Investigation of Tipping-Bucket Rain Gauges Using Digital Photographic Technology

MINHAN LIAO

*Nanjing Hydraulic Research Institute, and College of Hydrology and Water Resource,
Hohai University, Nanjing, China*

JIUFU LIU, AIMIN LIAO, AND ZHAO CAI

Nanjing Hydraulic Research Institute, Nanjing, China

YIXIN HUANG

College of Hydrology and Water Resource, Hohai University, Nanjing, China

PENG ZHUO AND XUEGANG LI

Nanjing Hydraulic Research Institute, Nanjing, China

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ABSTRACT

When studying the tipping-bucket rain gauge (TBR), it is rather difficult to make an objective and sophisticated measurement of the duration of bucket rotation. From the perspective of digital photographic technology, however, the problem can be easily solved. The primary interest of this research has been to use digital photographic technology to study the TBR under laboratory conditions. In this study, the interframe difference algorithm and a camera recording device were used. Based on three types of JDZ TBRs, the time variation characteristics of bucket rotation were obtained. The time from the beginning of a tip to the time that the bucket is horizontal T_1 and the time for a complete tip T_2 were analyzed in detail. The results showed that T_1 and T_2 were functions of rainfall intensity, and T_1 and T_2 decrease as the rain intensity increases significantly ($P < 0.001$). Moreover, excellent evidence shows that the averages of T_1 and T_2 were positively correlated with bucket mass. It took more time for the bucket to tip as the mass of the bucket increased. Furthermore, the error of each TBR was calculated by the new proposed error calculation formula, and the new method was compared with the traditional method. The results from the two methods were very close, which demonstrates the correctness and feasibility of the new formula. However, the traditional calibration cannot acquire the variation characteristics of the tipping time, but the proposed approach can achieve this.

1. Introduction

At present, tipping-bucket rain gauges (TBRs) have become the most common instrument for automatic rainfall measurement in basic national rainfall stations and in meteorological observation stations for observation and research (Giles 2010; Humphrey et al. 1997; Liu and Gu 2018; Santana et al. 2015; Shedekar et al. 2016; Upton and Rahimi 2003). Rainfall observation

accuracy plays an essential role in hydrological forecasting, flood control, landslide prediction, and many hydrological models (Feki et al. 2017; Lewlomphaisarl and Saengsatcha 2012). Because the TBR features a simple structure, is suitable for automatic recording, and has a relatively inexpensive design, much effort has been dedicated to achieving a fundamental understanding of the TBR (Ciach 2003; Vasvári 2005; Wang et al. 2008).

Many institutions, such as the World Meteorological Organization (WMO), have investigated the performance

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Corresponding author: Aimin Liao, seamsun1226@163.com

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of various models of TBRs and conducted intercomparisons of rainfall intensity gauges in the laboratory and in situ (Lanza et al. 2005; Lanza and Vuerich 2009). The major finding of the WMO was that the TBR with software correction can measure rainfall intensity better than other devices without correction and that uncorrected gauges have large errors. Calder and Kidd (1978) had earlier proposed the concept and method of dynamic calibration. They calibrated the TBR under different rainfall intensities, and the tipping times were calculated by the dynamic calibration method. Based on the rain gauge parameters determined, tipping time could be obtained by plotting the time between tips versus the reciprocal of applied flow rates. The TBR without correction is known to underestimate rainfall at higher intensities because of water loss during bucket rotation; Marsalek (1981) used time-lapse photography to measure the duration of bucket movement (from the start of bucket movement to the horizontal position), which ranged from 0.3 to 0.6 s. Measurement of the tipping time enables better comparison of the experimental calibration curve with its theoretical expression (Lanza et al. 2005). The rotation process is too short to be captured easily because the human eye and some instruments have difficulty in judging when the bucket starts to rotate due to the very slow initiation of bucket rotation, when the bucket reaches the horizontal position, when the bucket first strikes the stop screw, and when the bucket rebounds. Hence, it is difficult to define when the bucket starts to move. For this reason, the time of tipping is difficult to define, but the problem is fascinating and compelling.

Research on moving target detection has attracted widespread attention and has been done for a long time, such as to judge whether a vehicle is moving and to analyze flow and detect accidents in traffic management and intelligent monitoring systems (Nkoro and Vershinin 2014; Yang and Pun-Cheng 2018). In this domain, sequences of images are called videos, and each image is called a frame (Imrankhan Pathan and Chauhan 2015). There are many algorithms to judge whether an object is moving, for example, the inter-frame difference algorithm (IDA), the optical flow algorithm, the background subtraction algorithm, and so forth (Imrankhan Pathan and Chauhan 2015; Meyer et al. 1997; Ranftl et al. 2014; Sobral and Vacavant 2014). The optical flow algorithm is complex, and its real-time performance is unsatisfactory (Imrankhan Pathan and Chauhan 2015; Li et al. 2016; Zhang et al. 2009). The background subtraction algorithm uses the difference between a targeted frame and a background image. This method can easily extract a target (Li et al. 2016); however, the tipping bucket has left and right sides

(rotation from left to right and return), and therefore this method is not satisfactory for the present situation. Fortunately, the IDA seems to satisfy the needs of this research. The IDA is the most common method for moving target detection with a static background (Weng et al. 2010) and calculates the differences between adjacent frames. For images captured by a fixed camera recording device, the background can be considered static, and the changes mainly occur with the movement of tipping-bucket rotation. This algorithm is simple to implement, modest in computation requirements, fast in execution, and relatively insensitive to scene changes such as illumination. The greatest disadvantage of the algorithm is that it is sensitive to environmental noise. Because the environment in the laboratory is relatively stable, the IDA can be used to investigate the TBR.

There are relatively few published studies on the use of digital photographic technology to investigate the tipping time of TBRs. In a previous study, under conditions of low- and medium-intensity flow, digital photographic technology (a video sequence) was used to observe the water lost in bucket movement during the bucket rotation process (Lanza et al. 2005). The report argued that the tipping time was a function of rainfall intensity; however, there were no experimental data to support this argument, and no function was provided. In another previous study, a high-speed camera with analysis software was used to study the undercatch of a TBR in the laboratory (Duchon et al. 2014). The methodology in Duchon's study was excellent and creative; however, the start of the bucket movement was somewhat subjectively determined, and only one model of TBR was tested.

According to the above background on the TBR, the need for an objective and sophisticated measurement of the time of bucket rotation has not been thoroughly addressed. To enhance a better understanding of the bucket rotation process of TBRs, it is promising to use digital photographic technology (including a camera and image processing technology). The aims of this investigation are (i) to develop a sophisticated and objective measurement of the variation characteristics of the tipping time of the TBR and (ii) to propose a new formula to calculate the error of the TBR. These would provide a new approach to investigate the TBR.

2. Methodology

a. Laboratory setup

An automated rainfall intensity generation system (Fig. 1) was designed to perform laboratory simulations of various rainfall events with a variety of rainfall

FIG. 1. The experimental setup in laboratory. (a) Simplified schematic of the laboratory setup—1: TBRs for tested; 2: electronic balance 1; 3: electronic balance left; 4: electronic balance right; 5: camera recording device; 6: controlling machine; 7: transparent pipe; 8: windshield. (b) Photo of automated rainfall intensity generation system.

intensities employing a high-precision peristaltic pump (LLS Plus, Kamoer, China), which provides a constant flow and can be set to different flow rates. Moreover, a calibration curve was obtained by electronic balance 1 (CP4102, Ohaus, United States) and implemented into the control software to correctly drive the peristaltic pump. To reduce the impact of water density on the experimental results, deionized water was used (for the purpose of this research, the density of rainwater $\rho = 1 \text{ g cm}^{-3}$). In addition, the movement of the tipping bucket was recorded using an advanced camera recording device that can record 100 frames per second of video for tipping time analysis. Water draining from each bucket of the TBR was collected in glass containers and weighted on the left and right electronic balances (CP3102, Ohaus, United States). Forty tips were recorded for each rainfall intensity performed. The inflow rainfall intensity to the tipping bucket was fixed at 0.4, 1, 2, 3, and 4 mm min^{-1} . These five rainfall intensities were chosen according to the rainfall intensities range in the WMO intercomparison (Lanza et al. 2005). Moreover, good lighting was required (Duchon et al. 2014), and therefore a lamp was used. Finally, a

windshield was also used to ensure the stability of the experiment. In Table 1 the basic characteristics of the TBRs used for laboratory tests are summarized. JDZ series TBRs (Jiangsu Water Technology Company Ltd., China; see Fig. 2; J indicates precipitation, D indicates tipping bucket, and Z indicates solid-state storage) are widely used in China's basic rainfall stations, meteorological observation stations, research institutes, and other industries or departments involved in rainfall observation (Liao et al. 2020). Therefore, they are quite representative in rainfall observing stations and are worth investigating in China.

b. Interframe difference algorithm for measuring tipping time of TBRs

This experiment intended to use digital photographic technology, including a camera recording device, for experimental data acquisition, and then to use the MATLAB image processing technology for image extraction and analysis. In addition, a motion detection algorithm was used to judge bucket rotation. When the simulated rainfall event occurred, the camera recording device started at the same time and recorded these processes. According to this method, a computer is used

TABLE 1. Basic parameters of the rain gauges tested.

	Rain gauge type		
	JDZ02	JDZ05	JDZ10
Resolution (mm)	0.2	0.5	1
Receiver area (cm^2)	314.2	314.2	314.2
Nominal bucket volume (cm^3)	6.28	15.71	31.42
Bucket mass (g)	26.72	30.19	57.36
Bucket length (cm)	13.4	12.5	15.2
Angle of bucket rotation from one resting position to another ($^\circ$)	26.4	39.4	43.5

FIG. 2. (top) Three types of TBRs used in the laboratory experiment: (a) TBR-JDZ02, (b) TBR-JDZ05, and (c) TBR-JDZ10. (bottom) Views of the buckets only: (d) JDZ02, (e) JDZ05, and (f) JDZ10.

to judge whether the bucket is moving (Li et al. 2016; Weng et al. 2010). To obtain an accurate tipping time, this study chose to use the IDA for image processing to judge when the tipping bucket started to move. The principle of the IDA is described below.

The basic principle is to detect and extract the moving target in the image using the pixel-based time difference between two frames adjacent to the image sequence. First, the pixel value of the adjacent frame image is subtracted to obtain a difference image, and then the difference image is binarized (0 and 1 were left). If the ambient brightness does not change much, and if the corresponding pixel value changes less than a pre-determined threshold, then the pixel is a background pixel; if the pixel values of the image area vary greatly, this can be assumed to be caused by moving objects in the image. SUM is the sum of all the pixels value in the difference-binary image and SUM is the result of IDA. It should be emphasized here that SUM is the simplest and most direct indicator in use to judge bucket rotation. It processes two image frames to determine whether a

moving object is present in the video sequence. Figure 3 shows the main working steps.

The interframe difference method formula is given by the equation

$$D_t(x, y) = \begin{cases} 1, & [F_t(x, y) - F_{t-1}(x, y)] \geq R \\ 0, & [F_t(x, y) - F_{t-1}(x, y)] < R \end{cases} \quad (1)$$

where R is the threshold value, the two frames are subtracted, and the difference between the two frames is obtained. R is a parameter used to diagnose the starting time of bucket rotation. Motion of the two frames does not occur if $D_t(x, y)$ takes on a value of 0, but if there is a moving object, the value of $D_t(x, y)$ is 1.

The choice of R is critical: too low a threshold may yield noise, but too high a threshold may ignore useful movements in the image. In fact, after many experiments and comparisons, in this study, the R was chosen to be 10 (see Fig. 4). Figure 4 shows six difference images analyzed with the IDA algorithm; Fig. 4a (SUM = 5) shows only noise that should be excluded. Images in

FIG. 3. The main working steps of interframe difference algorithm. On the left side, F_t and F_{t-1} are the two images acquired at frame t and frame $t - 1$, respectively, and D_t is the difference of the two images. The effect of image binarization is to facilitate the extraction of information in images and can increase recognition efficiency when performing computer recognition.

FIG. 4. The basis for selecting the threshold to judge bucket rotation in the video sequence and in the lower right of each panel is the enlarged area for (a) frame 2 minus frame 1, SUM = 5; (b) frame 3 minus frame 2, SUM = 10; (c) frame 4 minus frame 3, SUM = 15; (d) frame 5 minus frame 4, SUM = 20; (e) frame 6 minus frame 5, SUM = 49; (f) frame 7 minus frame 6, SUM = 202.

Figs. 4b–d have SUM values of 10, 15, and 20, respectively, indicating a slow motion of the bucket. Finally, Figs. 4e and 4f, with values of SUM equal to 49 and 202, show a clear movement of the bucket. Therefore, evaluation of the start of bucket movement was objective, although the rotation rate was extremely slow when the bucket was just beginning to move off its stop screw.

Figure 5 shows 14 selected photos of bucket movement during one rotation, with the SUM result for each shown on the right side of the figure. There is evidence that, as the bucket rotated, the difference between two adjacent frames became obvious. Frame 645 was completely stationary; when frame 646 was subtracted from frame 645, the resulting SUM = 21 was greater than a predetermined threshold (the threshold = 10, as stated earlier). Therefore, it can be concluded that the bucket had started to move. The bucket reached the horizontal position in frame 677, and the bucket first strikes in frame 683. Finally, the rebound process is shown in

frames 685 and 686; however, less attention was given to the rebound process, although it still exists. The white image elements in the pictures of Fig. 5 indicate the change of bucket location between two contiguous frames. When the bucket starts with quite slow speed, the number of white image elements is small. With the bucket goes on rotating, the rotation speed increases, and thus the number of white image elements is larger. When the bucket approaches another bucket support, the rotation speed increases to the highest, and thus the number of white image elements is largest (see Fig. 6). When the bucket reaches its horizontal state, both the rotation speed and the value of SUM will appear as a knee point. Additionally, the environment in the laboratory was relatively stable, markers or stickers were not used for image processing. Therefore, the optics of light reflectance does not play a role in accuracy of the algorithm presented in this work. Although it may cause error, there exists a time error less than 0.01 s.

FIG. 5. A process of bucket rotation and the result of IDA.

FIG. 6. Variation of SUM with time for 4 mm min^{-1} rain intensity. (a) An example for JDZ02 only. (b) An example for JDZ02, JDZ05, and JDZ10 showing T_1 , T_2 , and T_3 .

The impact on the result is small, so the accuracy of 0.01 s is enough. The value of SUM was continuously increasing when the movement was underway, an observation that will be stated in detail later.

c. Analysis of the error of TBRs

In general, the error is calculated by the following formula (Colli et al. 2014; Wang et al. 2008):

$$e = \frac{\text{RI}_m - \text{RI}_r}{\text{RI}_r} \times 100\%, \quad (2)$$

where e is the error, RI_m is the rainfall intensity as measured by the TBRs, and RI_r is the reference rainfall intensity provided by the pump (Lanza et al. 2005). RI_m can be defined as

$$\text{RI}_m = \frac{hn}{\Delta T}, \quad (3)$$

where h is the resolution (mm), n is the number of tips, and ρ is the density of deionized water (1 g cm^{-3}). The denominator ΔT is the interval between two horizontal positions. RI_r can be computed as

$$\text{RI}_r = \frac{M_r}{0.1\rho S\Delta T}, \quad (4)$$

where M_r is the rainwater flow into the bucket as recorded by electronic balance 1; S is the receiver area (cm^2), the receiver area of JDZ rain gauges is 314.2 cm^2 and the other parameters are the same as above. Because ΔT is extremely difficult to measure, the error can also be expressed as the following equation (traditional calibration):

$$e = \frac{0.1hSpn - M_r}{M_r} \times 100\%, \quad (5)$$

where, in this equation, the measurement of ΔT is avoided, and only electronic balance 1 is used to obtain the error. However, in the present study, ΔT could be measured accurately, which improved the traditional method of calculating bucket error (taking no account of water loss during bucket rotation and of water residue in the bucket because this method only calculates how much water is flowing into the bucket in the interval between two horizontal positions). The error for one tip (single-bucket error) is

$$e = \frac{h - \text{RI}_r\Delta T}{\text{RI}_r\Delta T} \times 100\%, \quad (6)$$

where the time interval ΔT is recorded by video sequence and the other parameters are as given above. The error for n tips (the cumulative error) is

$$e_n = \left(\frac{hn - \text{RI}_r \sum_{k=1}^n \Delta T_k}{\text{RI}_r \sum_{k=1}^n \Delta T_k} \right) \times 100\%, \quad (7)$$

where all the parameters are the same as above.

Equations (5) and (6) are basically the same, but they are different from the point of view of the measured parameters. The first formula is used to calculate the error from the perspective of water mass or water volume, and to obtain the mass through the balance, which is the traditional method. The second one is used to calculate the error from the perspective of time. The IDA method is used to accurately obtain the time with a resolution of 0.01 s that can meet the requirement of measuring the error of TBRs.

d. Statistical analyses

We used t tests to analyze if the differences were statistically significant for T_1 and T_2 with rainfall intensities, where T_1 is the time elapsed from the start of bucket motion to the horizontal position [also a parameter of a regression equation (Shedekar et al. 2016)] and T_2 is the time elapsed from the start of bucket motion to the first strike (when the bucket strikes the stop screw). A one-way analysis of variance (ANOVA) was performed with a significance level of 0.01 to test the relation between the error and rainfall intensity for each type of TBR. All statistical analyses were conducted with Origin (version Pro 9.0) statistical software.

3. Results and discussion

a. Tipping time characteristics and undercatch error of TBRs

Data from 40 tips under different rainfall intensities were examined. When an object is moving in the video, a significant change occurs, and the value of SUM continually increases (see Figs. 5 and 6). In Fig. 6b, the insets are shown much magnified for clarity for JDZ02. The region of sudden continuous increase indicates that there is motion in the image (the bucket rotation). The movement of the bucket contains three parts: T_1 , T_2 , and T_3 , where T_3 is the bucket rebound process, which is also the bucket movement until the bucket stops completely. This study focused primarily on T_1 and T_2 .

Figure 6 shows one individual bucket rotation process, and other rotation processes are similar. There are four

points that contain start move, horizontal, first strike, and stop completely are also marked. The starting move, judged by the IDA and the value of SUM, starts to increase continuously. The horizontal position is the inflection point of the curve or near, moreover it can also see from the picture (like Fig. 5, frame 677). The first strike point is the peak of the curve or near, also see from the picture (like Fig. 5, frame 683). The point of stop completely can judge by the IDA, the SUM = 0; Although Fig. 6 does not represent all situations, it can reflect the trend and characteristics of SUM.

The formula for calculating undercatch error associated with a tip is (Duchon et al. 2014)

$$e_u = \frac{\text{RI}_r T_1}{A_t} \times 100\%, \quad (8)$$

where e_u is the undercatch error, RI_r is the reference rainfall intensity, and A_t is the accumulation per tip of each TBR.

Table 2 gives in detail the characteristics of T_1 , T_2 , coefficient of variation C_V , T_1/T_2 (time in undercatch), and undercatch error e_u for various rainfall intensities. The results of the tipping time in the relevant literature are consistent with our results (Duchon et al. 2014; Marsalek 1981; Shedekar et al. 2016). In our research, T_1 varied from 0.21 to 0.44 s for JDZ02, from 0.23 to 0.39 s for JDZ05, and from 0.31 to 0.4 s for JDZ10. T_2 varied from 0.26 to 0.5 s for JDZ02, from 0.29 to 0.45 s for JDZ05, and from 0.38 to 0.45 s for JDZ10. In addition, for a rainfall intensity of 0.4 mm min^{-1} , the time fluctuation range was the largest for JDZ02 and JDZ05. By contrast, the range of time fluctuations was minimal for the rainfall intensity of 4 mm min^{-1} . Part T_1 takes up most of the bucket rotation process because of its slow rotation speed in the initial stage of bucket rotation. Moreover, from the results for T_1 and T_2 , it was found that the duration of the bucket rotation from the horizontal position to the bucket first strike needs to be about 0.05–0.07 s (Duchon et al. 2014). The value of T_1 varies by a factor of 2 for JDZ02 and mainly for 0.4 mm min^{-1} , two reasons may explain it. First, the intensity of 0.4 mm min^{-1} corresponds to a light rain, and the water flow into the bucket from the rain receiver is slow and not continuous. Therefore, the undercatch of rain occurs in some bucket tipping but does not in other bucket tipping. As for larger rain intensity, the water flow into the bucket from the rain receiver is higher and continuous. Second, the JDZ02 is smaller than other two TBRs. The stability of the JDZ02 may be not as good as other two TBRs. It can be seen from the C_V of T_1 was high (19.11%, Table 2) that the stability of the JDZ02 needs to be improved.

TABLE 2. The result of T_1 , T_2 , C_V , and undercatch error for the TBRs tested. RI is rainfall intensity.

Type	RI (mm min ⁻¹)	$T_{1,min}$ (s)	$T_{1,max}$ (s)	$\bar{T}_1$ (s)	C_V for T_1 (%)	e_u (%)	$T_{2,min}$ (s)	$T_{2,max}$ (s)	$\bar{T}_2$ (s)	C_V for T_2 (%)	$\bar{T}_1/\bar{T}_2$ (%)
JDZ02	0.4	0.21	0.44	0.29	19.11	0.98	0.27	0.5	0.35	16.48	83.44
	1	0.22	0.36	0.27	11.80	2.31	0.27	0.42	0.33	10.65	83.05
	2	0.22	0.36	0.26	12.87	4.47	0.27	0.42	0.32	11.47	82.67
	3	0.22	0.33	0.26	10.89	6.55	0.27	0.39	0.31	10.29	82.67
	4	0.21	0.29	0.25	8.16	8.35	0.26	0.35	0.30	7.85	81.62
JDZ05	0.4	0.25	0.39	0.32	10.09	0.43	0.32	0.45	0.38	8.43	83.95
	1	0.25	0.36	0.29	9.53	0.97	0.31	0.42	0.35	7.96	82.71
	2	0.23	0.33	0.28	9.22	1.85	0.29	0.39	0.34	7.75	81.96
	3	0.23	0.36	0.29	9.59	2.88	0.29	0.42	0.35	7.93	82.74
	4	0.24	0.32	0.28	6.82	3.67	0.3	0.38	0.34	5.66	81.99
JDZ10	1	0.33	0.4	0.36	4.56	0.60	0.39	0.45	0.42	3.51	85.01
	2	0.33	0.37	0.35	3.69	1.17	0.39	0.44	0.41	3.31	84.89
	3	0.31	0.37	0.34	3.87	1.72	0.38	0.43	0.41	3.11	84.39
	4	0.31	0.35	0.33	2.78	2.20	0.38	0.41	0.39	2.10	83.77

The C_V of T_1 and T_2 decrease as the rain intensity increases significantly ($P < 0.01$) for the TBRs tested. Especially at 0.4 mm min^{-1} , the value of C_V is the largest for all three types of rain gauges, which is consistent with the description of the maximum fluctuation range under this rain intensity (Figs. 7 and 8). The value of e_u increases with increasing rain intensity. At lower rain intensity (0.4 mm min^{-1}), the e_u is slightly less than 1%, but at the higher rain intensity (4 mm min^{-1}) e_u is more than 8.3%, 3.68%, and 2.2% for rain gauges JDZ02, JDZ05, and JDZ10, respectively. The result of e_u is consistent with Duchon et al. (2014).

Figure 7 shows that the relationship between T_1 and rainfall intensity can be represented by linear regression. The standard error bars for each data point has been given. Scatterplots are average time under various rainfall intensities and solid line is linear regression. Dashed line and hollow dot are predicted by the function of linear regression. There was a significant

relationship between T_1 and rainfall intensity for JDZ02 and JDZ10. Moreover, the coefficients of determination R^2 for this regression were 0.97 ($P < 0.001$) and 0.94 ($P < 0.001$), but there was no clear relationship between T_1 and rainfall intensity for JDZ05, and R^2 for this regression was 0.43 ($P < 0.001$); however, it was found that a power function equation can fit better for JDZ05 and R^2 were 0.72 (Niemczynowicz 1986).

As illustrated in Fig. 8, the relationship between T_2 and rainfall intensity can also be represented by linear regression. The value of R^2 for JDZ02 was 0.92 ($P < 0.001$), for JDZ05, $R^2 = 0.44$ ($P < 0.001$), and for JDZ10, $R^2 = 0.97$ ($P < 0.001$). Calibration of TBRs is often time-consuming, as is well known (Humphrey et al. 1997). In the present study, this situation also exists; for example, the 0.4 mm min^{-1} rainfall intensity for JDZ10 was extremely time-consuming and data-intensive to calibrate, and therefore this rain intensity was not tested for JDZ10. Fortunately, both T_1 and T_2

FIG. 7. The relationship between T_1 and rain intensity for (a) JDZ02, (b) JDZ05, and (c) JDZ10. The sample size was 40 for each rain intensity. Standard error bars and linear regression lines are shown; note that a nonlinear relation is also shown for JDZ05.

FIG. 8. As in Fig. 7, but for T_2 .

were found to be functions of rainfall intensity. Moreover, the fitting function of JDZ10 was very well correlated (R^2 close to 0.9), and therefore T_1 and T_2 for JDZ10 under 0.4 mm min^{-1} rainfall intensity could be predicted by the fitting function. The results are indicated by the dashed line and hollow dots in Fig. 8c.

Three points in this discussion are worthy of attention. First of all, the results obtained in this work indicates that the tipping time of the JDZ05 seems inconsistent with those of JDZ02 and JDZ10, which is perhaps caused by the shape and structure of the bucket (see Fig. 2). The shape and structure of the JDZ02 and JDZ10 buckets are relatively conventional, but the bucket shape of JDZ05 is a cylinder, unlike the other two TBRs. Hence, the most likely reason for this difference would seem to be the bucket shape and structure. The second point is that the average of T_1 and T_2 is likely to be associated with bucket mass. Table 1 shows that the bucket masses of the TBRs tested were $BQ_{JDZ10} = 57.36 \text{ g}$, $BQ_{JDZ05} = 30.19 \text{ g}$, and $BQ_{JDZ02} = 26.72 \text{ g}$. As for the duration of the tipping time, JDZ10 had the longest time, JDZ05 the second longest time, and JDZ02 the shortest time under various rainfall intensities (see Table 2). Based on the results of this study, the average of T_1 and T_2 was positively correlated with bucket mass. This result can also be derived from Figs. 7 and 8. When this technique is used to catch the start and horizontal states of the tipping bucket, there exists a time error of less than 0.01 s , which will cause an undercatch error of 0.13% at the rainfall intensity of 4 mm min^{-1} . An error of 0.13% has little effect on our results. Therefore, this technique can be used to precisely estimate tipping times for TBRs.

b. Comparison with traditional calibration of the TBR

Table 3 shows a comparison of the new method with the traditional calibration. The absolute value of the

deviation does not exceed 1% (the maximum is 0.8% , and the minimum is 0.04%). The purpose of the “deviation” is to compare the absolute difference of error between the presented method and the traditional calibration. The small absolute difference between these two methods verified the correctness of the presented method. Furthermore, the traditional method gives the error of the TBR only, mainly the calibration curve (Colli et al. 2013; Shedeekar et al. 2016), but T_1 and T_2 remain unknown. Instead, using this new method, the error of the TBR and those of the time characteristics can be acquired at the same time. As for JDZ02 (0.2 mm), the rainfall intensity of zero-error point is about 1 mm min^{-1} and the error range was 8.2% (2.5% for 0.4 mm min^{-1} and -5.7% for 4 mm min^{-1}). If the rainfall intensity of zero-error point is set as 0.4 mm min^{-1} , the error will be less than -8% in the

TABLE 3. The new method compared with the traditional calibration. RI is rainfall intensity, Error-1 indicates the new method, and Error-2 indicates the traditional method.

Type	Rain intensity (mm min^{-1})	Error-1 (%)	Error-2 (%)	Deviation (%)
JDZ02	0.4	2.85	2.49	0.35
	1	0.88	0.21	0.67
	2	-1.54	-2.31	0.78
	3	-3.05	-3.70	0.66
	4	-5.20	-5.74	0.54
JDZ05	0.4	2.25	1.45	0.80
	1	0.68	0.29	0.39
	2	-0.55	-0.80	0.25
	3	-0.83	-1.14	0.31
	4	-1.12	-1.81	0.69
JDZ10	1	2.83	3.05	0.22
	2	1.72	1.76	0.04
	3	0.80	1.08	0.28
	4	0.10	0.37	0.27

FIG. 9. Gauge errors based on Eq. (7): (a) JDZ02, (b) left bucket of JDZ02, (c) right bucket of JDZ02, (d) JDZ05, (e) left bucket of JDZ05, (f) right bucket of JDZ05, (g) JDZ10, (h) left bucket of JDZ10, and (i) right bucket of JDZ10. In the box, the tiny dot is the mean. The dash lines are the reference line.

rainfall intensity of 4 mm min^{-1} . In published studies, such as the research of Colli et al. (2014), the error range was about 10% (-12% to -22% from 0.4 to 4 mm min^{-1} rainfall intensities). The range of the research of Colli et al. (2014) and this research were 10% and 8.2%, respectively; thus, they were quite close.

Figure 9 shows the bucket error calculated by the proposed new formula. Clearly, referring to the reference line (dashed line in Fig. 9), when $e > 0$, e decreases with rain intensity; when $e < 0$, e increases with rain intensity and the result is consistent with the traditional method because of water loss during bucket rotation. The error was significantly different at different rainfall intensities for the TBRs tested ($P < 0.01$). The differences at a single intensity (1, 2, 3, and 4 mm min^{-1} , $P < 0.01$) are statistically significant among different TBRs (JDZ02, JDZ05, JDZ10), mainly because of the resolution of the TBRs. JDZ02 has the largest error

fluctuation range, JDZ10 has the smallest error fluctuation range, and JDZ05 is between the other two rain gauges. As shown in Fig. 9, the left and right bucket errors were also taken into account. As for JDZ02, the left and right error ranges fluctuated most at 0.4 mm min^{-1} under light rain; however, for JDZ10, the left and right error ranges fluctuated most at 4 mm min^{-1} under heavy rain. The error range fluctuation seemed irregular, as for JDZ05.

4. Conclusions

Based on a review of the literature, this study was perhaps the first to investigate the tipping time of TBR using digital photographic technology with IDA. The investigation of three types of JDZ series TBRs indicated that this method can provide objective and sophisticated measurements of the variation characteristics

of the tipping time during bucket rotation. This paper has also proposed a new formula to calculate the error of the TBR. The results based on this new formula were also compared with the traditional calibration. The results of the two methods were very close, which indicates the feasibility of the new formula and the goodness of the traditional calibration, but the latter cannot acquire the variation characteristics of the tipping time, whereas the proposed new approach can. Nonetheless, the IDA method is available to determine the time characteristics and measurement error of TBRs.

We can improve the existing protocols from two aspects. First, it is necessary to increase the observation of the tipping time of the bucket, especially the observation of T_1 , and thus the undercatch error of TBR can be fully understood. Second, the measuring error of the two bucket compartments can be computed using T_1 , so the performance of TBRs can be determined by the obtained time characteristics of left and right bucket compartments, which can help us to calibrate and adjust TBRs.

All the methods have their own advantages and disadvantages. The disadvantage of the method proposed here is that the amount of video data needed is so large (more than 200 GB) that it is really time-consuming to deal with the video data. Hence, a high-performance computer to process video data is needed. Furthermore, to strive for objectivity in the experimental data, it is necessary to develop a computer program to identify whether the bucket is moving. If this identification is made manually, the measurement is likely to be inaccurate. In addition, the use of computer programs for judgment also improved the efficiency of the TBR calibration procedure.

One promising area of further research is to use the proposed method to provide a sophisticated measurement of the drainage time of the siphon (between the receiver and the bucket), which is also a very short time, after which the drainage rainfall intensity can be calculated by the relationship between drainage time and drainage water quantity, but this work is not shown in this paper. In conclusion, this study has shown that digital photographic technology has a good potential for rain gauge research.

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