INSTRUMENT TEST REPORT 679

The Uncertainty of the Hydrological Services Field Calibration Device

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10 Pages
1. AIM

The aim of this technical note is to describe and discuss the testing used to determine the mean mass of water delivered by the Hydrological Services Field Calibration Device (FCD) and its associated uncertainty. The nominal rainfall rate of these devices was also evaluated. The methodology used to calculate uncertainties was in accordance with the ISO Guide to Uncertainty in Measurement (ISO GUM)\(^1\). This document does not cover the uncertainty of Tipping Bucket Rain Gauges (TBRG).

2. BACKGROUND

The Bureau routinely inspects TBRGs at field sites to determine if they are within the Bureau inspection specification. The field-testing apparatus consists of the FCD, a mounting plate that holds the FCD over the TBRG and a McVan Instruments Cal-1 electronic counter.

For the field test, the FCD is emptied into the TBRG three times and the total number of tips recorded. The current field specification requires the TBRG to be within ± 9 tips of 303; where 303 tips is the expected number of tips delivered by three applications of the FCD. Study of the FCD was required to determine the expected number of tips delivered by three applications of the FCD, and to determine the uncertainty associated with the field inspection method attributable to the FCD.

The TBRG tips on accumulated mass, not volume, and therefore the key determinant is the mass delivered by a FCD to the gauge and not the delivered volume. The two parameters are linked via the temperature of the water.

3. TEST PROCEDURE

Five new FCDs were randomly selected from the stock at the Bureau’s Central Store. Statistics for the FCD were collected by allowing the FCD to empty into a beaker that was then weighed using electronic scales.

The empty beaker was placed on the scales and the scales were then tared to read zero. The beaker was removed from the scales and the FCD mounting plate placed on it as shown in figure 1.

The FCD was then allowed to empty into the beaker, and the time required to empty measured with a stopwatch. Next, the mounting plate and FCD was removed from above the beaker and the beaker weighed. When the scale reading had stabilised the mass of the delivered water was recorded. The beaker was then emptied and the procedure repeated a number of times.

The scale was a Sartorious Model LP1200S scales serial number 12603737. This scale was verified using the RIC’s mass set number M25. The combined uncertainty for the weighing procedure is calculated in the next section.

Nominal rainfall rates were calculated by measuring the time the FCDs took to empty using a Citizen WR100 digital stopwatch serial number 883564. The stopwatch was
started when the FCD tap was turned on, and stopped when the water flow was observed to cease. The combined uncertainty for the timing procedure is calculated in the next section. The device has an approximately constant flow rate for 88% of the tips recorded and approximately 90% of the measured time to empty.

The water used in these tests was Melbourne tap water filtered through an Aquapure-124 in-line water purification filter. Previous RIC testing has shown that there is no measurable difference in using filtered tap water when compared to distilled water\(^2\).

4. RESULTS

4.1 UNCERTAINTY IN DELIVERED RAINFALL RATE

The measurand was the time the FCD took to empty defined as:

\[ AT = \text{Stop} - \text{Start} \quad (1) \]

Where Stop is the time in seconds at which water flow from the FCD ceased, and Start is the time at which the FCD tap was turned on.

The mean time to empty for all runs of all FCDs tested was 398.5 seconds. When the values given in Table 1 are processed as per ISO-GUM, the expanded 95% uncertainty was 42.18 seconds with a coverage factor of 2.156 and 12 degrees of freedom.
Table 1. Uncertainty components in the measurement of the time to empty

<table>
<thead>
<tr>
<th>Component</th>
<th>Sensitivity</th>
<th>Standard Uncertainty (s)</th>
<th>Degrees of freedom</th>
<th>Distribution</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stop watch</td>
<td>1</td>
<td>$1 \times 10^{-2}$</td>
<td>20</td>
<td>normal</td>
<td>B</td>
</tr>
<tr>
<td>resolution</td>
<td>1</td>
<td>$2.8 \times 10^{-3}$</td>
<td>100</td>
<td>rectangular</td>
<td>B</td>
</tr>
<tr>
<td>Start</td>
<td>1</td>
<td>1.0</td>
<td>8</td>
<td>normal</td>
<td>B</td>
</tr>
<tr>
<td>Stop</td>
<td>1</td>
<td>1.0</td>
<td>8</td>
<td>normal</td>
<td>B</td>
</tr>
<tr>
<td>repeatability</td>
<td>1</td>
<td>10.0</td>
<td>41</td>
<td>normal</td>
<td>A</td>
</tr>
<tr>
<td>reproducibility</td>
<td>1</td>
<td>16.67</td>
<td>7</td>
<td>normal</td>
<td>A</td>
</tr>
</tbody>
</table>

The uncertainty for the start and stop times was estimated based on the human reflex which is approximately 0.5 seconds. The component for stopwatch uncertainty was taken from the manufacturer’s specification. The terms for repeatability and reproducibility were obtained experimentally.

Alternatively, this uncertainty can be expressed as a rainfall rate. The mean rainfall rate delivered by an FCD was 180.6 mm/h with an expanded 95% uncertainty of 17.0 mm/h and 12 degrees of freedom.

4.2 UNCERTAINTY IN MASS OF WATER DELIVERED

The mass of water required to cause a 0.2mm TBRG with a nominal funnel diameter of 203.00 mm to tips is 6.473 ml. Since this value is theoretical, it was assumed to be known precisely and has infinite degrees of freedom.

Table 2. Selected values for the density of tap water

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Mass/m³ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>999.99</td>
</tr>
<tr>
<td>20</td>
<td>998.23</td>
</tr>
<tr>
<td>40</td>
<td>992.25</td>
</tr>
<tr>
<td>60</td>
<td>983.89</td>
</tr>
</tbody>
</table>
The density of tap water for various temperatures is given in Table 2. The density values for pure water were not used since the purity of the water after filtration was unknown.

With little loss of accuracy, the values of water density can be approximated by a smooth curve and values between the known points given in Table 1 interpolated. The density of tap water at 17 °C was found to be approximately 998.458 kg/m³.

The measurand was the mass delivered by the FCD and defined as:

\[ \Delta M = M_{\text{final}} - M_{\text{start}} \]  

(1)

Where \( M_{\text{final}} \) is the mass of the beaker plus delivered water, and \( M_{\text{start}} \) is the mass of the empty beaker. Since the scales are tared to read zero with the empty beaker in place the value of \( M_{\text{start}} \) is approximately zero; however, it does have an associated uncertainty.

Uncertainty components for the delivered mass are presented in Table 3. The type B components are taken from an earlier RIC test report.

<table>
<thead>
<tr>
<th>Component</th>
<th>Sensitivity</th>
<th>Standard Uncertainty (g)</th>
<th>Degrees of freedom</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass</td>
<td>1</td>
<td>0.05</td>
<td>20</td>
<td>B</td>
</tr>
<tr>
<td>resolution</td>
<td>1</td>
<td>0.0005</td>
<td>100</td>
<td>B</td>
</tr>
<tr>
<td>mass per tip</td>
<td>1</td>
<td>0</td>
<td>100</td>
<td>B</td>
</tr>
<tr>
<td>density of water</td>
<td>1</td>
<td>0.143</td>
<td>100</td>
<td>B</td>
</tr>
<tr>
<td>repeatability</td>
<td>1</td>
<td>0.6004</td>
<td>12</td>
<td>A</td>
</tr>
<tr>
<td>reproducibility</td>
<td>1</td>
<td>2.215</td>
<td>6</td>
<td>A</td>
</tr>
</tbody>
</table>

The terms for repeatability and reproducibility were obtained experimentally.

The mean mass delivered by the FCDs tested was 652.46 g for a water temperature of 17 °C. When the values given in Table 3 are processed as per ISO-GUM, an expanded uncertainty was 5.43 g with 7 degrees of freedom and a coverage factor of 2.39.

Figure 2 is a box chart of the masses delivered by the 5 FCDs in 6 trials of each device. The box defines the 25 and 75 % quartiles and the whiskers define the 5 and 95 % quantiles.
Mean = 652.42  
Standard Dev. = 2.21

Figure 2. Box chart of the masses delivered by the 5 FCDs in 6 trials. The box defines the 25 and 75 % quartiles and the whiskers define the 5 and 95 % quantiles.

The uncertainty calculated can be converted to expected tips by dividing the expected delivered mass by the value of mass required to cause one tip. At a water temperature of 4 °C the expected number of tips for a 0.2 mm TBRG is 100.8 with an expanded 95% uncertainty of 0.84 tips with 7 degrees of freedom and a coverage factor of 2.39.

5. DISCUSSION

5.1 TRACABILITY OF FCDs.

The Hydrological Services FCDs are supplied without a serial number or other identifier. The FCDs in this experiment were labelled by the RIC sequentially from 1 to 5. The lack of a unique identifier leads to a break in the traceability chain when TBRGs are verified in the field since it is impossible to identify which FCD calibrated a particular TBRG. The results above have demonstrated that the largest component of uncertainty is the volume of each FCD and therefore different FCDs will produce differing biases in the rainfall record. While this bias is small, FCDs should have unique identifiers to ensure traceability.

Since the TBRGs are adjusted in the field based on the results of testing with a FCD, the only possible traceability path is via the FCDs. It therefore follows that, for completeness, all FCDs should be characterised by the RIC to determine the delivered volume of each device.

Rimco TBRGs exhibit a characteristic response that gives constant sensitivity\(^5\) for rainfall rates between 100 and 300 mm/h. Therefore, the variations in nominal rainfall rate seen in these experiments will have negligible impact on the verification of Rimco TBRGs and therefore the rainfall record from such devices.
5.2 TEMPERATURE OF WATER WITHIN THE FCD.

The density versus temperature curve in Appendix A shows a rapid drop off for temperatures above 40°C. Since the volume of the FCD is constant, the effect of increasing the temperature of the water used is to lower the number of expected tips as the water temperature is increased. This effect is estimated for some temperatures in Table 4.

Table 4 – Effect of water temperature on the number of expected tips for three applications of the FCD.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Density (kg/m³)</th>
<th>Correction (tips)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>999.99</td>
<td>0.0</td>
</tr>
<tr>
<td>20</td>
<td>998.23</td>
<td>0.5</td>
</tr>
<tr>
<td>40</td>
<td>992.25</td>
<td>2.4</td>
</tr>
<tr>
<td>60</td>
<td>983.89</td>
<td>4.9</td>
</tr>
</tbody>
</table>

At 60°C, the correction required for three applications of the FCD is approximately 4.9 tips when compared three applications at 4°C. At 40°C, the correction would be approximately 2.4 tips, and 0.5 tips at 20°C. The magnitude of the correction is significant when compared with the field specification of ± 9 tips. At least four options suggest themselves:

1. ignore the bias introduced by variations in water temperature;
2. supply a correction table and require the inspectors to measure the temperature of the water used in the FCD;
3. require the water used for calibration to be kept cool (T < 20°C); or
4. apply a correction of 0 if the water temperature is below body temperature and +3 tips if the water temperature is above body temperature.

The amount of bias introduced into the rainfall record will depend on the temperature of the water used to calibrate a TBRG versus the temperature of the rainfall the gauge measures. The temperature of the water within the FCD could be determined; the temperature of subsequent rain is unknown.

The adoption of option 1 would mean the acceptance of a bias in the rainfall record at a particular site of at worst approximately 1.6% since this is the difference in density between water at its most dense and water at 60°C (a realistic upper limit).

Option 2 would involve more work for the Inspectors but reduce the overall uncertainty in rainfall measurement.

Option 3 would lead to an error in the rainfall record of at worst approximately 0.2 %. The adoption of option 4 would lead to a bias of at worst 0.6 % for temperatures below 40°C and 0.5% for temperatures between 40 and 60°C.
5.3 WATER RETAINED IN THE TBRG

The uncertainty analysis of TBRG testing discusses the amount of water left in a TBRG at the end of a trial. That is, after a Boyle bottle or FCD has emptied into a gauge some water remains in the siphon and buckets. Since the water remaining in the gauge was part of the volume used to calculate the expected number of tips, the retained water must bias the number of detected tips down.

For example, in the worst case the siphon would be very near capacity (approximately two tips) and the bucket would be almost at the point of tipping (one tip). In the best case both the siphon and the bucket would be empty (zero tips) implying that all the water delivered led to tips. Since the water is delivered at a fixed rate, the probability distribution of retained water is presumed to be rectangular with a mean of 1.5 tips and a semi-range of 1.5 tips. The retained water leads to a bias in the TBRG verification and therefore must be subtracted from the expected tips. This further modifies the mean expected tips for a FCD to the values given in Table 5.

Table 5. Expected number of tips including temperature and retained water effects

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Expected tips</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>300.9</td>
</tr>
<tr>
<td>20</td>
<td>300.4</td>
</tr>
<tr>
<td>40</td>
<td>298.5</td>
</tr>
<tr>
<td>60</td>
<td>295.98</td>
</tr>
</tbody>
</table>

6. CONCLUSIONS AND RECOMMENDATIONS

1. For new purchases of FCD, Hydrological Services Pty Ltd should be required to ascribe a unique serial number to each FCD and that this number is clearly marked on the device.

2. All FCD should be characterised by the RIC on receipt by the Bureau.

3. The Bureau cycle existing FCDs through the RIC so that they can be allocated a unique identifier and their delivered volume determined and recorded.

4. The expected number of tips delivered by three applications of any arbitrary FCD is given in Table 5 and has a combined uncertainty of 0.83 tips to a 95% confidence level with 7 degrees of freedom.

5. The expected rainfall rate of any arbitrary FCD is 180.6 mm/h with a combined 95 % uncertainty of 17.0 mm/h with 12 degrees of freedom.
REFERENCES


4. CRC Handbook of Chemistry and Physics, 85th Ed, CRC Press, 2004

APPENDIX A

Polynomial fit of water density versus temperature

![Graph showing polynomial fit of water density versus temperature]