rain rate (R_{meas}) is and measurement resolution X (usually 0.1 mm, 0.2 mm, or 0.1 in):

$$R_{corr} = \frac{C_f}{\left(\frac{1}{R_{meas}} - \frac{T_{100}}{3600\ X}\right)} \tag{1}$$

If tipping were instantaneous, T_{100} would be 0, which would give $R_{corr} = C_f\ R_{meas}$. The calibration constant would likely be 1. The instrument would measure the corrected value at all rain rates. In a real world, other types of errors would cause differences between the measured and the corrected values.

DERIVATION OF THE EQUATION

Basic assumptions

We will make the following assumptions:

- The rain gauge is perfectly calibrated, meaning that when exactly C_f X mm falls into the bucket, the bucket starts tipping. X is usually 0.1 mm, 0.2 mm, or 0.1 in. And the calibration factor is usually from 0.98 to 1.02.
- The actual quantity of rain in ml depends on the bucket size and rain collecting area. For simplification, we will replace this quantity of rain by the rain height at standard temperature in our discussion.

- The tipping time taken by the tipping buckets is the same for the two buckets. That time is set equal to T_{tip}, in units of seconds.
- The bucket that tipped has the time to completely evacuate the water in it.
- The rain falls at a steady rate.
- When it tips, the bucket starts with a 0 rotational speed, accelerates to reach a terminal velocity with which he hits a bumper that stops it.

Case of a bucket non available during tipping

Let us define:

- R_{corr} the corrected rain that falls in one hour
- R_{meas}, the rain that is measured by the TBR in one hour.
- $Tips_{meas}$, the measured number of X mm tips in one hour
- $Tips_{corr}$, the corrected number of X mm tips in one hour that would have occurred in the absence of the mechanical problem (tipping time = 0)

When a tips occurs, the measured rain (R_{meas}) grows by X mm. Therefore, in hour we have:

$$R_{meas} = Tips_{meas} * X \tag{2}$$

A similar equation is valid for the corrected rain :

$$R_{corr} = Tips_{corr} * X \tag{3}$$

If we make the hypothesis that the collecting bucket is not available during the tipping time, then the time T_{NA} in seconds during which the bucket is not available during the hour would be equal to the number of measured tips multiplied by the time (T_{tip}) it takes to the bucket to tip.

$$T_{NA} = Tips_{meas} * T_{tip} \tag{4}$$

In the case of a rain falling at a constant rate, we can compute the rain that was missed (R_{mis}) during the tipping, as time the instrument is not available multiplied by the rain rate (total rain divided by 3600 s):

$$R_{mis} = T_{NA} * (R_{corr}/ 3600) \tag{5}$$

The total rain that should have been recorded is:

$$R_{corr} = C_f * R_{meas} + R_{mis} \tag{6}$$

Using (2), (4) and (5) into (6)

$$R_{corr} = C_f * R_{meas} + (R_{meas} * T_{tip} * R_{corr})/(X * 3600) \tag{7}$$

Isolating R_{corr}, we have:

$$R_{corr} = \frac{C_f}{\left(\frac{1}{R_{meas}} - \frac{T_{tip}}{3600\ X}\right)} \tag{8}$$

Case of a collecting bucket gradually becoming available during tipping

In reality, the collecting bucket becomes increasingly available to collect rain during tipping. Using the physical characteristics of an instrument, it should be possible to compute the quantity of rain not measured during tipping. This would be equivalent to use a shorter tipping time (T_{100}) than the real tipping time, with 100% non-availability. However, it is much simpler to replace T_{tip} by T_{100} in equation 8 and to estimate its value from data obtained during calibration made at various flow rates.

Our equation then becomes:

$$R_{corr} = \frac{C_f}{\left(\frac{1}{R_{meas}} - \frac{T_{100}}{3600\ X}\right)} \tag{9}$$

Where,

R_{corr} = corrected rainfall height in 1 hour.
R_{meas} = measured rainfall in 1 hour.
X = tipping bucket resolution, often 0.2 mm.
C_f = constant due to calibration (approximately 0.99).
T_{100} = equivalent time during which the collecting bucket does not measure 100% rain when tipping occurs.

Because our calculation involves rain accumulation over 1 hour, by dividing both sides of equation (10) par 1 hour, we transform R_{corr} and R_{meas} into hourly rainfall rates instead of accumulations.

COMPARISON WITH OBSERVATIONS

Duchon et al. (2013).

Duchon et al. (2013) have used a high-speed camera to study the behavior of a tipping-bucket rain gauge. The have estimated at 0.45 s the period during which undercatch occurs due to the tipping process. The elapsed time from the start of the bucket movement to the time it becomes horizontal is 0.53 s. The bucket strikes its post with a linear speed of approximately 0.5 m/s.

There is undercatch when the first bucket is still partly exposed to rain. It has to accelerate at first which implies that it will likely collect more rain than the second bucket. At the start of the bucket movement, undercatch will be at 100 %. At the end, it will be at 0%. It the bucket speed was the same during all of the tipping process, we would expect to have an average of 50% undercatchment. This would be equivalent to have a time of undercatchment of half the tipping time. Because of the initial acceleration, the first bucket remains exposed to rain longer than the second bucket. If we make the hypothesis that this increased the time of 100% undercatchement to 2/3 of the tipping time. The value of T_{100} would then be estimated at 0.35 s.

Their results are:

- 0.97% undercatch at 19.9 mm/h (real).
- 8.79% undercatch at 175.2 mm/h (real).

Using our equations with an undercatchment time of 0.35 s, we have:

- 0.97% undercatch at 19.9 mm/h (real).
- 8.52% undercatch at 175.2 mm/h (real).

Those values are close to the experimental values. We have assumed that the authors have used the measured precipitation rate in the values that they have cited.

With an undercatchment of 0.3613 s:

- 1.00% undercatch at 19.9 mm/h (measured).
- 8.79% undercatch at 175.2 mm/h (measured).

The last values are nearly identical to the reported values. The analysis was done only on 4 tips at both rates. Their values confirm that our equations represent well the phenomena, and that the corrected value of the equivalent tipping time with 100% undercatchment is between 0.35 and 0.36 s. That tipping time is expected to vary from one instrument to the next.

Habib et al., 2008.

Habib et al. (2008) have used the following equation to correct rainfall rates measured by a TBR:

$$R_{corr} = C_1 R_{meas} + C_2 R^2_{meas} \tag{10}$$

They have found values ranging from 0.99 to 1.04 for C_1 and from 0.0006 to 0.0008 for C_2. We have converted their notation to ours.

We have computed the values of R_{corr} as a function of R_{meas} by 5 mm/h increment, for various values of T_{100} ranging from 0.35 to 0.45 seconds and found by regression, the values in Table 1 for C_1 and C_2. We have fixed the calibration factor to 1. The correlation coefficient is very close to 1. This implies that our equation gives very close results to those of the empirical equations. The values of C_1 and C_2 have no physical meaning, whereas our T_{100} values is closely linked to the physics of the process.

Table 1 Estimation of C_1 and C_2 values for R_{corr} values between 5 and 300 mm/h. R_{corr} values were computed using our equations. r is the correlation coefficient.

T_{100} (s)	C_1	C_2	r
0.350	0.989184	0.000599	0.999998
0.375	0.987369	0.000652	0.999997
0.400	0.985377	0.000707	0.999996
0.425	0.983200	0.000763	0.999994
0.450	0.980830	0.000822	0.999993

EML

Environmental Measurements Limited (EML) is a UK-based company that manufactures meteorological instruments. They have proposed the following equation for rainfall intensity adjustment:

$$R_{corr} = 0.000654\, R_{meas}^2 + 0.96516\, R_{meas} \tag{11}$$

They have computed the measured rainfall rates by 3 of their instruments using 17 different flow rates. They have repeated their measurements 3 times. On page 5 of their document, they present a table of measured and corrected rainfall intensities, averaged over their 9 experiments. We have use this data to produce Table 2. We have estimated the calibration factor (C_f) to be 0.99 from the information in their document. We have adjusted the value of T100 in equation (9) to minimize the RMS error, and found a value of 0.32 s.

Table 2 Comparison of the adjustment of 2 equations computing the corrected rain rate (R_{corr}) from the measured rain rate (R_{meas}). Values are in mm/hr. Equation (11) is the equation used by EML and equation (9) is proposed in this document.

R_{meas}	R_{corr}	Eq. (11)	Eq. (9)	Err(10)	Err(9)
16.0	16.0	15.5	16.0	-0.5	0.0
20.6	20.6	20.0	20.6	-0.6	0.0
23.8	24.0	23.1	23.8	-0.9	-0.2
28.6	28.8	27.9	28.7	-0.9	-0.1
35.7	36.0	35.0	35.9	-1.0	-0.1
47.5	48.0	46.9	48.0	-1.1	0.0
69.9	72.0	70.0	71.4	-2.0	-0.6
114.2	120.0	117.7	119.1	-2.3	-0.9
154.9	167.2	163.8	164.7	-3.4	-2.5
188.3	205.4	203.2	203.4	-2.2	-2.0
240.5	271.2	267.8	266.6	-3.4	-4.6
303.5	350.1	350.4	347.3	0.3	-2.8
319.2	370.1	371.8	368.2	1.7	-1.9
352.8	420.5	418.7	414.2	-1.8	-6.3
525.7	670.4	683.4	679.1	13.0	8.7
592.4	789.6	795.9	796.0	6.3	6.4
650.2	911.1	898.2	905.3	-12.9	-5.8

The RMS error for the EML equation (10) is 1.21 mm/h, whereas it drops to 0.9 mm/hr for our proposed equation (9). Another advantage is that our equation has almost no errors below 50 mm/hr. The equation proposed by EML has relative errors of approximately 3%. In the case of EML, the uncorrected values are actually better than the corrected one below 50 mm/hr.

EML mentions that WMO recommends applying the correction to the data minute by minute. This would however cause the rainfall to be reported in 12 mm/hr increment for a TBR resolution of 0.2 mm. It would be advantageous to use times of tipping at low rain rates. At higher rain rates, the times of tipping may be advantageous if the time is measured with a greater accuracy than 1 s. At a rate of 120 mm/hr, we have 1 tips of 0.2 mm every 6 s; the rainfall rate measured using tipping time would have an approximate uncertainty of 1 s, which gives a 16.7% error in rate. Using the number of tips per minute, would give an uncertainty of approximately 1/10: 10%. With a time price to 0.1 s, the tipping time method would have an error of 1.7% in rain rate.

SHEDEKAR ET AL. (2009)

Shedekar et al. have studied the behavior of 2 TBR at various controlled rain rates. Our table 3 reproduces part of their table 1 for the TR-525 TBR. Their data is fairly noisy, but we have a very good agreement between their observed rain rate and our corrected rain rate: the correlation coefficient is 0.99925 and the root-mean-square error is 2.76 mm.

Table 3 Comparison between observed (R_{obs}), measured (R_{meas}) and corrected (R_{corr}) rainfall rates in Shedekar et al. (2009), for a TR-525 TBR. The corrected values used equation (9) with f_c = 1.034 and T_{100} = 0.7495 s.

R_{obs}	R_{meas}	$Tips_{meas}$	R_{corr}	R_{corr}-R_{meas}
6.6	5.5	27.5	5.7	0.9
12.6	12.5	62.5	13.1	-0.5
17.3	16.1	80.5	16.9	0.4
26.8	25.8	129.0	27.4	-0.6
38.8	37.2	186.0	40.0	-1.2
46.9	41.2	206.0	44.5	2.4
55.9	48.9	244.5	53.3	2.6
60.5	53.3	266.5	58.3	2.2
66.0	57.1	285.5	62.8	3.2
77.3	69.0	345.0	76.9	0.4
86.9	80.0	400.0	90.2	-3.3
100.0	88.5	442.5	100.8	-0.8
100.8	87.1	435.5	99.0	1.8
118.3	100.3	501.5	115.8	2.5
128.4	106.7	533.5	124.1	4.3
141.0	116.5	582.5	137.1	3.9
146.3	121.9	609.5	144.4	1.9
150.8	126.6	633.0	150.8	0.0
157.9	133.1	665.5	159.8	-1.9
162.2	132.3	661.5	158.6	3.6
172.3	138.2	691.0	166.9	5.4
184.2	147.5	737.5	180.2	4.0
187.4	152.4	762.0	187.3	0.1
195.9	158.2	791.0	195.8	0.1
203.3	163.8	819.0	204.2	-0.9
214.9	172.0	860.0	216.6	-1.7
237.4	189.8	949.0	244.6	-7.2

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GORMAN (2003)

Gorman (2003) has produced a report on laboratory evaluation of the RIMCO Model 8020H TBR focusing on the behavior of the instrument in heating mode. In section 10, there is an evaluation of its rainfall performance. From the graph, it is possible to extract the average correction factor at all the 6 rainfall rates tested (25, 50, 100, 200, 400 and 500 mm/hr). The correction factor is in tips per 100 tips. For example, a correction factor of -6 tips implies that the TBR reported 106 tips instead of 100 tips. Table 4 presents the observational results as compared to our theoretical results, using a time constant of 0.114 s and a calibration constant of 0.939. This implies that on average, rain falling at a low rainfall rate is overestimated by 6%. The estimated tipping time would be of the order of 0.17 s, which is slightly above the manufacturer's specification of 0.1±0.05 s. This is the fastest TBR for which we have found calibration information. The instrument that was tested seems to have been calibrated at a rain rate of approximately 350 mm/h, which is too high. Once corrected, the average corrected rain rates are generally less than 1% of the observed rain rates which were generated in laboratory.

Table 4 Observed, measured and corrected rain rates for a Rimco 8020 TBR from Gorman (2003) report, in mm/hr. The differences (Diff.) are between the observed and corrected rain rates.

R_{obs}	Corr. (%tips)	R_{meas}	$Tips_{meas}$	R_{corr}	Diff (mm)	Diff (%)
25.0	-6.17	26.5	132.7	25.0	0.0	-0.11%
50.0	-4.58	52.3	261.5	49.5	0.5	0.98%
100.0	-3.57	103.6	517.8	98.9	1.1	1.13%
200.0	-3.56	207.1	1035.6	201.1	-1.1	-0.54%
400.0	0.74	397.0	1985.2	397.8	2.2	0.55%
500.0	1.55	492.3	2461.3	501.3	-1.3	-0.26%

ONE-POINT CALIBRATION

The following rain rates should be used for calibration according to their manufacturers:

- All Weather Inc. 6011: 12.7 mm/hr (400 ml/h; 7.85 ml = 0.25 mm of rain)
- Weathertronics 6010: 12.7 mm/hr (400 ml/h; 7.85 ml = 0.25 mm of rain)
- Campbell Scientific, TE525: less than 13.3 mm/hr.
- Campbell Scientific, TE525: less than 13.3 mm/hr.
- Novalynk: 152.4 mm/h.

The manufacturers aim to have an accuracy of 3% or better over the range of 0 – 50 mm/h. They also take into account that rain occurs more often at lower rain rates than at higher rain rates. Calibrating for more precise results between 10 and 20 mm/h is a good technique for that goal. However, the errors can become quite important at higher rain rates.

CORRECTION WITH RESPECT TO STANDARD RAIN GAUGE

Traditionally, meteorological services have corrected the values reported by the TBR to render them directly comparable to the standard rain gauge data whose values were estimated more precise for the total period. For example, if the TBR reported 12 mm of rain and the standard gauge reported 13 mm of rain, all the TBR values were multiplied by a factor of (13/12). Most of the corrections tended to increase TBR values, but sometimes corrections lowered the TBR values. The corrections were applied one to four times a day, depending on standard gauge availability and internal policies of the meteorological service. That correction was made to reduce the errors mostly due to the mechanical effect of TBR and of wind induced under catchment. It was not a very good practice for high rainfall events because the correction for the tipping time error must take into account the rainfall intensity at short time intervals and not averaged over a day.

Using a correction factor based on the daily values would increase all TBR rainfall rates equally without taking into account the rainfall intensity. The highest short-term intensities are underestimated because instead of being corrected by a large amount, they remain corrected by a much smaller amount.

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