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A generalized correction equation for large tipping-bucket flow meters for use in hydrological applications

Takanori Shimizu[a,*], Masahiro Kobayashi[b], Shin'ichi Iida[a], Delphis F. Levia[c]

[a] Department of Disaster Prevention, Meteorology and Hydrology, Forestry and Forest Products Research Institute, Matsunosato, Tsukuba, Ibaraki 305-8687, Japan
[b] Department of Forest Soils, Forestry and Forest Products Research Institute, Matsunosato, Tsukuba, Ibaraki 305-8687, Japan
[c] Departments of Geography and Plant and Soil Sciences, University of Delaware, Newark, DE 19716, USA

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ABSTRACT

Large tipping-bucket flow meters (TBFs, one tip > 200 ml) have been employed by hydrologists to quantify various water fluxes in a variety of contexts. The over-arching goal of this study is to develop a generalized correction equation for various TBFs. Based on our testing, we recommend the following to minimize TBF error: (1) periodic checking of the static calibration volume (c) since c is a gauge-specific value which has been found to vary after field deployment; and (2) for dynamic calibration, the use of our newly derived generalized correction equation when the tipping rate is less than 0.2 Hz. In equation form, the generalized correction equation for common TBFs with flat triangular buckets is: $V = -0.75Q^2 + 0.72Q + 1$ ($R^2 = 0.843$; $p < 0.0001$), where $V = v/c$ and v is the water volume for one tip under dynamic conditions, and $Q = q/c$ [s^{-1}] and q is the water flow rate into the TBF. From our field test in a Japanese cedar forest stand, using stemflow (S_F) as an example, we found that use of the generalized correction equation was successful in eliminating the 2–3% error in S_F amounts. Moreover, we found that the generalized correction equation performed nearly as well as gauge-specific derived correction equations. Thus, our generalized correction equation is applicable to correct flow estimates of TBFs when one does not have time and/or laboratory set-up for the laborious task of testing individual TBFs themselves. Although our correction procedure may not completely eliminate all error, we recommend use of the generalized correction equation for TBFs to improve the accuracy of water flux calculations in hydrologic studies.

1. Introduction

A large tipping-bucket flow meter (TBF) is a convenient and widely applicable instrument to measure water flow. Tipping-bucket flow meters have been employed at the scale of square meters to measure outflow from trenches or soil pits excavated in forest hillslopes (e.g., Freer et al., 2002; Kim et al., 2005) and from lysimeters (e.g., Dunin et al., 1988; Storck et al., 2002; von Unold and Fank, 2008). Tipping-bucket flow meters also have been used to observe throughfall (T_F) and/or stemflow (S_F) in a forests and agroforestry ecosystems (e.g., Konishi et al., 2006; Liang et al., 2011; Holwerda et al., 2012; Iida et al., 2017). While weirs are well-suited for measuring long-term water flow from a watershed scale (e.g., Swank et al., 2001; Wilson et al., 2001; Kosugi and Katsuyama, 2007; Likens, 2017), a TBF is preferable for shorter term investigations due to its mobility, lower cost, and ease of installation. In addition, TBFs have been used with higher temporal resolution, without concern about overflow which can occur when using collectors (e.g., Masukata et al., 1990; Schroth et al., 1999; Marin et al., 2000; Macinnis-Ng et al., 2012).

It has long been recognized that both TBFs (Edwards et al. 1974; Calder and Kidd, 1978) and tipping-bucket rain gauges (TBRs) (e.g., Marsalek, 1981; Niemczynowicz, 1986; Habib et al., 2001; Iida et al., 2012; Shedekar et al., 2016; Iida et al., 2018) require dynamic calibration for a more precise estimation of volume inputs across a range of inflow rates. Some researchers obtained the calibration parameters for each individual TBF they used (e.g., Calder and Kidd, 1978; Hsu, 1990; Shimizu et al. 2015), while others presented the typical calibration equation for certain types of TBFs (e.g., Takahashi et al., 2011; Iida et al., 2012). Shiraki and Yamato (2004) derived an equation for smaller TBFs with c_m = 75–200 ml, where c_m is the water volume for one tip regulated by each TBR/TBF manufacturer. However, for TBFs including larger tipping thersholds (*i.e.*, c_m > 200 ml), a generalized correction equation has not been established due to the labor intensive nature of the task and/or preparation of a precise flow control system (*e.g.*, Humphrey et al., 1997; Vasvári, 2005; Iida et al., 2012) necessary to calibrate TBFs with c_m > 200 ml. The corresponding lack of

* Corresponding author.
E-mail address: simizuta@affrc.go.jp (T. Shimizu).

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correction equations for larger TBFs has hampered their use.

Another practical issue is the applicability of the calibration equation obtained from a laboratory test to field conditions. This is caused by the variation of flow velocities into the TBF which may usually occur in the field, while constant flow is supplied in the laboratory test. As such, it is recommended that the water passed through the TBF be re-collected and stored in the field to compare the water mass with that estimated from the tipping record and the calibration processes to check whether large differences have occurred. Although this kind of test was carried out in some studies (*e.g.*, Dunin et al. 1988; Staelens et al. 2006), no comparative results have been clearly presented to date.

Recognizing the need for a generalized correction equation for larger TBFs, we aim to: (1) develop a generalized correction equation for larger TBFs (with c_m > 200 ml) based on results of previous studies and our laboratory test of six additional TBFs, including larger c_m models (c_m = 500 ml); and (2) compare a TBF to field observations of S_F to examine the effect of both static and dynamic calibrations on decreasing the measurement error. The gauge specific static calibration value (c) is defined as the tipping volume under conditions of nearly zero inflow. The novelty of this study lies in the development of a generalized correction equation for larger TBFs for both static and dynamic calibrations, which is currently lacking in the scientific literature, and applying the generalized calibration equations to field observation data of S_F as an example hydrologic application. Based on accomplishment of these two aims, we describe a simple and recommendable calibration approach for TBF users. The results obtained will be of practical use not only to hydrologists who seek to use TBFs with a higher level of confidence but also those who have applied TBFs without considering the potential error caused by neglecting calibration procedures.

2. Materials and methods

2.1. Calibration equations from laboratory tests

Calibration tests were conducted for three types of TBFs, one was with c_m = 200 ml (UIZ-200, UIZIN Co. Ltd., Tokyo, Japan) and two others with c_m = 500 ml (UIZ-500, UIZIN and 500 ml model of Yokogawa Electric Corp., Tokyo, Japan; hereafter Yoko-500). A total of six TBFs were tested, which included three UIZ-200s, two UIZ-500s, and one Yoko-500. Among them, two UIZ-200 s and one UIZ-500 were tested twice in the laboratory, before field installation and 3 years after field deployment. The tests for the other three TBFs were performed only before field installation. For the UIZ-200 and UIZ-500, the heights of the support screws were adjustable, and thus c could be adjusted to be closer to c_m. Meanwhile, for the Yoko-500, the margin for such kind of adjustment was limited (*i.e.*, not within 1% of c_m in our case) because of the narrow range over which the support screws could be moved.

The details of the laboratory test are described in Shimizu et al. (2015) and illustrated schematically in Fig. 1. The gauge specific static volume (c) was directly tested for some of the TBFs as depicted in Fig. 1a, while the dynamic calibration test was conducted for all the TBFs. The maximum tipping rates were around 0.1–0.2 Hz for the three UIZ-200 s and 0.06–0.1 Hz for the two UIZ-500s and the Yoko-500. The dynamic calibration tests on each TBF were carried out as depicted in Fig. 1b, with tipping intervals (t [s]) measured for 6–8 different inflow rates.

Some calibration equations have been formulated for TBFs (Table 1). The best-fit function and parameter(s) for each TBF tested in this study were obtained by fitting equations utilized by past work. Since one of the fitting parameters of the Calder and Kidd's (1978) equation (p_{CK1} in Table 1) is compatible with the c obtained from the static test, we compared these values for some TBFs when the static test was skipped. Once c was determined, the inflow rate into a TBF (q) and tipping volume for one tip (v) was normalized by the value of c, and then the function of Q ($=q/c$) [s^{-1}] versus V ($=v/c$) [dimensionless] was established (e.g., Shiraki and Yamato, 2004; Iida et al., 2012).

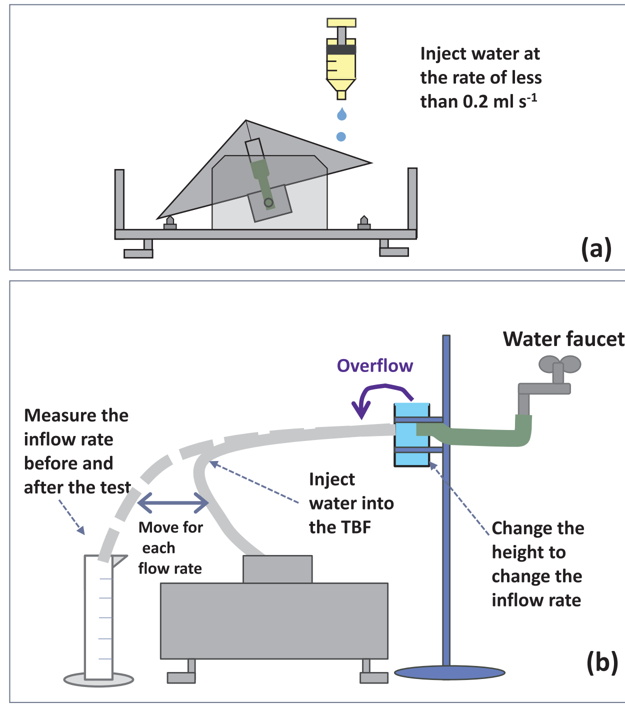

Fig. 1. Schematic of static (a) and dynamic (b) calibrations (modified from Shimizu (2015), Fig. 5.5).

2.2. Field measurement

The field experiment was conducted at the Kahoku Experimental watershed (KHEW, 33°08′N, 130°43′E) located on Kyushu Island in southwestern Japan. A detailed description of the measurement plot (plot 1) and methods are described in Shimizu et al. (2015). S_F was collected from four Japanese cedar (*Cryptmeria Japonica* D. Don) trees by using 3 cm thick urethane rubber (Levia and Germer, 2015) and funneled to a single Yoko-500 TBF. The date and time of each bucket tip was recorded by a datalogger (HOBO H07, Onset Computer Corp., Bourne, MA, USA) with a time resolution of 0.5 s. The number of tips and the tipping intervals were utilized for the estimation of water quantities. The volume of S_F was converted to depth equivalents by dividing the total canopy projection area of four measured trees (21.4 m^2).

The water inflow through the TBF was re-collected and weighed after each large rainfall event (Fig. 2). The TBF and the paired plastic tray was covered by a plastic bag to avoid incoming rain. The storage water data were successfully acquired for five periods (Table 2), without overflow from the tank. The average rainfall intensity [mm $hour^{-1}$] was calculated as the ratio of the gross rainfall (P) in the period divided by number of 1-hour blocks in which rainfall was recorded (or at least one tipping was occurred).

The values of P were measured in a small clearing near the watershed using a 0.5-mm tipping-bucket rain gauge (RT-5, Ikeda-Keiki seisakusho Co. Ltd., Tokyo, Japan) with a datalogger (HOBO H07 Onset Corp.) The accuracy of the TBR was checked monthly by using a rainfall storage bottle with a funnel whose orifice area was 705.6 cm^2 (corresponding to an approximate diameter of 30 cm). As the result, when assuming $c = c_m$ and applying no dynamic calibration, P measured by the TBR and that by the storage bottle agreed well ($R^2 \approx 1$) when the bottle did not overflow, and the difference in total P for 3 years was 0.4%. The maximum rainfall intensity when the TBR and the bottle values were successfully compared was 117.5 mm day^{-1}. These suggest, in our case, actual c of the TBR might be slightly smaller than c_m and it possibly compensated for the underestimation caused by skipping the dynamic calibration, whose effect on estimation of P would be rather small when using a 0.5-mm TBR, at least under rainfall intensities