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An Intercomparison of Precipitation Gauges at KNMI in De Bilt, Netherlands

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Abstract

The Royal Netherlands Meteorological Institute (KNMI) conducted an intercomparison of precipitation gauges to identify a suitable replacement for the floating-type gauge (FG) currently operational in its automated network. Replacement, by a commercial off-the-shelf instrument, is needed as KNMI designed gauges have been operational for 30 years, thus purchasing replacement parts and making repairs is becoming increasingly unsustainable.

The following two precipitation gauges, each with different collection methodologies, were installed in September 2020[1] on the test field at KNMI's headquarters in De Bilt, NL after successful lab tests were performed during the summer leading up to installation.

1. Lambrecht-Meteo's *rain[e]* H3 hybrid gauge (HG), combination of tipping bucket and weighing gauge
2. OTT HydroMet's Pluvio^2 L Weighing Gauge (WG)

These gauges under test were collocated with three of KNMI's current gauges and concurrently collected data at a 1-min resolution during a field trial of one year, covering a wide variety of meteorological conditions. One of these three was in a pit at ground level following the WMO recommended gauge configuration and is referred to as 'WMO'. This gauge was used as the reference gauge for the intercomparison. The other two (control gauges) were used to measure the quality of data and to confirm expected differences, for example differences due to exposure (i.e., wind.) One of these sensors, with its orifice 1-meter above ground, was like the gauges under test (hereafter, 'VONS'), and the other was in a so-called 'English pit' (hereafter, 'AWS'.) Ancillary measurements in the setup consisted of a (default) automatic weather station and surface wind and precipitation detection at orifice height.

In this paper, the analysis methodology will be outlined, challenges will be discussed, and results will be presented. Included in the analysis will be comparisons of precipitation amounts and intensities and their differences, as well as the duration of precipitation events. The results will assist KNMI in developing specifications for a European tender for the acquisition of a suitable replacement precipitation gauge for its automated network.

1. Introduction

An intercomparison of rain gauges was performed at KNMI's test field in De Bilt, Netherlands during the period between 1-April-2021 and 10-April-2022. The motivation behind this intercomparison was based on the need to replace the existing KNMI designed rain gauges that are used in KNMI's automated network of precipitation gauges. The existing rain gauges are of the float-type and were designed by KNMI. These rain gauges have been operational since the early 1990's and have become increasingly difficult to repair and costly to maintain over time. Additionally, they experience some technical and quality issues (i.e., delays in reporting wintry precipitation) [1]. Thus, there is a pressing need to replace these gauges with a new one.

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[1] A third tipping bucket gauge (TG) was also considered for the intercomparison but was ignored due to technical difficulties with the sensor.

KNMI investigated the performance of two commercially available rain gauges (figure 1) that use different measuring strategies to determine if an existing off-the-shelf gauge could be used to replace the KNMI designed gauges. To that end, the following rain gauges were selected and compared and are referred to as the 'gauges under test'.

Lambrecht's Rain[e]H3, hereafter 'LAM', is a hybrid gauge (HG) employing both tipping and weighing measurement principles to measure precipitation accumulation, intensity, and duration. The gauge was installed without a windscreen with its orifice 1-meter above the ground. The gauge has a 200-cm^2 collecting funnel with a maximum resolution of 0.001-mm for amount and 0.001-mm/h for intensity. This gauge is noteworthy for its compact design and lack of a collecting bucket; it is self-emptying after weighing. It uses a funnel to collect precipitation and is outfitted with a heater to melt frozen precipitation as it enters the funnel. Its intensity range is 0 to 1,200-mm/hr [9].

OTT Hydro Met Pluvio^2, hereafter 'OTT', is a weighing bucket gauge (WG) that measures both intensity and accumulation of precipitation. It was also installed without a windscreen with its orifice 1-meter above the ground. It also has a 200-cm^2 orifice for collecting precipitation and a 0.01-mm measurement resolution for accumulation and a 0.01 mm/min for intensity resolution. The total recording capacity is 1,500-mm. This gauge has no mechanical parts, so it requires less maintenance than a tipping-bucket gauge, however, its bucket needs to be emptied periodically. This gauge has a heating element at the orifice to prevent accumulation of frozen precipitation. Because this gauge measures precipitation by accumulation, it is capable of recording liquid, solid or mixed precipitation without melting. Real-time and non-real-time data is provided with a 5-minute delay for non-real time data. We chose to use the output parameter 'Accu NRT' since it provides more accurate data and applied the 5-minute correction to ensure it was properly synched with the other gauges. This parameter has a threshold of 0.05 mm thus if this threshold is not met within 1-hour, then the precipitation amount is not recorded, otherwise it is reported after a delay. Its real-time intensity range is between 0.00 and 3,000.00 mm/h [8].

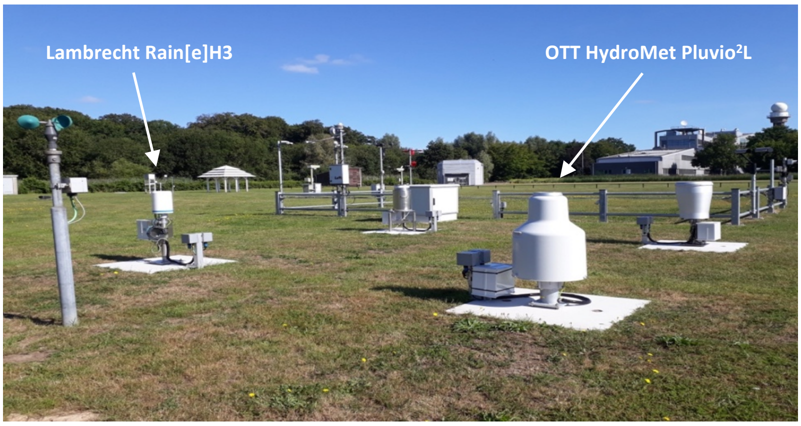

Figure 1: Photograph of commercially available rain gauges used in intercomparison installed at KNMI's test field in De Bilt, NL.

The gauges under test were collocated following the WMO guidelines with spacing between each gauge equal to 4.0-m, which is consistent with the World Meteorological Organization recommendation that "objects should not be closer to the gauge than a distance of twice their height above the gauge orifice" [14].

The aim of this study to examine how well the commercially available gauges performed in comparison to KNMI's designed gauge, specifically in terms of how well they can measure precipitation accumulation, intensity, and duration. To that end, this paper attempts to address the following research question:

- *Can a commercial "off the shelf" automatic rain gauge and be used as a viable replacement for KNMI's current automatic rain gauge?*

This paper is organized in the following manner. Section 2 describes the experimental design including calibration and lab tests performed, configuration of the gauges on the test field, technical details of each gauge, and the data processing and filtering. The results of the field test are discussed in Section 3 which focuses on the accumulation, intensity, and duration performance of the gauges. Select case studies are discussed to illustrate how the gauges performed under different intensities and weather conditions. The paper ends with a conclusion identifying the strengths and weaknesses of the test gauges in measuring accumulation, intensity, and duration data.

2. Test Setup and Procedures

KNMI collects in-situ measurements of precipitation from its network of 33 automated float-type precipitation gauges (FG). The gauges were designed by KNMI in 1992 and are currently operational in the KNMI national network. They are set-up in two ways across the country as shown in figure 2. Eighteen gauges (or 55%) are above the ground with orifice at 1-m and have a Tretyakov-type windscreen to minimize the known wind affect. The remaining 15 (or 45%) gauges are set-up in a so-called 'English pit' to also minimize the wind effect [12]. KNMI is replacing the so-called 'English' pit set-ups with the Tretyakov-type windscreen in locations where the 'English' pit set-up is costly and difficult to maintain [2].

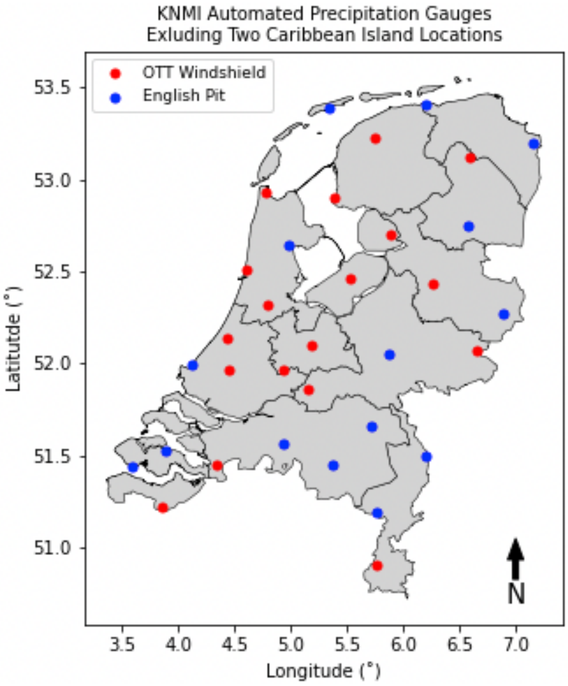

Figure 2: Spatial distribution of automatic rain gauges across mainland Netherlands[2]. The red circles are locations where KNMI's FG rain gauge is set-up with a windshield. The blue circles are locations where KNMI's FG rain gauge is set-up in an 'English' pit.

This study took place at KNMI's test field in De Bilt, and a site layout has been provided to orient the reader (see figure 3.) Three KNMI FGs (a.k.a., 'WMO', 'AWS', and 'VONS') were included in the study. The gauges were initially placed on the field in September 2020 and were taken off the field in August 2022. Data used in this analysis is for a one-year period starting on 1-April-2021 and ending on 10-April-2022.

The KNMI FGs determine precipitation amount and intensity from a change in the water level in a reservoir. They have a collecting area of 400-cm^2 with a resolution of 0.001-mm for precipitation accumulation. The resolution for precipitation intensity is 0.006 mm/hr. Measurements of precipitation intensity in μm/h at a time resolution of 12-sec are reported. From this, 1-min and 10-min average intensities and accumulations are

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[2] There are three additional stations located in the Caribbean on the islands of St. Eustatius, Saba, and Bonaire that have a Tretyakov windscreen set-up.

derived. Both the funnel and catchment are heated to melt solid precipitation [11]. The only difference between these three gauges is their site set-up.

‘WMO’ is in a so-called ‘WMO pit’ [figure 4.a] with its gauge orifice rim at ground level. For this study, this reference gauge is used to represent the ‘ground truth’ for precipitation accumulation and intensity during the study period as it is designed to minimize the wind impact that occurs when rain gauges are not sheltered or exposed to the wind [14]. The sunken reference gauge was installed according to the design and specifications reported in EN 13798:2010 standard for reference gauges [14].

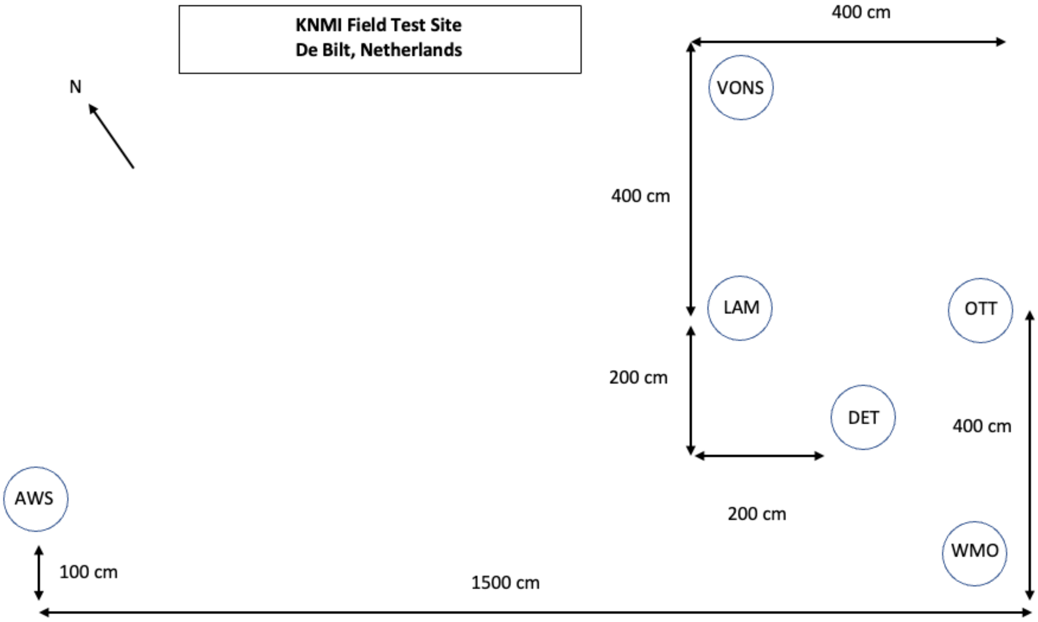


Figure 3: Test site configuration at KNMI in De Bilt, NL with indication of the location of the sensors considered in this intercomparison.

‘AWS’ is in a so-called ‘English pit’ [figure 4.b] which is also designed to reduce the wind impact. Its orifice is at an elevated ground level of 0.4-meters with the surface sloping upward to the circular wall surrounding the gauge. This control gauge is used since approximately 45% of KNMI’s automatic rain gauges are set-up this way and can serve as a comparison to those.

‘VONS’ is located 1-meter above the ground at the same height as the test gauges [figure 4.c]. In KNMI’s automated network, 55% of the rain gauges are set-up this way so it also serves as a control for the gauges under test. However, as already noted, the above-ground gauges in the automated network have a Tretjakov-type wind shield to reduce errors in measurements due to wind [11], while VONS did not have a wind shield installed. Therefore, a direct comparison to gauges in KNMI’s automated network cannot be made.

(a) (b) (c)

Figure 4: Photographs of KNMI’s FG precipitation gauges used in the intercomparison. (a) ‘WMO’ gauge in ‘WMO pit’. (b) ‘AWS’ gauge in so-called ‘English pit’. (c) ‘VONS’ gauge above surface at height of 1.0-m

In addition to catchment style precipitation gauges used for measuring precipitation accumulation and intensity, a Thies Clima optical precipitation monitor (hereafter, ‘DET’) was used to determine the duration of precipitation events. Data from the sensor is collected every 12-sec and if precipitation falls above a certain threshold (50-µm/hr) during that 12-sec, then the gauge assumes that precipitation fell for the entire 12-sec period. These values (multiples of 12) are then summed to produce precipitation duration for 1-min and 10-min time periods [5].

2.1 Calibration

All reference and test gauges were successfully calibrated *prior* to the field test. For the OTT and LAM gauges, known weights were placed on the weighing mechanism and the provided software completed the calibration check. Due to technical difficulties with the LAM that are currently being addressed by the manufacturer, only the OTT gauge was successfully calibrated *after* the field test. The FB gauges are scheduled for a calibration check in late-September 2022.

2.2 Lab Tests

Before the field trial, the gauges under test were tested in KNMI’s lab under constant flow rates to determine how well the gauges performed under controlled conditions. These same tests were performed after the field-study to determine how well the gauges performed after being in the field for close to two years. The tests included using a peristaltic pump to deliver a constant flow of water from a water reservoir to each test gauge. The flow rates chosen for the lab tests corresponded to seven reference intensities used in the WMO Laboratory Intercomparison of Rainfall Intensity Gauges [15]. These reference intensities were 2, 20, 50, 90, 130, 170 and 200-mm/hr. The lab set-up with equipment identified is shown in figure 5.

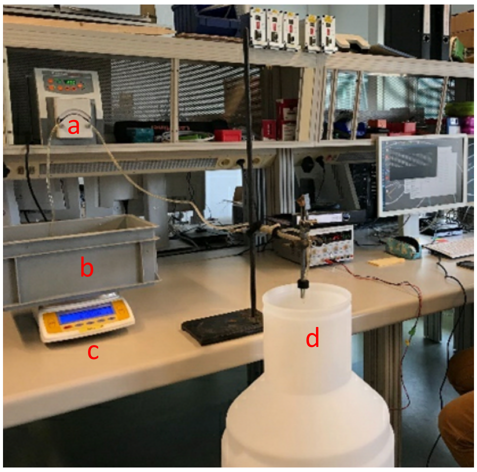
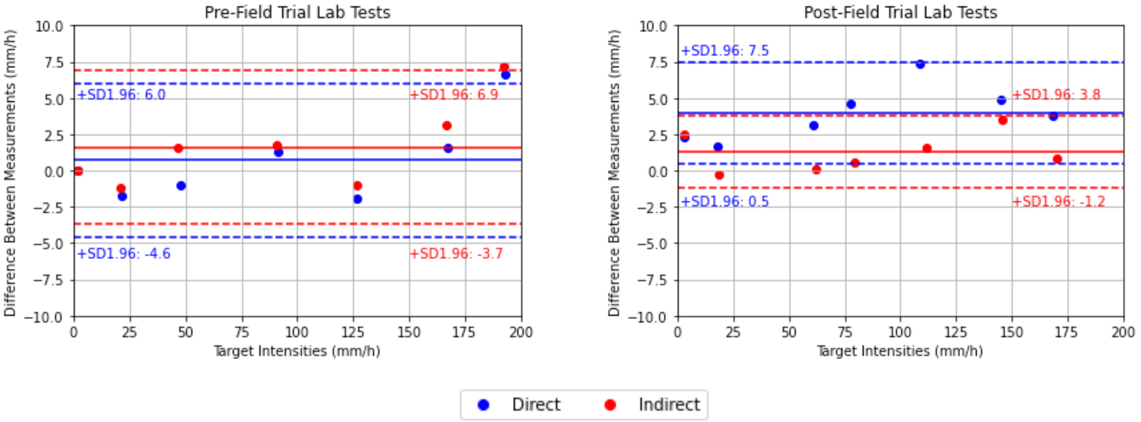


Figure 5: Lab set-up including Heidolph peristaltic pump (a), water reservoir (b), scale (c), and OTT Weighing Precipitation Gauge (d).

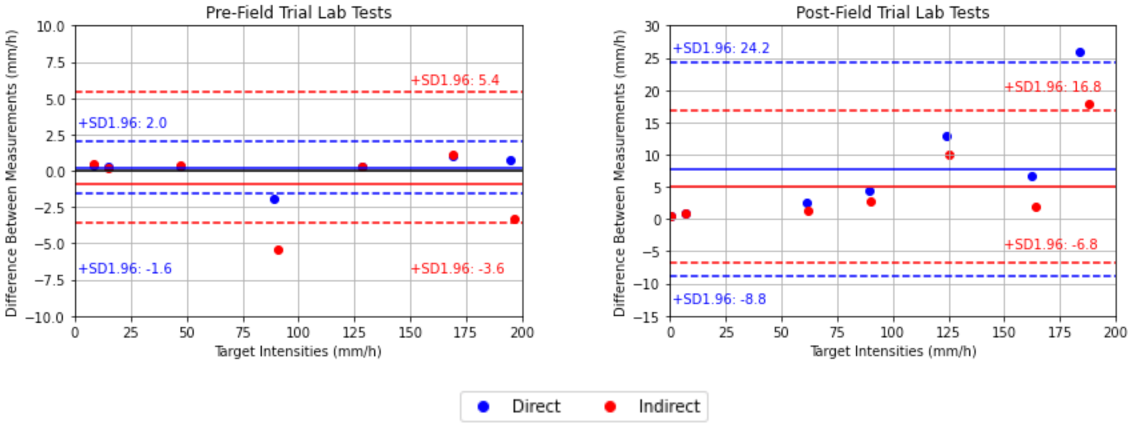
Once a steady flow rate was achieved, a 5-minute test duration was used and the change in mass of the water (in the water reservoir) during this time was measured in grams. From this, the intensity of the water flow was calculated and then compared to the intensity values reported by the gauges. The gauges provided both **direct** and **indirect** intensity values. Direct intensity measurements were those real-time intensity values produced by the gauge, while indirect intensity measurements were those that were derived from the accumulation output reported during the 5-minute testing period.

The results of the tests are shown in figures 6a and 6b which are Bland-Altman plots illustrating the difference between intensity value pairs produced by different measuring techniques. In this case, the pairs included the intensity values derived from the change in mass of the water in the reservoir (hereafter, scale) and either the direct or indirect intensity values reported by the gauge (i.e., scale-direct and scale-indirect.) Objects in blue correspond to scale-direct intensity pairs while objects in red correspond to scale-indirect intensity pairs. Solid lines on plots represent the mean difference between the pairs of intensity values. Dashed lines on the plots represent the upper and lower limits of the 95% confidence interval for the pairs.


Pre-Field Trial Lab Tests

Post-Field Trial Lab Tests

Figure 6a: LAM: Measurement differences between pairs of intensity values. Pre-field trial lab results on the left. Post-field trial lab results on the right. Solid lines represent mean differences between pairs. Dashed lines represent the upper and lower limits of the 95% confidence interval.


Pre-Field Trial Lab Tests

Post-Field Trial Lab Tests

Figure 6b: OTT Measurement differences between pairs of intensity values. Solid lines represent mean differences between pairs. Dashed lines represent the upper and lower limits of the 95% confidence interval. Pre-field trial lab results on the left. (b) Post-field trial lab results on the right. **Note the scale change to y-axis for OTT.**

Results from the lab tests, both before and after the field trial, indicate that the LAM gauge had excellent agreement in measuring the rate of precipitation, both directly and indirectly as seen by the mean differences in figures 6a. Prior to the field-test, the mean differences between intensity pairs for the LAM ranged between 0.7- and 1.6-mm/h (for scale-direct/scale-indirect intensity pairs.) After the field-test, the range was between

4.0- and 1.3-mm/h (for scale-direct/indirect intensity pairs.) These differences are likely caused by errors during the data collection such as not reading the scale values (in grams) at exactly the right moment at the start and end of each test. Since the mean difference for the sale-direct intensity pair after the field test includes a greater range, it is possible that the LAM sensor experienced some drift during the field test and a proper calibration may rectify this. Still, the differences are acceptable, and the gauge showed no signs of degradation after 2 years in the field.

The results of the lab tests for the OTT gauge were less favorable with considerable spread in the differences after the field-trial. Prior to the field-trial, the mean differences between intensity pairs for the OTT ranged between 0.9- and 0.2-mm/h (for scale-direct/scale-indirect intensity pairs.) After the field-test, the mean difference was between 5.0- and 7.7 mm/hr (for scale-direct/indirect intensity pairs.) The prior field-trial differences are likely due to measurement error during data collection (i.e., reading scale values.) However, this is unlikely the case for the after the field-trial.

After the field-trial, considerable differences emerged when the gauge attempted to measure higher intensities such as 130-mm/h and 200-mm/h. For example, the maximum difference for the scale-direct intensity pair is 26.0-mm/h when attempting to measure a 200-mm/h intensity. Similarly, the maximum difference for the scale-indirect intensity pair is 17.8-mm/h for a target intensity of 200-mm/h. For a target intensity of 130-mm/hr the differences are 12.9-mm/h for the scale-direct intensity pair and 9.9-mm/h for the scale-indirect intensity pair. This is likely the result of gauge drift. The implication of this is that the OTT may have degraded during the 2 years it was in the field resulting in difficulty accurately measuring higher-intensity precipitation. To determine if this is the cause, it is recommended that the lab-tests be performed again now that the gauge has been calibrated.

2.3 Data Processing and Filtering

During the study period, the FB gauges collected observations at a rate of 1-observation / 12-sec, while the OTT and LAM collected observations at a rate of 1-observation / 1-min. Due to the highly variable nature of precipitation intensity, the World Meteorological Organization recommends that intensity be measured at a 1-min resolution [15]. Therefore, the data from the FB gauges was down sampled with five precipitation intensity values being averaged to represent the 1-minute average precipitation intensity.

To arrive at comparable 1-min data for each gauge, any time a gauge was offline for a particular minute, the data for that minute was not included in the analysis. Thus, daily, monthly, and yearly accumulations do not represent the actual precipitation accumulation, intensity, or duration during said time-period.

The raw data used in the analysis includes the FB gauges 1-min average intensity values in mm/min. These average intensity values were used to determine the 1-min total accumulation in mm. When analyzing the intensity data, the intensity values in mm/min were converted to mm/hr.

The LAM gauge outputs both accumulation and intensity data. The data used from this gauge for this study is from the ‘intensity since last retrieval’ parameter. These intensity values were reported in mm/hr and were used to derive the accumulation (in mm) values [9].

For the OTT gauge, the ‘non-real-time accumulation’ in mm was used to derive 1-min average intensity values in mm/min. Based on the manufacturer’s documentation, these values are considered more accurate than real-time data and are reported with a 5-min delay [8]. Given the highly variable nature of precipitation, both in time and space, it was essential that a time stamp correction be made to the output data before analysis. To that end, before deriving the intensity values, the data was time-corrected to account for the delay.

3. Results and Discussion

3.1 Yearly and Monthly Precipitation Accumulation Comparisons

Monthly cumulative accumulation data is shown in figure 7 and overall study period cumulative accumulation data is shown in table 1. Unexpectedly, AWS reported a higher total accumulation for the study period when compared to WMO as shown in table 1[3]. This is not what is expected based on the set-up of these two gauges. Since the WMO gauge is in a World Meteorological Organization recommended pit configuration, it was expected that this gauge would report more precipitation than AWS which is in the so-called 'English' pit, a non-WMO recommended pit configuration. The design of the WMO pit offers better protection from the wind effect than does the so-called 'English' pit [14]. While there does exist a difference between the accumulation values between these two gauges, it is relatively small at 2.1%. Note: Percent differences between gauge pair measurements for accumulation, intensity, or duration, equation were calculated following equation 1.

$$Difference\ (\%) = \left(\frac{x-y}{y}\right) * 100 \qquad \text{(Eq. 1)}$$

$$where, x\ represents\ the\ value\ for\ the\ gauge\ under\ test,$$
$$and\ y\ represents\ the\ value\ for\ the\ reference\ or\ control\ gauge$$

Compared to the three reference gauges, the OTT underestimated precipitation accumulations between -0.72 and -5.05%, with the largest difference with AWS and the smallest difference with VONS. On the other hand, the LAM overestimated precipitation accumulations between 1.05 and 5.66% with the smallest difference between AWS and the largest difference between VONS. This finding is consistent with results from a field trial of the LAM in 2015/2016 conducted at Stratfield Mortimer Meteorological Observatory where the gauge reported higher daily totals by about 7% [4]. Overall, these differences show excellent agreement between the gauges under test and the reference gauge and are within the WMO recommended accuracy of 5.0% [14]. See table 2.

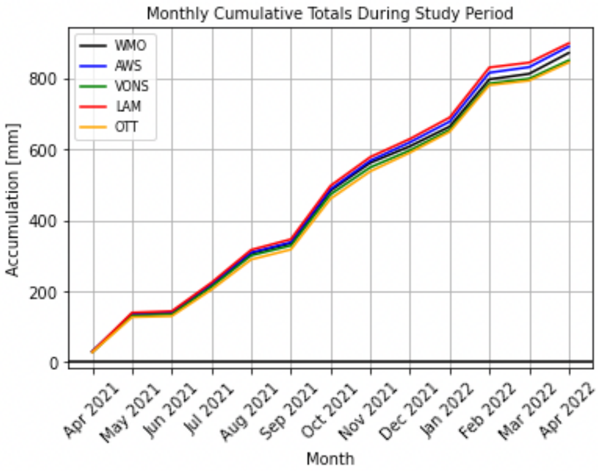


Figure 7: Cumulative accumulations per study month.

Gauge	Total Accumulation (mm)
WMO	870.9
AWS	888.8
VONS	850.2
LAM	898.1
OTT	844.0

Table 1: Accumulation reported by each gauge.

Gauge	Differences (%)
LAM-WMO	3.11
LAM-AWS	1.05
LAM-VONS	5.66
OTT-WMO	-3.11
OTT-AWS	-5.05
OTT-VONS	-0.72

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[3] The KNMI gauges in these locations were interchanged in June 2022 to determine if there were systematic errors with these gauges leading to this result. The data collected after the swap did not confirm nor refute this hypothesis. Regardless of location, the gauges exhibited the same behavior with respect to accumulations. The upcoming scheduled calibration of the gauges may reveal more information.

Table 2: Gauge pair differences for total study period accumulations.

The monthly sums by gauge are listed in table 3. Of note, is the WMO gauge which under-reports accumulation totals for all study months (except April 2022) when compared to the AWS gauge. This is a surprising result as the WMO gauge is in a pit designed to reduce the wind impact the most.

As shown in table 4, OTT underestimates precipitation accumulation for 11 of the 13 study months when compared to WMO and AWS, and 8 of 13 study months when compared to VONS. LAM overestimates precipitation accumulation for 9 of 13 study months when compared to WMO, 8 of 13 study months when compared to AWS, and 13 of 13 study months when compared to VONS. Monthly differences are illustrated in figure 8.

	Monthly Accumulation Totals (mm)				
Month	**WMO**	**AWS**	**VONS**	**LAM**	**OTT**
Apr 2021	30.0	30.2	29.0	29.9	28.5
May 2021	105.2	106.0	102.6	110.1	98.8
Jun 2021	4.2	4.2	3.6	4.0	2.8
Jul 2021	78.2	79.3	77.4	80.4	74.5
Aug 2021	89.3	89.5	88.2	92.3	84.9
Sep 2021	28.3	28.9	27.9	29.8	28.1
Oct 2021	148.0	149.4	144.2	150.7	143.0
Nov 2021	78.4	80.2	76.0	80.7	77.0
Dec 2021	46.7	51.8	47.9	51.1	52.6
Jan 2022	55.5	58.2	57.7	60.3	58.9
Feb 2022	132.9	137.7	130.5	140.8	131.2
Mar 2022	15.4	15.5	13.4	13.6	12.6
Apr 2022	59.0	58.0	51.7	54.5	51.1

Table 3: Monthly accumulation totals in mm for all gauges in study**.**

	Monthly Differences (%) Between Gauge Pairs					
Month	**LAM-WMO**	**LAM-AWS**	**LAM-VONS**	**OTT-WMO**	**OTT-AWS**	**OTT-VONS**
Apr 2021	-0.33	-0.99	3.10	-5.00	-5.63	-1.72
May 2021	4.66	3.87	7.31	-6.08	-6.79	-3.70
Jun 2021	-4.76	-4.76	11.11	-33.33	-33.33	-22.22
Jul 2021	2.81	1.39	3.88	-4.73	-6.05	-3.75
Aug 2021	3.36	3.13	4.65	-4.93	-5.14	-3.74
Sep 2021	5.30	3.11	6.81	-0.71	-2.77	0.72
Oct 2021	1.82	0.87	4.51	-3.38	-4.28	-0.83
Nov 2021	2.93	0.62	6.18	-1.79	-3.99	1.32
Dec 2021	9.42	-1.35	6.68	12.63	1.54	9.81
Jan 2022	8.65	3.61	4.51	6.13	1.20	2.08
Feb 2022	5.94	2.25	7.89	-1.28	-4.72	0.54
Mar 2022	-11.69	-12.26	1.49	-18.18	-18.71	-5.97
Apr 2022	-7.63	-6.03	5.42	-13.39	-11.90	-1.16

Table 4: Monthly differences in accumulation between test gauges and reference gauges.

The OTT significantly underreported monthly precipitation accumulation in June 2021 (between 22.11 and 33.33%) and March 2022 (between 5.97 and 18.71%) when compared to the reference gauge. During both months, a relatively small amount of precipitation was measured which partially explains the large percent differences. In June 2021, the WMO reported a total of 4.2-mm and in March 2022, WMO reported 15.4-mm. Additionally, the OTT has an accumulation threshold value of 0.05-mm. If this threshold is not met within 1-hour, then no accumulation is reported. This can lead to significant differences during light-intensity events. (See case study 2.)

3.2 Daily Precipitation Accumulation Comparison

Daily accumulation totals during the study period were generated using the 1-minute average accumulation data reported by each sensor. The regression plots in figures 9a, b, and c show that the cumulative daily accumulations for each gauge under test against each KNMI gauge were in excellent agreement. All of the r-squared values exceed 0.99 which supports this finding.

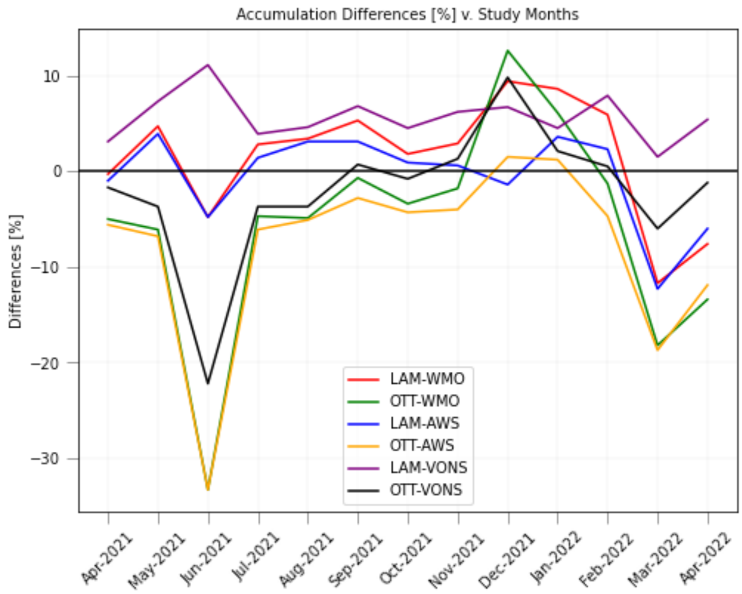


Figure 8: Monthly percent difference in accumulation between gauge pairs.

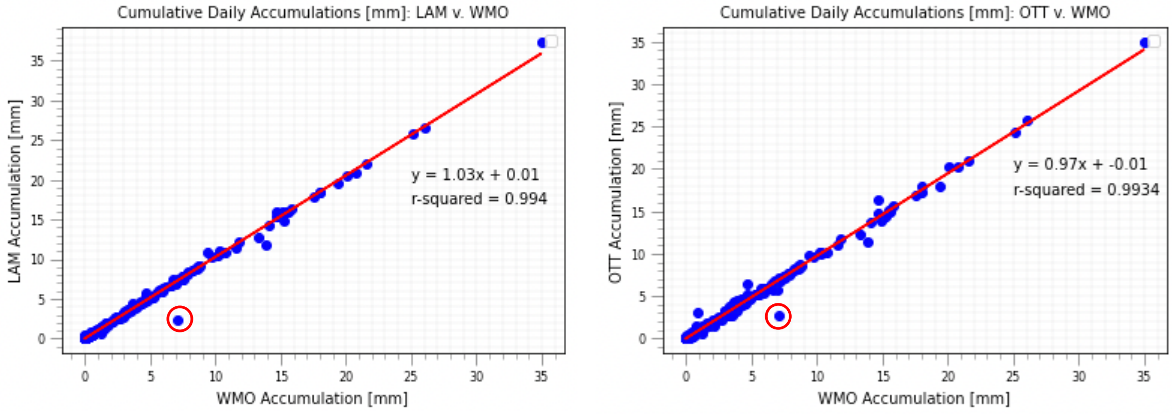


Figure 9a: Daily accumulation comparison. (a) LAM to WMO and (b) OTT to WMO.

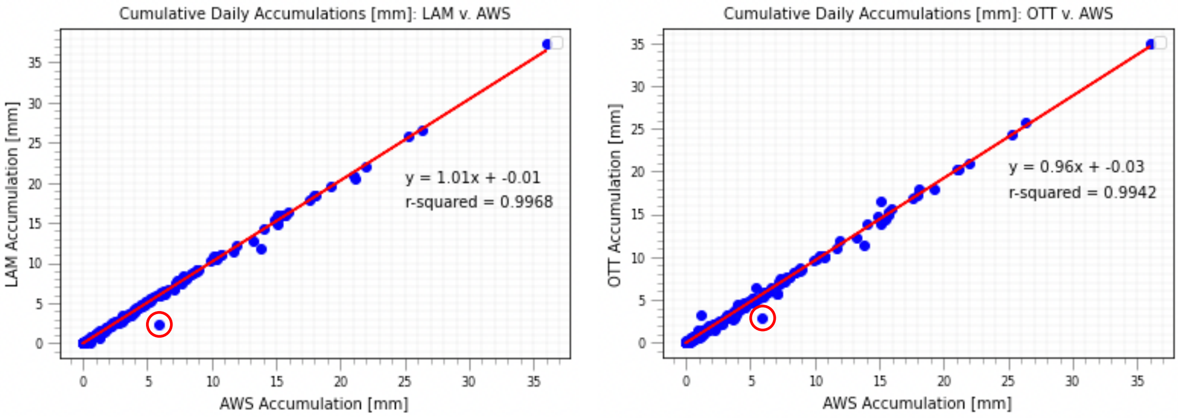


Figure 9b: Daily accumulation comparison. (a) LAM to AWS and (b) OTT to AWS.

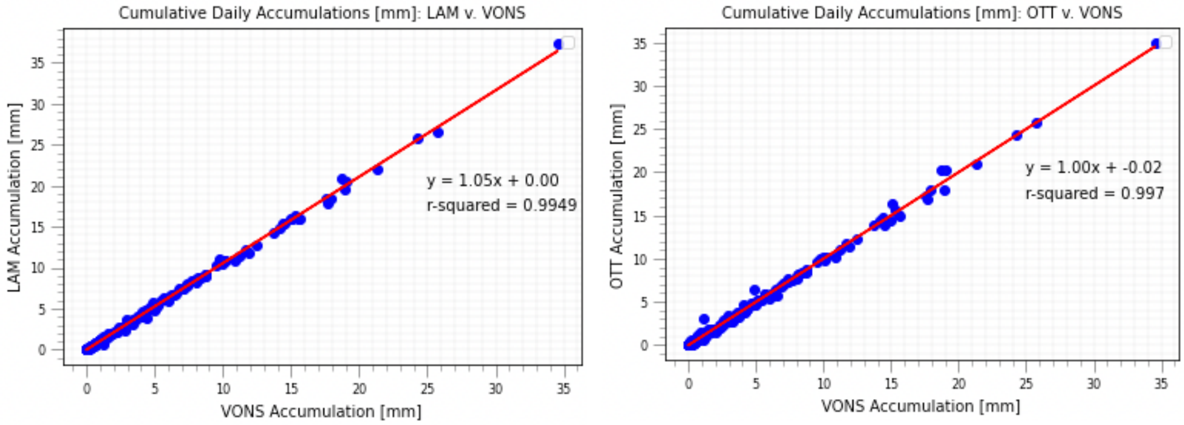


Figure 9c:Daily accumulation comparison. (a) LAM to VONS and (b) OTT to VONS.

One significant outlier exists in the data and can be traced to when WMO and AWS measured about 7.0-mm of precipitation. The outlier is circled in figures 9a and b and corresponds to a wet snow event that occurred on 1-April-2022. Accumulation data and percent differences for this date are displayed in figure 10 and table 5.

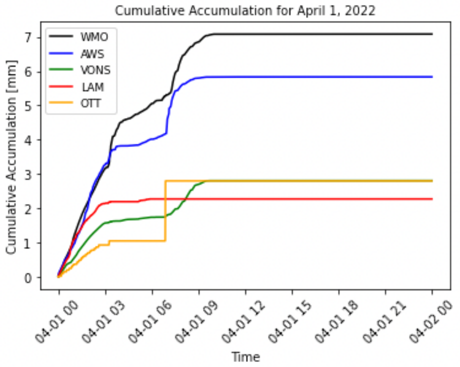


Figure 10: Cumulative Accumulation 1-April-2022.

Gauges	WMO	AWS	VONS
LAM	-67.9	-61.0	-19.1
OTT	-60.5	-52.0	-0.3

Table 5: Differences (%) between gauges under test and KNMI gauges for cumulative accumulation on 1-April-2022.

It is noteworthy that both WMO and AWS reported higher accumulations than the other gauges, and the gauges under test matched closest to VONS for this date. Both WMO and AWS are in pits to reduce the known wind effect [14]. Based on the reference gauge set-up used in WMO's Intercomparison of Rainfall Intensity Gauges [15], the so-called 'WMO pit' is more effective at reducing the wind-effect than the so-called 'English pit'. VONS is above ground with its orifice at the same height (1-meter) as LAM and OTT which suggests that these three gauges under-report frozen accumulation due to the wind impact [14]. Further investigation of the wind speed on this day would be needed to confirm this hypothesis. Additionally, it is not surprising that the LAM under-reported accumulation for this wet snow event compared to the other gauges as tipping-bucket gauges are known to underestimate during frozen precipitation events due to time to melt and potential evaporative losses during this time due to the heating element in the funnel [14].

3.4 Precipitation Intensity Comparison

A distribution of all the 1-minute average intensity values for the study period is shown in figure 11. The intensity values are classified by type based on the rate of fall [7].

- **Light rain**: varying between trace (0.01-mm) and 2.5-mm/h (<0.04-mm/min)
- **Moderate rain**: between 2.6-mm/h and 7.5-mm/h
- **Heavy rain**: between 7.6-mm/h and 50.0-mm/h
- **Violent rain**: greater than 50.0 mm/h

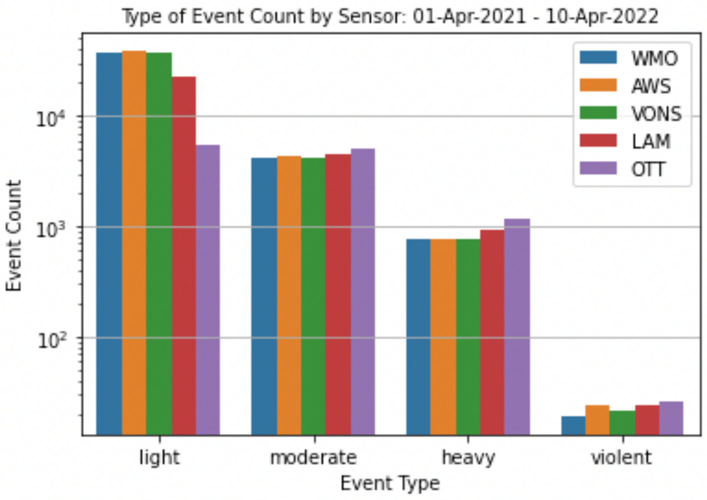


Figure 11: Distribution of 1-minute average intensity values. (Note log scale on y-axis.)

When comparing the number of light intensity events reported by each gauge under test with KNMI's gauges, the difference is apparent and shows that the gauges under test under-report these events. For the LAM gauge, the difference between it and the other gauges ranges between 38.65 and 40.54%. When comparing the OTT gauge to the other gauges, the difference is between 85.36- and 85.81%. However, these results are not surprising given the higher sensitivity of the KNMI gauges when compared to the gauges under test. The differences are based on the number of minutes with a 1-minute intensity value greater than 0.0-mm/h, for all time stamps where all gauge data was available.

Differences (%)	WMO	AWS	VONS
LAM	-38.65	-40.54	-39.18
OTT	-85.36	-85.81	-85.49

Table 6: Percent difference values for light-intensity events between gauge pairs.

Precipitation intensities varied throughout the study period with a maximum intensity value reported by all gauges at 14:09:00 on 9-August-2021. The maximum intensity value reported by the LAM gauge was, for the most part, less than the values reported by the other gauges, except for the VONS gauge. Similarly, The OTT gauge's maximum intensity value was only greater than the value reported by the VONS gauge. The under-reporting of the VONS when compared to the LAM and OTT can be explained. The OTT uses an algorithm to compensate for the wind effect. Since the VONS does not have a windshield, it is likely that the VONS experienced more wind-induced loss than the OTT given its lack of a windshield. Second, the LAM has a higher intensity resolution when compared to the VONS (i.e., 0.001-mm/h [LAM] v. 0.006-mm/h [VONS]) so it is also able to compensate for the wind-induced loss experienced by the VONS. However, the LAM's lower value when compared to the reference sensor is aligned with the known problem of tipping gauges that water can splash out during high-intensity precipitation [14]. The maximum 1-minute average intensity reported by each sensor is listed in table 7a and the differences between gauge pairs is listed in table 7b.

Gauge	Maximum Intensity (mm/h)
WMO	185.0
AWS	177.0
VONS	150.0
LAM	164.6
OTT	172.2

Table 7a: Maximum intensity values (in mm/h) for entire study period reported by all sensors on 9-August-2021 at 14:09:00.

Gauge	WMO	AWS	VONS
LAM	-11.0	-7.0	+9.7
OTT	-6.9	-2.7	+14.8

Table 7b: Differences (in %) of maximum intensity values for each pair of gauges during the study period.

3.4 Precipitation Duration Comparison

Monthly duration data is presented in table 8. To arrive at duration data for the detector, the 1-minute duration data output parameter was used. Every 1-minute, the detector outputs a value in multiples of 12.0 to correspond to the number of seconds that precipitation was detected during the previous minute with 12-sec being the minimum output. These 1-minute values were summed and converted to hours to find the reference value. For the gauges, the 1-minute average intensity data was used with a set threshold value of 0.0-mm/h. To compute the duration from the gauges, a simple count of all non-zero intensity values was made since the gauges all reported a value once per minute. This count represents the total number of minutes that a gauge reported precipitation.

There is excellent agreement among the KNMI gauges, but they unexpectedly report higher values than the detector. This is surprising given the higher sensitivity of the detector when compared to the KNMI gauges. Not surprisingly, the both the LAM and OTT gauges reported lower values for the duration (22.49% lower for LAM and 67.92% lower for OTT.) For the LAM gauge, this is likely due to its lower sensitivity when compared to the KNMI gauges. For the OTT gauge, it is likely a combination of its lower sensitivity and its accumulation threshold value of 0.05-mm in 1-hour. This results in the OTT gauge reporting many more 0.0-mm/h intensity values compared to the other gauges.

While the under-reporting of the precipitation for duration hours from the detector is unexpected due to its higher sensitivity when compared to the gauges, the under-reporting of the OTT and LAM are not since both gauges have a lower sensitivity. Additionally, a similar study conducted by Wauben [12] also showed that the OTT, with its threshold value, significantly under-reported duration hours when compared to the detector and reference gauge. At that time, the OTT was not identified as a suitable gauge to measure precipitation detection.

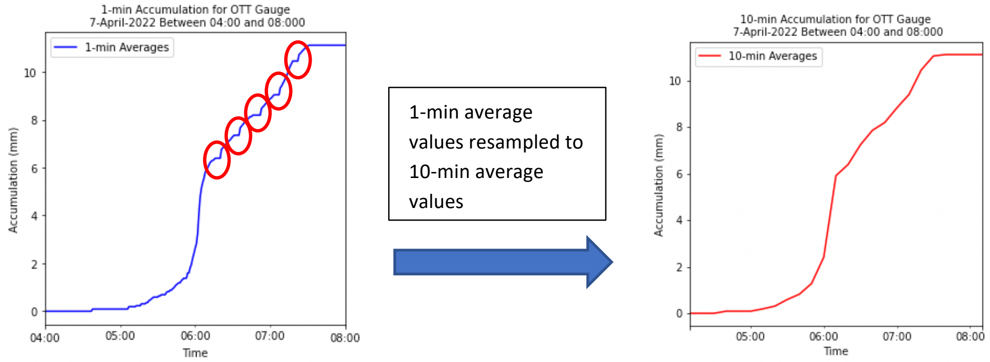
For this particular analysis, the intensity value threshold was set to 0.0-mm/h. During any minute a gauge reported a positive intensity value, it was included in the count. If a higher threshold value was used to compensate for the higher sensitivity of the KNMI gauges, it is likely that the KNMI gauges would report fewer duration hours and may be in better agreement with the LAM gauge. This is an area for future investigation.

Month	DET	WMO	AWS	VONS	LAM	OTT
Apr 2021	31.6	38.5	39.7	36.8	22.0	9.5
May 2021	52.0	62.1	64.5	57.4	36.3	13.9
Jun 2021	6.5	11.4	13.3	9.5	6.5	1.2
Jul 2021	31.4	43.8	45.6	44.2	25.5	10.4
Aug 2021	32.7	41.5	44.9	44.3	23.8	8.9
Sep 2021	11.4	15.3	15.7	15.6	9.6	3.8
Oct 2021	72.3	87.5	86.1	87.6	62.7	29.9
Nov 2021	70.5	85.5	85.5	86.2	57.4	25.3
Dec 2021	61.7	63.9	75.3	75.4	46.9	18.2
Jan 2022	53.4	50.9	53.6	55.9	38.4	15.6
Feb 2022	90.2	93.0	94.1	93.0	71.9	32.1
Mar 2022	16.5	17.0	17.4	16.6	12.5	4.1
Apr 2022	46.8	54.4	51.8	50.1	33.8	12.2
Total	**577.0**	**664.8**	**687.5**	**672.6**	**447.3**	**185.1**

Table 8: Precipitation duration in hours for each KNMI gauge and the gauges under test.

3.5 Under-reporting of Total Accumulation by OTT Gauge

The OTT outputs precipitation data after a threshold of 0.05-mm within 1-hour is reached. If the threshold value is not met, the output value is set to 0.0-mm [8]. Otherwise, the output is delayed until it is met. This results in the OTT reporting more 0.0 mm/min intensity values and fewer light intensity events than the other gauges resulting in an under-reporting of accumulation during light-intensity events. (See case study 2.) This delayed output can be seen as "jumps" in the accumulation data at a 1-min temporal resolution, and results in no accumulation being reporting until the 0.05-mm threshold is met. Resampling the data from 1-min to 10-min time resolution smooths the 'jumps' in data and eliminates the lag in accumulation data.



(a) (b)

Figure 12: Comparison of OTT 1-min (a) to 10-min (b) resolution accumulation data.

Shown in figure 13 is a comparison of how the WMO and OTT performed during a mixed-intensity event that occurred between 04:00 and 08:00 on 7-April-2022. During the light intensity portions of the event, the OTT gauge reported precipitation accumulation after the threshold was met and results in 0.0-mm/h intensity values followed by false high-intensity values being reported. However, during the actual high-intensity (50.4 mm/h) portion of the event (approximately 06:00), the gauge reports precipitation accumulation in a smooth manner.

Further, the OTT has an intensity lower-limit threshold of 6.0-mm/h [8]. Based on the lab tests conducted by Saha et. al., it was *"revealed that many intensity values were zero when the intensity was set to less than 6.5-mm/h indicating the gauge may not be effective in measuring intensity close to the lower threshold" [10].* This problem is particularly troublesome when making direct comparison accumulation, intensity, and duration between gauges during low-intensity events using 1-minute values. (See case study 2.)

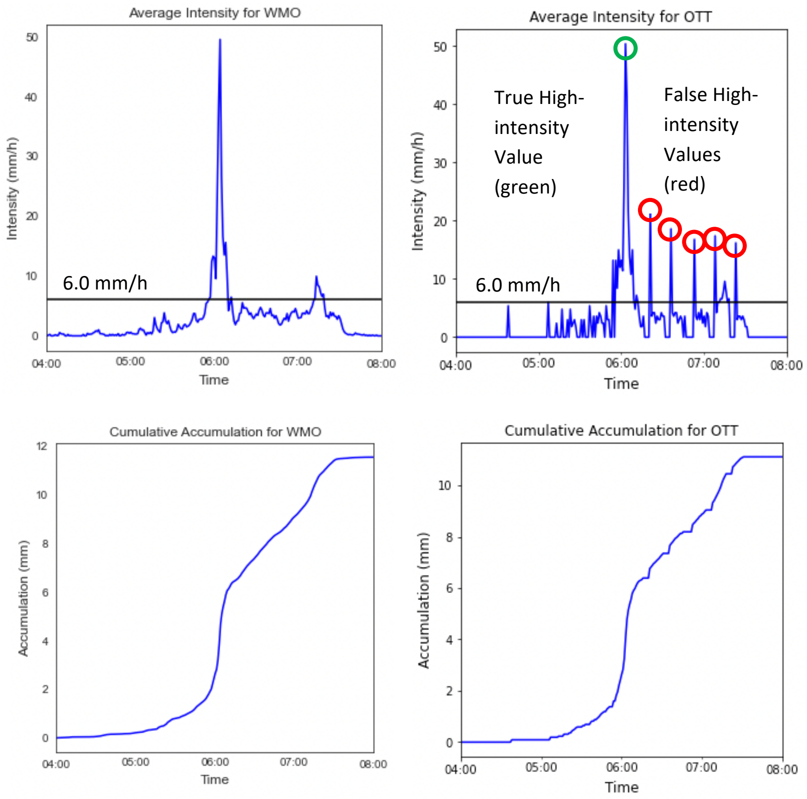
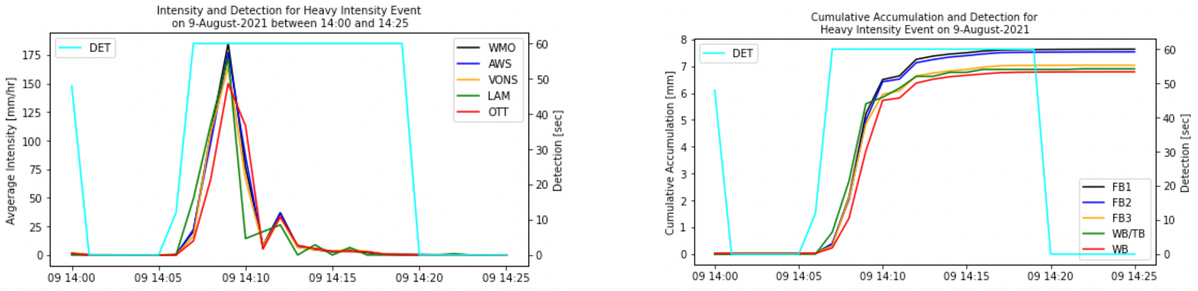


Figure 13: Intensity and accumulation data for 7-April-2022 between 04:00 and 08:00. Top row: 1-minute average intensity data for WMO and OTT in mm/h. The black horizontal line indicates the 6.0 mm/h threshold for the OTT's intensity output. Bottom row: cumulative Accumulation data for WMO and OTT in mm.

3.6 Case Studies

3.6.1: High Intensity Rain Event

On 9-August-2021 between 14:00:00 and 14:25:00, a strong rainstorm moved through the test field. In fact, it was at this moment that the highest-intensity value of the test period occurred. The range of intensities measured for the reference, control, and test gauges was between 150.0- and 185.0-mm/h. The range of 1-min average cumulative accumulations was between 6.79- and 7.63-mm with VONS measuring the least and WMO measuring the most. The accumulation, intensity, and duration data for this event are shown in figure 14a and b. The percent differences are shown in tables 9a, b, and c.



(a) (b)

Figure 14: Intensity, accumulation, and detection data for all gauges for **heavy** intensity event. (a) 1-minute average intensity values (b) 1-min accumulation values.

Total Cumulative Accumulation (mm)				Difference (%)	
KNMI Gauge		**LAM**	**OTT**	**LAM-KNMI**	**OTT-KNMI**
WMO	7.6	6.9	6.8	-7.73	-9.57
AWS	7.5			-6.51	-8.37
VONS	7.0			+3.68	+1.62

Table 9a: Percent difference values for accumulation during **heavy** intensity event.

Maximum Intensity (mm/h)				Difference (%)	
KNMI Gauge		**LAM**	**OTT**	**LAM-KNMI**	**OTT-KNMI**
WMO	185.0	164.6	172.2	-11.04	-6.92
AWS	177.0			-7.02	-2.71
VONS	150.0			+9.72	+14.8

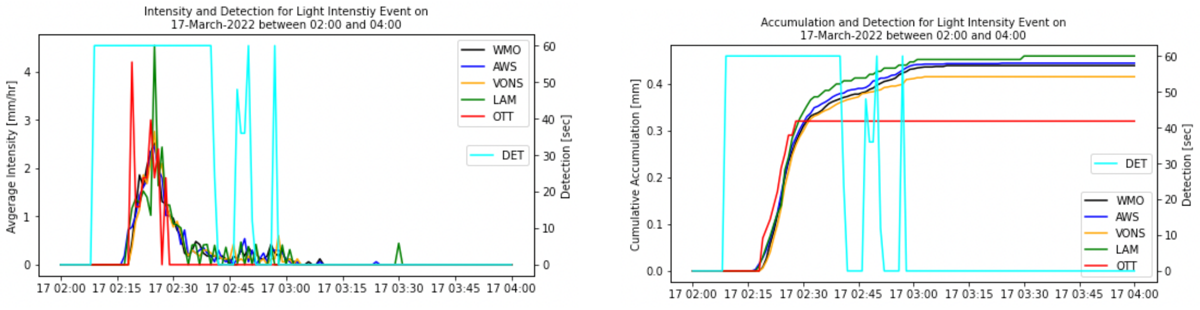
Table 9b: Percent difference values for intensity during **heavy** intensity event.

Total Duration (hours)				Difference (%)	
KNMI Gauge		**LAM**	**OTT**	**LAM-KNMI**	**OTT-KNMI**
DET	0.2	0.3	0.1	+50.0	-50.0
WMO	0.4			-25.0	-75.0
AWS	0.4			-25.0	-75.0
VONS	0.3			0.0	-66.7

Table 9c: Percent difference values for duration during **heavy** intensity event.

3.6.2: Case Study 2: Light Intensity Rain Event

During the early morning hours of 17-March-2022, light rain was recorded on the test field. The range of maximum intensities recorded during the time-period between 02:00:00 and 04:00:00 was between 2.46- and 4.54-mm/h, with AWS reference gauge recording the lowest maximum 1-minute averaged intensity and the LAM test gauge recording the highest maximum intensity. The minimum cumulative accumulation was measured by OTT at 0.32-mm and the maximum cumulative accumulation was measured by LAM at 0.44-mm. The accumulation, intensity, and duration data for this event are shown in figure 15a and b. The percent differences are shown in tables 10a, b, and c.



(a)

(b)

Figure 15: Intensity and accumulation data for all gauges for **light** intensity event. (a) 1-minute average intensity values (b) 1-min accumulation values.

Total Cumulative Accumulation (mm)				**Difference (%)**	
KNMI Gauges		**LAM**	**OTT**	**LAM-KNMI**	**OTT-KNMI**
WMO	0.4	0.5	0.3	+4.55	-27.27
AWS	0.4			+4.55	-27.27
VONS	0.4			+12.2	-21.95

Table 10a: Percent difference values for accumulation during **light** intensity event.

Maximum Intensity (mm/h)				**Difference (%)**	
KNMI Gauges		**LAM**	**OTT**	**LAM-KNMI**	**OTT-KNMI**
WMO	2.5	4.5	4.2	+80.2	+66.67
AWS	2.5			+84.59	+70.73
VONS	2.8			+64.53	+52.17

Table 10b: Percent difference values for intensity during **light** intensity event.

Total Duration (hours)				**Difference (%)**	
KNMI Gauges		**LAM**	**OTT**	**LAM-KNMI**	**OTT-KNMI**
DET	0.7	0.5	0.1	+50.0	-85.7
WMO	0.8			-37.5	-87.5
AWS	0.8			-37.5	-87.5
VONS	0.7			-28.6	-66.7

Table 10c: Percent difference values for duration during **light** intensity event.

4. Conclusions

KNMI conducted an intercomparison of rain gauges between 1-April-2021 and 10-April-2022 at its headquarters in De Bilt, Netherlands. The goal of this intercomparison was to identify a suitable replacement gauge for KNMI's self-designed float gauge that is currently deployed in its automated network of approximately 35 gauges. The current gauge is approximately 30 years old, is costly to maintain, and experience some technical difficulties. The data used in this study were 1-minute average intensity values which was either a direct output from the gauges or was derived from accumulation data (OTT). In the case of the OTT, the data was also timestamp corrected for the 5-minute reporting delay for 'non-real-time' output.

For this intercomparison, two commercially available off-the-shelf rain gauges were chosen each with its own measuring principle. Lambrecht's Rain[e]H3 is a hybrid rain gauge that uses a combination of a tipping bucket and a high-precision load cell to measure precipitation amount and intensity. OTT HydroMet's Pluvio^2 uses a weighing bucket to measure precipitation amount and intensity. Both gauges were situated with their orifices 1-meter above the ground. They were adjacent to KNMI's float gauge, located in a 'WMO-style' pit to reduce the effect of wind. This gauge served as the reference gauge for the intercomparison. Additionally, two other KNMI FG were used as control gauges: one in a pit and one with its orifice 1-meter above the ground. A precipitation detector was also present and located 1-meter above the ground. Overall, both the LAM and OTT performed well when comparing accumulation totals to the reference gauge but performed less well when comparing precipitation intensity and duration to the reference gauge.

All gauges used in this intercomparison were calibrated prior to the field test but only the OTT was calibrated after the field test, due to scheduling issues. Only the gauges under test underwent a series of lab tests to identify any systematic errors/biases before and after the field test. The lab tests consisted of measuring the intensity of a flow of water from a reservoir that was pumped at a variety of constant flow rates that corresponded to the target intensities used in the WMO's intercomparison lab tests. When comparing the target intensities to the intensities derived from the accumulation output of the gauges, the results were favorable for the LAM gauge with percent differences ranging between 4 and 18%. However, for the OTT gauge, the results were less favorable with a percent error of 100% when attempting to measure a 2-mm/h intensity and 66% when attempting to measure a 20-mm/h intensity. These results are consistent with the results found when the instruments measured intensity during the field trial.

In terms of accumulation, the gauges under test reported study period total accumulations within 3.11% of the reference gauge. In this case, the LAM over-reported by 3.11% and the OTT under-reported by 3.11%. These differences are acceptable and within the guidelines set by the WMO.

Monthly accumulation comparisons between gauges under test and the reference gauge were also favorable and followed a similar pattern. The LAM consistently over-reported precipitation amounts by up to 9.42% while the OTT consistently under-reported precipitation amounts by as much as 33.33%. The biggest differences between the reference accumulation and the accumulations reported by the gauges under test occurred during the months of June 2021 and March 2022. Both months featured very little precipitation with the reference gauge reporting 4.2-mm in June 2021 and 15.4-mm in March 2022. The high differences can be partially explained by the small total accumulations.

For daily totals, the regression plots between the gauges under test and the reference sensor reported r-squared values that exceeded 0.99 indicating excellent agreement among the daily totals reported by the gauges. One outlier existed in the data and can be traced to 1-April-2022, a day on which wet snow fell on the test field. The reference sensor reported 7.08-mm of precipitation compared to 2.27-mm and 2.80-mm by the LAM and OTT respectively. Of note, the control sensor (AWS) located in a pit, also reported a relatively high accumulation total of 5.83-mm while the control sensor (VONS) not in a pit and with no windscreen reported an accumulation of 2.81-mm, like the gauges under test. This likely shows that wind was a factor on this day.

When comparing intensity data, it was shown that both the LAM and OTT under-report light precipitation intensity values, with the OTT significantly under-reporting. When compared to the reference sensor, the LAM under-reported light precipitation intensities by 38.65% compared to 85.36% by the OTT. For all other categories of events (moderate, heavy, and violent), the gauges under test over-reported the cases of each type between 8.84% and 54.71%, with the OTT over-reporting the most. The over-reporting by the OTT is likely the result of the delay in reporting light intensity precipitation totals that end up being aggregated into a false high intensity precipitation total at the 1-minute time resolution used with this data. Resampling to 10-minute average intensity values, resolves this issue.

With respect to the maximum intensity value reported during the study period, this occurred at 14:09 on 9-August-2021 during a convective event. The reference gauge reported an intensity value of 185.0-mm/h while the gauges under test reported 164.6-mm/h (LAM) and 172.2-mm/h (OTT). Splashing of water in the tipping bucket is a known issue during high-intensity events which could explain this 11.00% difference.

For the analysis of precipitation duration, a count of the number of minutes for which each gauge reported precipitation (i.e., 1-minute average intensity value > 0.0-mm/h) was used to determine duration in hours. These values were compared to the sum of the detector's duration output (converted to hours.) With the detector having a higher sensitivity to precipitation than the gauges, it was surprising that the detector measured fewer hours of precipitation when compared to the gauges. Unsurprisingly, both the LAM and OTT under-reported precipitation duration hours when compared to the detector. Given the higher sensitivity of the detector, this is an expected outcome.

While both gauges performed similarly with respect to accumulations, they differ in how they perform when reporting intensity and duration data. A large part of this difference can be attributed to the OTT time delay and under-reporting of precipitation totals during low-intensity events (under 6-mm/h.) During these events, a threshold value of 0.5-mm needs be overcome (within 1 hour) for an output to be generated. This can lead to delays in reporting precipitation intensity and duration which makes it an unsuitable option if one wishes to have a gauge that can accurately measure these parameters.

The LAM on the other hand, tends to under-report during high intensity precipitation events. This is due to the water splashing out of the tipping mechanism that leads to an under-reporting of precipitation intensity and accumulation. While it also under-reported precipitation duration, it was closer to the number of hours reported by the detector (when compared to the OTT) by a considerable amount. The difference between the OTT and detector was 67.92% while the difference between the LAM and detector was 22.49%.

The mid-latitude maritime climate of the Netherlands dictates that weather conditions favor liquid precipitation throughout the year, typically relatively light in intensity. Given the common experience of frequent light precipitation events, it is important that the next rain gauge that KNMI deploys in its automated network be able to accurately report these events. Based on the results of this intercomparison, the Lambrecht Rain[e]H3 would be a better choice than the OTT HyrdoMet Pluvio^{2}L since it better performed during light intensity events.

5. Acknowledgements

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