Atmospheric Research 178–179 (2016) 445–458

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Assessment of measurement errors and dynamic calibration methods for three different tipping bucket rain gauges

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ARTICLE INFO

Article history:
Received 30 October 2015
Received in revised form 7 April 2016
Accepted 28 April 2016
Available online 30 April 2016

Keywords:
Precipitation
Tipping bucket rain gauge
Calibration
Accuracy
Rainfall measurement
Hydrologic monitoring

ABSTRACT

Three different models of tipping bucket rain gauges (TBRs), viz. HS-TB3 (Hydrological Services Pty Ltd.), ISCO-674 (Isco, Inc.) and TR-525 (Texas Electronics, Inc.), were calibrated in the lab to quantify measurement errors across a range of rainfall intensities ($5\ \mathrm{mm \cdot h^{-1}}$ to $250\ \mathrm{mm \cdot h^{-1}}$) and three different volumetric settings. Instantaneous and cumulative values of simulated rainfall were recorded at 1, 2, 5, 10 and 20-min intervals. All three TBR models showed a substantial deviation ($\alpha = 0.05$) in measurements from actual rainfall depths, with increasing underestimation errors at greater rainfall intensities. Simple linear regression equations were developed for each TBR to correct the TBR readings based on measured intensities ($R^2 > 0.98$). Additionally, two dynamic calibration techniques, viz. quadratic model ($R^2 > 0.7$) and T vs. 1/Q model ($R^2 = > 0.98$), were tested and found to be useful in situations when the volumetric settings of TBRs are unknown. The correction models were successfully applied to correct field-collected rainfall data from respective TBR models. The calibration parameters of correction models were found to be highly sensitive to changes in volumetric calibration of TBRs. Overall, the HS-TB3 model (with a better protected tipping bucket mechanism, and consistent measurement errors across a range of rainfall intensities) was found to be the most reliable and consistent for rainfall measurements, followed by the ISCO-674 (with susceptibility to clogging and relatively smaller measurement errors across a range of rainfall intensities) and the TR-525 (with high susceptibility to clogging and frequent changes in volumetric calibration, and highly intensity-dependent measurement errors). The study demonstrated that corrections based on dynamic and volumetric calibration can only help minimize—but not completely eliminate the measurement errors. The findings from this study will be useful for correcting field data from TBRs; and may have major implications to field- and watershed-scale hydrologic studies.

1. Introduction

In the United States, weather records have been collected and compiled at many stations for more than a century. The current network of meteorological stations consists of greater than 10,000 weather stations (Cook, 2010), spread throughout the country. Precipitation is being monitored at more than 8000 of these stations. Standard 8″ non-recording precipitation gauges (SNRG) are the official precipitation measurement instrument for the U.S. climate station network monitored by the National Weather Service (NWS). Approximately 30% of all weather stations use one or more of three main types of automated recording gauges: Tipping Bucket Rain gauges (TBRs), Universal Weighing rain gauges, and Fischer and Porter-Belfort rain gauges (Groisman et al., 1999). Tipping bucket rain gauges became popular because of their simple, durable, and inexpensive design; and most importantly, their adaptability to remote areas. They can be easily installed in remote areas and connected to a variety of monitoring and/or recording devices. Because of these advantages, TBRs are often used for continuous and reliable precipitation measurements in watershed-scale monitoring and research studies.

1.1. Accuracy of precipitation data collected/measured by TBRs

The accuracy of point precipitation measurements is often a concern due to underestimation, ranging from 5% to 40% (Legates, 1987; Legates and Willmott, 1990; Groisman and Legates, 1994). Underestimations result from wetting and evaporation losses, gauge height, wind-induced turbulence at the gauge orifice, extremely light or intense rainfall, and snowfall (Parsons, 1941; Neff, 1977; Sevruk and Hamon, 1984; Legates and Willmott, 1990; Groisman et al., 1999; Sansom and Gray, 2002; Upton and Rahimi, 2003; Molini et al., 2005; Lanza and Stagi, 2009; Lanza and Vuerich, 2009). Underestimations are generally more pronounced in the winter compared to summer (Legates and

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http://dx.doi.org/10.1016/j.atmosres.2016.04.016
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DeLiberty, 1993). At intensities greater than 25 mm·h^{-1}, the underestimations increase nonlinearly with increases in intensity (Marsalek, 1981; Alena et al., 1990; Humphrey et al., 1997).

The errors in TBR measurements can be categorized as either systematic/mechanical or random. Systematic/mechanical biases in the TBRs can be attributed to both catching and counting inaccuracies which are in turn related to the positioning and mechanics and/or electronics of the instrument. Positioning refers to wetting, splashing, evaporation and wind-induced errors. Mechanical or electronic errors include limited tipping rate, and double tips due to an out of level instrument. Systematic errors are due to design or material limitations and hence are more predictable. Random errors refer to the biases caused by some unforeseen factors, such as leakage or damage to the gauge, human errors (introduced by observers measuring and recording data), and interference from animals. Both systematic and random errors may cause biases in a positive or negative direction.

Calibration of TBRs can be carried out in two ways: static (volumetric) calibration and dynamic calibration. A detailed description of both of these methods has been given by Humphrey et al. (1997). Static or volumetric calibration refers to adjusting the volume required to tip the bucket, which corresponds to the resolution of the TBR. Dynamic calibration refers to estimation of the under-catchment errors by calibrating the TBR while the buckets are in motion. Several dynamic calibration approaches have been proposed to account for the systematic errors associated with TBRs (Calder and Kidd, 1978; Marsalek, 1981; Niemczynowicz, 1986; Costello and Williams, 1991; Legates, 1992; Humphrey et al., 1997; Fankhauser, 1998; Vasvàri, 2005). Some of the methods involve physical or mechanical adjustments in the TBRs prior to data collection, while others involve post-collection processing of data for elimination of errors. Although, most of these dynamic calibration approaches have been studied extensively and implemented into monitoring protocols (Vasvàri, 2005), few studies report the interaction of volumetric and dynamic calibrations. Furthermore, the validity of correction methods developed in lab experiments needs to be tested for correcting actual field collected data by the TBRs.

The objectives of this study were to: 1) calibrate three commonly used TBR models and quantify the measurement errors associated with each of them as affected by the interaction between volumetric and dynamic calibration; 2) develop statistical models to correct the rainfall measurements by the three TBRs; 3) validate and compare the performance of the statistical models using field-measured rainfall data; and 4) describe and discuss the implications of errors in TBRs to hydrologic studies.

2. Materials and methods

Based on their widespread use in hydrologic and water quality monitoring projects, the three TBR models (Table 1) selected for this study were: HS-TB3 (Hydrological Services Pty. Ltd., New South Wales, Australia); ISCO-674 (Teldyne, Isco, Lincoln, NE, USA); and TR-525 (Texas Electronics, Inc., Dallas, TX, USA).

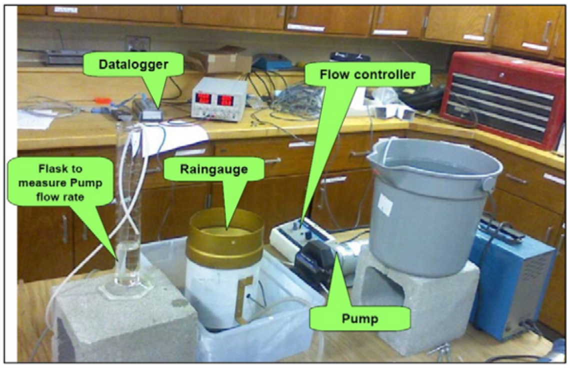

Fig. 1. Experimental set up for TBR calibration in laboratory (Model TR-525 is shown).

2.1. Laboratory assessment

The laboratory assessment was accomplished through a series of calibrations: volumetric calibration of rain gauges; calibration of the supply pump, and dynamic calibration of rain gauges (Fig. 1). The data from lab experiments were used for estimating errors and developing statistical models for each TBR.

Volumetric calibration of each TBR model was conducted prior to dynamic calibration. Each TBR was placed on a level platform, and the tipping bucket mechanism was tested for volume of water required to tip the bucket. A 10 ml pipette held at the same height as the outlet of the funnel was used to supply water. One bucket tip was equivalent to 0.254 mm of rainfall. The nominal bucket volumes, defined as volumes equivalent to a rainfall depth of 0.254 mm, were: HS-TB3 (8.24 ml); Isco-674 (8.24 ml); and TR-525 (4.73 ml) (Table 1). The volume required to tip the bucket was calculated as:

$$V_{tip}(\mathrm{ml}) = 0.0254\ \mathrm{cm} \times \left(\pi \times D^2\right)/4 \tag{1}$$

where, D is collecting diameter of the rain gauge, cm.

If the measured V_{tip} for a TBR was not equal to the V_{tip} calculated from Eq. (1), the calibration screws below the tipping bucket mechanism were adjusted such that each bucket tipped at a volume (V_{tip}), is equivalent to 0.254 mm of rainfall.

A peristaltic pump (Masterflex, Inc., Vernon Hills, IL, USA) was used to generate a range of flow rates that simulated different rainfall intensities. The peristaltic pump was calibrated for consistent discharge over a range of flow rates. The pump discharge at each flow rate was measured in two replications of 10 + readings at 30 s intervals using a graduated cylinder and a stop-watch. Following pump calibration, dynamic calibration of each TBR was conducted by subjecting the TBRs to a range of constant flow rates simulated by the pump system. Different flow rates were obtained by changing pump speed and/or the size of tubing. A constant water head was maintained at the pump inlet during

Table 1
Specifications of TBRs used during volumetric and dynamic calibration.

Rain gauge Make ➔	HS-TB3	ISCO-674	TR-525
Manufacturer	Hydrological Services Pty. Ltd.	Isco, Inc.	Texas Instruments Inc.
Model	TB3	674	525I
Resolution	0.254 mm (0.01 in)	0.254 mm (0.01 in)	0.254 mm (0.01 in)
Receiver diameter, D	20.3 cm (8 in)	20.3 cm (8 in)	15.4 cm (6.06 in)
Receiver area	324.3 cm^2	324.3 cm^2	186.3 cm^2
Nominal bucket volume per tip (V_{tip})	8.24 ml	8.24 ml	4.73 ml
Tipping time ± standard error (s)	0.36 ± 0.038	0.32 ± 0.019	0.38 ± 0.036
Volumetric settings used in lab experiment			
Lowest	6.0 ml	7.0 ml	4.15 ml
Medium	7.5 ml	8.1 ml	4.7 ml
Highest	8.3 ml	9.0 ml	5.4 ml