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Evaluation of Dual Tipping-Bucket Rain Gauges Measurement in Arid Region Western Saudi Arabia

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Abstract In this study, a dual tipping-bucket (TB) rain gauge station is installed in an arid region in western Saudi Arabia. The size of the gauge collector was the only difference between the two installed rain gauges. Records of both gauges for the period 2006–2013 are collected, analyzed and compared, focusing on characteristics of rainfall events as well as rainfall temporal variability. The two gages recorded almost the same total rainfall depth but significantly different mean storm depth values. For the large storms, both gauges recorded the same mean storm depth. However, significantly variable values throughout the storm duration are observed. The TB gauge with the larger funnel size (TEMM) has the advantage of recoding more storms with depth less than 1 mm though it underestimates the depth for storms of high intensities. This study also shows the importance of using dual rain gauges in arid regions where large storms are rare and hence can be missed if only one gauge is used due to gauge failure, which is not a surprise in such harsh environment.

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

1 Introduction

Large areas of our planet can be considered arid or semiarid. In fact, 47 % of the surface of Earth can be classified as dry land [1]. In such regions, proper management of water resources is essential for survival and to maintain various activities by their inhabitants. Availability of hydrologic data is the main constraint challenging proper water resource planning and management in arid regions [2]. In arid regions within Saudi Arabia, major rain storms are rare and valuable and their temporal as well as spatial characteristics need to be measured with the highest possible accuracy. Unavailability or inaccuracy of rainfall data can cause negative impacts on ongoing research that often aims to evaluate the accuracy of remote sensing rainfall products [3,4]. Arid mountainous region located in western Saudi Arabia is affected by the occurrence of flash floods which are usually caused by short-duration highly intense rainfall events. Flash floods, with their short duration, demonstrate high destructive powers that can be attributed to high velocity surface flow from high intensity and short-duration major rainfall events. Recent flooding events in western Saudi Arabia have resulted in significant loss of lives and infrastructure damage. One of the major abstractions to investigating flash flood in arid regions is the lack of accurate and sufficient rainfall data. For example, the only rainfall data available for researchers to investigate the flash flood occurred in Jeddah in the 30th of November 2009 were a total daily rainfall from only one gauge station. Kotwicki and Al Sulaimani [5] expect that the Arabian Peninsula will witness more violent floods due to the expected increase in rainfall intensity due to the overall acceleration of the hydrologic cycle.

Rainfall measurements are fundamental to many climatological reinvestigations and hydrologic designs. Reliable quantitative knowledge of precipitation is required for investigating spatial and temporal distribution of rainfall necessary for the quantification and prediction of rainfall phenomena. Despite recent developments in the use of remote sensing, rain gauge data are still essential for operational and calibration purposes. In Saudi Arabia, the arid and semiarid regions are not only suffering from water shortage but also from hydrometeorological data shortage [6,7]. Therefore, rainfall studies in Saudi Arabia are rare and mostly deal with analy-

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sis of daily, monthly and annual rainfall. A study by Wan [8] demonstrated rainfall characteristics in Saudi Arabia using a series of annual rainfall maxima for selected durations up to 24 h and by applying the station-year method. Wheater et al. [9] used short-term rainfall data from a comprehensive hydrometric network to investigate design rainfall in southwest Saudi Arabia. Alyamani and Sen [10] used data from 29 rainfall gauge stations to conduct a study of regional variations of monthly rainfall amounts in Saudi Arabia. Intensity duration frequency curves for nine operational regions in Saudi Arabia were derived by Al-khalaf [11] using data from 28 rainfall stations. Awadallah and Younan [12] proposed design storm distributions using short-duration rainfall data from 18 rainfall stations in Saudi Arabia, Egypt, Oman and Qatar. Subyani et al. [13] investigated the relationship of annual and seasonal rainfall with elevation in western Saudi Arabia utilizing records of 30 stations over the course of 35 years. Almazroui [6] calibrated TRMM rainfall amounts with respect to the rain gauge data recorded at 29 stations across Saudi Arabia. Al-Ahmadi and Al-Ahmadi [14] investigated the relationships between rainfall and altitude of the terrain in Saudi Arabia using monthly rainfall data from 180 stations. Most of the above investigations dealt with annual, seasonal, monthly and daily rainfall data due to the unavailability of rainfall records for shorter durations.

The invention of the rain gauge is often attributed to Castelli in 1639 [15]. Numerous types of rain gauges have been utilized for precipitation measurement such as weighing gauges, capacitance gauges, tipping-bucket (TB) gauges, optical gauges and others. However, TB rain gauges are the most widely used type of telemetered rain gauge. It is often used for precipitation measurements by agencies such as the U.S. National Weather Service, the U.S. Geological Survey and the U.S. Forest Service [16]. Tipping-bucket (TB) rain gauges are commonly utilized for rainfall measurements in arid regions. They offer automated recording capability of rainfall at any specified time interval. In addition, they are easily maintained, generally uncomplicated, durable and dependable. However, they can often under collect during events of very low and very high rainfall intensities [16]. According to Habib et al. [17], TB gauges also suffer from unpredictable mechanical and electrical problems as they may occasionally fail to tip during an event. The failure may be caused by partial or complete clogging of the funnel that drains into the bucket, data transmission interruption or temporary power failure. To help detect faulty gauges, Krajewski et al. [18] and Ciach and Krajewski [3] recommended the use of dual rainfall gauges. For instance, Nikolopoulos et al. [19] used data from a dual rain gauge to conduct a comparative analysis of rainfall data from several ground-based instruments. The instruments include two vertically pointing Doppler radars, S-band and X-band, an optical disdrometer, and a dual tipping-bucket rain gauge. Ciach and Krajewski [20] derived statistical characteristics of rainfall using two-year-long data samples from a dense cluster of dual rain gauges in Central Oklahoma. Ciach [21] concluded that quality of rainfall measurements could be improved through establishing measurement networks that have more than one rain gauge within each station.

Using dual rain gauges gives researchers the advantage of comparing two independently collected measurements which, hence, improves early detection of gauge failure. Additionally, it helps in spotting minor measurement inaccuracies that may not be noticed on a single rain gage data. The literature records only a few attempts to investigate advantages of utilizing dual rain gauges in general and in arid regions in particular. For example, a network of 25 dual tipping-bucket rain gauges was installed in Iowa through a collaborative effort between NASA, NOAA, the University of Maryland and the University of Iowa [22]. In our present work, we aim at understanding the ability of the dual TB gauges to represent characteristics and temporal variability of rainfall observed at the dual gauges as well as to assess the advantages of the utilization of dual gauge in arid regions.

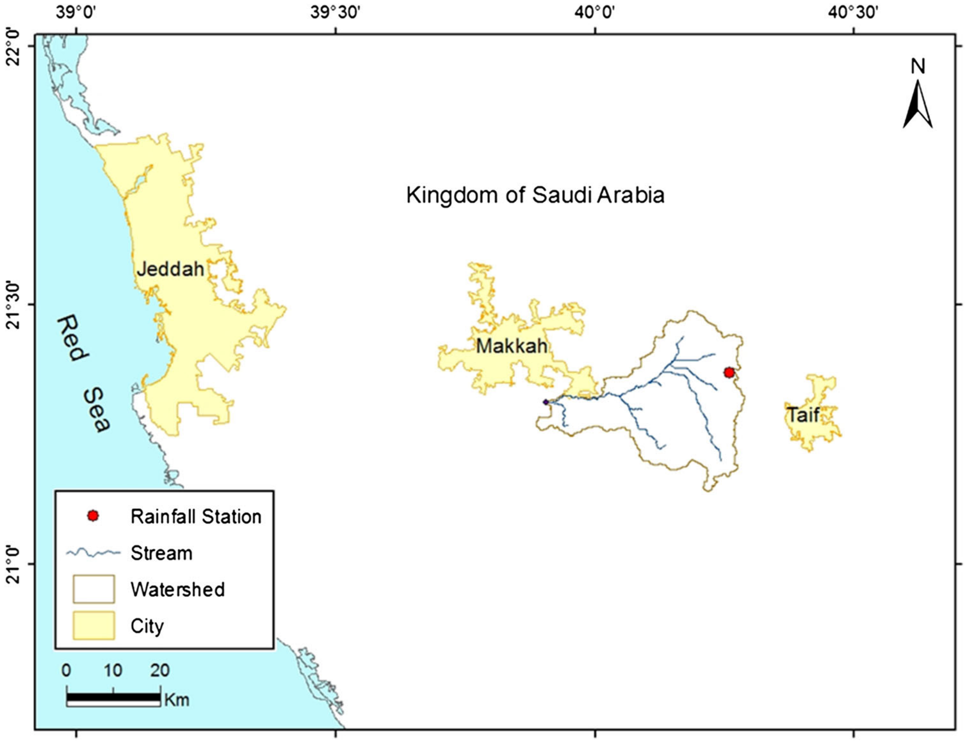
2 Materials and Method

2.1 Installation of Dual Rain Gauge

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 major basins in western Saudi Arabia where its relatively surplus groundwater that supplied the famous historic underground galleries of AinZubaidah. The basin extends between longitudes 40°00′ and 40°20′E, and latitudes 21°07′ and 21°30′N. It is located between two major cities of western Saudi Arabia namely Makkah and Taif as shown in Fig. 1. Rainfall, runoff and groundwater recharge of Numan basin were investigated by several researchers e.g. [23–29]. The primary objective of the installed rainfall stations was to focus on monitoring rainfall in the upper catchment of the basin which occasionally causes flash floods that contribute to groundwater recharge of Numan basin. The station consists of two TB gauges, data logger, battery and solar cell. The location of the gauge station site is shown in Fig. 1. The station is located in Hadda escarpments at a mountainous area with elevation of about 1,800 m above mean sea level. It is installed at the roof of a building that belongs to the Ministry of Transportation (40°15′34″ E and 21°22′10″N). Such building provides a safe and well-maintained environment.

Rainfall is measured by two tipping-bucket rain gauges: Texas Electronics rain gauges TE525MM (TEMM) and TE525 (TE). 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).

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



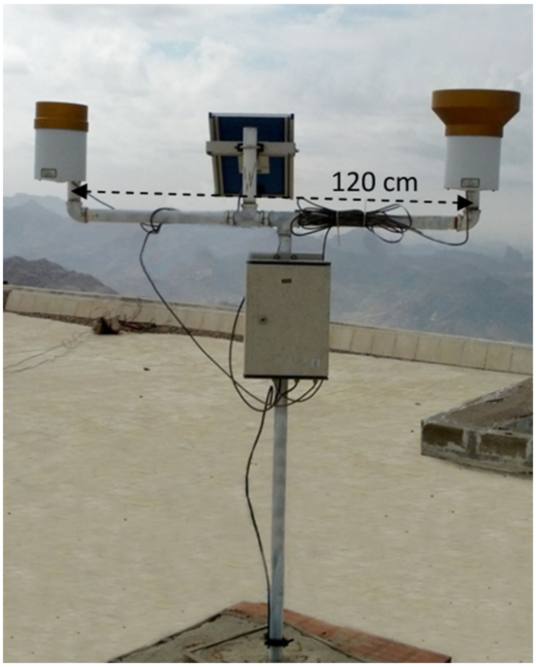


Fig. 2 Photograph of the dual gauge station

The only difference between the two gauges is the size of the gauge collector. The TEMM gauge has a 9.6-inch collector, while the TE gauge has a 6-inch collector. Although the tipping-bucket volume is the same for both gauges, the resolution (in terms of rain depth) of each tip is different due to the differences in funnel size, which may lead to different tipping counts for the same rainfall depth. The TEMM and TE gauges measure 0.10 and 0.254 mm (0.01 in) of rainfall per bucket tip, respectively. Every 5 min, the Campbell Scientific data logger (CR510) reports the number of tips that occurred in the preceding 5 min (converted to mm), as well as the accumulated rainfall since midnight.

2.2 Data Collection and Analysis

The gauges are periodically (every 3 months on average) cleaned, checked and leveled at the same time, and data are downloaded to a storage module, which can then be transferred to any PC. The raw data consist of a series of nonzero rainfall records with time (every 5 min) and date. The cumulative daily rainfall depth is also recorded at the end of the day. Data of each rain gauge are dealt with separately. 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. Storm start and finish time is extracted from the raw data for each storm, and their values are used to compute storm duration. Storm depth is computed as the accumulated rainfall amount that occurred during the period of storm duration. Finally, values of storm depth and duration are used to determine storm intensity. Comparison of records from both gauges is performed by calculating the correlation coefficients between the two gauges for rainfall depth, duration and intensity.

In this study, rain storms were classified into three categories: storm depth of nonzero (all storms), greater than 1 mm and greater than 10 mm. Storms of total depth of 1 mm or less have no hydrologic significance and are usually ignored, but they have been considered in this study for comparative reason only. Storms of 1–10 mm are very important to set the initial soil moisture condition, which plays an important role in flood generation and flood magnitude. Statistics such as mean, maximum and standard deviation of storm depth duration and intensity is computed for each category of storms. Statistics is also performed on rainfall depth and intensity on 5-min basis. Moreover, cumulative frequency distribution of both 5-min storm duration and total storm duration are determined. Values of maximum rainfall depth for several durations (5, 10, 20, 30, 40 min and 1, 3 12 and 24 h) for each year of the records (2006–2013) are also extracted and used to construct the IDF curves for both TB gauge stations. The IDF curves are developed using the frequency analysis procedure described by Chow et al. [30].

3 Results and Discussions

Records of dual rain gauges rainfall depths and durations for the period between 2006 and 2013 are used in the study. During this period, more than 200 events were recorded according to the criteria set in the above mentioned. The accumulated rainfall depth during the whole collection period is more than 1,000 mm. Total rainfall depth per storm varied from less than 1 mm to about 60 mm. Average rainfall intensity varied from less than 1 mm/h to about 50 mm/h, with an overall average of about 4 mm/h. Storm maximum duration is about 24 h, with duration of most events being less than 4 h.

Both gauges have recorded many storms with very small rainfall depths. Perhaps days in which these storms occur may not be considered as rainy days according to some researchers. However, several researchers have different definition of rainy days. For example, Schulze [31] defined the rain day with at least 0.5 mm of rainfall. In this study, no rainfall event is excluded, but rainfall data are investigated as described above for different categories based on rainfall depth. Table 1 presents storm characteristics for both gauges classified into three categories according to storm depths namely nonzero depths, greater than 1 mm, and greater than 10 mm. Difference (as percentage values) between the two rain gages is calculated according to the following equation:

$$Diff\ ratio\ \% = \frac{(TEMM - TE)}{TEMM} \times 100$$

where TEMM and TE are the values of interest recorded at TEMM and TE stations, respectively. Both gauges recorded the same number of storms for major storms (depth >10 mm), while TEMM gauge recorded more storms for storm depth greater than 1 mm. The difference in number of recorded storms is high (20.3 %) when storms with small depths (depth <1 mm) are considered. However, discrepancies on rainfall spectrum induced by considering the small storms have no significant influence on the hydrology of the study

Table 1 Storm characteristics for the dual station (TEMM and TE)

Storm property	Gauge	Rainfall categories		
		>0 mm	> 1 mm	>10 mm
No. of storms	TEMM	261	125	30
	TE	208	118	30
	Diff ratio %	20.31	5.6	0
Mean storm depth (mm)	TEMM	4.08	8.2	22.71
	TE	5.18	8.83	22.71
	Diff ratio %	−26.96	−7.68	0.00
Mean storm duration (min)	TEMM	100	163.6	227.5
	TE	105.8	161.4	201.5
	Diff ratio %	−5.80	1.34	11.43
Mean storm intensity (mm/h)	TEMM	2.99	4.91	8.56
	TE	4.45	6.03	10.21
	Diff ratio %	−48.83	−22.81	−19.28
Maximum storm depth (mm)	TEMM	56.4	56.4	56.4
	TE	59.2	59.2	59.2
	Diff ratio %	−4.96	−4.96	−4.96
Maximum storm duration (min)	TEMM	1,120	1,120	1,105
	TE	1,410	1,410	1,105
	Diff ratio %	−25.89	−25.89	0.00
Maximum storm intensity (mm/h)	TEMM	29.1	29.1	29.1
	TE	52.3	52.3	52.3
	Diff ratio %	−79.73	−79.73	−79.73

area as mentioned above. The two gauges also have identical values for mean storm depth of large storms and significantly different means when small storms are included. Differences between values of mean storm duration are not significant for all storm depths. As for extreme values, both gauges reported not very different values for maximum storm depth (−5 %) but different values for maximum storm duration when small storms are included with a difference of −26 %. The difference between mean storm intensity values decreases when storms of small depths are discarded. Values of maximum storm intensity are significantly different (about −80 %) for the two gauges regardless of the considered storm depths in the computations.

Both gauges record rainfall depth at 5-min intervals for the whole period. The 5-min rainfall depth ranged from less than 1 mm to about 9 mm with an average depth of about 0.6 mm. The 5-min storm average intensity ranges from less than 1 mm/h to about 100 mm/h, with an average intensity of about 7 mm/h. Table 2 presents the main characteristics of the 5-min rainfall reported by TE and TEMM rainfall gauges. Although both gauges records show a difference of about 0.69 % of total rainfall depth, TE gauges fail to record more than one-third of the 5-min rainfall depths that were recorded by the TEMM gauge with a difference of about 36 %. However, TE gauge reported higher values of mean depth, maximum depth and intensity with differences of −61, −20 and −20 %, respectively.

The relative differences between the 5-min rainfall depth of both gauges were investigated. The relationship between mean relative differences in the 5-min rainfall depth and the 5-min rainfall depth of TEMM gauge is shown in Fig. 3. The figure indicates that the absolute value of the relative difference between the two gauges increases from 4.2 to 20.1 % with the increase of the value of the 5-min rainfall depth. Therefore, TE gauge tends to report higher rainfall depth relative to TEMM gauge for storms with high rainfall intensity. This can be attributed to undercatchment during heavy rainfall events which is a typical error associated with tipping-bucket rain gauges [16]. During intense rainfall events, water loss occurs while the bucket is in the act of tipping and therefore, the gauge may have not collected all of the rainfall entering the outer funnel. This error is expected to be larger for gauge TEMM for which the buckets need to flip more since it has larger funnel.

Table 2 Characteristics of the 5-min rainfall

Rainfall property	Gauge	Values
No. of rainfall records	TEMM	2,311
	TE	1,487
	Diff ratio %	35.66
Total rainfall depth (mm)	TEMM	1,070.2
	TE	1,077.6
	Diff ratio %	−0.69
Mean rainfall depth (mm)	TEMM	0.46
	TE	0.74
	Diff ratio %	−60.87
Maximum rainfall depth (mm)	TEMM	7.4
	TE	8.89
	Diff ratio %	−20.14
Maximum rainfall intensity (mm/h)	TEMM	88.8
	TE	106.6
	Diff ratio %	−20.05

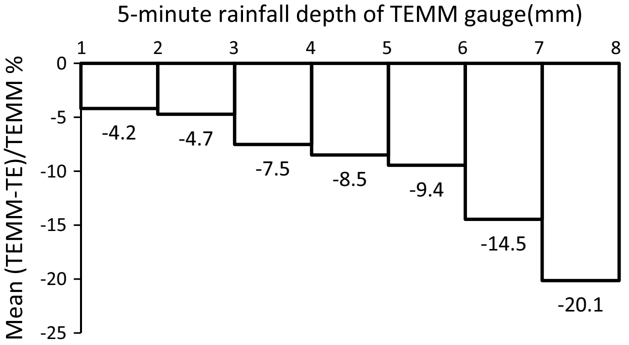
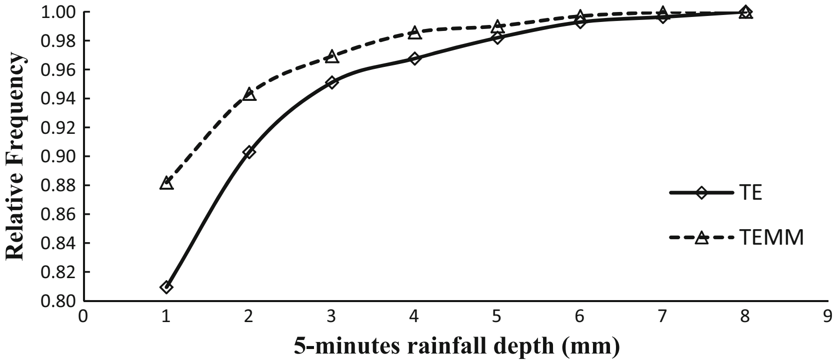


Fig. 3 Mean relative differences in 5-min rainfall versus TEMM 5-min rainfall depth

Figure 4 shows the relative cumulative frequency distribution of the 5-min rainfall depths computed from the entire dataset of both gauges. The figure indicates that most of the records (81–87 %) have rainfall depth less than 1 mm for both stations in the 5-min interval. Additionally, gauge TEMM recorded more events of small rainfall compared with station TE. This can be attributed to its ability to capture as small amount of rainfall as 0.1 mm compared with 0.254 mm for TE gauge. The relative frequency distributions of rainfall depths for all storm events are shown in Fig. 5. It is clear that gauge TEMM has higher percentage of storms with depths less than 10 mm. Ignoring storms with depths less than 1 mm, the relative cumulative frequency distributions for both gauges are almost identical except for rainfall depths less than 2 mm as shown in Fig. 5.

The relative frequency distribution of the difference between the two gauges 5-min rainfall totals (TEMM–TE) is presented in Fig. 6. For more than 90 % of the recorded 5-min totals, the difference ranged between −0.25 and 0.25 mm. The TEMM gauge recorded higher 5-min rainfall depths in about 60 % of the records. Figure 7 shows the relation between 5-min rainfall depths for both gauges. The relationship indicates that records of the two gauges are very comparable for rainfall depths less than 4 mm. For higher 5-min rainfall depths (and hence intensities), the TE reported higher rainfall amount compared with TEMM gauge.

Fig. 4 Relative cumulative frequency of 5-min rainfall depths



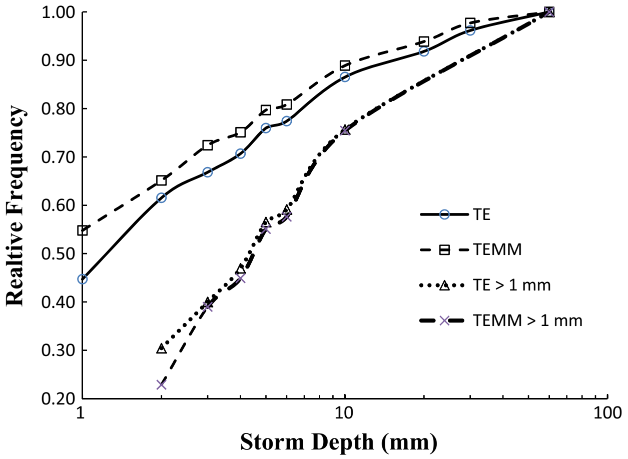


Fig. 5 Relative cumulative frequency of storm depth

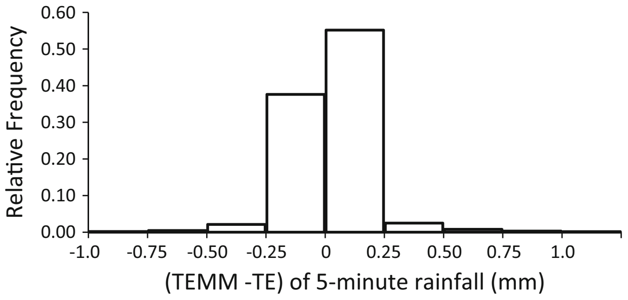


Fig. 6 Relative frequency of TEMM–TE 5-min rainfall

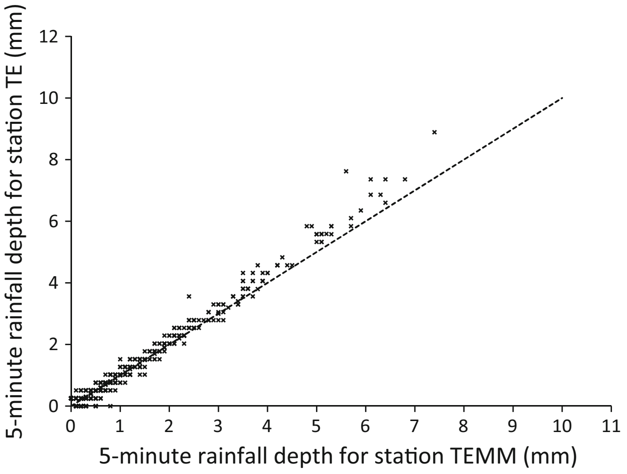


Fig. 7 Five-minute rainfall depth of TEMM gauge versus TE gauge

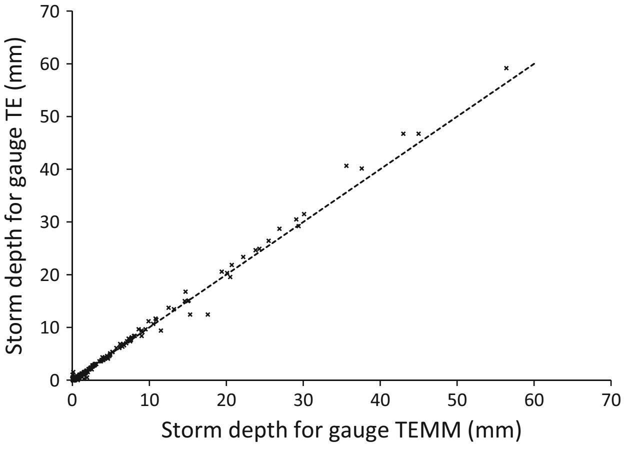


Fig. 8 Storm depth of TEMM gauge versus TE gauge

The number of rain storms that are recorded at least by one of the gauges was 169 events. The relationship between depths of these events is shown in Fig. 8. This shows that TE gauge reported higher rainfall depth for storms which have rainfall depth higher than 30 mm. This is almost similar to the above conclusion for the 5-min rainfall events for which TE reported higher depths for storms greater than 4 mm.

To check if there is any trend in the performance of the two gauges, values of annual rainfall depth for both stations were computed and presented in Fig. 9. These values are very comparable for both gauges. The maximum difference between annual rainfall depths of the two gauges occurred in 2011 and it was about 7 mm which represents 4 % of the total rainfall depth of TEMM gauge.

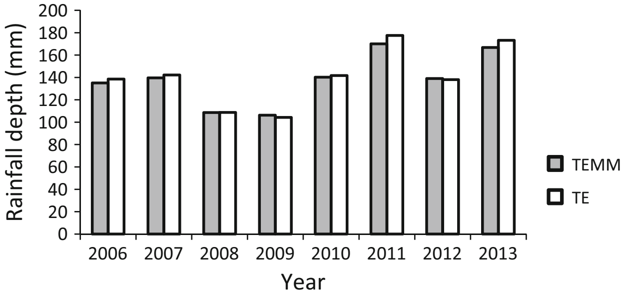


Fig. 9 Annual rainfall depth of TEMM and TE gauges

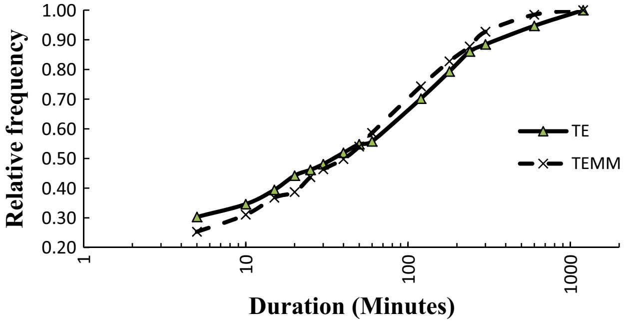


Fig. 10 Relative cumulative frequency of storm duration

The relative cumulative frequency distributions of rainfall duration for both gauges are presented in Fig. 10. It indicates that the distributions are almost similar and that gauge TE recorded relatively higher percentage of short-duration storms and lower percentage of long-duration storms than TEMM. Additionally, duration of about 50 % of the storms are less than 40 min, while most of storm durations (86 %) are less than 4 h.

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 two days are presented in Table 3. For short durations (less than 30 min), values of maximum recorded rainfall depth for gauge TE were higher than those of gage TEMM in most of the cases. Values of annual maximum rainfall depth for the different durations are used to construct IDF curves using the procedure recommended by (Chow et al. [30]). IDF curves for return periods 2 and 10 years for both gauges are presented in Fig. 11. This figure shows that IDF curves for the same return period are almost identical except for the short durations where significant differences of rainfall intensity can be noticed. This can probably be attributed to the ability of gauge TE to record rainfall depth more precisely for high intensity events compared with gauge TEMM.

Occasionally, the two gauges recorded different rainfall depths. This was examined more closely through computing the correlation coefficients between the records of both gauges for rainfall depth, duration and intensity. The correlation coefficients were 0.9967, 0.8160 and 0.9021 for storm depth, duration and intensity, respectively. The values of correlation coefficients indicate high degree of agreement between the two gauges. After considering only observations where rainfall is recorded by both gauges, the correlation coefficients varied only slightly to 0.9966, 0.8159 and 0.9074 for storm depth, duration and intensity, respectively. Among the three storm properties, storm duration shows the lowest degree of agreement, while storm depth showed almost perfect agreement.

Table 3 Maximum rainfall depth for specific durations for both gauges

Duration (min)	Maximum depth (mm)		Relative difference (%)
	TEMM	TE	
5	7.4	8.9	20.1
10	13.2	14.0	−5.8
15	18.3	19.6	−6.9
20	22.0	23.1	−5.0
25	26.0	27.2	−4.5
30	29.5	30.0	−1.6
35	31.2	30.5	2.3
40	32.0	32.5	−1.6
45	32.7	35.0	−7.2
50	34.2	36.8	−7.7
55	38.6	40.1	−4.0
60	41.2	42.9	−4.2
90	44.1	46.0	−4.2
120	44.6	46.5	−4.2
180	47.1	50.0	−6.2
24 h	67.9	70.6	−4.0
48 h	76.9	78.7	−2.4

The two gauges may record different rainfall depths due to a fault in one of the gauges. Table 4 shows the record of both gauges for a storm that occurred on the 30th of December, 2010. The funnel of gauge TE was almost clogged by dirt and only small amount of rainfall managed to drain into the buckets. Temporal rainfall depth of the storm is shown in Table 4. TE gauge recorded about 20 % of rainfall depth and completely failed to record the correct time of its occurrence. According to TEMM gauge, storm depth was 9.1 mm which is a major rainfall event in arid regions. This emphasizes the importance of installing dual rain gauge in arid regions where storms are rare and environmental conditions are harsh which may lead to missed valuable events when only single rain gauge is used.

4 Conclusions

In this study, comparison of rainfall measurements by two tipping-bucket rain gauges (TE and TEMM) installed at a dual station in an arid region located in western Saudi Arabia was undertaken. The current study is probably the first

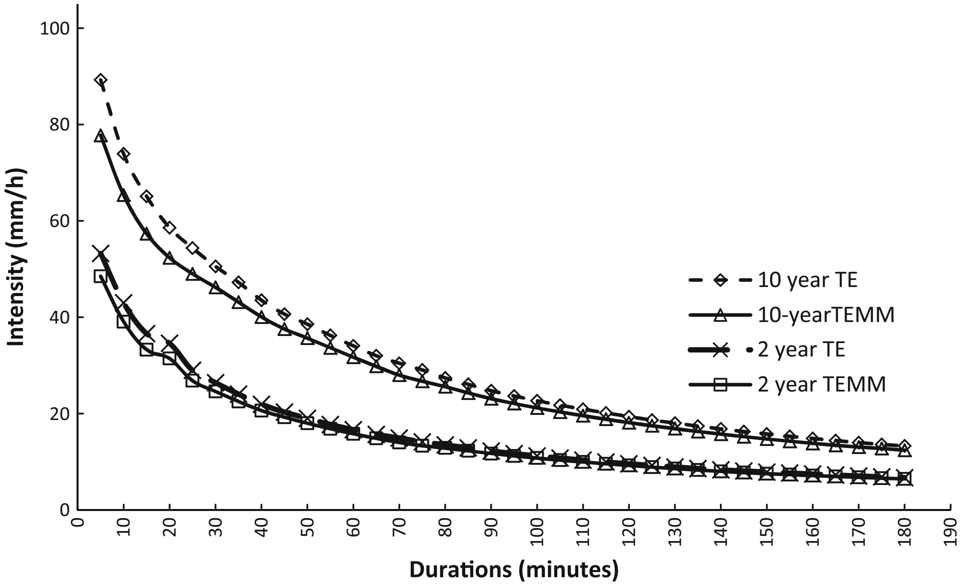


Fig. 11 IDF curves for TE and TEMM gauges

Table 4 Records of rainfall depth from gauges TE and TEMM for the storm of 30/12/2010

Time	Rainfall depth (mm)	
	TEMM	TE
10:00	0.10	0.00
10:05	0.10	0.00
11:10	0.10	0.00
14:00	0.20	0.00
14:05	0.60	0.00
14:10	0.20	0.00
14:15	1.90	0.00
14:20	3.20	0.00
14:25	0.40	0.00
14:30	0.90	0.00
14:35	0.70	0.00
14:40	0.10	0.00
14:45	0.30	0.00
14:50	0.10	0.00
14:55	0.10	0.00
15:30	0.00	0.254
17:20	0.00	0.254
19:15	0.00	0.254
20:40	0.00	0.254
21:50	0.10	0.254
22:20	0.00	0.254
23:35	0.00	0.254
Total	9.10	1.778

attempt to undertake such study in a mountainous arid region to the best of the author's knowledge. However, the study has a limitation due to the use of only one pair of gauges. Another limitation of the current investigation is that the tipping-bucket gauges can suffer from spurious tips due to the resonance effect of malfunctioning reed switch. By setting the data logger to the regime used in this study (counting tips per 5 min interval), it is difficult to detect this problem. The dual gauge setup is not a universal remedy for all possible errors in rain gauge measurements since they are subject to random and systematic errors, the most important of which are induced by wind [32]. In the current study, wind field may have affected the two gauges in different ways. Correcting for this effect remains difficult and beyond the scope of this investigation.

The analysis of eight years of continuous rainfall record of both gauges indicated that most of the 5-min rainfall records have rainfall depth less than 1 mm for both stations. Although both gauges recorded almost the same total rainfall depth, TE gauge fails to record about one-third of the 5-min rainfall depths that are recorded by the TEMM gauge. Both gauges recorded the same number of storms for major storms (depth > 10 mm), while TEMM gauges recorded more storms with depth greater than 1 mm. The difference in number of recorded storms was high (20.3 %) when storms with small depths (depth < 1 mm) are considered. Station TEMM recorded greater number of small rainfalls compared with station TE. This may be attributed to its ability to capture small amounts of rainfall as 0.1 mm compared with 0.254 mm for TE station. TE gauge tends to report higher rainfall depth for storms with high rainfall intensity. The relative cumulative frequency distributions for both stations are almost identical except for rainfall depths less than 2 mm. Analysis of IDF curves shows that significant differences of rainfall intensity values between the two gauges can be noticed for short duration rainfall events (less than 60 min). This indicates the importance of using dual gauge stations in arid regions where a good number of events may have duration less than 60 min. The significant differences of rainfall intensity values may be attributed to the ability of gauge TE to record rainfall depth of high intensity events more precisely than TEMM gauge. TEMM gauge tends to lose more rainfall as it requires more tips for the same depth of rainfall due its large size funnel. Correlation between values of storm depth, intensity and duration of the two gauges was generally high with correlation coefficients of 0.9967, 0.8160 and 0.9021 for storm depth, duration and intensity, respectively.

Comparing the performance of the two gauges, we find each gauge has its own strengths and limitations. For estimating annual rainfall depth, records of the two stations were very comparable. TEMM gauge can be considered more accurate in estimating the start and end time of the storm, since it has higher sensitivity to as small amount of rainfall as 0.1 mm. Therefore, it is expected to provide a better estimation of storm duration and temporal variation. On the other hand, the TE gauge provides more accurate 5-min rainfall depth for intense storms and hence it provides more accurate values of rainfall intensity for short durations as shown in the IDF curves presented in the paper. It is believed that by utilizing dual gauges, unforeseen errors in rainfall measurements can be detected easily and that data can be corrected and adjusted. This supports the recommendation of the current study to install dual rain gauge in arid regions.

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