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ORIGINAL PAPER

Comparative study of rainfall measurement by optical disdrometer, tipping-bucket rain gauge, and weighing precipitation gauge

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Abstract

In this study, the rainfall measurement characteristics of an optical particle size velocity (Parsivel) disdrometer, tipping-bucket rain gauge (TBG), and Pluvio weighing precipitation gauge (WPG) were analyzed and compared. Correlation analysis was performed between the 10-min and 1-h rainfall data observed with the Parsivel, TBG, and Pluvio from 2010 to 2019 at the Cloud Physics Observation Site which is located in northeast area of South Korea (N37.6869, E128.7586). At higher rainfall intensities, the Parsivel observed more rainfall; however, the TBG lost more rainfall during observation. The correlation between the Pluvio and Parsivel data was higher than that between the TBG and Parsivel data. Additionally, the Pluvio showed reduced loss in the rainfall observation than that by the TBG. The correlation between the Pluvio and TBG data was the highest, and the coefficient of determination increased by a maximum of 42.08% for 1-h rainfall compared to that for 10-min rainfall. Therefore, the Pluvio can generate relatively accurate rainfall data for water resource utilization.

Keywords Rainfall measurement · Optical disdrometer · Tipping-bucket rain gauge · Weighing precipitation gauge

1 Introduction

Rainfall is an important primary factor in hydrological and meteorological research. Owing to the fact that climate change causes various disasters related to rainfall occurrence and rate, such as droughts and flash floods, it is very important to generate accurate and reliable rainfall data (Shrestha et al. 2017; Zhang et al. 2018; De Vos et al. 2019). Moreover, as public interest in the concentration of airborne dust has increased, accurate rainfall data are needed for environmental research to improve air quality (Jha et al. 2018; Chen et al. 2020; Jin et al. 2021). Further, various meteorological disasters are greatly affected by rainfall;

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therefore, securing accurate rainfall data is a critical priority (Casale 2004; Ismail-Zadeh et al. 2014).

The most common instrument for rainfall observation is a rain gauge, which collects rainwater using a cylinder that is manufactured to a certain standard and measures the amount of rainfall. In Korea, rainfall is observed in real time using rain gauges as well as a tipping-bucket rain gauge (TBG). As rainfall enters the inlet and collects in the tipping bucket, it inclines due to the weight of water, which empties the bucket. Rainfall is measured using an electrical signal generated by the overturning of the bucket and recorded in a data logger (Kelway 1975). A dual tipping-bucket rain gauge (DTBG) that utilizes two buckets has also been introduced for precise rainfall observations (Al-Wagdany 2015). TBG can be installed in many areas because they are light, inexpensive, and easy to install. However, because they only measures rainfall when a certain amount of rainwater fills the bucket, they may not provide observations if the amount of rainfall is very small. However, if the rainfall intensity is extremely high, losses may occur during observation because of the time required for the bucket to tip. In addition, a TBG can be greatly affected by wind speed and topographical factors (Habib et al. 2001; Ciach 2003).

Despite the introduction of remote observation instruments, such as radar and satellites, generating quantitative rainfall data remains challenging because of uncertainty arising from the difficulties in observations over mountains and oceans (Tesfagiorgis et al. 2011; Seo et al. 2015; Kim et al. 2018). Studies have attempted to merge radar and ground observations or use machine learning to generate quantitative rainfall data (Tang et al. 2018; Shin et al. 2019; Ro and Yoo 2020). These studies showed the importance of accurate ground observation data for analysis of water resources and the water cycle. Therefore, instruments that can sensitively detect precipitation phenomena, generate precise precipitation information, and create an observation network are required.

The Korea Meteorological Administration (KMA) observes rainfall using ground observation equipment, such as a weighing precipitation gauge (WPG), an optical disdrometer, and a vertical rainfall radar. A WPG is a rain gauge that monitors both rainfall and snowfall by directly observing the weight of the precipitation (Molini 2007). An optical disdrometer is a device that can observe the size and falling velocity of the precipitation particles. The particle size velocity (Parsivel) disdrometer is a type of optical disdrometer that has been used for precipitation observations and atmospheric water classification in the hydrological and meteorological fields (Battaglia et al. 2010; Jaffrain and Berne 2012; Park et al. 2017). It can sensitively detect precipitation, but it is expensive. However, WPGs are relatively inexpensive, and if the wind speed is not high, precipitation can be observed more precisely than with a rain gauge, increasing its utility (Savina et al. 2012; Colli et al. 2013).

Pluvio is a type of WPG, and its use has increased as the reliability of its precipitation observations has been verified (Nitu et al. 2019; Saha et al. 2021). The Pluvio can detect small amounts of precipitation with more sensitivity than TBGs, and observation losses heavy precipitation are minimal. Moreover, heating wires on the surface of the buckets can melt snow to measure snowfall. Therefore, many research institutes that require precipitation observations have installed Pluvio units. In Europe, an observation network has been created using Pluvio units in areas that are difficult for humans to access. In USA and Canada, Pluvio has become a standard instrument for precipitation observations. The National Weather Service and US Geological Survey introduced the National Atmospheric Deposition Program and conducted verification tests for rain gauges, which included a Pluvio (Lamb and Bowersox 2000). In Korea, the National Institute of Meteorological Sciences (NIMS) first installed a Pluvio in 2006 and later secured three additional units. However, creating an observation network has been difficult because fewer than 10 of these instruments are currently installed in Korea. In addition, it is necessary to continuously manage the installed equipment and observation data.

In this study, the observational characteristics of a Pluvio were examined and compared to those of existing rainfall observation instruments. For this purpose, ten years of Pluvio, TBG, and Parsivel observation data at the NIMS of the KMA were analyzed. The characteristics of the equipment installed in the observation area and the data analysis method used in this study are presented in Sect. 2. In Sect. 3, the rainfall observation characteristics of the Pluvio are compared to those of the Parsivel and TBG by analyzing the observations of each piece of equipment for two rainfall cases. In Sect. 4, the reliability of the Pluvio observational data is confirmed, and future research for increasing the usefulness of the data is discussed. The results of this study are expected to contribute to securing accurate rainfall information.

2 Instrumentation and methods

2.1 Description of instrumentation

In this study, rainfall data observed at the Cloud Physics Observation Site (CPOS) of the NIMS were analyzed. The CPOS is an observation site established to verify artificial rainfall aerial experiments and is equipped with rain gauges, optical disdrometers, vertical rainfall radars, aerosol particle detectors, and automatic cloud observation systems. Figure 1 shows the validation site where the Parsivel, Pluvio, and rain gauges were installed. For the rain gauges, a TBG was used through 2017, and a DTBG was used from 2019 onwards, after replacing the TBG during 2018. As shown in Fig. 1, the Parsivel, Pluvio, and TBG

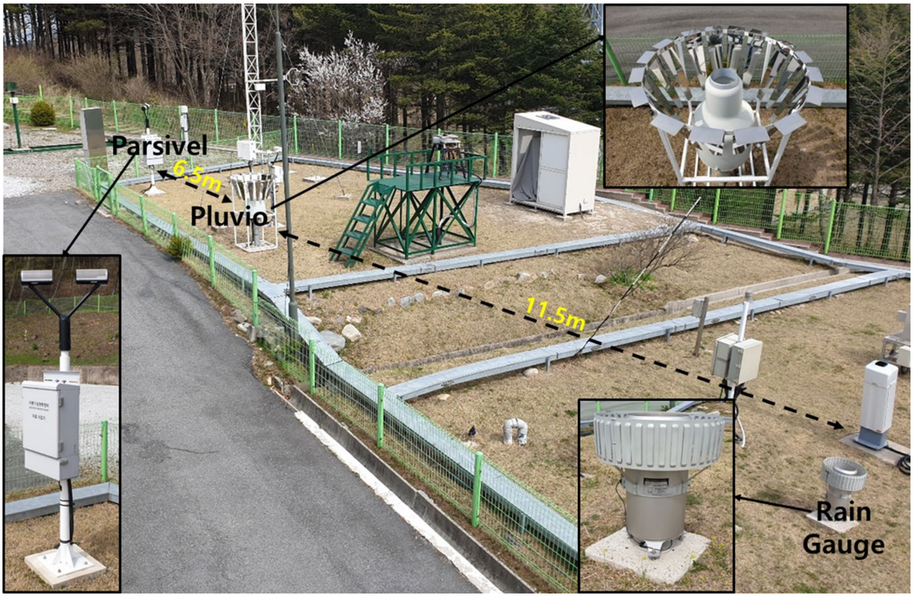

Fig. 1 Instruments of Parsivel, Pluvio, and rain gauge in CPOS

are installed in a straight line, and the TBG is approximately 18.0 m away from the Parsivel. The Pluvio is 6.5 m from the Parsivel and 11.5 m from the TBG. Windshields surround the Pluvio and TBG.

As shown in Fig. 1, the Parsivel is an optical instrument that measures the size and fall velocity of precipitation particles as they pass through a laser beam between a transmitter and a receiver branched in Y shape. PM Tech developed the first optical rain meter (Löffler-Mang and Joss 2000), and in 2005, OTT Hydromet obtained the rights to the technology and created Parsivel 1 (Battaglia et al. 2010). In 2011, OTT developed Parsivel 2, which can generate a more homogeneous laser than Parsivel 1 can. Parsivel 2 has a laser wavelength of 780 nm, sampling area of 54 cm^2 (length 180 mm, width 30 mm, and height 1 mm), and frequency of 50 kHz, which can provide 32×32 channels of information about precipitation particles. This instrument may overestimate precipitation as its intensity increases (Lanza and Vuerich 2009; Thurai et al. 2011), but Parsivel 2 shows smaller observational errors than Parsivel 1 does (Tokay et al. 2014). If the raindrops are less than 2 mm, size class errors of ± 1 for Parsivel 2 and ± 3 for Parsivel 1 may occur. If the raindrops are larger than 2 mm, these errors decrease to ± 0.5 for Parsivel 2, and ± 2 for Parsivel 1. At the CPOS, Parsivel 1 was used through 2014; thereafter, Parsivel 2 was used. The data from these instruments were recorded at 1-min intervals.

The TBG is a device that measures rainfall by collecting a set amount of rainwater in a bucket. A data logger installed in the rain gauge measures the number of times the bucket overturns; if the bucket does not overturn, no rain is recorded. Depending on the number of times the bucket overturns per hour, rainfall up to 0.1 mm can be observed, but as the overturning frequency increases, rainfall may be overestimated. The DTBG was introduced to solve this problem and measure rainfall more precisely. It measures the amount of rainfall using electrical signals generated from buckets of different capacities. Since 2018, the NIMS has improved their rainfall observation data by using a DTBG at the CPOS (Choi et al. 2018). Both the TBG and DTBG can observe rainfall each minute and record daily rainfall.

Pluvio is a device that collects precipitation using a bucket, similar to a rain gauge. The equipment installed in the CPOS is the OTT Pluvio, which was the first unit installed in Korea. Pluvio observes precipitation each minute and records the daily precipitation. The CPOS periodically examines the inside of the instrument and empties the bucket when the accumulated precipitation exceeds 400 mm. As shown in Fig. 1, windshields surround the Pluvio to minimize the influence of wind speed on precipitation observations. In addition, unlike the ground-based TBG, the Pluvio was installed above a certain height to minimize capping at the bucket entrance during heavy snowfall. The Pluvio support is made of a sturdy material to prevent the bucket from shaking during strong winds. Compared to a rain gauge, the Pluvio can record precipitation to three decimal places; therefore, it can accurately observe precipitation if the losses are not large.

2.2 Rainfall data analysis

To evaluate the performance of the Pluvio during heavy rains, this study compared the yearly time series of accumulated rainfall observed with the Parsivel, TBG, and Pluvio. Using these data, the overall rainfall observation results of the three instruments were compared, and the monthly rainfall occurrences and annual rainfall characteristics in Korea were analyzed. Considering the monsoon climate and the tendency of rainfall to be concentrated in summer, data observed from June to September were selected, and the relationships between the Parsivel and TBG, Parsivel and Pluvio, and Pluvio and TBG data were compared.

To compare the rainfall observation ability of the Parsivel and other rain gauges, this study analyzed data that were collected for 10 years, from January 2010 to December 2019. In consideration of seasonal effects, quality-controlled data were used for the data analysis according to the characteristics of each instrument. To exclude the effects of snowfall, only the data judged to be rainfall (rain, drizzle) by the Parsivel were analyzed. A 10-min observation period was set as the standard, and analysis data were generated by accumulating the observations from each minute. Unlike the Parsivel, which can observe precipitation particles, the TBG and Pluvio can only measure precipitation above a set limit; therefore, if the accumulated rainfall over 10 min was less than 0.1 mm, it was excluded from the analysis. In addition, to exclude excessively large observation values, if the rainfall rate was greater than 2 mm within a minute (> 120 mm/h), it was excluded from the analysis. Additionally, any cases where precipitation in the Pluvio evaporated due to wind, humidity, or atmospheric pressure during the observation period were excluded from the analysis. The overall performance for the entire study period was analyzed by comparing the correlations between the 10-min cumulative rainfall and the 1-h cumulative rainfall.

In this study, the Parsivel and Pluvio data were compared based on the data from the TBG and DTBG, which were used as true values for rainfall. The mean deviation (MD), mean absolute deviation (MAD), root mean square deviation (RMSD), and correlation of determination (R^2) were used, as shown in Eqs. (1)–(4).

$$\mathrm{MD} = \frac{1}{n}\sum_{i=1}^{n}(X_i - Y_i) \tag{1}$$

$$\mathrm{MAD} = \frac{1}{n}\sum_{i=1}^{n}\left|X_i - Y_i\right| \tag{2}$$

$$\mathrm{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - Y_i)^2} \tag{3}$$

$$R^2 = \frac{\left(\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)\right)^2}{\sum_{i=1}^{n}(X_i - \overline{X})^2\sum_{i=1}^{n}(Y_i - \overline{Y})^2} \tag{4}$$

Here, n represents number of data, X_i and Y_i represent the rainfall data of the two observation instruments to be compared, and $\overline{X}$ and $\overline{Y}$ represent the averages of each data point. The closer MD, MAD, and RMSD are to 0, the smaller the data bias, whereas R^2 is a measure of the fit of the regression line.

3 Results

3.1 Comparisons of annual rainfall data

Figure 2 shows the 10-min cumulative and annual total rainfall data collected with the Parsivel, TBG, and Pluvio from 2010 to 2019; only the data judged as rainfall by the Parsivel were included. In 2018, only the Parsivel and Pluvio were used because of the installation of the DTBG. As the figure shows, the rain fell primarily during June–September owing to the influence of the monsoon climate, and rainfall was minimal during spring (March–May) and winter (December–February).

Table 1 shows the total yearly rainfall observed using the three instruments. When the annual rainfall was relatively low during 2010, the accumulated rainfall observed with the three instruments was similar; however, the Parsivel observed more rainfall than the other two instruments did. The Parsivel is more sensitive to precipitation; thus, its rainfall observations can be high. However, with the TBG and Pluvio, a film of raindrop can be broken up at the entrance to the bucket as the precipitation intensity increases, resulting in losses. In addition, precipitation may have been underestimated because Pluvio and TBG measure the water equivalent of melting snow. This difference can be quite large because snow and

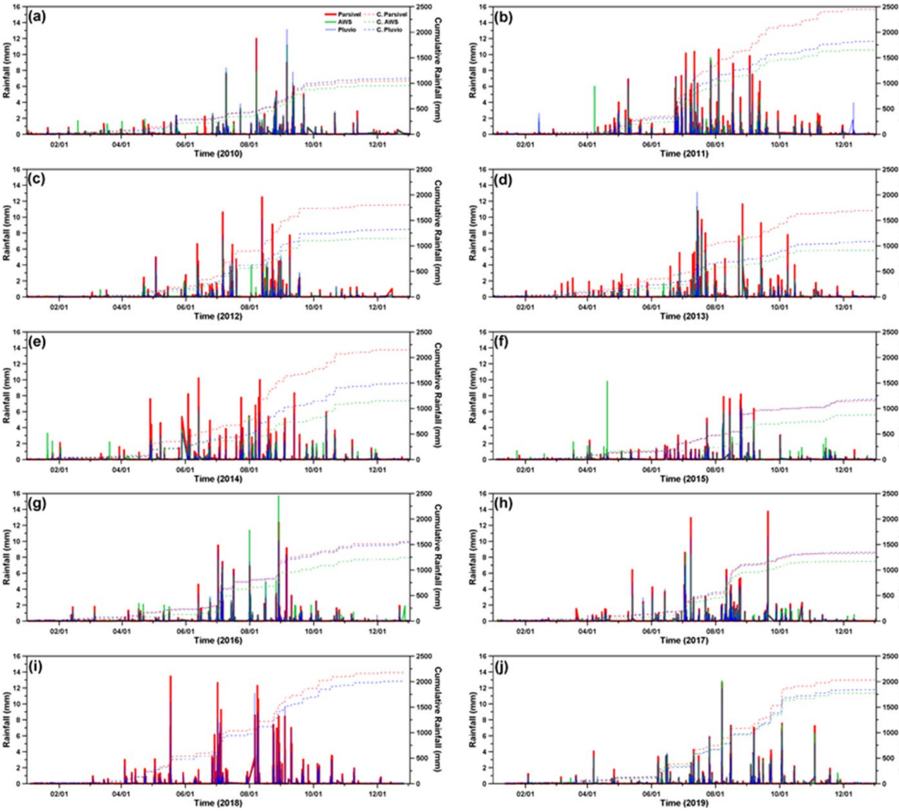

Fig. 2 Annual measured rainfall data of Parsivel, rain gauge, and Pluvio (**a**: 2010, **b**: 2011, **c**: 2012, **d**: 2013, **e**: 2014, **f**: 2015, **g**: 2016, **h**: 2017, **i**: 2018, **j**: 2019)

Table 1 Total amount of annual rainfall of Parsivel, TBG, and Pluvio

Year	Parsivel (mm)	TBG/DTBG (mm)	Pluvio (mm)
2010	1049.2	949.4	1096.9
2011	2445.8	1648.5	1821.6
2012	1801.8	1144.1	1323.5
2013	1688.6	911.6	1086.3
2014	2151.5	1152.5	1492.6
2015	1151.9	874.7	1178.5
2016	1560.4	1242.5	1538.6
2017	1323.0	1168.2	1346.8
2018	2177.6	–	2007.2
2019	2030.1	1771.7	1842.1

water have different densities. Overall, the total annual observed rainfall for the Pluvio was the same or slightly larger than that for the TBG. These results confirm the precise rainfall observation performance of the Pluvio.

3.2 Comparisons between Parsivel and TBG data

In this study, data correlation analysis was performed to examine the relationships among the rainfall data observed with the three devices. To reduce the deviations in the analyzed data (Fig. 2), data from June to September, when the rainfall primarily occurred, were used. First, as shown in Fig. 3, we compared the 10-min TBG and Parsivel data from 2010 to 2019; both annual data and data for the entire study period were analyzed. In 2018, data were not observed due to the replacement of the DTBG; therefore, it was excluded from the analysis.

As shown in Fig. 3, the Parsivel observed a greater amount of rainfall than the TBG did. This is because, unlike the TBG, which measures the amount of water that fills the bucket, the Parsivel observes the particle size, which causes extra observations as the rainfall intensity increases. This trend was notable from 2011 to 2014 (Fig. 3b–e) and can also be confirmed in Table 1. In 2010, when the annual precipitation was relatively low, the correlation between the TBG and Parsivel data was high. After 2015, when the Parsivel was replaced with Parsivel 2, the rainfall difference between it and the TBG was lower. As described by Tokay et al. (2014), this is because the observation error of the Parsivel 2 is smaller than that of the Parsivel 1. In 2016, the variance in the data was larger than in other years; thus, the correlation between the TBG and Parsivel data was small (Fig. 3g), which can also be confirmed in Fig. 2g. This was because higher rainfall intensity increased the precipitation losses owing to raindrop breakup at the bucket inlet of the TBG. Figure 3i shows that this observation error decreased in 2019, as the DTBG was used during that period. Additionally, Fig. 3j shows that the deviation between the Parsivel and TBG observations was large.

To minimize the observational differences between the two instruments, this study compared their 1-h rainfall data. Figure 4 shows that the correlation between the Parsivel and TBG 1-h data was significantly higher than that of the 10-min data. Beginning in 2015, when Parsivel 2 was installed, the deviation between the two datasets decreased, and the correlation increased. Comparing the data for the entire study period, the correlation between the 1-h data increased significantly (Fig. 4j). This result shows the correlation

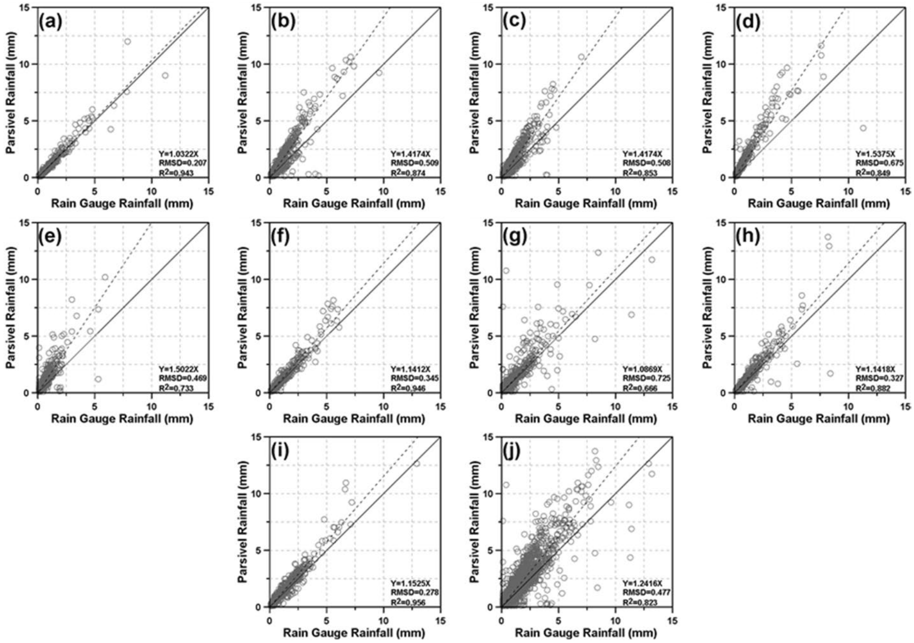

Fig. 3 Comparison of 10-min rainfall data for rain gauge and Parsivel (**a**: 2010, **b**: 2011, **c**: 2012, **d**: 2013, **e**: 2014, **f**: 2015, **g**: 2016, **h**: 2017, **i**: 2019, **j**: 2010–2019)

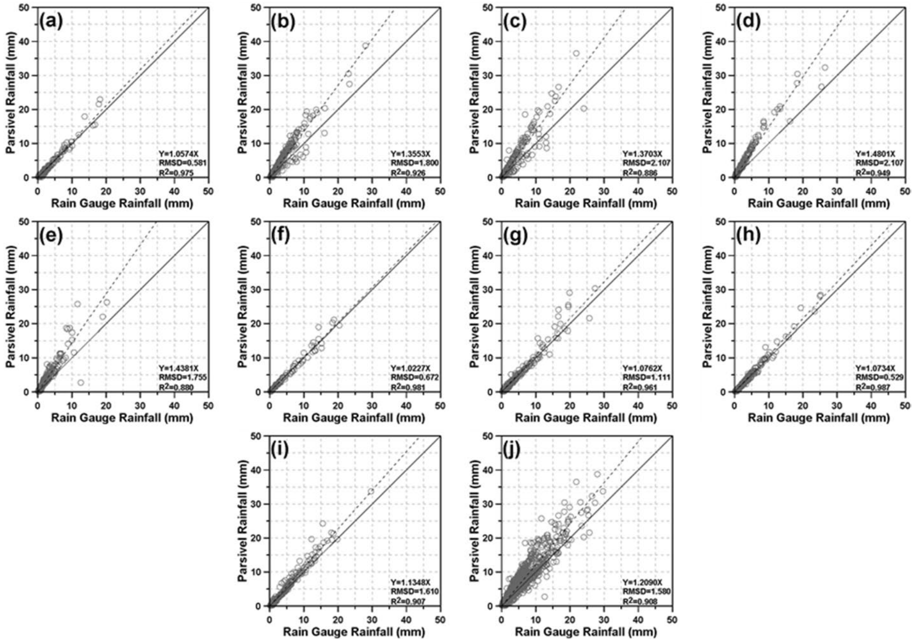

Fig. 4 Same as Fig. 3, but for 60-min rainfall data

between the Parsivel and the TBG data is large though observation method of two instruments is different.

Table 2 shows the deviations and coefficients of determination of the Parsivel and TBG data for the 10-min and 1-h rainfall using Eqs. (1–4). As shown in Table 2, the MD, MAD, and RMSD for the 1-h data were larger than those for the 10-min data, except during 2015 and 2017. The coefficient of determination indicated that the 1-h rainfall data were more highly correlated that the 10-min rainfall, except for 2019, when the coefficient of determination for the 10-min rainfall reached its maximum. Thus, it showed higher correlation than that of the 1-h data. However, for most years, the coefficient of determination for the 10-min rainfall was small and depended on the distribution of the data, but for 1-h rainfall, it was approximately 0.9 or higher. In particular, the 1-h data in 2017 had the largest coefficient of determination (0.987). These results show the consistent performances of the TBG and Parsivel for rainfall observations.

3.3 Comparison between Pluvio and Parsivel data

Figure 5 shows the comparison between the Parsivel and Pluvio rainfall data. The 10-min rainfall data measured from June to September (Fig. 2) were analyzed, and the year-by-year comparisons are shown from 2009 to 2020. To evaluate the correlation between the Parsivel and Pluvio data, the same analysis method described Sect. 3.2 was applied.

As shown in Fig. 5, the comparisons between the Pluvio and Parsivel data were similar to those between the TBG and Parsivel data. This is because the observation

Table 2 Evaluation criteria of Parsivel against rain gauge data

Year	Data	MD (mm)	MAD (mm)	RMSD (mm)	R^2
2010	10-min	−0.021	0.096	0.207	0.943
	60-min	−0.054	0.303	0.581	0.975
2011	10-min	0.206	0.273	0.509	0.874
	60-min	0.879	1.083	1.800	0.926
2012	10-min	0.205	0.277	0.508	0.853
	60-min	0.851	1.081	2.107	0.886
2013	10-min	0.317	0.348	0.675	0.849
	60-min	1.133	1.168	2.107	0.949
2014	10-min	0.154	0.226	0.469	0.733
	60-min	0.709	0.839	1.755	0.880
2015	10-min	0.075	0.164	0.345	0.946
	60-min	0.033	0.337	0.672	0.981
2016	10-min	0.070	0.238	0.725	0.666
	60-min	0.075	0.447	1.111	0.961
2017	10-min	0.044	0.119	0.327	0.882
	60-min	0.030	0.262	0.529	0.987
2019	10-min	0.078	0.138	0.278	0.956
	60-min	0.450	0.656	1.610	0.907
2010~2019	10-min	0.133	0.213	0.477	0.823
	60-min	0.528	0.747	1.580	0.908

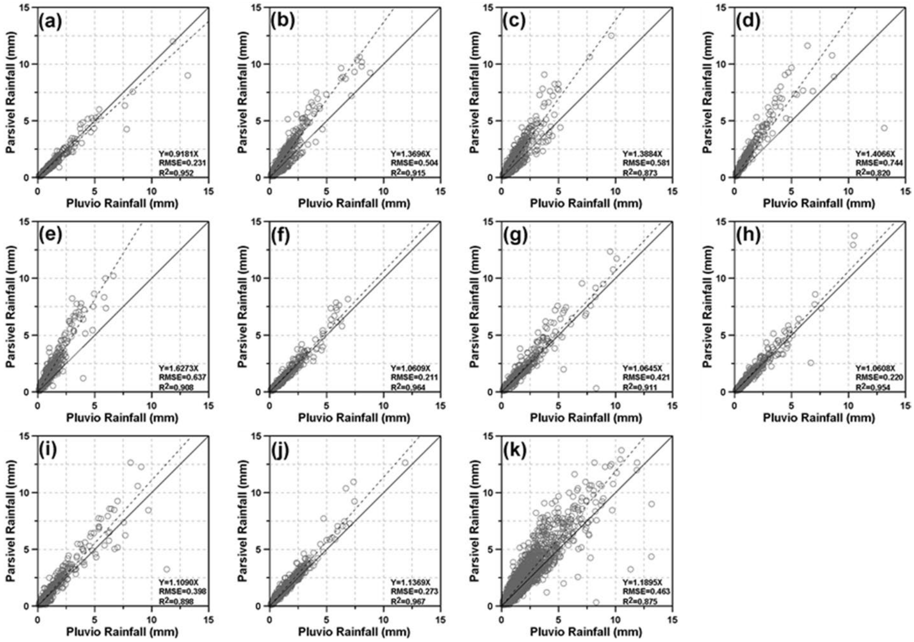

Fig. 5 Comparison of 10-min rainfall data for Pluvio and Parsivel (**a**: 2010, **b**: 2011, **c**: 2012, **d**: 2013, **e**: 2014, **f**: 2015, **g**: 2016, **h**: 2017, **i**: 2018, **j**: 2019, **k**: 2010–2019)

methods of the WPG and TBG are not significantly different. However, the Pluvio data showed a greater correlation with the Parsivel data than with the TBG data. This can also be confirmed by the similarities between the Pluvio and Parsivel data in Table 1. After the Parsivel 2 observations began in 2015, the correlation between the Pluvio and Parsivel data increased, and the data deviations decreased compared to those before 2015. The same result was obtained for the data over the entire study period (Fig. 3k).

The comparisons between 1-h rainfall data for the Pluvio and Parsivel, which has smaller data deviations, are shown in Fig. 6. The correlation between these instruments for 1-h rainfall was significantly higher than that for 10-min rainfall. Moreover, variance in the data was lower, and after Parsivel 2 was introduced in 2015, the data were approximately concentrated around a line, $y=x$. By comparing the data for the entire period, we found that the deviation decreased compared to the 10-min data.

Table 3 summarizes the test statistics for the two datasets from Pluvio and Parsivel. The coefficients of determination for the yearly Pluvio and Parsivel data were generally 0.9 or higher. The highest coefficient of determination was 0.967 for the 10-min rainfall in 2019 and 0.987 for the 1-h rainfall in 2017. In 2013, the coefficient of determination for both the Pluvio and Parsivel datasets was the smallest, at 0.820 for the 10-min rainfall and 0.949 for the 1-h rainfall, which was 15.73% higher. The deviation was larger in the 1-h data than in the 10-min data, but since 2015, when the Parsivel 2 was introduced, this deviation decreased. The large correlation between the datasets suggests that the Pluvio had less rainfall observation loss than the TBG.

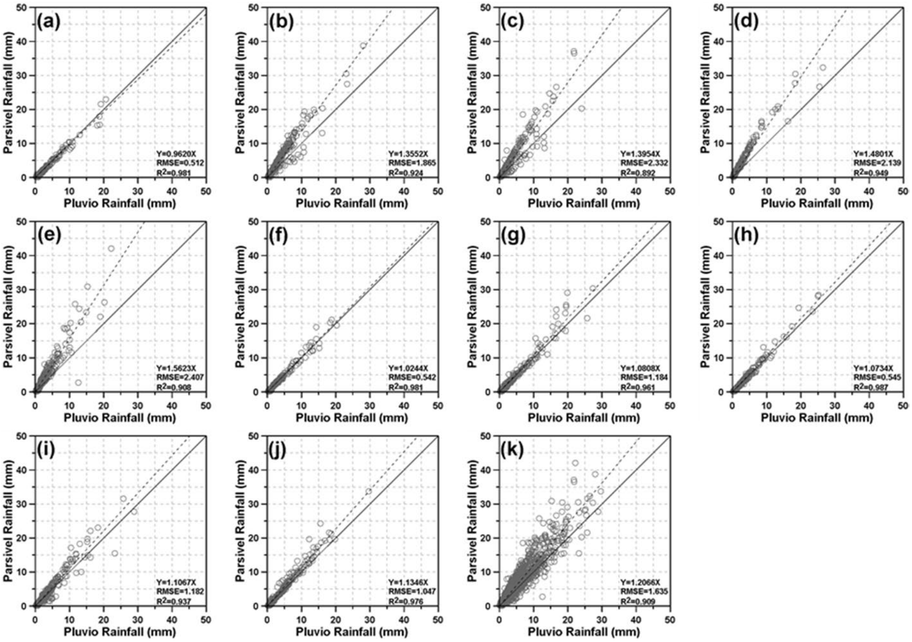

Fig. 6 Same as Fig. 5, but for 60-min rainfall data

3.4 Comparison between Pluvio and TBG data

Using the same methods as the Pluvio and Parsivel data comparison, the Pluvio observation data were compared against the TBG, which was considered the true value for rainfall observation. The comparisons between the two datasets for the 10-min observation data by year are shown in Fig. 7. No TBG observations were made during 2018; therefore, that year was excluded from the analysis.

Figure 7 shows that the correlation between the Pluvio and TBG data was higher than that between the Pluvio and Parsivel data. Except for 2016, when the data deviation was large, the regression line was approximately $y=x$. Additionally, the Pluvio data were slightly higher than those of the TBG. This indicates that the rainfall observation loss was small; therefore, the Pluvio can observe rainfall more precisely than the TBG. Moreover, in 2016, the TBG data were significantly different from that of the other two devices, due to large losses during observation (Fig. 3 and Table 1). These losses decreased in 2019, owing to the use of the DTBG (Fig. 7i).

Figure 8, which compares the 1-h rainfall data of the Pluvio and TBG, shows that these datasets had the greatest correlation among all results in this study. The regression line for the observation data was approximately $y=x$, and the data scattering in 2016, which showed a large deviation for the 10-min data, also decreased. Figure 8j also shows that the rainfall observations of the two instruments over the entire study period were approximately identical.

Table 4 shows the test statistics of the two datasets used to analyze the observed rainfall loss of the TBG. Similar to the other analysis results, the deviation between the Pluvio and TBG data was smaller for the 10-min rainfall than for 1-h rainfall. The coefficients of determination were larger for the 1-h rainfall, except in 2014, and the largest

Table 3 Same as Table 2, but for Parsivel against Pluvio

Year	Data	MD (mm)	MAD (mm)	RMSD (mm)	R^2
2010	10-min	0.044	0.092	0.231	0.952
	60-min	0.204	0.308	0.512	0.981
2011	10-min	−0.268	0.310	0.504	0.915
	60-min	−0.960	1.150	1.865	0.924
2012	10-min	−0.285	0.343	0.581	0.873
	60-min	−0.993	1.221	2.332	0.892
2013	10-min	−0.400	0.418	0.744	0.820
	60-min	−1.178	1.199	2.139	0.949
2014	10-min	−0.329	0.339	0.637	0.908
	60-min	−1.060	1.155	2.407	0.908
2015	10-min	−0.022	0.098	0.211	0.964
	60-min	0.022	0.288	0.542	0.981
2016	10-min	−0.045	0.153	0.421	0.911
	60-min	−0.128	0.482	1.184	0.961
2017	10-min	−0.023	0.088	0.220	0.954
	60-min	−0.039	0.271	0.545	0.987
2018	10-min	−0.093	0.173	0.398	0.898
	60-min	−0.256	0.616	1.182	0.937
2019	10-min	−0.092	0.126	0.273	0.967
	60-min	−0.281	0.482	1.047	0.976
2010~2019	10-min	0.163	0.221	0.463	0.875
	60-min	0.537	0.773	1.635	0.909

was 0.996 in 2019, observed with the DTBG. In 2016, the coefficient of determination for 10-min rainfall was the smallest at 0.682; however, that for 1-h rainfall was 0.969, an increase of approximately 42.08%. Because the TBG determines rainfall by the number of times the bucket overturns, these results show that losses during observation can increase if there is a large, rapid change in rainfall intensity. Therefore, using Pluvio, which exhibits fewer losses, can secure consistent data for water resource utilization.

4 Conclusions and discussions

In this study, the observation characteristics of an optical disdrometer, TBG/DTBG, and WPG for rainfall were analyzed. Precipitation data observed with the Parsivel, TBG, and Pluvio installed at the CPOS at the NIMS were used, and the observational performance of the Pluvio was compared to that of the TBG and Parsivel. The 10-min rainfall and 1-h rainfall observed from June to September from 2010 to 2019 were analyzed, and both yearly data and data for the entire period were compared. Correlation analysis was performed between the TBG and Parsivel, Pluvio and Parsivel, and Pluvio and TBG data, and the results are as follows.

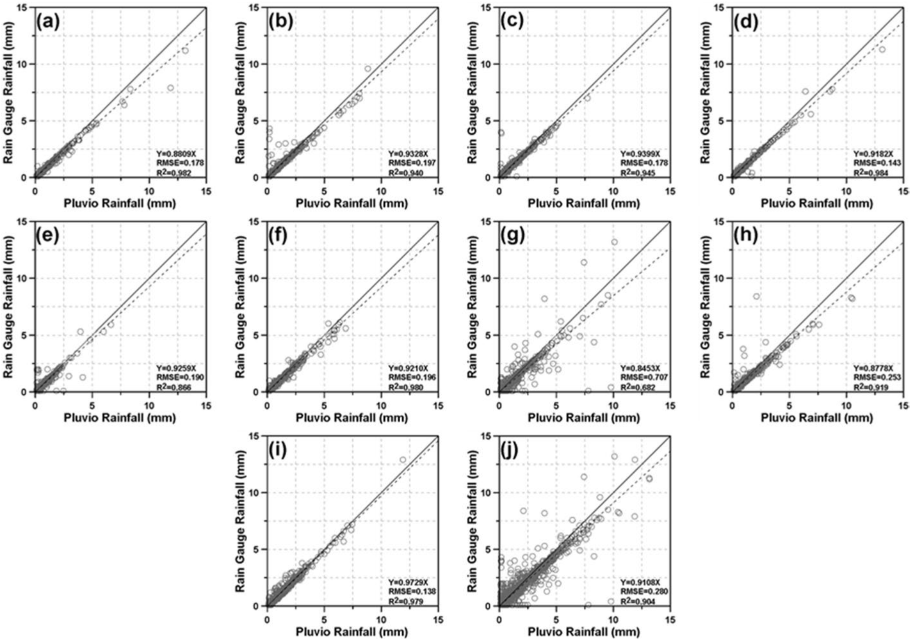

Fig. 7 Comparison of 10-min rainfall data for Pluvio and rain gauge (**a**: 2010, **b**: 2011, **c**: 2012, **d**: 2013, **e**: 2014, **f**: 2015, **g**: 2016, **h**: 2017, **i**: 2019, **j**: 2010–2019)

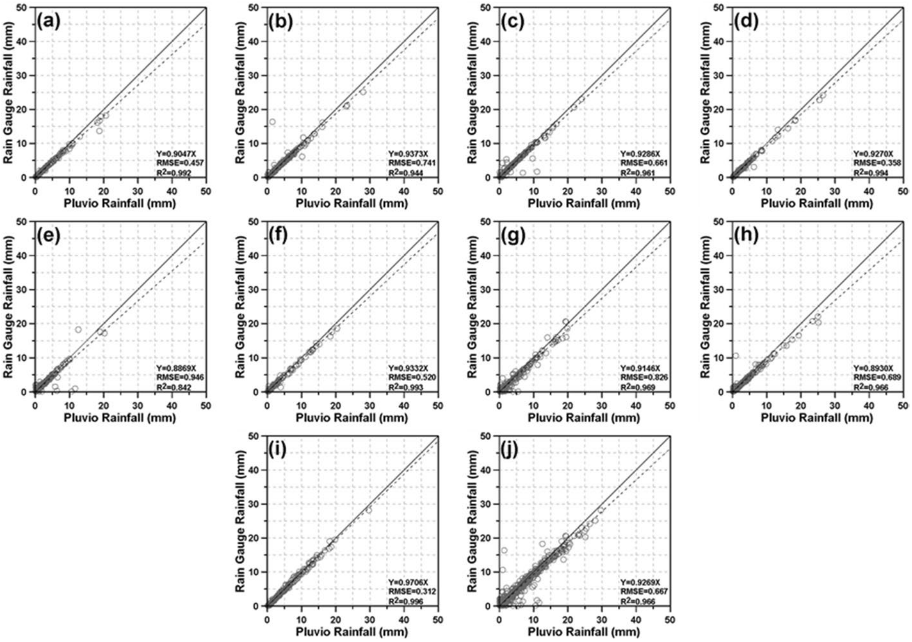

Fig. 8 Same as Fig. 7, but for 60-min rainfall data

Table 4 Same as Table 2, but for Pluvio against rain gauge

Year	Data	MD (mm)	MAD (mm)	RMSD (mm)	R^2
2010	10-min	0.041	0.067	0.178	0.982
	60-min	0.164	0.190	0.457	0.992
2011	10-min	0.019	0.069	0.197	0.940
	60-min	0.084	0.199	0.741	0.944
2012	10-min	0.018	0.067	0.178	0.945
	60-min	0.106	0.207	0.661	0.961
2013	10-min	0.032	0.065	0.143	0.984
	60-min	0.125	0.158	0.358	0.994
2014	10-min	0.007	0.064	0.190	0.866
	60-min	0.079	0.236	0.946	0.842
2015	10-min	0.065	0.108	0.196	0.980
	60-min	0.224	0.297	0.520	0.993
2016	10-min	0.079	0.211	0.707	0.682
	60-min	0.317	0.469	0.826	0.969
2017	10-min	0.050	0.092	0.253	0.919
	60-min	0.181	0.277	0.689	0.966
2019	10-min	0.027	0.079	0.138	0.979
	60-min	0.162	0.226	0.312	0.996
2010~2019	10-min	−0.034	0.087	0.280	0.904
	60-min	−0.147	0.243	0.667	0.966

1. A comparison of the annual rainfall observed by the TBG and Parsivel revealed that the Parsivel observed more rainfall than the TBG did. This is because as the rainfall intensity increases, the Parsivel tends to overestimate; nevertheless, losses due to raindrop breakage can occur in the TBG. The Parsivel 2 showed a smaller deviation from the TBG compared with Parsivel 1. As for the deviation and coefficient of determination of the two datasets, the yearly values for the 1-h rainfall were larger than those for the 10-min rainfall, and the same results were obtained when the data for the entire period were analyzed.
2. When comparing the Pluvio and Parsivel data, the correlation was greater than that when comparing the TBG and Parsivel data. When the Parsivel 2 was used, the correlation between the data increased, and the deviation from the Pluvio data decreased. Compared with the 10-min rainfall, the correlation for the 1-h cumulative rainfall was significantly higher, and when Parsivel 2 was used, the data were approximately concentrated on the regression line. The coefficient of determination was up to 15.73% higher for the 1-h rainfall compared to the 10-min rainfall. The high correlation between the two datasets indicated that the Pluvio may have smaller losses during rainfall observations than those of the TBG.
3. The correlation between the Pluvio and TBG data was the largest compared with the other two correlations. The Pluvio observed a slightly larger amount of rainfall than the TBG did. Considering that the observation methods of the two instruments were similar, these results indicate that the losses from the Pluvio were smaller. The DTBG data also showed less losses. As for the coefficient of determination, the 1-h data showed

a maximum increase of 42.08% compared to the 10-min data. Additionally, the losses from TBG may increase due to large, rapid changes in rainfall intensity.

The above results confirm that the Pluvio can generate relatively accurate data for water resource utilization, compared to the TBG and Parsivel. The Pluvio was analyzed to have less observation loss than the rain gauge due to its continuous observation of accumulated precipitation, which are consistent with previous results that the Pluvio is capable of quantitative precipitation observation (Saha et al. 2021). However, the disadvantages are remained in precipitation observations using the Pluvio. Snow capping at the bucket entrance can block the successive observation for heavy snowfall, and the bucket heating preventing the capping can evaporate snowfall in Pluvio (Ro et al. 2019). The amount of observed precipitation can be decreased if wind speed is over 9 m/s (Milewska et al. 2019). The Pluvio is typically more expensive than the bucket-type rain gauge, and its management is more inconvenient because of the periodical emptying the bucket. Despite these disadvantages, the Pluvio gives the quantitatively better observed data of precipitation, especially for the hydrometeorological use. Considering that there are few Pluvio units currently installed in Korea, expectations are high for the establishment of a new observation network and data utilization that can replace TBGs in the future. In addition, improved rainfall information is critical for establishing a warning system for disasters such as torrential rains, typhoons, and flash floods.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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