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Evaluation of precipitation measurements obtained from different types of rain gauges

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Abstract

The results of parallel measurements of precipitation sums at the Polish Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI), made by 4 types of automatic rain gauges (SEBA, A-STER, MET ONE and MPS) and a manual Hellmann rain gauge, indicate significant differences between instruments. On average, the A-STER, MET ONE, MPS and SEBA rain gauges understate the precipitation sums relative to the Hellmann rain gauge annually by approximately 14 %; 13 %; 8 % and 5 %, respectively. The distribution of monthly and seasonal deviations of daily precipitation sums in automatic rain gauges relative to the Hellmann rain gauge indicates that regardless of the type of rain gauge, the largest negative deviations occur in the winter months, with a maximum of 20–25 %, and in MET ONE rain gauges even up to 30 %. The most common errors in automatic rain gauges are small errors (0.1 < daily sum ≤ 1.0 mm). On average per year, they range from 45 % of days in SEBA rain gauges to 52 %–54 % of days in other types of rain gauges. Large errors (1.0 < daily total ≤ 5.0 mm) are most common in A-STER, MET ONE, MPS and SEBA rain gauges. On average per year, they are approximately 16 %, 16 %, 7 % and 6 % of all days, respectively. The analysis of the deviations of the daily precipitation sums from automatic rain gauges relative to the Hellmann rain gauge indicates a clear asymmetry in their distribution. Negative deviations dominate over positive ones. The absence of differences occurs most often in SEBA rain gauges and amounts on average to 23 %. It occurs least frequently, at an average of 10 %, in MET ONE rain gauges. SEBA rain gauges are characterized by the smallest mean deviation value of the daily precipitation sums: −0.13 mm. In the MPS weighing rain gauges it is −0.26 mm. The largest mean deviations occur in the A-STER and MET ONE rain gauges, where they are respectively: −0.52 mm and −0.48 mm.

Keywords: precipitation, Hellmann gauge, tipping-bucket gauge, weighing gauge, differences in precipitation measurements

1 Introduction

Providing high-quality automatic measurements of meteorological elements is one of the priorities of modern meteorology. Therefore, any automatic instruments and measurement systems operating in variable external conditions should, without the need for constant human supervision, provide reliable data (Różdżyński, 2004; Nash, 2006; Liu et al., 2013; Rashid et al., 2015; Valík et al., 2020).

Accurate precipitation measurement is very important, among others, for hydro-climatological research, agriculture, forecasting applications and flood hazard prediction. However, precipitation measurement is much more complicated than usually assumed, despite the fact that different rain gauges have been used for many decades (Strangeways, 2010; Yoo et al., 2015). The amount and intensity of precipitation measured with different instruments shows a number of discrepancies in the results obtained (Lednický and Priadka, 1984; Sevruk, 1986, 1996; Chandrasekar and Gori, 1991; Nystuen et al., 1996; Frankhauser, 1998; Filipiak, 2000–2001; Perini and Beltrano, 2003; Tokay et al., 2003; Upton and Rahimi, 2003; Kuśmierek–Tomaszewska, 2009; Knežínková et al., 2010; Wójcik et al., 2010; Kotowski et al., 2011; Liu et al., 2013; Matuszko and Nowak, 2017; Padrón et al., 2020; Valík et al., 2020). All rain gauges are used not only to measure the amount of precipitation but also to calibrate other measuring instruments, e.g., meteorological radars. Therefore, it is very important that they are as accurate and reliable as possible (Collier, 1986; Upton and Rahimi, 2003; Erdin, 2009; Strangeways, 2010).

In order to assess the performance of different types of measuring instruments, the World Meteorological Organization (WMO) has organized a series of international comparisons of the efficiency of liquid precipitation measurement in an area (e.g., Goodison et al., 1998; Sevruk et al., 2009; Lanza and Vuerich, 2009) and in the laboratory (Lanza et al., 2005; Lanza and Stagi, 2009; Colli et al., 2014; Pollock et al., 2018). These comparisons have highlighted the need to properly calibrate, and correct measurements made with tipping bucket rain gauges and to cope with filtering errors in electronic weighing rain gauges (Vuerich et al., 2009; Savina et al., 2011).

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According to the WMO, comparisons between different types of rain gauges and precipitation measurement techniques should continue as the main tool for developing continuously better rain gauges (Sevruk et al., 2009). Intercomparisons of different gauge types and measurement techniques continue to be the main tool in precipitation measurement investigations and development of better gauges (Sevruk et al., 2009). Conducting experimental comparative studies should be carried out whenever and wherever possible, which will help to select the best type of rain gauge in the measurement network used for current operational purposes as well as for long-term use (Tokay et al., 2010; Acquaotta et al., 2016).

In the Polish Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI), which is the owner of the largest measurement database in Poland in the field of meteorology and hydrology, there is a shortage of publications on the comparison of the results of simultaneous precipitation measurements by automatic rain gauges with previously standard instruments (Hellmann rain gauge, which until the end of 2013 was the primary method in measuring the daily precipitation sum). Apart from earlier publications by Filipiak (2000–2001), Lorenc (2006), Wójcik et al. (2010) or Kotowski et al. (2011) there is practically no further papers addressing the problem of assessing the accuracy and causes of errors of different types of rain gauges at the IMWM-NRI. Moreover, there are no papers documenting this problem well in the long term throughout Poland. The work of Kotowski et al. (2011) is based only on the warm half of 2009 from the Legnica station. In turn, the work of Wójcik et al. (2010) does not include any stations from south-western Poland and the data series are of different length. On the other hand, the paper by Lorenc (2006) concerns parallel measurements only for three stations (Łeba, Płock, Katowice) for part of 2003. The cited publications are based on the Hellmann rain gauge, pluviographs, and automatic instruments that use only the functioning SEBA rain gauge.

However, in recent years, the number of automatic rain gauges in the network of IMWM-NRI stations has increased, and new types of automatic rain gauges have also appeared (A-STER and MET ONE tipping bucket rain gauges and MPS weighing gauges). Therefore, undertaking further comparative studies has become a necessity. The introduction of a new instrument to the measurement network makes it necessary to assess the accuracy of measurements made with this instrument relative to the instruments used previously. Unfortunately, one of the new automatic rain gauges (MPS weighing rain gauge) purchased and installed in the network of IMWM-NRI stations in the years 2015–2016 within the framework of the MeteoRisk project still does not have published results concerning the assessment of measurement accuracy. Objections were also raised to the manufacturer regarding their proper operation (Pismo nr PP-510-34/PS-155/NP-960/2016). The above facts are important because in the case of measuring precipitation, breaking the homogeneity of the precipitation series is very likely and may result, for example, from the design of the instrument, the way the measurement was performed, and meteorological conditions prevailing at the time of precipitation as well as afterwards (Filipiak, 2000–2001; Valík et al., 2020).

In the network of stations of various national services, the measurements obtained from an installed rain gauge must be considered as reliable, unless serious systematic measurement errors are found. Then, the quality of both operational and research data without verification, is insufficient (Ciach and Krajewski, 1999; Steiner et al., 1999; Ciach, 2003). A natural and relatively inexpensive solution is to build a measuring network equipped with two or more rain gauges at a single station (Ciach and Krajewski, 1999; Ciach, 2003; Acquaotta et al., 2016). It also improves early detection of a failure of a given instrument or a partial deterioration of measurement quality by one of the instruments, which might have gone unnoticed if the other instrument was not present. Such solution was also applied in the network of measurement stations of IMWM-NRI.

In accordance with Circular Letter No. 11/2016 of the Director of IMWM-NRI dated 22 September 2016, data from automatic sensors constitute basic values for operational and historical purposes, while values read by observers should be treated as backup and control (Pismo Okólne nr 11/2016). The other internal document from IMWM-NRI informs that the standard rain gauge from which the data should be used for operational purposes is the tipping bucket rain gauge. On the other hand, the data from the Hellmann rain gauge constitute the material for the verification of measurements made with the use of automatic instruments (Pismo nr PP-510-34/PS-155/NP-960/2016). In turn, the Letter of the Deputy Director for PSHM and MOLC from 15 February 2017 (Pismo nr PP-510-11/PS-37/NP-200/2017), informs that in the winter season, measurements of the precipitation height conducted by observers at meteorological stations using Hellmann rain gauges should be treated as primary values and recorded by tipping bucket rain gauges as backup data. On the other hand, the recent changes (from 1 January 2021) in the operating mode in the network of meteorological stations of IMWM-NRI mean that the 6-hour precipitation sums for SYNOP messages come from an automatic, tipping bucket rain gauge. Data from the Hellmann rain gauge will be entered into the message only in the event of an automatic rain gauge failure (missing data). This rule applies to the entire year (Pismo nr BSHM-510-16/CS-277/2020). The above-mentioned documents confirm the authors' belief that there are still doubts regarding the choice of the standard rain gauge, hence the necessity to conduct comparative research.

Moreover, significant differences in indications between the Hellmann rain gauge and the automatic tipping bucket rain gauge have been identified so far in Poland (including at IMWM-NRI) and abroad, and the introduction of weighing rain gauges at IMWM-NRI synoptic stations, which so far have not been approved for operation in operational mode (Pismo nr PP-510-55/PS-230/NP-1268/2016), indicate the need to undertake the proposed research. The undertaken topic is of particular importance in connection with the planned installation of new automatic rain gauges in the network of IMWM-NRI stations starting in 2021 and the withdrawal of some of the currently operating ones. Electronic rain gauges are installed in a rapidly expanding network of automatic meteorological stations and are often advertised as very precise devices that do not require constant supervision. However, practical experiences with the use of these instruments contradict the full validity of the above statement (Frankhauser, 1997, 1998; Bergmann et al., 2001; Filipiak, 2000–2001; Licznar et al., 2005; Knežínková et al., 2010; Wójcik et al., 2010; Valík et al., 2020).

The primary objective of this paper is to evaluate precipitation measurements obtained from different types of rain gauges in south-western Poland. The main objective was achieved through the following sub-objectives:

Comparison of the amount of precipitation obtained from different types of automatic rain gauges with the reference Hellmann rain gauge,

Indication of the most accurate types of rain gauges suitable for common use in the network of IMWM-NRI stations.

2 Source data, methods and instruments

The measurement data came from the base resources of the Polish IMWM-NRI. Data from a manual Hellmann rain gauge and four automatic (digital, electronic), heated rain gauges were used:

- Tipping bucket RG-50 H (SEBA), German production,
- Tipping bucket TPG-037-H24 (A-STER), Polish production,
- Tipping bucket 60030 H (MET ONE), American production,
- Weighing TRWS 205 (MPS), Slovak production (Fig. 1).

Rain gauges represented three basic groups of devices for measuring precipitation, i.e., manual, tipping bucket (tipping) and weighing (WMO, 2008).

Data analysis was performed for the hydrological years 2017–2019 (1 November 2016–31 October 2019), mainly for the annual mean values (XI–X) and for selected average characteristics from the warm half-year (V–X), cool half-year (XI–IV), quarterly seasons (winter: XII–II, spring: III–V, summer: VI–VIII, autumn: IX–XI) and for individual months. Hence, the work fulfills the requirement of the World Meteorological Organization that the results from new measuring devices be verified on the basis of classic instruments for a minimum of one year (WMO, 2008).

The research area covered south-west Poland with an area of approximately 50,000 km^2. The results of measurements from rain gauges at 22 stations of different rank (synoptic, climatological and rainfall) located at an altitude of 90 to 855 m a.s.l. in various geographic regions were compared (Table 1, Fig. 2). The synoptic stations at IMWM-PIB are equipped with a Hellmann rain gauge, a SEBA tipping bucket rain gauge and an MPS weighing rain gauge. On the other hand, climatological and rainfall stations measure precipitation with the Hellmann rain gauge and the A-STER or MET ONE tipping bucket rain gauge (Table 1, Fig. 2). The selected stations were characterized by an uninterrupted sequence of parallel measurements made with different rain gauges, constant observer supervision and representativeness for the environment in accordance with the requirements for meteorological stations (Różdżyński et al., 2014). The rain gauges operating in the stations were not more than 5 m apart. Moreover, it was assumed that each type of automatic rain gauge will represent a similar number of stations (7 or 6), including those with a lowland and mountain location. The average height of SEBA, A-STER, MET ONE and MPS rain gauges at the analyzed stations is, respectively: 296, 275 and 198 m a.s.l. The highest stations: Jakuszyce (855 m a.s.l.) and Kamienica (682 m a.s.l.), were excluded from the average analyzes for the MET ONE rain gauge, as they significantly exceeded the average height a.s.l., which made comparability of results difficult (Table 1).

It should be noted that the MPS rain gauges are maintenance-free. They are only subject to periodic checks, especially in terms of fluid content, which prevents the water coming from the atmosphere from freezing. A-STER and MET ONE rain gauges are repaired, cleaned, and washed by the service in the event of failure, lack of data, or clogging. On the other hand, SEBA rain gauges operating in synoptic stations are, like Hellmann's rain gauges, under constant observer supervision.

Data from automatic rain gauges were recorded every 10 minutes in the system: "Amount of precipitation/lack of precipitation" or in a cumulative way. It should be noted that the first data recording system was characterized by a relatively large number of measurement interruptions (SEBA and MPS rain gauges at all stations where they were installed and A-STER at Tarnów Śląski and Szklarska Poręba stations). On the other hand, the second system (all MET ONE and A-STER rain gauges in other stations, except Tarnow Śląski and Szklarska Poręba) generated them very rarely (Table 2).

In this paper, all data analyzes covered only those days when the daily sum of precipitation in the Hellmann rain gauge was at least 0.1 mm – the so-called day with precipitation (Niedźwiedź et al., 2003) and registration with an automatic rain gauge did not contain any interruptions (Table 2). According to the WMO recommendation, the measurement of the daily precip-

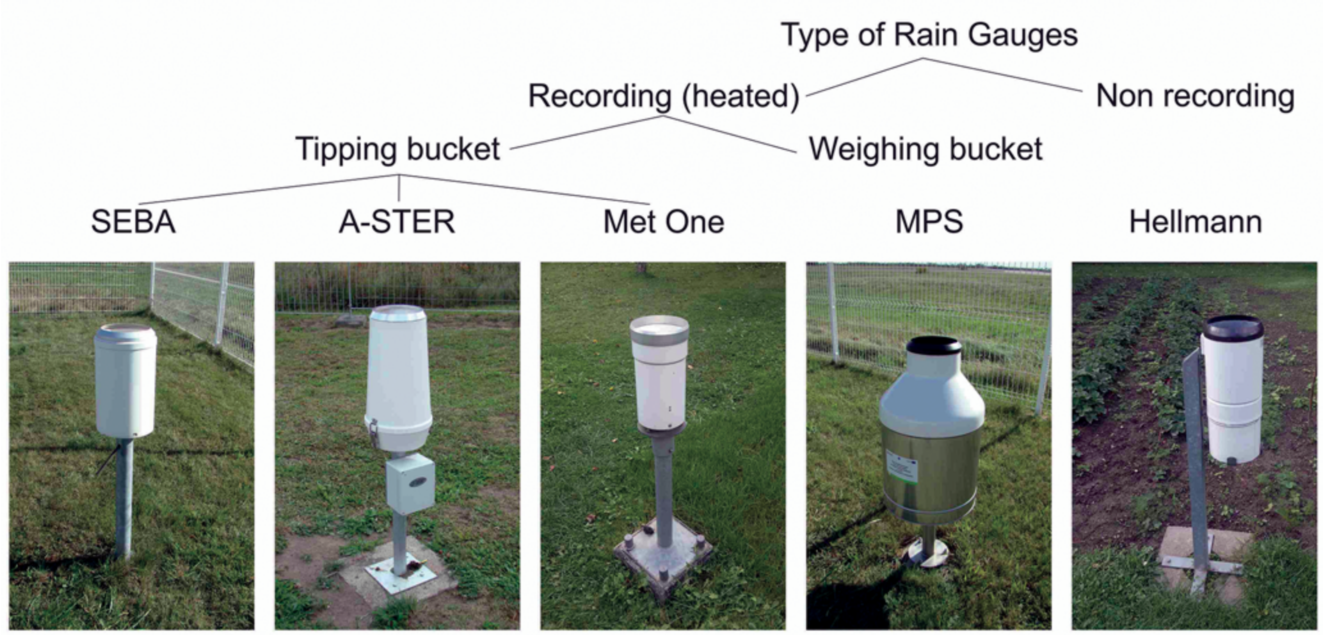

Figure 1: Rain gauges used at the Institute of Meteorology and Water Management National Research Institute (Photos by K. Strug, own work).

Table 1: Analyzed stations and their operating rain gauges.

Station	Altitude [m a.s.l.]	Physico-geographical regions of Poland according to Solon et al. (2018)	Year of installation rain gauges				
			Recording (heated)				Non recording
			Tipping bucket			Weighing bucket	Hellmann
			SEBA	A-STER	MET ONE	MPS	
Leszno[1]	90	Southern Wielkopolska Lowlands	1999			2015	1957
Żagań[3]	96	Silesian-Lusatian Lowlands		2005			1946
Wrocław[1]	120	Silesian Lowlands	1999			2015	1945
Legnica[1]	122	Silesian-Lusatian Lowlands	1999			2015	1945
Bierutów[3]	141	Silesian Lowlands			2006		1947
Borów[3]	145	Silesian Lowlands			2005		1947
Polkowice Dolne[2]	160	Silesian-Lusatian Lowlands		2009			1971
Opole[1]	163	Silesian Lowlands	1999			2016	1952
Zielona Góra[1]	192	Zielona Góra Hills	1999			2016	1945
Otmuchów[2]	212	Sudeten Foothills		2009			1949
Twardocice[3]	252	Western Sudetes Foothills			2005		1949
Bierna[3]	267	Western Sudetes Foothills			2006		1948
Tarnów Śląski[2]	296	Sudeten Foothills		2016			1974
Bolków[3]	310	Western Sudetes Foothills			2005		1949
Jelenia Góra[1]	342	Western Sudetes	1999			2015	1945
Jarnołtówek[3]	346	Eastern Sudetes			2005		1945
Kłodzko[1]	356	Central Sudetes	1999			2016	1945
Długopole-Zdrój[2]	364	Central Sudetes		2015			1961
Kamienna Góra[3]	462	Central Sudetes			2006		1946
Szklarska Poręba[2]	648	Western Sudetes		2009			1948
Kamienica[3]	682	Eastern Sudetes			2005		1972
Jakuszyce[2]	855	Western Sudetes			2005		1976

Explanations: [1] – synoptic station, [2] – climatological station, [3] – rainfall station.

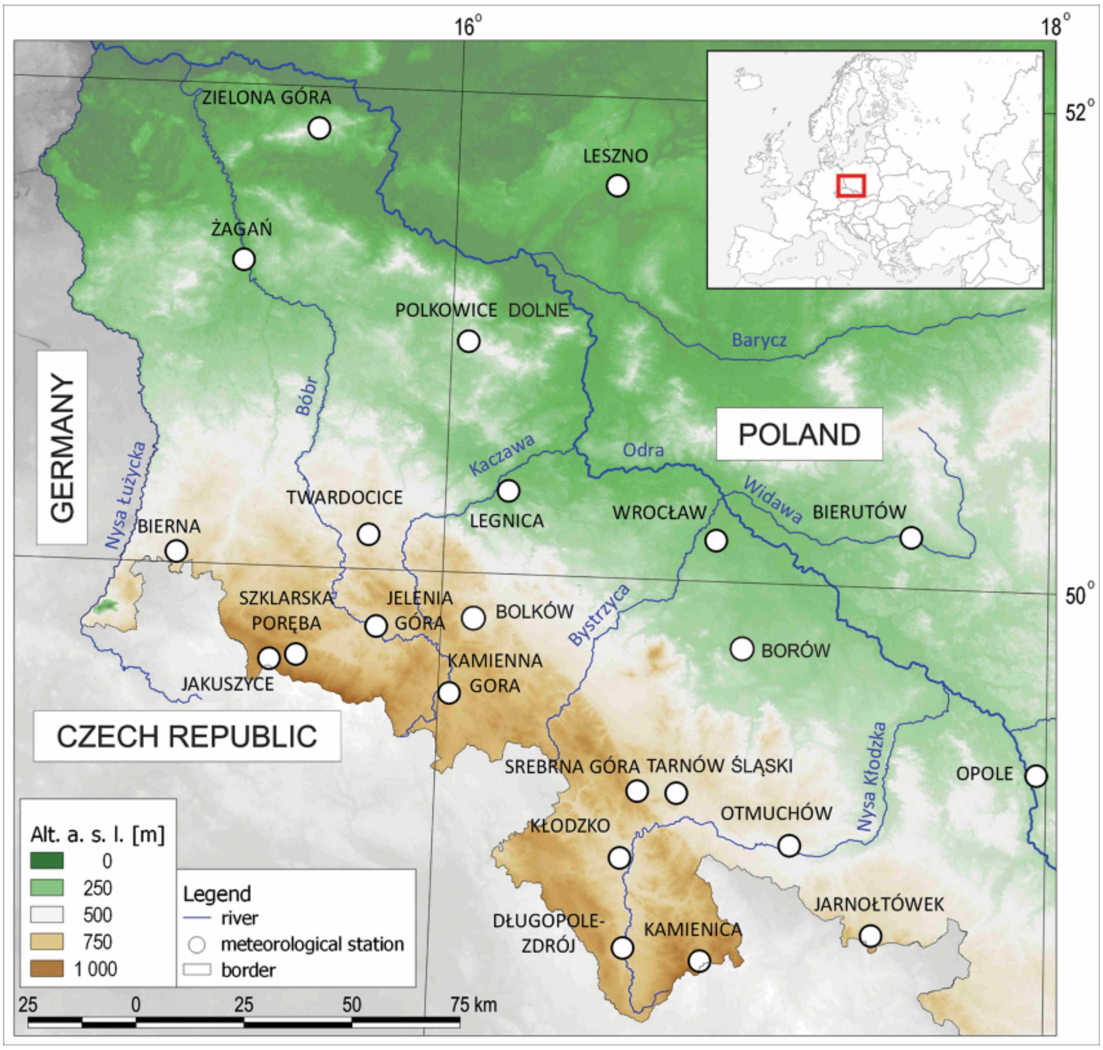

Figure 2: Location of meteorological stations analyzed in this paper against the background of the research area (Krasowski, W., Strug K. – own work).

itation sum in the Hellmann rain gauge is performed at 06:00 UTC and covers the preceding 24-hour period – the so-called precipitation day. After measuring the amount of precipitation, its result is recorded under the date of the preceding day with an accuracy of 0.1 mm (Różdżyński et al., 2014).

This paper primarily compares the extent of differences in the number of days with precipitation and in the sums of daily precipitation between individual automatic rain gauges and the Hellmann rain gauge. A negative difference value means that the daily amount of precipitation obtained with the automatic rain gauge is lower than that obtained with the Hellmann rain gauge. On the other hand, a positive value means a higher precipitation height measured with an automatic rain gauge.

Using the *Student's t-test*, the statistical significance of the determined differences in the sums of daily precipitation between the automatic rain gauges and the Hellmann rain gauge at the analyzed stations was checked at a significance level of 0.01.

The mean sums of monthly, semi-annual, and annual precipitation were also compared. It should be noted that the analyzed days with precipitation and precipitation sums are only a certain approximation of the reality at a given time (month, season, year), because automatic rain gauges that had days with an interruption in registration (of different genesis) were deliberately removed from the analyzed data population. Of course, there are stations with almost no interruptions in registration, but these are rare cases (Table 2).

The reasons for the differences in the results of parallel precipitation measurements have not been investigated. They have only been specified hypothetically or partially quoted from the literature.

This paper uses a division into four intervals (classes) with the absolute difference in mm between the daily precipitation sum (D) measured with individual automatic rain gauges and in the Hellmann rain gauge:

1. very small or no difference of ($D \leq 0.1$ mm), indicates a practically identical measurement result by the automatic and manual rain gauge; the limit of this range is associated with the accuracy of the graduated cylinder reading of 0.1 mm;

Table 2: The total number of days in the analyzed period (N), the analyzed number of days with a precipitation of at least 0.1 mm in the Hellmann rain gauge (NA) and the number of days with no record or an interruption in recording the daily precipitation sums (NN) in individual rain gauges at the analyzed stations.

Station	N	NA	NN			
			SEBA	A-STER	MET ONE	MPS
Leszno*	365	135	11	—	—	37
Żagań	1095	467	—	0	—	—
Wrocław	1095	386	59	—	—	57
Legnica	1095	324	92	—	—	91
Bierutów	1095	497	—	—	0	—
Borów	1095	472	—	—	3	—
Polkowice Dolne	1095	457	—	1	—	—
Opole	1095	380	53	—	—	53
Zielona Góra	1095	418	46	—	—	46
Otmuchów	1095	451	—	3	—	—
Twardocice	1095	535	—	—	1	—
Bierna	1095	512	—	—	2	—
Tarnów Śląski**	1053	437	—	45	—	—
Bolków	1095	498	—	—	1	—
Jelenia Góra***	730	302	18	—	—	58
Jarnołtówek	1095	475	—	—	0	—
Kłodzko	1095	433	54	—	—	55
Długopole—Zdrój	1095	528	—	0	—	—
Kamienna Góra	1095	520	—	—	2	—
Szklarska Poręa	1095	594	—	16	—	—
Kamienica	1095	536	—	—	0	—
Jakuszyce	1095	622	—	—	7	—

Explanations: * – data only from the hydrological year 2017; ** – data from 13 December 2016; *** – data from the 2017–2018 hydrological years.

2. small ($0.1 < D \leq 1.0$ mm), indicates a slight difference in the measurement between the automatic and manual rain gauge; this range corresponds to the division into the number of days with precipitation with a threshold value used in climatology, e.g., ≥ 0.1 mm; ≥ 1.0 mm;
3. large ($1.0 < D \leq 5.0$ mm), indicates a large difference in measurement between the automatic and manual rain gauge; this range is half of the division into the number of days with threshold precipitation ≥ 10 mm used in climatology; an explanation of this criterion is provided in Section 4;
4. very large ($D > 5.0$ mm), indicates a very large difference in measurement between the automatic and manual rain gauge; in this paper, applying the criterion of ≥ 10 mm would be difficult to present, as the average number of days with the absolute difference in total precipitation between rain gauges, meeting this criterion, was below 1.0 %.

In this paper, the Hellmann rain gauge was considered to be the reference one relative to automatic rain gauges. The basis for this assumption, apart from a long series of measurements, were the guidelines contained in the applicable instruction for meteorological stations of the IMWM-NRI (Różdżyński et al., 2014) regarding the construction, maintenance, operation of the rain gauge and simple measurement methodology. Among them, constant contact of the observer with the device should be emphasized (cleaning and checking for leakage of the precipitation receiver, using a snow insert, measuring the amount of precipitation, depending on the rank of the station, at the main observation hours – 00, 06, 12, 18 or at 06 UTC). The inlet area of the Hellmann rain gauge, like all automatic rain gauges, is 200 cm^2 and is 100 cm a.g.l. (stations up to 500 m a.s.l.) or 150 cm a.g.l. (stations located above 500 m a.s.l.).

The Hellmann manual rain gauge, consisting of a receiver, base, and container, is used to measure the amount of precipitation in liquid or solid form (Fig. 1). The sum of precipitation is measured using a graduated cylinder.

The cylinder is adapted to the standard rain gauge inlet area of 200 cm^2 and is marked in mm of the precipitation height in the range from 0.1 to 10.0. After pouring the accumulated water from the container of the rain gauge to the graduated cylinder, a reading is made with an accuracy of 0.1 mm. The Hellmann rain gauge has been used at the meteorological stations of the IMWM-NRI as the standard one since 1945 (Table 1).

The principle of operation of the weighing rain gauge is similar to that of the Hellmann rain gauge, with the difference that the container in which the precipitation is collected is located on the scale. The scale is integrated

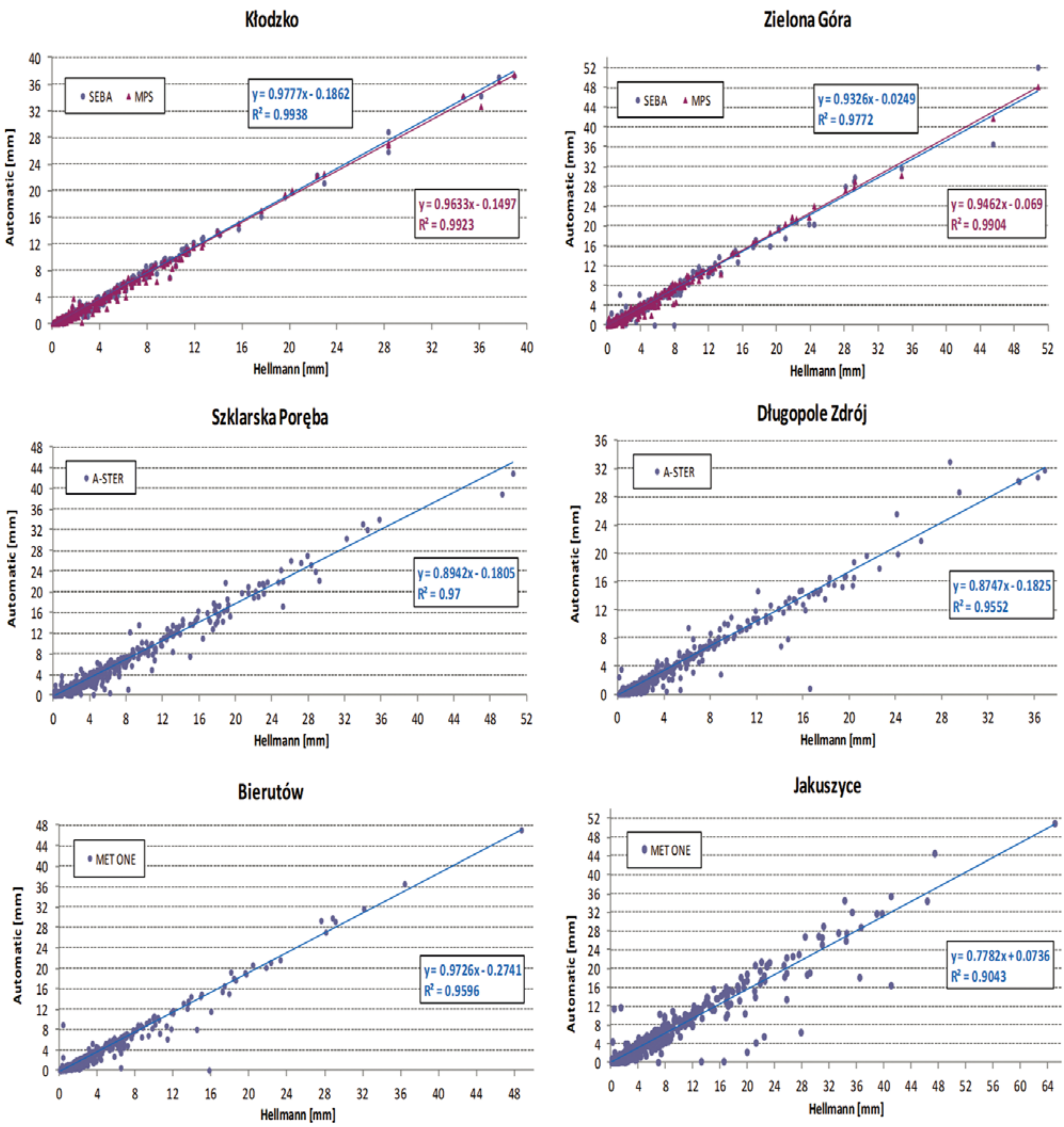

Figure 3: The relationship of daily precipitation sums between the Hellmann rain gauge and different types of automatic rain gauges (SEBA, MPS, A-STER, MET ONE) at selected stations in the hydrological years 2017–2019.

with a recorder that records the increase in the precipitation volume over time, which is automatically converted to its height.

The tipping bucket rain gauge, in turn, consists of two buckets (containers) of preset volume, supported in a pivot point. During precipitation, one of the buckets is filled with water. After it is completely filled (water volume corresponding to 0.1 mm of precipitation), it becomes overbalanced and the device tilts. One of the buckets is then emptied and the other begins to fill. The recorder counts the number of tilts of the device and on this basis the sum of precipitation over time is determined. Tipping bucket rain gauges generally decrease in measurement quality due to systematic nonlinear errors and significant measurement errors, heavily dependent on precipitation. Especially at higher intensities, errors can be 20 % for some types of tipping bucket rain gauges (Lanza et al., 2006).

Digital rain gauges such as tipping bucket rain gauges, due to their relatively low installation and operating costs, are the standard rain gauges of the systems known as RTC ("Real Time Control"), i.e. the con-

Table 3: Selected operating parameters of the analyzed automatic rain gauges.

Parameter	Tipping bucket			Weighing bucket
	RG-50 (SEBA)	TPG-037-H24 (A-STER)	60030H (MET ONE)	TRwS 205 (MPS)
Precision	2–5 % (depends of the sum of precipitation)	0.1–0.2 mm (for precipitation ≤ 10 mm) ≤ 2 % (for precipitation > 10 mm)	0.1–0.2 mm (for precipitation ≤ 10 mm) ≤ 2 % (for precipitation > 10 mm)	0.1– (for precipitation ≤ 5 mm) ≤ 2 % (for precipitation > 5 mm)
Temperature range [°C]	−20 to +65	−30 to +60	−30 to +60	−40 to +70

trol of surface runoff in the catchment area in real time. They are mainly used to monitor precipitation intensity and are usually combined with short-term hydrological forecasts (Licznar et al., 2005). According to WMO research results, tipping bucket rain gauges account for about half of all types of rain gauges used and are manufactured by over 40 companies (Sevruk, 2002). Over 50 types of rain gauges are used in WMO member countries (Sevruk and Klemm, 1989). These instruments differ in size, shape, material, installation height and the windscreen used. Their measuring accuracy varies greatly. For example, the measurement efficiency of some rain gauges can range from 20 % to 70 % at a wind speed of 6 m/s (Goodison et al., 1998; Yang et al., 2001). Selected operating parameters of the analyzed automatic rain gauges are presented in the table below (Table 3).

3 Results and discussion

The two sets of daily precipitation sums were compared and described with linear regression equations for individual stations. The obtained correlations are strong and directly proportional. The coefficients of determination R^2 range from 0.90 in Jakuszyce to 0.99 in Kłodzko, Wrocław and Legnica. Examples of their compounds are presented below 3). Strong correlations provided the basis for further analyzes in accordance with the methodology described in Chapter 2.

When comparing the results of measurements from rain gauges operating in the IMWM-PIB network with rain gauges used in other countries, one should be aware that only a few can be directly compared with each other. This is due to the multitude of instruments used to measure precipitation, as mentioned in Chapter 2 (Goodison et al., 1998; Ciach, 2003; Lanza and Vuerich, 2009; Sevruk et al., 2009; Duchon and Biddle, 2010; Savina et al., 2012; Colli et al., 2014; Muñoz et al., 2016; Santana et al., 2018; Padron et al., 2020; Tabada and Loretero, 2020). This problem was highlighted in the latest publication by Valík et al. (2020).

In the hydrological years 2017–2019 in the studied area, an average of 149 days a year with daily precipitation ≥ 0.1 mm was recorded in the Hellmann rain gauge, of which on average 11 of them were omitted from the analysis due to the existing interruptions in registration from the automatic rain gauge. In the studied area, the average number of days in a year with precipitation with other threshold values, i.e.: ≥ 1.0 and ≥ 5.0 mm was respectively: 91 and 33 days. In all automatic rain gauges, the average number of days with precipitation in each of the threshold values was about 10 % lower compared to the Hellmann rain gauge (Fig. 4). This result is almost identical to that obtained in Italian studies, where the average annual number of days with precipitation recorded by PMB2 automatic rain gauges compared to the manual UM 8100, out of 55 stations, is 9 % lower (Acquaotta et al., 2016). The smallest difference in the average number of days with precipitation compared to the Hellmann rain gauge in almost each of the individual threshold values was recorded for the SEBA rain gauge while the largest differences were indicated by the MET ONE and A-STER rain gauges (Fig. 4).

On the other hand, the frequency of days with an absolute difference between the daily sum of precipitation (D) measured in automatic and Hellmann rain gauges indicates that the most common errors in automatic rain gauges (except for the SEBA type) are small errors (0.1 < D≤ 1.0 mm). In all automatic rain gauges, this error is on average 51 %. On the other hand, very small or no errors (D ≤ 0.1 mm) are in the second place (except for the SEBA type) in terms of the frequency of occurrence. In all rain gauges they constitute on average 36 % (Fig. 5). The results of simultaneous measurements with the METRA 886 manual rain gauge (Hellmann's equivalent) and the MR3H automatic tipping bucket rain gauge for 26 stations of the Czech Hydrological and Meteorological Institute (CHMI) from 1999–2007 also showed the highest relative frequency of daily differences in the range from −0.1 to 0.1 mm. Moreover, they showed a higher frequency of positive differences, indicating an underestimation of the values measured with the MR3H rain gauge (Knežínková et al., 2010). The frequency of very small errors in rain gauges in south-western Poland is also much less satisfactory, compared, for example, to the latest results obtained in the CHMI from 2000–2019, where their frequency in individual seasons ranged from 50 to 60 % (Valík et al., 2020). On the other hand, large (1.0 < D≤5.0 mm) and very large (D > 5.0 mm) errors appear most often in rain gauges in the following order: A-STER, MET ONE, MPS and SEBA (Fig. 5).

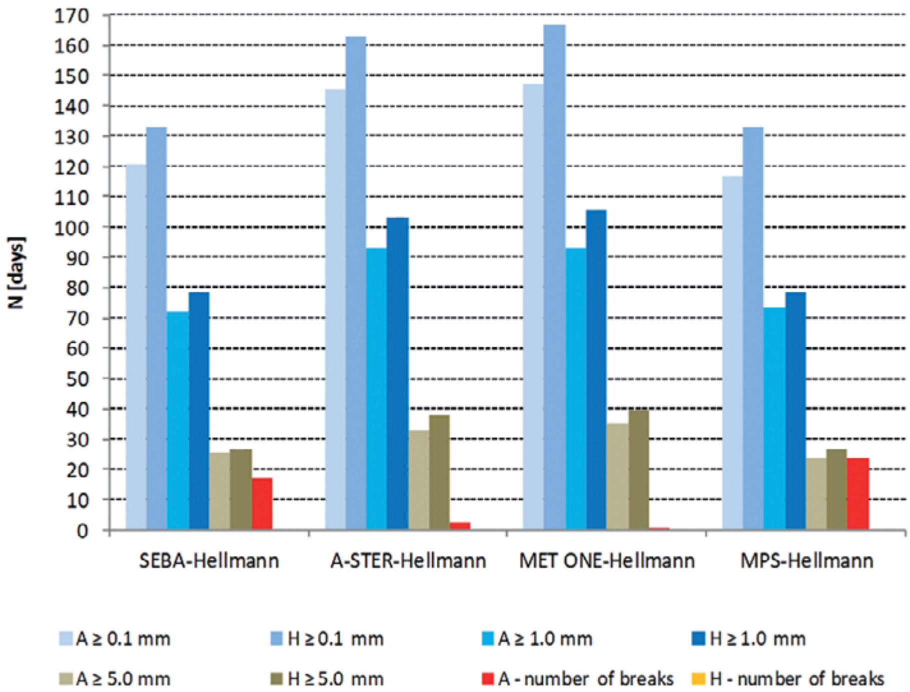

Figure 4: Average number of days with precipitation (N) with threshold values (≥ 0.1; ≥ 1.0; ≥ 5.0 mm) in automatic rain gauges (A) and Hellmann rain gauge (H) in the 2017–2019 hydrological years.

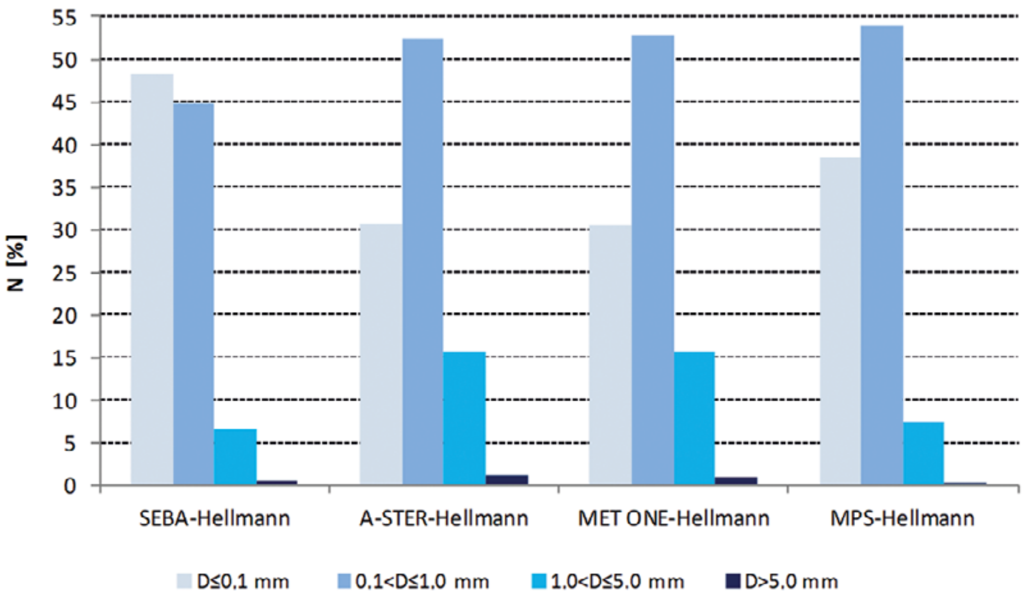

Figure 5: The frequency of days (N) with an absolute difference (D) in the daily sum of precipitation in precipitation intervals in the selected type of automatic rain gauge and in the Hellmann rain gauge in the hydrological years 2017–2019.

The frequency of days with an absolute difference between the daily sum of precipitation measured in automatic rain gauges and Hellmann rain gauges in individual stations confirms the occurrence of large (usually several %) and very large errors (approx. 1 %) in stations with MET ONE and A-STER rain gauges. At the highest stations a.s.l. with the MET ONE rain gauge (Jakuszyce and Kamienica), the average annual number of days with an absolute difference with large errors amounted to approx. 32 % of the total. On the other hand, at the Bierna and Kamienna Góra stations (MET ONE rain gauges) as well as Długopole Zdrój and Szklarska Poręba (A-STER rain gauges) the difference with days with large errors exceeded 20 % of the total number of days. Large and very large errors seldom occur in SEBA and MPS rain gauges (Fig. 6).

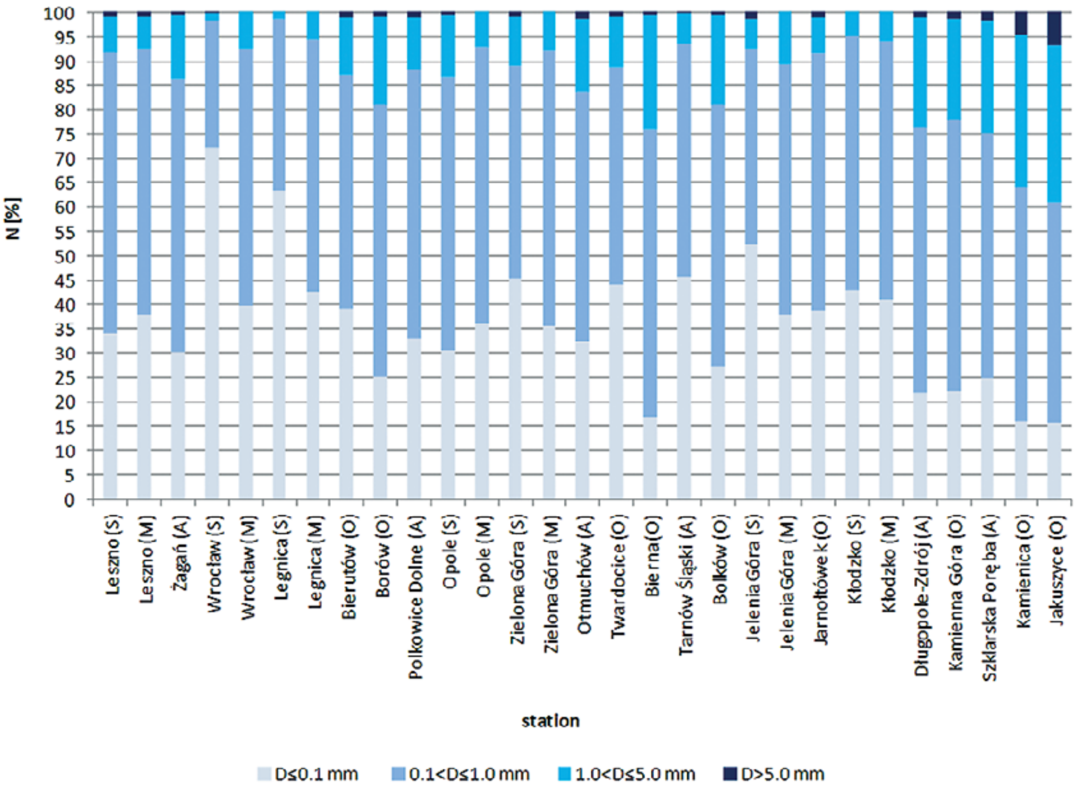

Figure 6: The frequency of days (N) with an absolute difference (D) in the daily sum of precipitation in precipitation intervals in the selected type of automatic rain gauge (S – SEBA, A – A-STER, O – MET ONE, M – MPS) and in the Hellmann rain gauge at individual stations in the hydrological years 2017–2019. Stations ranked by increasing altitude a.s.l. – see Table 1.

The analysis of the deviations of the daily precipitation sums from automatic rain gauges relative to the Hellmann rain gauge in the studied area indicates a clear asymmetry in their distribution. Negative deviations dominate, which are several times higher than the share of positive deviations. In the case of A-STER and MET ONE rain gauges, it is even 5–6 times more. On the other hand, the lack of differences (zero deviation) in the indications between the tested rain gauges occur most often in SEBA rain gauges and is on average 22.6 %. This result corresponds to that obtained from parallel CHMI measurements between the manual METRA 886 rain gauge and the MR3H and MR3H-FC automatic rain gauges (Valík et al., 2020). The rarest, on average at the level of 9.7 %, zero deviation occurs in MET ONE rain gauges (Fig. 7). Due to the fact that individual automatic rain gauges of the same type do not show the same sign of deviation with respect to the Hellmann rain gauge, it is most likely impossible to establish continuous corrections.

Thus, it can be concluded that due to a relatively large percentage of zero deviations (Fig. 7), the highest proportion of very small absolute differences and the lowest percentage of large and very large differences (Fig. 5–6) in daily precipitation sums, SEBA rain gauges are the best devices operating among automatic rain gauges.

Among the analyzed types of automatic rain gauges, the SEBA rain gauges are characterized by the smallest deviation equal to −0.13 mm. The mean deviation in the MPS weighing rain gauges is slightly lower (−0.26 mm). On the other hand, the largest mean deviations and values of standard deviation are characteristic for A-STER and MET ONE rain gauges (Fig. 8). Hence, the last two types of rain gauges are characterized by the largest errors in the registration of daily precipitation sums. A similar value of the mean daily deviation of −0.6 mm, compared to the Hellmann rain gauge, was found in the A-STER rain gauge at the research station of the Jagiellonian University in Krakow (Matuszko and Nowak, 2017).

The value of the mean deviation in the daily precipitation sum in individual stations and the different types of rain gauges installed there, which is a detailed description of Fig. 8, confirms the occurrence of the largest mean negative deviations in stations with MET ONE and A-STER rain gauges, and the smallest average in SEBA rain gauges (Fig. 9). The slight positive mean deviation in Leszno in the SEBA rain gauge may result from the fact that the data from this station cover only the hydrological year 2017 with a relatively small amount of data (Table 2). In addition, the differences found in the daily precipitation sum between the automatic rain gauges and the manual Hellmann rain gauge are statistically signifi-

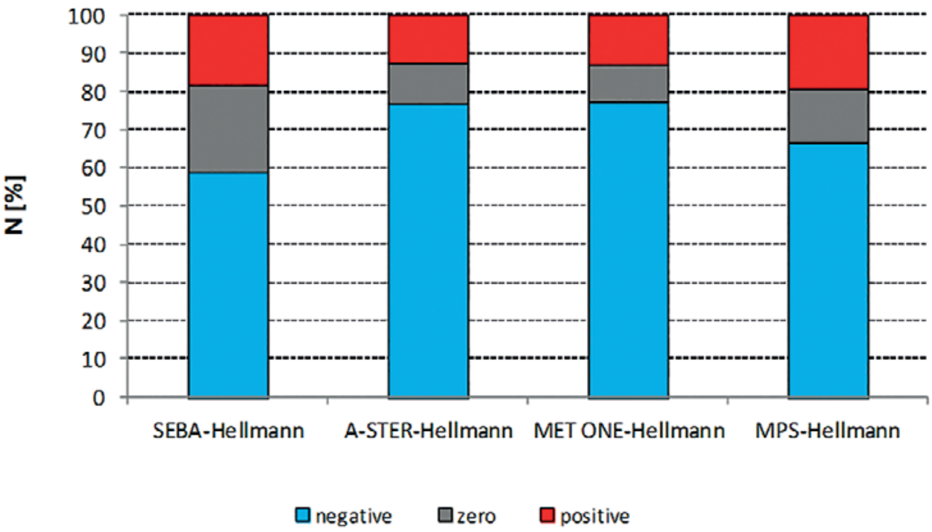

Figure 7: Average frequency of deviations of daily precipitation sums (N) from different types of automatic rain gauges relative to the Hellmann rain gauge in the hydrological years 2017–2019.

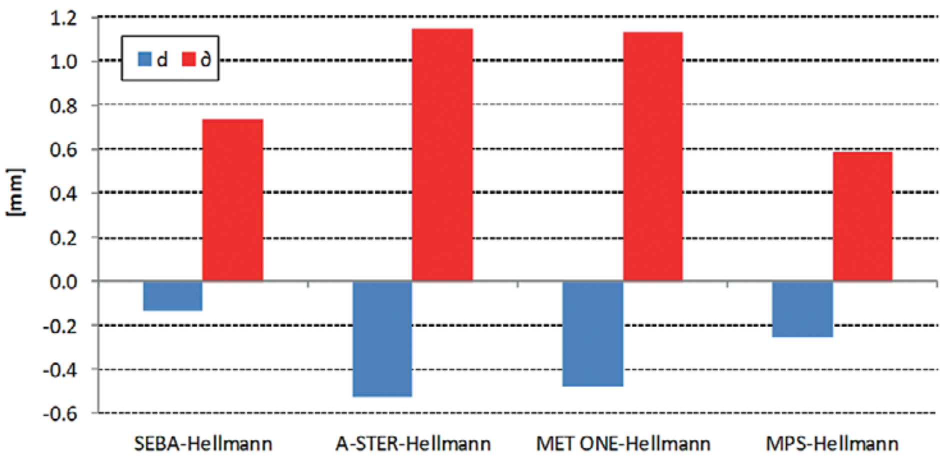

Figure 8: The value of the mean deviation (d) and the standard deviation of the deviations (ϑ) in the sums of daily precipitation [mm] from automatic rain gauges relative to the Hellmann rain gauge in the hydrological years 2017–2019.

cant at the statistical significance level of 0.01 in all analyzed stations.

It should be noted that the location of the station a.s.l. also has an impact on the size of average errors in stations with different types of rain gauges. However, the size of errors in stations located above sea level with the MET-ONE (Bierutów, Twardocice) and A-STER (Żagań, Polkowice Dolne, Otmuchów) rain gauges indicates that the errors recorded by these devices are still significant and greater than in the case of SEBA or MPS rain gauges. Similarly, comparing the MET ONE rain gauge with the A-STER rain gauge at stations with similar altitudes a.s.l. i.e., Kamienica (682 m) and Szklarska Poręba (648 m), there are greater negative mean deviations in MET ONE than in A-STER (Fig. 9).

The range of extreme deviations is significant and strongly diversified. Extreme negative deviations exceed 32 mm, while extremely positive deviations reach 11–12 mm. The amplitude of deviations in the hydrological years 2017–2019 was the smallest in the MPS rain gauges and the largest in the MET ONE rain gauges. For the vast majority of stations, regardless of the type of rain gauge (except for SEBA in Leszno and Jelenia Góra and MPS in Kłodzko), the absolute values of extreme negative deviations are greater than the extreme positive values (Fig. 10).

According to the Lorenc criterion for daily precipitation sums from the automatic rain gauge, the critical value of deviation that does not break the homogeneity of the Hellmann rain gauge data series is a height of 0.5 mm. However, the paper by Lorenc (2006) lacks justification for the allowable deviation criterion, and according to the authors, it appears to be grossly overstated. The data from 22 stations analyzed in this paper show that as many as 8 of them do not meet the quoted criterion. The value of the mean deviation usually increases with the altitude of the station a.s.l. and with its decreasing rank (synoptic, climatological, pre-

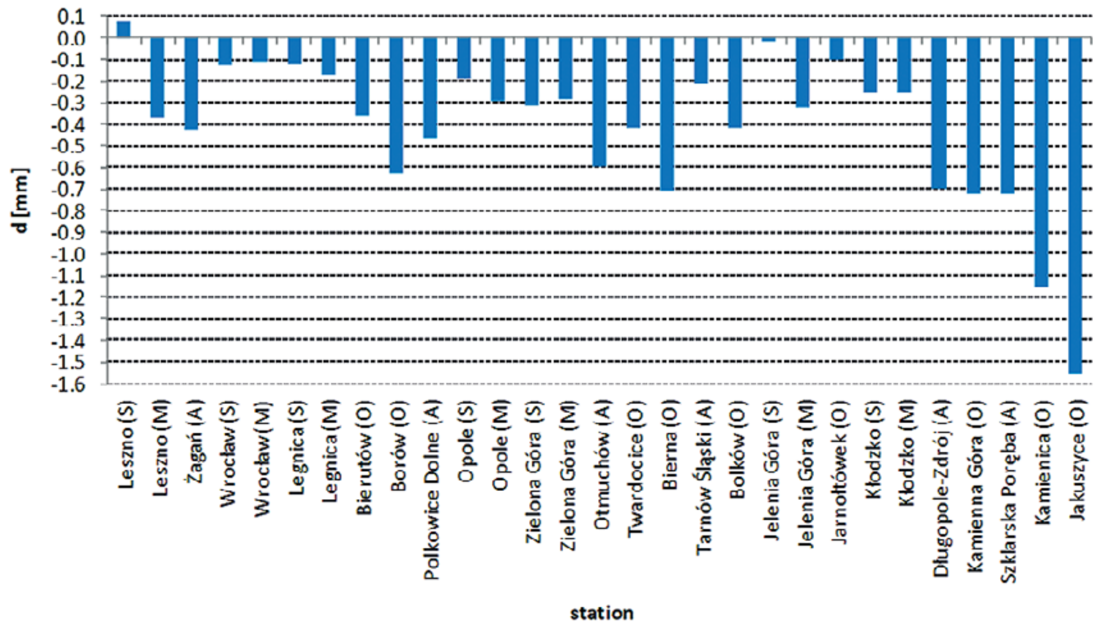

Figure 9: The size of the mean deviation in the daily sum of precipitation d (mm) between the automatic rain gauge (S – SEBA, A – A-STER, O – MET ONE, M – MPS) and the Hellmann rain gauge at the analyzed stations in the hydrological years 2017–2019. Stations ranked by increasing altitude a.s.l. – see Table 1.

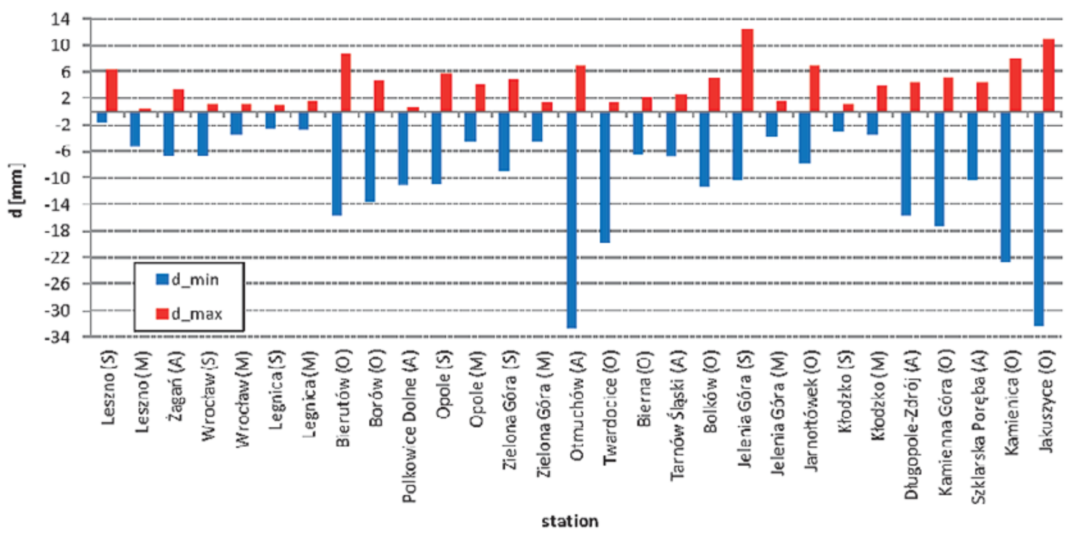

Figure 10: Extreme values of deviations in the daily sum of precipitation d (mm) between the automatic rain gauge (S – SEBA, A – A-STER, O – MET ONE, M – MPS) and the Hellmann rain gauge at the analyzed stations in the hydrological years 2017–

cipitation) and thus with the limited influence of the human observer (Fig. 9, Table 1). Wang et al. (2008) or Sypka (2019), in their considerations on the causes of measurement errors, point out, among other things, the need for frequent human inspection of the tipping bucket rain gauge.

On the other hand, the distribution of monthly and seasonal deviations of daily precipitation sums in automatic rain gauges in relation to the Hellmann rain gauge indicates that regardless of the type of rain gauge, the largest negative deviations occur in the colder season (XI–IV), with a maximum of 20–25 %, and in MET ONE rain gauges even up 30 %, occurring in January. The smallest occurrences are in the warm season and range from a few percent in SEBA or MPS rain gauges to 10–15 % in MET ONE or A-STER (Fig. 11). Compared to differences in monthly averages from 2000–2019, which reached a maximum of 15 % in parallel measurements of precipitation sums at CHMI (Valík et al., 2020), the result obtained is unsatisfactory. Similarly, the high correlation and lack of consistent differences between the tipping bucket rain gauge and

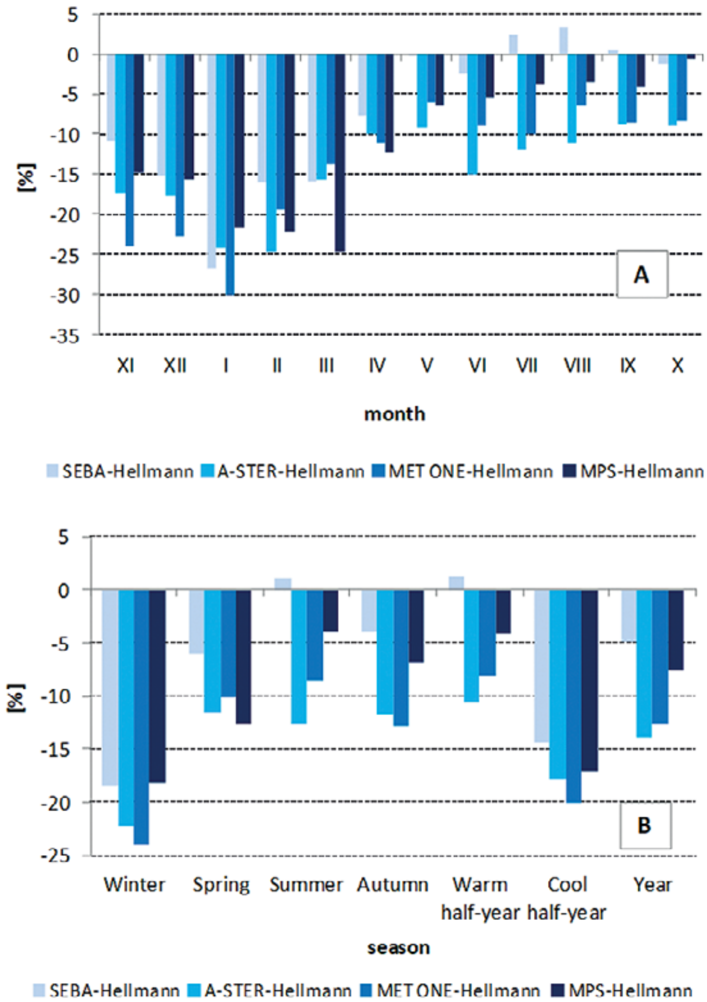

Figure 11: Mean value of deviations [%] of daily precipitation sums from automatic rain gauges relative to Hellmann rain gauge for months (A) and seasons (B) from hydrological years 2017–2019.

the Hellmann rain gauge were shown by the results of an experimental, short (January 2016) parallel study at the Pontianak Marine Station, Indonesia (Maftukhah et al., 2016).

The size of the deviations of the months of the cold half-year as well as the coldest quarter is about twice that of the months of the warm half-year and the warmer quarter (Fig. 11). Among the analyzed rain gauge types, the largest negative deviations occur for the A-STER and MET ONE rain gauges, the smallest for the SEBA type. The obtained mean annual deviations are significantly higher for A-STER, MET ONE and MPS rain gauges than the mean annual deviations obtained from analogous studies at CHMI, where they were 4 % (Valík et al., 2020). In contrast, precipitation series collected by two Italian agencies: the older Italian Hydrographic Mareographic Service with standard UM 8100 rain gauges, later gradually combined (since 2003) with measurements recorded from automatic PMB2 tipping bucket rain gauges provided by the Regional Agency for Environmental Protection Piedmont, covering 5 years for 55 stations, indicate an underestimation of annual precipitation totals by automatic rain gauges, similar to IMWM-NRI, by an average of 12 % (Acquaotta et al., 2016). Similarly, parallel precipitation measurements with a Hellmann rain gauge and an automatic tipping bucket rain gauge type TPg-034-h230 from A-STER, conducted in 2014 at the Jagiellonian University research station in Krakow, Poland, indicate that A-STER recorded 70–90 % of the daily total from the Hellmann rain gauge, while underestimating the annual total by about 15 % on average (Matuszko and Nowak, 2017).

Considering the acceptable 5 % error range for automatic rain gauges established at the WMO expert meeting in Switzerland in December 2005 (WMO, 2005; Lanza and Vuerich, 2009), it is noted that only the average annual results from SEBA rain gauges meet this criterion.

For SEBA rain gauges, even slight positive deviations occurred in the months of July-September, which also determined positive values (about 1 %) in the summer and warm half-year (Fig. 11). The positive deviation was due to the fact that at the stations: Leszno, Jelenia Góra and Opole, SEBA rain gauges recorded higher average total precipitation in some months of the warm half of the year compared to the Hellmann rain gauge (Fig. 11). The cause of this unusual situation is unknown. It is possibly due to incorrect calibration of the instrument. For example, Bergmann et al. (2001) pointed out that when using tipping bucket rain gauges, due to aging (wear and tear) of the material, there is usually a significant reduction in the accuracy of the results obtained. This creates the need to periodically calibrate the instruments and use calibration curves to correct the resulting registrations.

Significant differences between SEBA and Hellmann rain gauge readings were pointed out by Lorenc (2006). According to the author, in annual precipitation sums, the automatic rain gauge can underestimate precipitation totals by up to more than 20 % relative to the Hellmann rain gauge. The results of her paper show clearly larger negative differences than those shown in this study. This may be due to the fact that the author relied on parallel precipitation measurements made for the incomplete year 2003 and for only three stations. Moreover, in terms of precipitation, 2003 was an exceptionally dry year in Poland (Dubicki et al., 2004; Tomczyk and Bednorz, 2020). On the other hand, Filipiak (2000–2001), on the basis of two measurement seasons from May to October 1999–2000 for three synoptic stations in the Gulf of Gdańsk, demonstrated a high conformity of precipitation sums measured with the Hellmann rain gauge, a float pluviograph and an automatic tipping bucket rain gauge, especially during moderate and heavy precipitation. For low intensity precipitation, this author observed the lowest accuracy of the automatic rain gauge records. Similarly, Kotowski et al. (2011), based on the results of a study on the warm half-year 2009 at the synoptic station of IMWM-NRI Legnica, found that for the periods: month, day, 6 hours, the results obtained from the SEBA rain gauge, pluviographs and rain gauges are comparable. However, analysis of short-term precipitation (up to 360 minutes) showed that the greatest differences in precipitation amount occur in the first 5 minutes. In the case of very intense precipitation, reaching several millimeters in 5 minutes, underestimation of precipitation by the SEBA rain gauge was found to be 10–20 % in relation to the classic pluviograph.

Other research carried out on the example of several measurement stations in Poland, with different length of measurement lines, showed that the precipitation sums measured with SEBA rain gauges are smaller than those measured with the Hellmann rain gauge. The average differences found are statistically significant and reach 10–15 % and are up to 30 % for precipitation up to 2 mm (WÓJCIK et al., 2010). Moreover, these authors point out that the scale of detected differences makes it possible to conclude that changes in the measurement apparatus and the use of data from SEBA rain gauges for historical purposes may become the cause of breaks in the homogeneity of long-term precipitation measurement series.

The results from comparative measurements at the Geneva airport also indicate that daily precipitation by the automatic tipping bucket rain gauge is underestimated relative to the Hellmann rain gauge. The mean precipitation sum from 576 days in 1980–1985 in the automatic rain gauge was 14 % lower than in the Hellmann rain gauge (Sevruk, 1996). Thus, the difference found is analogous to the annual average obtained in this study from MET ONE and A-STER tipping bucket rain gauges. Underestimation of daily precipitation by automatic tipping bucket rain gauges relative to the manual METRA 886 rain gauge is indicated by results from parallel measurements at the Czech stations Brno-Žabovřesky and Ostrava-Poruba from 2000–2019 (Valík et al., 2020) as well as by earlier studies performed for 26 CHMI stations from 1999–2007 (Knežínková et al., 2010).

The lower number of days with precipitation recorded by the automatic rain gauges and the dominance of negative deviations in daily precipitation sums relative to the Hellmann rain gauge results in a significant relative difference. On average, the A-STER, MET ONE, MPS and SEBA rain gauges underestimate the precipitation sums relative to the Hellmann rain gauge annually by approximately 14 %, 13 %, 8 % and 5 %, respectively. This fact may be of significant importance for the estimated water balance in a given area as well as cause erroneous conclusions in the studies of precipitation trends, atmospheric droughts, etc.

Automatic rain gauges in almost all stations (except for the SEBA rain gauge in Leszno, Jelenia Góra and Opole) show less precipitation than the Hellmann rain gauge. As a rule, the differences in the warm half-year are smaller than cool half-year. It can be noticed that the smallest differences in the average annual sum (except for the Jarnołtówek and Tarnów Śląski stations), not exceeding 40–50 mm, are characteristic of SEBA rain gauges operating at the synoptic stations. These stations have 24-hour human supervision (qualified meteorological observer) over the measuring instruments. In addition, a clear underestimation in the sum of precipitation recorded by the automatic rain gauges A-STER and MET ONE is noted at stations located higher than 360 m a.s.l. Above this absolute threshold, the differences in the mean annual total precipitation between the A-STER and MET ONE automatic rain gauges and the Hellmann rain gauge are increasing (Fig. 12). When analyzing absolute precipitation measurement results, it is important to remember that they are understated relative to actual amounts, which is especially true for the MPS and SEBA rain gauges. This is due to the fact that this study omits some of the days with precipitation ≥ 0.1 mm in which there were breaks in registration in automatic rain gauges. Similar conclusions that automatic rain gauges record lower precipitation than manual rain gauges and that the differences in precipitation between them become greater with higher total precipitations and an increase in station altitude are drawn from the parallel measurements at the CHMI (Lednický and

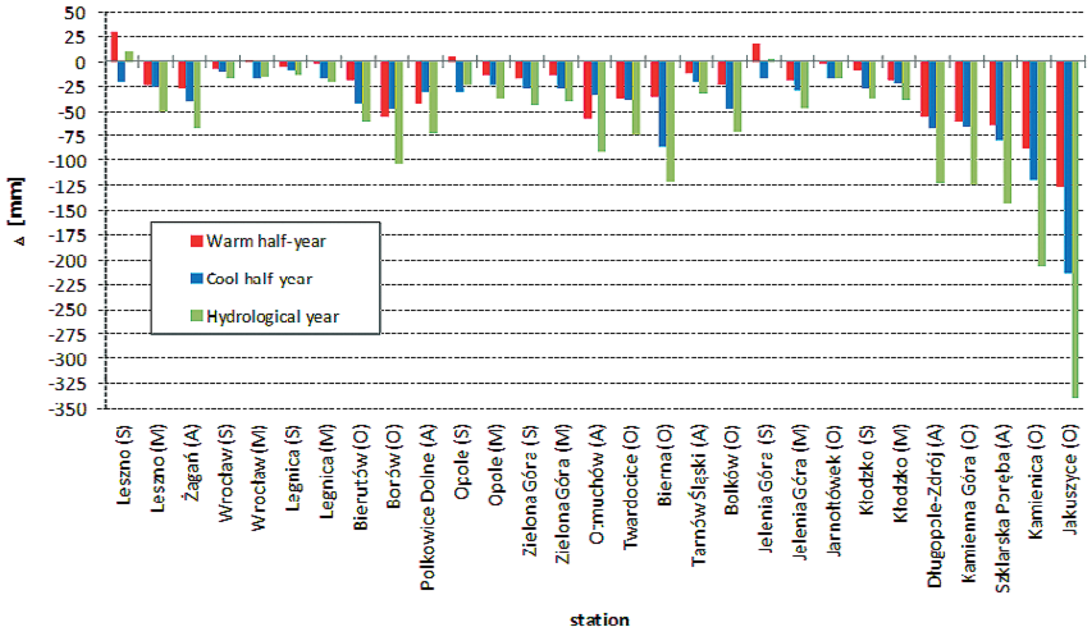

Figure 12: The difference in the mean total precipitation Δ (mm) between the automatic rain gauge (S – SEBA, A – A-STER, O – MET ONE, M – MPS) and the Hellmann rain gauge at the analyzed stations in the hydrological years 2017–2019. Stations ranked by increasing altitude a.s.l. – see Table 1.

Priadka, 1984; Knežínková et al., 2010; Valík et al., 2020).

When analyzing the results of parallel measurements for both types of instruments, various factors should be taken into account (e.g. observer, instrument defects and even the nature of precipitation). On the one hand, the accuracy and consistency of measurements made with manual rain gauges is strongly related to the observer's approach, while the maintenance of automatic rain gauges also requires a meticulous approach. Automatic measurements may be influenced by technical issues, including thermostat failure with continuous precipitation or even basic electrical failures, which happened during the tests. Furthermore, heating automatic rain gauges may not be sufficient to melt solid precipitation, thus delaying its recording and possibly leading to more evaporation from the instrument. For example, one conclusion from a comparison of WMO precipitation measurements was that "heated automatic rain gauges are not recommended for measuring solid precipitation" (Goodison et al., 1998).

Considering the above observations, the understatement of precipitation by automatic rain gauges is most likely due to the following reasons:

- clogging of automatic tipping bucket rain gauges throughout the year (especially during the growing season) by bird droppings, flower petals, insects, leaves and needles, dusts blowing in from the surrounding fields, which is observed mainly at the stations of lower rank (precipitation or climatological), where the instruments are only periodically cleaned by the service technician (except for the SEBA rain gauge, which is under constant control of an observer);
- evaporation or sublimation processes caused by heating automatic rain gauges during the winter;
- failure of the automatic rain gauge heating system;
- power interruption to the telemetry station;
- rainwater losses (splashing) in tipping bucket rain gauges due to the small volume of tanks (buckets) that are not able to collect water during heavy rainfalls;
- precipitation intensity;
- method of measurement;
- wind impact;
- probable errors generated by measuring devices and/or having to do with data transmission or the proper functioning of the data collection system (this applies more to weighing rain gauges);
- wetting of the internal circuitry of the instrument.

4 Summary and conclusions

The results obtained from parallel measurements of daily precipitation sums indicate that there is a clear difference between the automatic rain gauges and the manual Hellmann rain gauge. In automatic rain gauges, the average number of days with precipitation was about 10 % lower than the Hellmann rain gauge. The smallest difference in the average number of days with precipitation compared to the Hellmann rain gauge in each of the individual threshold values (≥ 0.1, ≥ 1.0, ≥ 5.0 mm) was recorded for the SEBA rain gauge (9–5 %). In contrast, the largest difference in the average number of days with precipitation was indicated by the MET ONE rain gauge (12 % at each threshold).

The most common errors in automatic rain gauges are small errors ($0.1 < D \le 1.0$ mm). On average, in a year they constitute from 45 % of days in SEBA rain gauges to 52 %–54 % of days in other types of rain gauges. In addition, large ($1.0 < D \le 5.0$ mm) and very large ($D > 5.0$ mm) errors are most common in sequence in A-STER, MET ONE, MPS, and SEBA rain gauges. On average, in the year they are approximately 16 %, 16 %, 7 % and 6 %, respectively, on all days for large errors and 1 %, 1 %, 0.1 % and 0.5 % of all days for very large errors. At the highest stations a.s.l. with the MET ONE rain gauge (Jakuszyce and Kamienica), the average annual number of days with an absolute difference with large errors amounted to approx. 32 % of the total.

The analysis of the deviations of the daily precipitation sums from automatic rain gauges relative to the Hellmann rain gauge indicates a clear asymmetry in their distribution. Negative deviations dominate over positive ones. In the case of A-STER and MET ONE rain gauges, it is even 5–6 greater. On average, they range from 59 % in SEBA rain gauges to 77 % in MET ONE rain gauges. The absence of differences (zero deviation) happens most often in SEBA rain gauges, with an average of 23 %. The rarest, on average at the level of 10 %, is found in MET ONE rain gauges. Due to the fact that individual automatic rain gauges of the same type do not show the same sign of deviation with respect to the Hellmann rain gauge, it is very difficult if not impossible to establish continuous corrections.

SEBA rain gauges are characterized by the smallest mean deviation value of the daily precipitation sums, amounting to −0.13 mm. The mean deviation in the MPS weighing rain gauges is slightly lower (−0.26 mm). On the other hand, the largest mean deviations are characteristic for A-STER and MET ONE rain gauges, where they are respectively: −0.52 mm and −0.48 mm.

On a monthly, semiannual, or annual basis, the absolute sums are clearly less than the Hellmann's rain gauge. Mean annual precipitation sums obtained from automatic rain gauges at stations (above 360 m a.s.l.), where the proportion of winter precipitation increases with altitude, show that precipitation is understated in the annual sum from about 120 mm to over 330 mm (Jakuszyce). The A-STER, MET ONE, MPS and SEBA rain gauges understate the average precipitation sums relative to the Hellmann rain gauge annually by approximately 14 %, 13 %, 8 % and 5 %, respectively. The distribution of monthly and seasonal deviations of daily precipitation sums in automatic rain gauges in relation to the Hellmann rain gauge indicates that regardless of the type of rain gauge, the largest negative deviations occur in the colder season (XI–IV), with a maximum of 20–25 %, and in MET ONE rain gauges even up 30 %, occurring in January. When analyzing absolute measurement results, it is important to remember that they are understated relative to actual amounts, which is especially true for the MPS and SEBA rain gauges. This is due to the fact that this study omits some of the days with precipitation in which there were breaks in registration in automatic rain gauges.

The differences found relate to earlier results of analogous studies, cited in this paper, both in Poland (mainly works on SEBA rain gauge from IMWM-NRI or A-STER from Jagiellonian University) and in Europe. The methodological assumptions made in this paper and the length of the parallel measurements indicate that the results obtained are highly reliable. The inclusion in the study of days with interruptions in precipitation recording or with trace precipitation could result in even greater differences in daily, monthly, and annual mean sums between the analyzed rain gauges.

Among the analyzed measurements from automatic rain gauges, the results from the SEBA tipping bucket rain gauge proved to be the most consistent with Hellmann's rain gauge readings, followed by MPS, A-STER and MET ONE. The best results from the SEBA rain gauge were most likely also directly related to the fact that it was the only automatic device, like the Hellmann rain gauge, that was under constant observer supervision (cleaning and checking the inlet hole and tipping mechanism). Although previous results indicate that the use of SEBA rain gauge data may break the homogeneity of long-term measurement series (Lorenc, 2006; Wojcik et al., 2010), this type still appears to function best among the automatic rain gauges analyzed. The results from the MET ONE rain gauge were the least consistent. This indicates that it should be replaced by another automatic rain gauge (e.g., SEBA or MPS) - especially at stations located in varied terrain with limited human supervision.

Although the differences were investigated only in south-western Poland, the results obtained can be interpolated to the whole Poland, because the principle of operation and the errors shown in the analyzed automatic rain gauges in relation to Hellmann rain gauge will be analogous, irrespective of the place where the instrument is installed.

IMWM-NRI lacks automatic instrument, which could replace Hellmann rain gauge, without loss of quality and quantity of obtained data. This is especially noticeable during the winter and in mountainous conditions. This problem is a sore point for all measurement services in the world.

Despite the variety of instruments for measuring precipitation, accurate measurement of this meteorological element is still a difficult task. Each instrument has its own advantages and disadvantages. Despite their shortcomings, automatic rain gauges are a valuable source of knowledge about the intensity of precipitation and the functioning of the devices in different meteorological conditions.

In the situation of understating precipitation by automatic rain gauges, it seems reasonable to use the data from the Hellmann rain gauge first in climatological studies and for operational purposes. Uncritical acceptance of the results obtained from them can lead, for example, to incorrect estimates of water balance or conclusions about trends in the amount of precipitation. Furthermore, data from automatic rain gauges can break the homogeneity of long-term measurement series obtained from Hellmann rain gauge.

To ensure the comparability of traditional and automatic data, work on the correctness of automatic rain gauges must continue to improve, data must be continuously verified, and correction factors must be introduced. Hence, it is necessary to conduct further research on this issue, especially when further development of automatic measurement network is planned, which will also take place in the near future in IMWM-NRI.

References

Acquaotta, F., S. Frantianni, V. Venema, 2016: Assessment of parallel precipitation measurements networks in Piedmont Italy. – Int. J. Climatol. **36**, 3963–3974. DOI:10.1002/joc.4606.

Bergmann, H., H. Breinhälter, O. Hable, R. Krainer, 2001: Calibration of tipping bucket hyetographs. – Phys. Chem. Earth. **26**, 731–736. DOI:10.1016/S1464-1917(01)95017-2.

Chandrasekar, V., E.G. Gori, 1991: Multiple disdrometer observations of rainfall. – J. Appl. Meteorol. **30**, 1514–1518. DOI:10.1175/1520-0450(1991)030<1514:MDOOR>2.0.CO;2.

Ciach, G.J., 2003: Local random errors in tipping-bucket rain gauge measurements. – J. Atmos. Ocean. Technol. **20**, 752–759. DOI:10.1175/1520-0426(2003)20<752:LREITB>2.0.CO;2.

Ciach, G.J., W.F. Krajewski, 1999: On the estimation of radar rainfall error variance. – Adv. Water Resour. **22**, 585–595. DOI:10.1016/S0309-1708(98)00043-8.

Colli, M., L.G. Lanza, P. La Barbera, P.W. Chan, 2014: Measurement accuracy of weighing and tipping-bucket rainfall intensity gauges under dynamic laboratory testing. – Atmos. Res. **144**, 186–194. DOI:10.1016/j.atmosres.2013.08.007.

Collier, C.G., 1986: Accuracy of rainfall estimates by radar, 1. Calibration by telemetering rain-gauges. – J. Hydrol. **83** (3), 207–223. DOI:10.1016/0022-1694(86)90152-6.

Dubicki, A., B. Glowicki, G. Urban, 2004: Obszary dotkniete susza w dorzeczu górnej i srodkowej Odry w latach 2003–2004 (Areas of drought phenomenon occurrence in the upper and middle river Odra basin during 2003–2004). – Zeszyty Naukowe Akademii Rolniczej we Wroclawiu. Inzynieria Srodowiska **13**, 81–89 (in Polish).

Duchon, C., C.J. Biddle, 2010: Undercatch of tipping-bucket gauges in high rain rate events. – Adv. Geosci. **25**, 11–15. DOI:10.5194/adgeo-25-11-2010.

Erdin, R., 2009: Combining rain gauge and radar measurements of a heavy precipitation event over Switzerland: Comparison of geostatistical methods and investigation of important influencing factors. – Veröffentlichungen der MeteoSchweiz **81**, 108 pp.

Filipiak, J., 2000–2001: Problem doskonalosci serii opadowych w aspekcie instalacji cyfrowych deszczomierzy rejestrujacych (The new automatic precipitation gauges and the problem of the accuracy of precipitation series). – Ann. UMCS. **15/16, 17** (B), 145–152 (in Polish).

Frankhauser, R., 1997: Measurement properties of tipping bucket rain gauges and their influence on urban runoff simulation. – Wat. Sci. Tech. **36**, 7–12. DOI:10.1016/S0273-1223(97)00625-2.

Frankhauser, R., 1998: Influence of systematic errors from tipping bucket rain ganges on recorded rainfall data. – Wat. Sci. Tech. **37**, 121–129.

Goodison, B., P. Louie, D. Yang, 1998: WMO solid precipitation measurement intercomparison. – Final report. Instruments and observing methods report No. 67. WMO/TD-No. 872. Geneva, Switzerland: World Meteorological Organization, 211 pp.

Knežínková, B., R. Brazdil, P. Štepánek, 2010: Porovnání merení srážek srážkomerem METRA 886 a automatickým clunkovým srážkomerem MR3H ve stanicní síti Ceského hydrometeorologického ústavu (Comparison of precipitation measurements between the METRA 886 rain-gauge and the MR3H automatic tipping-bucket rain-gauge in the Czech Hydrometeorological Institute station network). – Meteorologické zprávy **63**, 147–155.

Kotowski, A., A. Dancewicz, B. Kazmierczak, 2011: Accuracy of measurements of precipitation amount using standard and tipping bucket pluviographs in comparison to Hellmann rain gauges. – Env. Prot. Eng. **37**, 23–34.

Kusmierek-Tomaszewska, R., 2009: Porównanie wyników pomiarów opadów atmosferycznych wykonywanych standardowy, deszczomierzem Hellmanna i kolebkowym stacji automatycznej (Intercomparison of precipitation measurements recorded with traditional and automated tipping-bucket rain gauges). – Infrastruktura i Ekologia Terenów Wiejskich **9**, 85–95 (in Polish).

Lanza, L.G., L. Stagi, 2009: High resolution performance of catching type rain gauges from the laboratory phase of the WMO field intercomparison of rain intensity ganges. – Atmos. Res. **94**, 555–563. DOI:10.1016/j.atmosres.2009.04.012.

Lanza, L.G., E. Vuerich, 2009: The WMO field intercomparison of rain intensity ganges. – Atmos. Res. **94**, 534–543. DOI:10.1016/j.atmosres.2009.06.012.

Lanza, L.G., M. Leroy, J. Van der Meuken, M. Ondras, 2005: The WMO laboratory intercomparison of rainfall intensity ganges. Instruments and Observing Methods. – WMO/TD no. 82, World Meteorological Organization, Geneva, 8 pp.

Lanza, L.G., M. Leroy, C. Alexandropoulos, L. Stagi, W. Wauben, 2006: Instruments and Observing Methods. – Report No. 84. WMO/TD-No. 1304. Genewa, 139 pp.

Lednický, V., O. Priadka, 1984: Comparison measurements of precipitation by means of different types of rain gages. – Meteorologicke Zpravy **37**, 21–23.

Liu, X.C., T.C. Gao, L. Liu, 2013: A comparison of rainfall measurements from multiple instruments**.** – Atmos. Meas. Tech. **6**, 1585–1595. DOI:10.5194/amt-6-1585-2013.

Licznar, P., J. Lomotowski, M. Rojek, 2005: Sposoby pomiaru natezenia deszczu na potrzeby projektowania i eksploatacji systemów odwodnienia terenów zurbanizowanych (Methods of rainfall intensity measurement for the needs of urban drainage systems' design and exploitation). – Woda-Srodowisko-Obszary Wiejskie **5**, 209–219 (in Polish).

Lorenc, H., 2006: Ocena jakosci danych meteorologicznych po wprowadzeniu automatycznych przyrzadów rejestrujacych do sieci IMGW (Quality assessment of meteorological data after inputting automatic measuring instruments). – Ann. UMCS **61**, 256–266 (in Polish).

Maftukhah, T., S. Wijonarko, D. Rustandi, 2016: Comparsion and correlation among measurement results of observatory, Hellmann and tipping-bucket sensors. – Instrumentasi **40**, 7–14. DOI:10.14203/instrumentasi.v40i1.52.

Matuszko, D., R. Nowak, 2017: Porównanie wyników pomiarów meteorologicznych wykonanych przyrzadami tradycyjnymi i automatycznymi (na przykladzie danych z Krakowa). Comparison of selected results of meteorological measurements made with traditional and automatic instruments (according to data from Kraków). – Ann. UMCS, sectio B, **LXXII**, 73–89. DOI:10.17951/b.2017.72.1.73.

Muñoz, P., R. Célleri, J. Feyen, 2016: Effect of the resolution of tipping-bucket rain gauge and calculation method on rainfall intensities in an Andean Mountain gradient. – Water **8**, 534, 1–13. DOI:10.3390/w8110534.

Nash, J., 2006: Challenges posed by the WMO Integrated Observing System. – WMO Technical Conference on Instruments and Methods of Observations. Genewa, Switzerland, 4–6 December 2006.

Niedzwiedz, T., M. Babka, J. Borkowski, E. Cebulak, D. Czekierda, A. Dziewulska-Losiowa, M. Falarz et al., 2003: – In: Kossowska-Cezak, U., T. Niedzwiedz, J. Paszyński (Eds.): Slownik meteorologiczny (Glossary of meteorology). – IMGW, Warszawa, 495 pp.

Nystuen, J.A., J.R. Proni, P.G. Black, J.C. Wilkerson, 1996: A comparison of automatic rain gauges. – J. Atmos. Ocean. Technol. **13**, 62–73. DOI:10.1175/1520-0426(1996)013<0062:ACOARG>2.0.CO;2.

Padrón, R., J. Feyen, M. Córdova, P. Crespo, R. Célleri, 2020: Rain gauge inter-comparison quantifies differences in precipitation monitoring. – Revista Ciencias de la Vida, La Granja **31**, 7–20. DOI:10.17163/lgr.n31.2020.01.

Perini, L., M. Beltrano, 2003: Linking of traditional and automatic stations data: operational experience of UCEA. – 3a Conferencia International Sombre Experiencias con Estaciones Meteórologicas Automáticas, Torremolinos.

Pismo Okólne nr 11/2016 z dn. 22.09.2016 r. – Dyrektora IMGW-PIB (Circular Letter No 11/2016 of 22 September 2016 by Director IMGW-PIB) (in Polish).

Pismo nr PP-510-34/PS-155/NP-960/2016 z dn. 23.08.2016 r. – Z-cy Dyrektora ds. Sluzby Hydrologiczno-Meteorologicznej i Meteorologicznej Oslony Lotnictwa Cywilnego Główny Synoptyk Meteorologiczny (Letter No. PP-510-34/PS-155/NP-960/2016 dated 23 August 2016 by Deputy Director for Hydrological and Meteorological Service and Civil Aviation Meteorological Shield Chief Meteorological Synoptician) (in Polish).

Pismo nr PP-510-55/PS-230/NP-1268/2016 z dn. 9.11.2016 r. – Z-cy Dyrektora ds. Sluzby Hydrologiczno-Meteorologicznej i Meteorologicznej Oslony Lotnictwa Cywilnego Główny Synoptyk Meteorologiczny (Letter No. PP-510-55/PS-230/NP-1268/2016 dated 9 November 2016 by Deputy Director for Hydrological and Meteorological Service and Civil Aviation Meteorological Shield Chief Meteorological Synoptician) (in Polish).

Pismo nr PP-510-11/PS-37/NP-200/2017 z dn. 15.02.2017 r. – Z-cy Dyrektora ds. Sluzby Hydrologiczno-Meteorologicznej i Meteorologicznej Oslony Lotnictwa Cywilnego (Letter No. PP-510-11/PS-37/NP-200/2017 dated 15 February 2017 by Deputy Director for Hydrological and Meteorological Service and Meteorological Protection of Civil Aviation) (in Polish).

Pismo nr BSHM-510-16/CS-277/2020 z dn. 14.12.2020 r. – Dyrektora Centrum Hydrologiczno-Meteorologicznej Sieci Pomiarowo-Obserwacyjnej IMGW-PIB (Letter No. BSHM-510-16/CS-277/2020 dated 14 December 2020 by Director of the Centre for Hydrological-Meteorological Measurement and Monitoring Network IMWM-NRI (in Polish).

Pollock, M.D., G. O'Donnell, P. Quinn, M. Dutton, A. Black, M.E. Wilkinson, M. COLLI, M. Stagnaro, L.G. Lanza, E. Lewis, C.G. Kilsby, P.E. O'Connell, 2018: Quantifyingand mitigating wind-induced undercatch in rainfall measurements. – Water Resour. Res. **54**, 3863–3875. DOI:10.1029/2017WR022421.

Rashid, M.M., M. Romlay, M. bin Rabani, M.M. Ferdaus, 2015: Development of electronic rain gauge system. – J. Electr. Electron. Eng. **3**, 245–249. DOI:10.12720/ijeee.3.4.245-249.

Rózdzyński, K., 2004: Podstawy telemetrycznego miernictwa meteorologicznego (Fundamentals of telemetry meteorological surveying). – IMGW, Warszawa, 478 pp. (in Polish).

Różdżyński, K., P. Derek, A. Górka, E. Grzelak-Agaciak, K. Jurczak, M. Kamińska, B. Kieloch, H. Lech, J. Letachowicz, G. Ragin, W. Stepko, ST. Suchecki, J. Trzebunia, Ł. Woźniak, 2014: Instrukcja dla stacji meteorologicznych IMGW-PIB (Instruction for meteorological stations IMWM-NRI). – Warszawa, 389 pp. (in Polish).

Santana, M.A.A., P.L.O. Guimaraes, L.G. Lanza, 2018: Development of procedures for calibration of meteorological sensors. Case study: calibration of a tipping-bucket rain gauge and data-logger set. – J. Phys. Conf. Ser. **975**, 012006. DOI:10.1088/1742-6596/975/1/012006.

Savina, M., B. Schäppi, P. Molnar, P. Burlando, B. Sevruk, 2012: Comparison of a tipping-bucket and electronic weighing precipitation gage for snowfall. – Atmos. Res. **103**, 45–51. DOI:10.1016/j.atmosres.2011.06.010.

Sevruk, B., 1986: Correction of precipitation measurements. in: Proc. workshop on the correction of precipitation measurements. – Zürcher Geographische Schriften, ETH Zurich 23, 289 pp.

Sevruk, B., 1996: Adjustment of tipping-bucket precipitation gauge measurements. – Atmos. Res. **42**, 237–246. DOI:10.1016/0169-8095(95)00066-6.

Sevruk, B., 2002: WMO questionnaire on recording precipitation gauges: state-of-the-art. – Wat. Sci. Technol. **45**, 139–145. DOI:10.2166/wst.2002.0039.

Sevruk, B., S. Klemm, 1989: Types of standard precipitation gauges [in] Proceedings of the Workshop on Precipitation Measurements, edited by B. Sevruk. – WMO/IAHS/ETH, 227–236, Geneva, Switzerland.

Sevruk, B., M. Ondras, B. Chvila, 2009: The WMO precipitation measurement intercomparisons. – Atmos. Res. **92**, 376–380. DOI:10.1016/j.atmosres.2009.01.016.

Solon, J., J. Borzyszkowski, M. Bidlasik, A. Richling, K. Badora, J. Balon, T. Brzezińska-Wójcik, L. Chabudziński, R. Dobrowolski, I. Grzegorczyk, M. Jodlowski, M. Kistowski, R. Kot, P. Kraz, J. Lechnio, A. Macias, A. Majchrowska, E. Malinowska, P. Migoń, U. Myga-Piatek, J. Nita, E. Papińska, J. Rodzik, M. Strzyz, S. Terpilowski, W. Ziaja, 2018: Physico-geographical mesoregions of Poland: Verification and adjustment of boundaries on the basis of contemporary spatial data. – Geogr. Pol. **91**, 143–170. DOI:10.7163/GPol.0115.

Steiner, M.J., A. Smith, S.J. Burges, C.V. Alonso, R.W. Darden, 1999: Effect of bias adjustment and rain gauge data quality control on radar rainfall estimation. – Water Resour. Res. **35**, 2487–2503. DOI:10.1029/1999WR900142.

Strangeways, I., 2010**:** A history of rain gauges. – Weather **65**, 133–138. DOI:10.1002/wea.548.

Sypka, P., 2019: Dynamic real-time volumetric correction fortipping-bucket rain gauges. – Agric. For. Meteor. **271**, 158–167. DOI:10.1016/j.agrformet.2019.02.044.

Tabada, M.T., M.E. Loretero, 2020: Innovative configuration design of two-wire tip mechanisms for a tipping-bucket rain-gauge. – J. Eng. Technol. Innov. **10**, 156–164. DOI:10.46604/ijeti.2020.4772.

Tokay, A., D.B. Wolff, K.R. Wolff, P. Bashor, 2003: Rain gauge and disdrometer measurements during the keys area microphysics project (KAMP). – J. Atmos. Ocean. Technol. **20**, 1460–1477. DOI:10.1175/1520-0426(2003)020<1460:RGADMD>2.0.CO;2.

Tokay, A., P.G. Bashor, V.L. McDowell, 2010: Notes and correspondence. Comparison of rain gauge measurements in the Mid-Atlantic Region. – J. Hydrometeorol. **11**, 553–565. DOI:10.1175/2009JHM1137.1.

Tomczyk, A.M., E. Bednorz, 2020: The extreme year-analysis of thermal conditions in Poland in 2018. – Theor. Appl. Climatol. **139**, 251–260. DOI:10.1007/s00704-019-02968-9.

Upton, G.J.G., A.R. Rahimi, 2003: On-line detection of errors in tipping-bucket raingauges. – J. Hydrol. **278**, 197–212. DOI: 10.1016/S0022-1694(03)00142-2.

Valík, A., R. Brázdil, P. Zahradnícek, R. Tolasz, R. Fiala, 2020: Precipitation measurements by manual and automatic rain gauges and their influence on homogeneity of long-term precipitation series. – Int. J. Climatol. **4**, E2537–E2552. DOI: 10.1002/joc.6862.

Vuerich, E., C. Monesi, L. Lanza, L. Stagi, E. Lanzinger, 2009: WMO field intercomparison of rainfall intensity ganges. Instruments and Observing Methods. WMO/TD no. 1504, World Meteorological Organization, Geneva, 96 pp.

Wang, J., B.L. Fisher, D.B. Wolff, 2008: Estimating Rain Rates from Tipping-Bucket Rain Gauge Measurements. – J. Atmos. Ocean. Technol. 25, 43–56. DOI:10.1175/2007jtecha895.1.

WMO, 2005: Joint CIMO Expert Team on Surface-Based Instrument Intercomparison and Calibration Methods and IOC on Surface-Based Instrument Intercomparison, Geneva, 5–9 December 2005. – Available at www.wmo.int/pages/prog/www/IMOP/reports.

WMO, 2008: World Meteorological Organization. Guide to Meteorological Instruments and Methods of Observation: (CIMO guide). – WMO No. 8. Secretariat of the WMO. Geneva. Chairperson Publications Board. Accessed 16 January 2019. Available at www.wmo.int/pages/prog/www/IMOP/publications.

Wójcik, R., A. Zebik, D. Biernacik, M. Mietus, 2010: Porównanie rejestracji natezenia i sum dobowych opadów atmosferycznych za pomoca urzadzeń tradycyjnych i elektroniczych (Comparison of precipitation amounts measured with Hellmann rain gauges and automatic sensors). – In: Rózdzyński, K. (Ed.): Metody kontroli jakosci dla polskiej Państwowej Sluzby Hydrologiczno-Meteorologicznej (Quality control methods for the Polish National Hydrological and Meteorological Service). – Monograph's series. IMGW-PIB. Warszawa, 107–124 (in Polish).

Yang, D., B. Goodison, J. Metcalfe, P. Louie, E. Elomaa, C. Hanson, V. Golubev, T. Gunther, J. Milkovic, M. Lapin, 2001: Compatibility evaluation of national precipitation gage measurements. – J. Geophys. Res. **106**, D2, 1481–1491. DOI:10.1029/2000JD900612.

Yoo, C., M. Park, H.J. Kim, J. Choi, J. Sin, C. Jun, 2015: Classification and evaluation of the documentary-recorded stormevents in the annals of the Choson dynasty (1392–1910), Korea. – J. Hydrol. **520**, 387–396. DOI: 10.1016/j.jhydrol.2014.11.023.