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Inconsistency in rainfall characteristics estimated from records of different rain gauges

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Abstract The goal of this work is to assess the effect of utilizing different types of tipping bucket rain gauges in investigating rainfall characteristics. A dual tipping bucket (TB) rain gauge station is installed in the upper catchment of Numan basin in Saudi Arabia. The main difference between the two gauges is that the Hydrological Services (HS) gauge is equipped with a siphon tube which reduces undercatchment particularly during heavy rainfall. Records of both gauges for the period 2006 to 2013 are collected, analyzed, and compared, focusing on the characteristics of rainfall events as well as rainfall temporal variability. The HS gauge recorded higher values of total rainfall depth compared to the Texas Electronics (TEMM) gauge. For the individual storms as well as the 5-min rainfall, HS gauge also reported higher mean rainfall depths. Regarding temporal characteristics of reported rainfall, no significant variations are observed between the values of storm duration of the two gauges. The TEMM gauge has the advantage of recoding more storms with depth less than 1 mm. The current study suggests the use of a corrective factor for rainfall record of the TEMM gauge.

Keywords Rainfall measurement · Dual rain gauges · Arid region · Saudi Arabia

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Introduction

Arid and semiarid regions are under the pressure to develop and accommodate growing populations, rising water consumption, and limited water resources. Despite the vital importance of water in arid regions, hydrologic information is limited. Lack of accurate and reliable observations has been widely acknowledged as the major restriction to the development of arid zone hydrology (McMahon 1979; Nemec and Rodier 1979; Pilgrim et al. 1988; Michaud and Sorooshian 1992). In fact, a serious challenge facing development efforts in arid regions is the lack of water resources and their management bureaus to meet the increasing need for hydrological information. In arid regions, major rain storms are infrequent and characteristics should be estimated with the highest possible accuracy. Unavailability or inaccuracy of rainfall data and lack of experimental research lead to more dependence on tools and data from humid zones (Wheater 2002). Therefore, arid and semi-arid areas around the world not only suffer from water shortage but also from lack of reliable hydrometeorological data which can be utilized in development efforts (Ragab and Prudhomme 2002).

Arid mountainous regions located in western Saudi Arabia are subject to infrequent but damaging flash floods. These floods are characterized by short duration and high damaging powers. Lack of reliable and adequate precipitation data is the main drawback to investigate flash flood using more suitable techniques for arid regions. Despite this limitation, several climatological and hydrological investigations have been carried out in the western and southwestern regions of Saudi Arabia. Due to the unavailability of short duration rainfall data, most of these investigations deal with analysis of daily, monthly, and annual rainfall series. Furthermore, most of these investigations are carried out in the southwestern region of Saudi Arabia. Rainfall investigations are very rare in the

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western Saudi Arabia. An example would be the analysis of daily, monthly, and annual rainfall data carried out by Al-Wagdany (2008). Spatial rainfall distribution in the southwestern region was investigated by Wheater et al. (1991) as well. The relationship between rainfall depth and elevation in western and southwestern regions was investigated by Al-Wagdany and Al-Shahri (2000); Subyani et al. (2010), and Al-Ahmadi and Al-Ahmadi (2013). Nouh (1987) investigated the regional rainfall distribution in the southwest of Saudi Arabia. The mean annual rainfall distribution of the southwestern region was investigated by Abdullah and Al-Mazroui (1998). Subyani and Al-Dakheel (2009) conducted a geostatistical investigation of mean annual and seasonal rainfall in southwest Saudi Arabia. The annual and seasonal trends in precipitation amount in the region were also studied by Furl et al. (2014).

Accurate measurements of precipitation are necessary for different planning and management purposes such as hydrological designs and environmental protection. In fact, reliable estimation of precipitation is essential to decision makers such as hydrologists, agriculturalists, and disaster managers. Ground-based rain gauge observations are the prime source of precipitation data. They can also be used to validate rainfall data obtained from other sources of precipitation data such as radar and satellite rainfall estimates. Rain gauges are instruments that collect rainfall via an orifice of specified size and measure its water-equivalent volume or mass which was collected during a certain interval of time. Nowadays, rain gauges are commonly utilized in operational networks to estimate precipitation rates and depths. Three types of rain gauges are widely used for rainfall measurement; these are weighing gauges, float gauges and tipping bucket (TB) gauges. However, TB rain gauges are the most common automatic device for measuring rainfall depth and intensity. TB rain gauge was invented by Christopher Wren in 1662 (Biswas 1967). The mechanism of their operation is very simple; rainwater falls into the gauge collector which is then directed into a two-compartment bucket. The bucket will overbalance and hence tip when a specific amount of rainfall fill one compartment. As the bucket is tipped, it closes an electrical contact which sends a signal so that the number of tips in any specified time can be counted and recorded in a data logger.

Tipping bucket rain gauges are fairly accurate, reliable, and durable. Additionally, they provide automated recording capability of precipitation at any specified time interval. Nevertheless, they are subject to systematic and random instrumental inaccuracies. Underestimation may occur during high rainfall intensities because rainfall amounts maybe lost during the tipping process (Al-Wagdany 2015. Other known sources of error in tipping gauge measurements include wind-induced undercatch, wetting–evaporation losses, unpredictable mechanical and electrical problems, as well as partial or complete clogging of the funnel (Habib et al. 2001). Several researchers recommended the utilization of dual rain gauges to detect faulty gauges and to improve quality of rainfall measurements (Krajewski et al. 1998; Ciach and Krajewski 1999). In the last two decades, dual rain gauges were used in different regions of the world. For instance, Nikolopoulos et al. (2008) conducted a rainfall characterization investigation using data from a dual rain gauge and three other ground-based instruments. Ciach and Krajewski (2006) used rainfall data from a dense cluster of dual rain gauges in Central Oklahoma to conduct an investigation of the spatial correlation of the rainfall. Kimball et al. (2010) compared rainfall data from 21 dual rain gauges in Alabama State and concluded that in most cases, the Hydrological Services tipping bucket rain gauges recorded more rainfall compared to the Texas Electronics gauges. The recent study of Al-Wagdany (2015) is probably the first attempt to evaluate rainfall measurements using dual rain gauges in arid regions.

The current study aims to investigate the inconsistencies emerging from utilizing different gauge types to estimate rainfall characteristics as well as temporal variability of rainfall. This paper is arranged in four sections. The first is an introduction in which the importance of rainfall data to arid regions is highlighted, followed by literature review of previous studies in the region as well as rainfall investigations using tipping bucket rain gauges. Specifications and installation of the dual rain gauges used in this study are provided in the second section. In the third section, the results of analyzing rainfall data collected by the dual gauges are presented. The last section of the paper provides the main conclusions of the study.

Materials and method

The study area is located in western Saudi Arabia which is one of the driest and hottest countries in the world. Saudi Arabia lies approximately between latitudes 17° and 31° N and longitudes 37 ° and 56 ° E. The western parts of the Kingdom are mostly mountainous and characterized by moderate climate while the east is lowland, with very hot climate. Except for the southwestern and western mountains, the average annual rainfall in the country ranges from 80 to 140 mm (Alkolibi 2002). The occurrence of rainfall and its spatial and temporal distributions on western regions of Saudi Arabia, in which the study area is located, are strongly influenced by topography and wind direction. Most winter rainfall comes from storms caused by moist air extending westwards from the Red Sea in the west towards the high western mountains. During the fall season, rainfall occurs in the mountains due to movements of air from north to south. On the other hand, summer season rainfall events are caused by thunderstorms affected by the strong southwesterly low-level winds and strong orographic effects (Atlas 1984). In the study area, rainfall is usually initiated in the mid-afternoon and characterized in general by high intensity and short duration (typically 1–2 h) with extreme spatial variability (Al-Wagdany 2008).

A rainfall monitoring station with dual TB rain gauges was installed in the upper catchment of Numan basin located in western Saudi Arabia. Numan basin is one of the main basins draining the western slope of Hadda escarpments in western Saudi Arabia. Numan basin has always played a key role in supplying water to the well-known historic underground galleries of AinZubaidah. The basin is located between two main cities of western Saudi Arabia namely Makkah and Taif as shown in Fig. 1. Hydrological as well as hydrogeological characteristics of Numan basin were investigated by various researchers such as Jamman (1978); Bazuhair and Wood (1995); Es-Saeed et al. (2004); El-Hames and Al-Wagdany (2013); Sharaf (2011, 2013), and many others. The main purpose of the installed rainfall station was to monitor precipitation in the upper catchment of the basin which intermittently produces flash floods that contribute to groundwater recharge of Numan basin. The station consists of two TB gauges, data logger, battery, and a solar cell. The station is located at the downhill of Hadda escarpments with elevation of 636 m above mean sea level. The location of the station (Fig. 1) is well protected since it is within the fence of Faqih Poultry farm on the Taif Makkah Road (40° 11′ 21.5″ E and 21° 21′ 33.6″ N).

The two tipping bucket rain gauges utilized in the current study are Texas Electronics rain gauge TE525MM (TEMM) and Hydrological Services rain gauge (HS). The TEMM gauge has a 24.5-cm collector and measures 0.10 mm of rainfall per bucket tip. On the other hand, the HS gauge has a 20-cm collector and measures 0.254 mm per bucket tip. The HS gauge has the advantage of possessing a siphon tube which delivers a preset volume of collected water to each bucket, reducing undercatchment during heavy rainfall (Kimball et al. 2010). The siphon mechanism is expected to provide more accurate rainfall measurements during heavy rainfall events (Kimball et al. 2010). The two gauges are placed at the two ends of a 120-cm steel bar, lifted by a pole fixed to the ground (Fig. 2). Rainfall data and time are stored in a Campbell Scientific data logger (CR510). According to Lanza and Stagi (2008), accuracy of estimation of rainfall intensity increases when a shorter time interval is used to store the rainfall data. Therefore, a short time interval (every 5 min) is followed to store the number of rain gauge tips that occur during a rainfall event. The logger also stores the accumulated rainfall depth since midnight.

The gauges are periodically checked, during which data is transferred to a storage module which is used to download the data to the computer. The raw data consists of a series of non-zero rainfall records with time (every 5 min) and date. Additionally, total daily rainfall depth is recorded at the end of the day. Different rainfall events are isolated based on a given criteria in which a separate rainstorm event is initiated if rainfall seized for at least 3 h. This criterion helps in reducing storm duration, as rainfall is extremely intermittent in these areas. Duration of each storm is computed from the values of times of storm beginning and ending which are extracted from the raw data. Storm depth is calculated as the total rainfall depth during the storm duration. Storm intensity is determined by dividing the value of storm depth by the value of storm duration.

The current study is an important addition to the previous investigation of Al-Wagdany (2015). The common point between the two investigations is that both studies utilized dual

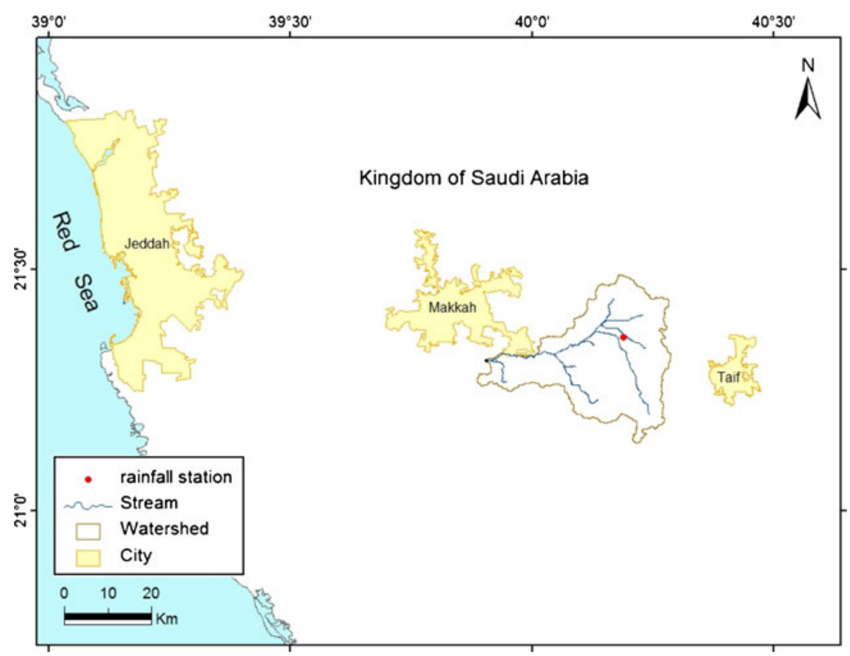

Fig. 1 Location of Numan basin and the dual gauge station

Fig. 2 Photograph of the dual gauge station

rainfall gauges (but different sets of rain gauges) to investigate rainfall measurements in Numan basin (but at different locations). However, the two studies use completely different and independent data sets. The data of Al-Wagdany (2015) are from a dual rain gauges station installed at Hada escarpments at the upstream of the basin (40° 11′ 21.5″ E and 21° 21′ 33.6″ N) at elevation of about 1800 m above mean sea level, while the data utilized in the current study belongs to another dual rain gauges station that is installed on the Taif Makkah Road (40° 15′ 34″ E and 21° 22′ 10″ N) at elevation of about 600 m above mean sea level. In addition, the two researches employ different types of gauges that have different specifications. The investigation of Al-Wagdany (2015) compares data from two gauges produced by Texas Electronics (TE525MM and TE525) which have a different size of the gauge collector. The TEMM gauge has a 9.6-in. collector, while the TE gauge has a 6-in. collector. On the other hand, the current investigation compares data from gauges produced by Hydrological Services (HS) and Texas Electronics (TEMM). The sizes of the two gauge collectors are also different, 20 and 24.5 cm, respectively. Moreover, the HS gauge has the advantage that it is equipped with a siphon tube, which reduces undercatchment particularly during heavy rainfall. Both gauges used in the study of Al-Wagdany (2015) are not equipped with the siphon. Such large difference in elevation as well as in location is expected to have a significant effect on rainfall characteristics and thus the outputs of these studies. This produces a wider scope of results and makes them applicable to broader cases.

In this study, the procedure suggested by Al-Wagdany (2015) is adopted in which rain storms are classified into three classes: storm depth of non-zero (all storms), greater than 1 mm, and greater than 10 mm. Main rainfall characteristics such as number of events as well as mean, maximum of rainfall depth, duration, and intensity are computed for each storm class. These characteristics are also determined for the 5-min rainfall events.

Results and discussion

The rainfall data used in this study consists of records of rainfall depths and durations of the dual rain gauges for the period 2006 to 2013. The number of recorded rainfall events during this period was more than 160 events. The total accumulated rainfall depth was more than 850 mm. Rainfall depth per storm varied from less than 1 mm to about 50 mm. On the other hand, average rainfall intensity varied from less than 1 to about 35 mm/h, with an overall average of about 6 mm/h. Maximum storm duration was about 15 h, with duration of most events being less than 2 h. All recorded rainfall depths (as small as 0.1 mm) are considered and are classified according to the abovementioned three groups namely non-zero depths, greater than 1 mm, and greater than 10 mm. The characteristics of the recorded storms are shown in Table 1. The variation (as percentage values) between the two rain gauges is computed according to the following equation:

$$\text{diff ratio}\% = \frac{(\text{HS}-\text{TEMM})}{\text{HS}} \times 100 \qquad (1)$$

where HS and TEMM are the values of interest recorded at HS and TEMM gauges, respectively.

For major storms (depth >10 mm), both gauges recorded the same number of storms. The two gauges also recorded almost the same number of storms with depth greater than 1 mm. When storms with very small depths are considered, the difference in number of recorded storms is high (−17.4 %). The difference between the mean storm depths of both gauges reduced from 22.8 % for all storms to 6.5 % when only storms with depth greater than 1 mm are considered. Differences between values of mean storm duration are not very high (3 to 11 %) for all storm depths. Regarding extreme values, both gauges reported different values for maximum storm depth (9.3 %) but not very different values for maximum storm duration with a difference of −1.6 %. Values of maximum storm intensity are also different (10 %) for the two gauges regardless of the considered storm depths in the computations.

Rainfall is recorded by both gauges at an interval of 5 min. The main characteristics of the 5-min rainfall reported by HS and TEMM rainfall gauges are presented in Table 2. The 5-

Table 1 Storm characteristics for HS and TEMM gauges

Storm property	Gauge	Rainfall depth		
		>0 mm	>1 mm	>10 mm
No. of storms	HS	161	104	32
	TEMM	189	100	32
	Diff. ratio %	−17.4	3.8	0.0
Mean storm depth (mm)	HS	5.86	8.85	19.81
	TEMM	4.52	8.27	17.65
	Diff. ratio %	22.8	6.5	10.9
Mean storm duration (Min.)	HS	65.7	94.2	141.6
	TEMM	63.6	104.7	148.6
	Diff. ratio %	3.3	−11.1	−5.0
Mean storm intensity (mm/h)	HS	7.38	9.73	15.64
	TEMM	4.79	7.49	12.53
	Diff. ratio %	35.0	23.0	19.9
Maximum storm depth (mm)	HS	53.3	53.3	53.3
	TEMM	48.4	48.4	48.4
	Diff. ratio %	9.3	9.3	9.3
Maximum storm duration (Min.)	HS	915	915	915
	TEMM	930	930	930
	Diff. ratio %	−1.6	−1.6	−1.6
Maximum storm intensity (mm/h)	HS	37.3	37.3	37.3
	TEMM	33.6	33.6	33.6
	Diff. ratio %	10.0	10.0	10.0

min rainfall depth ranged from less than 1 mm to about 13 mm with an average depth of about 0.8 mm. The 5-min storm average intensity ranges from less than 1 mm/h to about 155 mm/h, with an average intensity of about10 mm/h. While both gauges records show a difference of about 19.8 % of number of storms (Table 1), HS gauges fail to record large number (351) of the 5-min rainfall depths that were recorded by the TEMM gauge with a difference of about 37 %. On the other hand, HS gauge reported higher values of mean depth, maximum depth, and intensity of the 5-min rainfall with differences of 34, 18.9, and 18.9 %, respectively.

The relative frequency distribution of the difference between the two gauges 5-min rainfall totals (HS − TEMM) is presented in Fig. 3. For more than 80 % of the recorded 5-min totals, the difference ranged between −0.25 and 0.25 mm. The HS gauge recorded higher 5-min rainfall depths in about 51 % of the records.

Rainfall measurements obtained from the dual rain gauges station utilized in the current study (downstream station) are compared with those obtained from the station used in the investigation of Al-Wagdany (2015) (upstream station). Table 3 presents a comparison of main rainfall characteristics recorded by the rainfall stations used in the two investigations. The records are for the same period (2006–2013). The comparison indicates that there are significant differences in the values of rainfall characteristics recorded by the two stations. The upstream station reported significantly higher rainfall total depth and number of storms compared to the downstream station, as expected. The values of mean storm depth and mean storm duration are also higher for upstream station compared to the downstream station. On the other hand, records of

Table 2 Characteristics of the 5-min rainfall for HS and TEMM gauges

Rainfall property	Gauge	Values
No. of rainfall records	HS	949
	TEMM	1304
	Diff. ratio %	−37.4
Total rainfall depth (mm)	HS	943.1
	TEMM	855.4
	Diff. ratio %	9.3
Mean rainfall depth (mm)	HS	0.99
	TEMM	0.66
	Diff. ratio %	34.0
Maximum rainfall depth (mm)	HS	12.95
	TEMM	10.50
	Diff. ratio %	18.9
Maximum rainfall intensity (mm/h)	HS	155.4
	TEMM	126.0
	Diff. ratio %	18.9

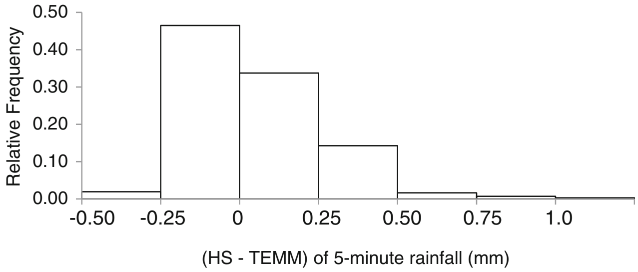

Fig. 3 Relative frequency histogram of (HS − TEMM) of 5-min rainfall

rainfall data indicate that values of mean storm intensity in the downstream of the basin are higher than those recorded in the upstream of the basin. It can be concluded that in the study area, rainfall storms are characterized by having higher depth and durations in the upstream of the basin and higher intensity in the lower parts of the basin.

The relationship between 5-min, storm, and annual rainfall depths recorded by both gauges were investigated. Figure 4 shows a scatter plot of 5-min rainfall depths of the two gauges along with the line of the best fit. The relationship indicates that records of the two gauges are very comparable for rainfall depths less than 7 mm. For higher 5-min rainfall depths (and hence intensities), the HS reported higher rainfall amount compared to TEMM gauge. However, the figure shows that the values of the 5-min rainfall depths (HS_{5m} and $TEMM_{5m}$) of the two gauges are highly correlated (R^2 = 0.977) and the linear equation which best fit the data is:

$$HS_{5m} = 1.139\ TEMM_{5m} \quad (2)$$

The number of rain storms that are recorded by both gauges was 147 events. The relationship between depths of these

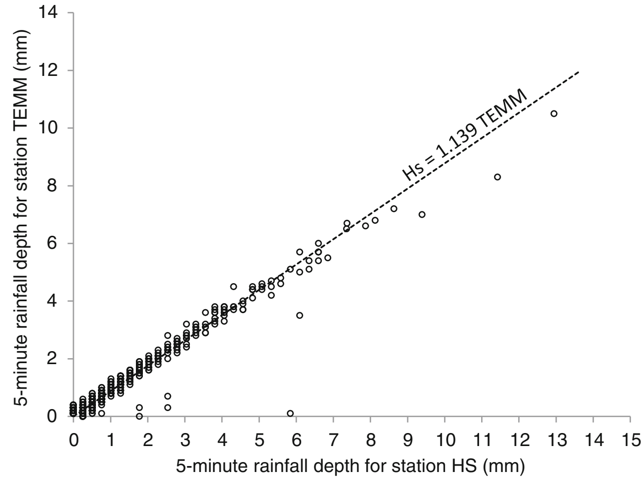

Fig. 4 Five-minute rainfall depth of HS gauge versus TEMM gauge

events (HS_{st} and $TEMM_{st}$) is shown in Fig. 5. This shows that HS gauge reported higher rainfall depth for most of the recorded storms. The figure also presents the line of the best fit (R^2 = 0.994) for storm depth of the two gauges. This linear relationship relation is:

$$HS_{st} = 1.112\ TEMM_{st} \quad (3)$$

The above equation indicated that values of rainfall depth recorded by gauge HS are usually higher than those of the TEMM gauge by about 11 %. This is almost similar to the above conclusion for the 5-min rainfall events for which HS reported higher rainfall depths.

Values of annual rainfall depths of the two gauges (HS_{an} and $TEMM_{an}$) were computed and plotted in Fig. 6. The figure also presents the line of the best fit (R^2 = 0.994) for annual

Table 3 Comparison of rainfall characteristics obtained from downstream and upstream stations

Rainfall characteristics	Downstream station	Upstream station
Number of storms	175	235
Total rainfall depth (mm)	899.3	1073.9
Mean storm depth (mm)	5.19	6.90
Mean storm duration (hr)	64.7	102.9
Mean storm intensity (mm/h)	6.09	3.72
Maximum storm depth (mm)	50.9	57.8
Maximum storm duration (min)	923	1265
Maximum storm intensity (mm/h)	35.5	40.7
Mean number of 5-min rainfall records	1127	1899
Mean 5-min rainfall depth (mm)	0.825	0.6
Maximum 5-min rainfall depth (mm)	11.73	8.15
Maximum 5-min rainfall intensity (mm/h)	140.7	97.7
Maximum 24-h rainfall depth (mm)	50.9	67.9
Maximum 48 -h rainfall depth (hr)	56.3	77.8

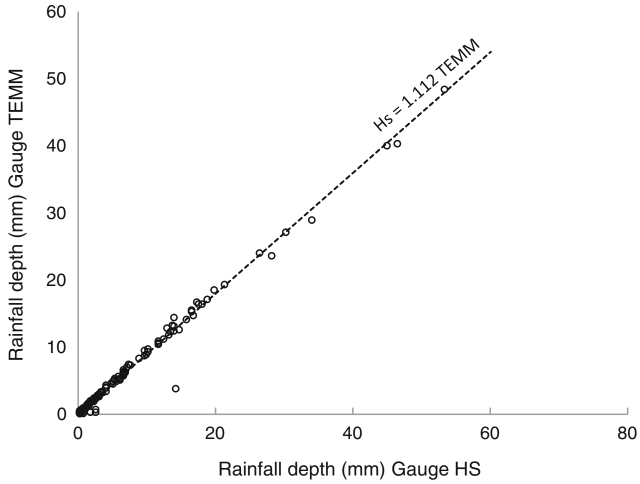

Fig 5 The relationship between storm depth of HS and TEMM gauges

series. The linear relationship between the annual rain depths is found to be:

$$HS_{an} = 1.103\ TEMM_{an} \tag{4}$$

Equation 4 supports the conclusion derived from Eqs. 2 and 3 which indicates that depths of rainfall recorded by the HS gauge are higher than those recorded by the TEMM gauge. A universal relationship between rainfall depths of the two gauges may be presented as shown in Eq 4:

$$HS = \beta\ TEMM \tag{5}$$

where β is a fitting coefficient.

Eqs. 2, 3, and 4 show that values of the coefficient β vary within small range (1.103 to 1.139). The small variations of the values of the coefficient β for Eqs. 2 through 4 may suggest that the value of the coefficient β in the universal relation (Eq. 5) can be assumed to be equal to the mean value of the coefficients of Eqs. 2, 3, and 4. Based on this assumption, the value of the coefficient β in Eq. 5 is computed and found to be equal to 1.118. In other words, the HS gauge tends to provide about 12 % higher values of rainfall depth compared to the TEMM gauge.

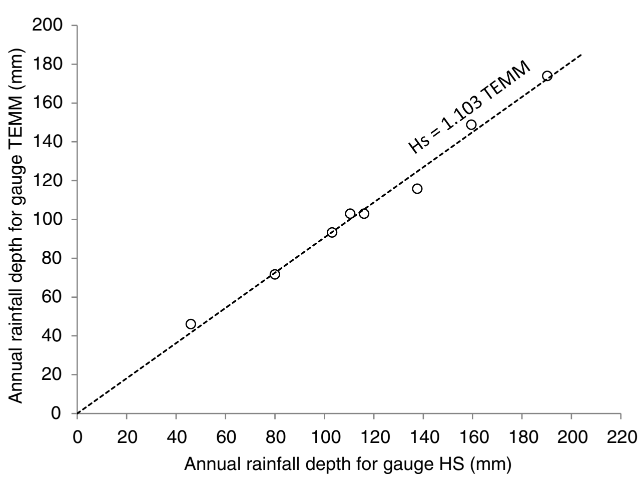

Fig. 6 Annual rainfall depth of gauge HS versus gauge TEMM

Although most of the data in Figs. 4 and 5 are close to the fitted lines, few points are relatively not close to the lines. For the six values of rainfall records shown in Fig. 4 and one in Fig. 5, variation between the values of rainfall depth of the two gauges is large. For all of these points, TEMM gauge underestimates the rainfall depth compared to the HS gauge. In-depth investigation of the original data shows that these values belong to three storms that occurred on 22 August 2009, 20 October 2009, and 21 June 2010. The second and third storms have very short duration (5 min), and in both of them, HS gauge recorded 2.54 mm while TEMM gauge recorded 0.70 and 0.30 mm, respectively. The record of both gauges for the third storm which occurred in 22 August 2009 is shown in Table 3. The duration of the storm was 25 min according to the HS gauge. The bucket of gauge TEMM temporally failed to tip during the storm and only portion of rainfall depth was recorded by the gauge. Temporal distribution of rainfall depth of the storm is shown in Table 4. TEMM gauge recorded only about 26 % of rainfall depth and completely failed to record the correct time of its occurrence. According to the measurements by the HS gauge, storm depth was 14.2 mm which is a major rainfall event in arid regions. This highlights the advantage of utilizing dual rain gauge in arid regions in which rainstorms are infrequent and environmental conditions are harsh which may lead to loss of valuable events when only single rain gauge is used.

Kimball et al. (2010) conducted a research in the USA in which they collected data from several Hydrological Services gauges similar to the one used in the current study (called TB3). The study by Kimball et al. (2010) utilizes a Texas Electronic gauges which is slightly different from the gauge used in the current study by only the size of their funnel (called TE). As a result, they published comparative data between the values of all rainfall rates greater than 165 mm/h (42 records)

Table 4 Records of rainfall depth from HS and TEMM gauges for the storm of 22 August 2009

Time	Rainfall depth (mm)	
	TEMM	HS
1620	0.10	0.00
1625	0.10	0.00
1810	3.5	6.096
1815	0.1	5.842
1820	0.0	1.778
1825	0.0	0.254
1830	0.0	0.254
Total	3.8	14.224

for the TB3 and TE gauges. Values of 1-min rainfall depths of TB3 gauge and TE gauge were computed from the rainfall data published by Kimball et al. (2010) and presented as a scatter plot in Fig. 7. The figure shows that the values of the 1-min rainfall depths of the two gauges are highly correlated ($R^2 = 0.91$) and the linear equation which best fit the data is:

$$\mathrm{TB3} = 1.118\ \mathrm{TE} \tag{6}$$

The above equation supports the finding of the current study as it shows that the TE gauge underestimates the measured rainfall depth compared to the Hydrological Services gauge. Moreover, the value of the fitting coefficient that is equal to 1.118 surprisingly has exactly the same coefficient value suggested by the universal relation (Eq. 5) in the current study.

Characteristics of maximum rainfall depth, intensity, and total depth for different durations are investigated for both gauges. For the period from 2006 to 2013, statistics of maximum rainfall depth for durations from 5 min to 2 days are presented in Table 5. The values in Table 5 indicated that HS gauge always reported higher values of maximum rainfall depth compared to the TEMM gauge. These discrepancies may partially be attributed to the ability of gauge HS to record rainfall depth more precisely particularly for high-intensity events compared to gauge TEMM. It also highlighted the importance of trying to perform a sort of rainfall data correction (for gauge type) before utilizing the data in practical applications.

Seasonal variations of the monthly rainfall of the gauge station are investigated and presented in Fig. 8. This figure shows that values of both number of storms and rainfall depth are high during fall, winter, and spring seasons and low during summer. Therefore, it can be concluded that there are two

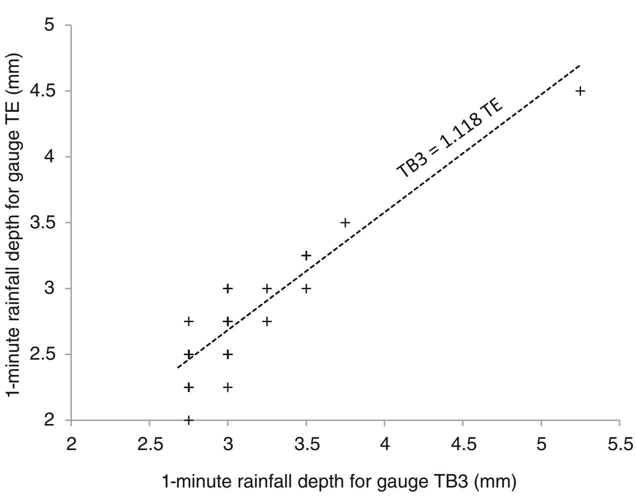

Fig. 7 One-minute rainfall depth of gauge TB3 versus gauge TE (data adopted from (Kimball et al. (2010))

Table 5 Maximum rainfall depth for specific durations for HS and TEMM gauges

Duration (m)	Maximum depth (mm)		Relative difference %
	HS	TEMM	
5	12.9	10.5	23.4
10	22.3	17.5	27.7
15	27.2	22.0	23.5
20	31.0	25.7	20.6
25	34.0	28.2	20.7
30	34.8	29.1	19.6
35	35.3	29.6	19.3
40	37.6	33.0	13.9
45	40.9	35.8	14.2
50	41.2	36.5	12.8
55	46.7	42.0	11.3
60	49.3	44.3	11.2
90	52.8	48.0	10.1
120	53.3	48.3	10.4
180	53.3	48.4	10.2
24 h	53.3	48.4	10.2
48 h	59.9	52.6	14.0

rainy seasons in the study region, one is during spring and the other is during fall and it extends until the middle of the winter.

Results of the current study support and coincide with the findings of the recent study of Al-Wagdany (2015) and enhance broader scope. The current study investigates relationships of rainfall characteristics obtained from the records of the two gauges. It introduces three regression equations for the 5-min, event, and annual rainfalls as illustrated in Eqs. 2, 3, and 4, respectively, which show high correlation coefficients. In the investigation of Al-Wagdany (2015), these relations were not investigated. Moreover, in the current study, results produced by Kimball et al. (2010) were compared with the

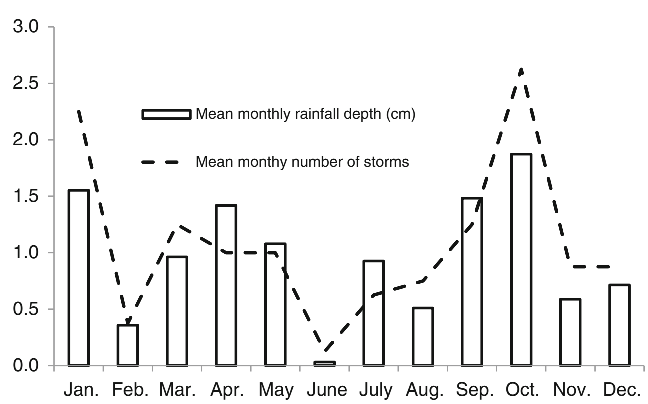

Fig. 8 Seasonal trend of rainfall depth and number of storms (2006–2013).

results of the current study as explained by Eq. 6 and Fig. 7. In addition, the current study recommends the use of a correcting factor for rainfall records of TEMM gauge by increasing its values by 12 %. This value of the correcting factor was found to be perfectly applicable to the dual rain gauges data provided by Kimball et al. (2010).

Conclusions

Documentation and quantification of the catch difference among rainfall gauges are essential and valuable in determining the homogeneity of the rainfall data collected by various gauges within national and regional networks. This study examines the inconsistency among precipitation observations of two tipping bucket gauge (HS and TEMM) measurements at 5-min, storm, and annual temporal resolutions. The two gauges are installed at a dual station in an arid region located in western Saudi Arabia.

Precipitation data were collected and analyzed for the period 2006 to 2013. For both gauges, most of the 5-min rainfall records have rainfall depth less than 1 mm. The HS gauge fails to record about 27 % of the 5-min rainfall depths that are recorded by the TEMM gauge. For major storms (depth >10 mm), both gauges recorded the same number of storms. Although the TEMM gauges recorded more storms with depth greater than 1 mm, the difference in number of recorded storms was high (17.4 %) when storms with small depths (depth <1 mm) are considered. The TEMM gauge recorded greater number of small rainfalls compared with the HS gauge. This can be ascribed to its ability to capture small amounts of precipitation as small as 0.1 mm compared with 0.254 mm for HS station. HS gauge tends to report higher rainfall depth for storms with high rainfall intensity. One possible reason for the significant differences of rainfall intensity values of the two gauges may be the ability of gauge HS to record rainfall depth of high-intensity events more precisely than TEMM gauge.

HS gauge reported higher values of annual, storm, and 5-min rainfall depths compared to the TEMM gauge. The relationships between values of rainfall depths of the two gauges were found to be linear with values of coefficients ranging between 1.103 and 1.139 and an average value of 1.118. The current study recommends the use of a correcting factor for rainfall records of TEMM gauge by increasing their values by 12 %. The suggested value of the correcting factor was found to be perfectly applicable to the dual rain gauges data provided by Kimball et al. (2010). This suggestion may be applicable to all non-siphon rain gauges. However, this is only an initial recommendation which needs to be verified in future studies through using data from more siphon and non-siphon gauges.

Data from the dual gauges indicates that each gauge has its own strengths and limitations. For estimating annual rainfall depth, records of the HS gauge are always higher than those of the TEMM gauge and it can be considered more accurate in this regard. On the other hand, the HS gauge provides more accurate 5-min rainfall depth for intense storms and hence it provides more accurate values of rainfall intensity for short durations. However, the TEMM gauge can be considered as more accurate in estimating the start and end time of the storm, since it has higher sensitivity to rainfall as small as 0.1 mm. This is expected to give a better estimation of storm duration and temporal variation. It is believed that by using dual gauges, unanticipated errors in precipitation measurements can be detected easily and data can be corrected and adjusted. This supports the recommendation of Al-Wagdany (2015) to install dual rain gauge in arid regions.

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