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A New Method for Automated Dynamic Calibration of Tipping-Bucket Rain Gauges

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ABSTRACT

Existing methods for dynamic calibration of tipping-bucket rain gauges (TBRs) can be time consuming and labor intensive. A new automated dynamic calibration system has been developed to calibrate TBRs with minimal effort. The system consists of a programmable pump, datalogger, digital balance, and computer. Calibration is performed in two steps: 1) pump calibration and 2) rain gauge calibration. Pump calibration ensures precise control of water flow rates delivered to the rain gauge funnel; rain gauge calibration ensures precise conversion of bucket tip times to actual rainfall rates. Calibration of the pump and one rain gauge for 10 selected pump rates typically requires about 8 h. Data files generated during rain gauge calibration are used to compute rainfall intensities and amounts from a record of bucket tip times collected in the field.

The system was tested using 5 types of commercial TBRs (15.2-, 20.3-, and 30.5-cm diameters; 0.1-, 0.2-, and 1.0-mm resolutions) and using 14 TBRs of a single type (20.3-cm diameter; 0.1-mm resolution). Ten pump rates ranging from 3 to 154 mL min^{-1} were used to calibrate the TBRs and represented rainfall rates between 6 and 254 mm h^{-1} depending on the rain gauge diameter. All pump calibration results were very linear with R^2 values greater than 0.99. All rain gauges exhibited large nonlinear underestimation errors (between 5% and 29%) that decreased with increasing rain gauge resolution and increased with increasing rainfall rate, especially for rates greater than 50 mm h^{-1}. Calibration curves of bucket tip time against the reciprocal of the true pump rate for all rain gauges also were linear with R^2 values of 0.99. Calibration data for the 14 rain gauges of the same type were very similar, as indicated by slope values that were within 14% of each other and ranged from about 367 to 417 s mm h^{-1}. The developed system can calibrate TBRs efficiently, accurately, and virtually unattended and could be modified for use with other rain gauge designs. The system is now in routine use to calibrate TBRs in a large rainfall collection network at Yucca Mountain, Nevada.

1. Introduction

Tipping-bucket rain gauges (TBRs) have been used extensively for collecting rainfall intensity data ever since their inception and subsequent use in the 1600s (Middleton 1969; Biswas 1970). TBRs are widely used by agencies such as the National Weather Service, U.S. Forest Service, U.S. Geological Survey, and other organizations within the United States and abroad mainly because they are simple and durable. Other advantages are that they can be installed in remote areas, can be connected to a variety of monitoring or recording devices, and are relatively inexpensive. Disadvantages are that measurement errors can be significant during heavy rainfall or light drizzle, losses from evaporation and wind effects can occur, and calibration is often difficult and time consuming (Nemec 1969).

Two methods of TBR calibration are commonly used: 1) static or 2) dynamic. In the static calibration method, the rain gauge is leveled, and the stop under a bucket is adjusted until application of a specified volume of water (usually added to the bucket drop by drop using a pipette) causes the bucket to tip. This procedure is repeated several times for each bucket, and an average volume for both buckets is calculated. Measured bucket volumes can vary as much as 5% depending on the kind of water used (rainwater versus tap water), whether the buckets were initially dry or wet, or if the inside surfaces of the buckets were pretreated (Marselek 1981). Rain gauge resolution r (the amount of rainfall the rain gauge is set to detect) is usually expressed in millimeters and can be defined by

$$r = \frac{4V}{\pi d^2}, \tag{1}$$

where V is the bucket volume, and d is the rain gauge diameter (of the outer funnel).

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Static calibration methods assume that the volume of water needed to cause the bucket to tip is independent of the rainfall intensity. This assumption may be invalid because the inherent design and mechanical motion of the tipping-bucket rain gauge is such that the buckets cannot reposition themselves fast enough after a tip to collect all of the rainfall entering the outer funnel. This is commonly referred to as ‘‘undercatchment’’ and results in underestimation of rainfall intensities and total amounts. These underestimation errors can range from 10% to 30% for rainfall intensities greater than 25 mm h^{-1} (Alena et al. 1990; Marsalek 1981; World Meteorological Organization 1983) and increase nonlinearly with increasing rainfall intensity. Total rainfall amounts can be significantly underestimated for short-duration, high-intensity storms, or for any long-duration storm with an intensity greater than 25 mm h^{-1}. Several modifications to TBR design have been introduced in an attempt to reduce undercatchment including changes in bucket profile, use of a siphon tube to deliver a preset volume of collected water to each bucket, and measurement of water mass as water accumulates in the bucket (Simic and Maksimovic 1994, 1993; Edwards et al. 1974; Hewston and Sweet 1989). However, it is believed that these modifications cannot eliminate bucket undercatchment entirely even under optimal conditions (Niemczynowicz 1986; Edwards et al. 1974).

Dynamic calibration methods attempt to account for undercatchment by calibrating the TBR while the buckets are in motion and have been proven to be effective. In dynamic calibration, measured rain gauge rates are compared to actual rainfall rates that are computed from applied flow rates and the rain gauge diameter and bucket volume. Calder and Kidd (1978) proposed a dynamic calibration method based on the determination of the gauge parameters V and t, where V is the bucket volume and t is the time taken for the bucket to move from its stopped (tipped) position to a position that places the division between the buckets directly underneath the inner funnel. Rainfall intensities ranging from 10 to 150 mm h^{-1} were applied manually to the rain gauge, and time between tips versus the reciprocal of applied flow rates was plotted to obtain V and t.

Niemczynowicz (1986) used a similar method to dynamically calibrate TBRs by applying rainfall intensities ranging from about 1 to 350 mm h^{-1}. The resulting data were accurately described by the simple power equation $I = aN^b$, where I is measured rain gauge rate, N is tipping rate, and a and b are fitting parameters. Changes in apparent bucket volume at different rainfall intensities are thus accounted for.

Marsalek (1981) performed dynamic calibrations on three types of TBRs for rainfall rates between 6 and 400 mm h^{-1} using a constant-head siphon. Tipped water mass, elapsed time, and the number of tips were recorded for each of the applied rates to plot actual intensity versus measured intensity. For rainfall intensities less than 25 mm h^{-1}, measured intensity did not significantly differ from actual intensity. For intensities greater than 25 mm h^{-1}, however, the measured intensity was consistently lower than actual intensity in all cases, differing as much as 10%. An analytical expression relating measured intensity, i_r, to actual intensity, i_a, was derived of the form $i_r i_a^{-1} = h_n(h_n + \Delta t i_a)$, where h_n is the nominal rainfall depth increment per one tip, and Δt is the time required for the full bucket to start its downward motion up to the point where it no longer receives water (i.e., bucket tip speed). Underestimation errors between 20% and 30% occurred when bucket movement was slow ($\Delta t \geq 0.75$ s), nominal depth was small ($h_n \leq 1$ mm), and rainfall intensities were extreme ($i_r > 200$ mm h^{-1}).

All of the preceding methods describing dynamic calibration of TBRs involve application of many flow rates and quantifying the response time of the tipping bucket. Accurate application of these flow rates can be time consuming and laborious especially when using conventional devices such as calibration bottles or constant-head siphons. This paper describes a new automated system that dynamically calibrates tipping-bucket rain gauges, analyzes the data, and applies correction factors to actual field data. The new system can significantly reduce calibration time for TBRs allowing more frequent calibration and thus improved accuracy of rainfall measurement.

2. Description of the automated rain gauge calibration system

a. Hardware

The calibration system consists of a personal computer, programmable pump,[1] datalogger, digital balance, constant-level water reservoir, support stand, collection flask, and RS232 switchbox (Fig. 1). The computer is interfaced to the pump through a serial port and is also interfaced to the balance (during pump calibration) or to the datalogger (during rain gauge calibration) using a second serial port and switchbox. The constant-level reservoir supplies water to the pump, and the support stand is used to position the pump outlet tube to a prescribed height above the collection flask (during pump calibration) or the rain gauge outer funnel (during rain gauge calibration). The pump can be programmed to deliver from 0.06 to 228 mL min^{-1} depending on the choice of pumphead, pumphead speed, tubing diameter, and tubing composition. The rain gauge to be calibrated is connected to the datalogger that detects tip occurrences (by momentary closure of a magnetic reed

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[1] Pump: Cole-Parmer Instrument Co., Masterflex model, 7550-90, Niles, IL; datalogger: Campbell Scientific, Inc., Model 21X, Logan, UT; and digital balance: Mettler-Toledo AG, Model AT 6000, Greifensee, Switzerland. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. government.

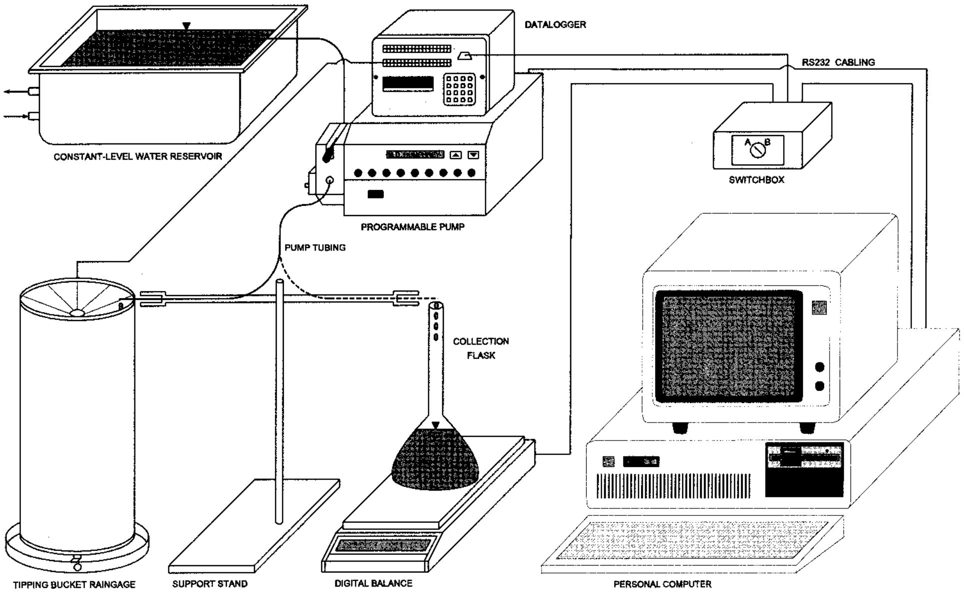

FIG. 1. Components and wiring diagram for the automated dynamic rain gauge calibration system.

switch, mercury switch, or other device mounted on the bucket) and sends a signal to the computer that records the time of the tip.

b. Software

Figure 2 depicts the steps involved for calibration of a rain gauge and subsequent data analysis. Pump and rain gauge calibrations are controlled by two developed BASIC computer programs: PUMPCAL and RAINCAL. Up to 10 randomized pump rates can be chosen using PUMPCAL at delivered (target) volumes of 10–2000 mL for each rate. When the target volume for a rate has been delivered to the collection flask, the balance reading is recorded and the pump begins the next rate. Calibration information (i.e., chosen pump rates, delivered volumes, water temperature, etc., input by the user) and results of the pump calibration are saved to a user-specified ASCII file. The time required for pump calibration depends on the number and values of the applied rates and on the target volume selected. For example, it requires about 68 min to calibrate the pump delivering 100 mL of water for each of 10 pump rates ranging from about 3 to 137 mL min^{-1} (equivalent to rainfall rates between 6 and 254 mm h^{-1} for a 20.3-cm-diameter rain gauge).

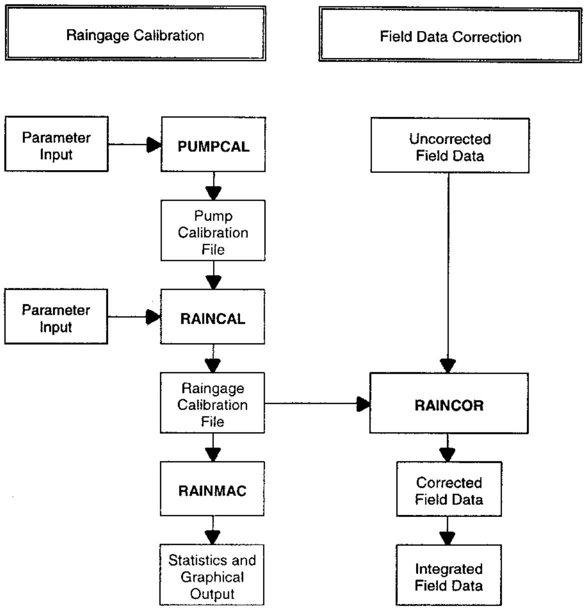

FIG. 2. Steps involved in rain gauge calibration and field data correction using the automated dynamic rain gauge calibration system. Names of developed software are shown in bold type.

Data from the pump calibration are passed on to RAINCAL, which performs calibration of the rain gauge. During calibration, RAINCAL displays a plot of measured rain gauge rate versus true pump rate. The measured rain gauge rate is computed for each retained tip from the frequency of bucket tips and the known resolution of the gauge. This rate is displayed both numerically and graphically on the screen and updated after each tip. All information and results regarding the calibration are saved to an ASCII file. Calibration time depends on a variety of factors including rain gauge diameter, resolution, number of discarded (for bucket wetting purposes) and retained tips, and the number and value of the rates selected. For a 20.3-cm-diameter, 0.1-mm resolution rain gauge using 10 rainfall rates ranging from 6 to 240 mm h^{-1} (calculated using true pump rate values) with 10 discarded and 150 retained tips, calibration can be achieved in about 7 h.

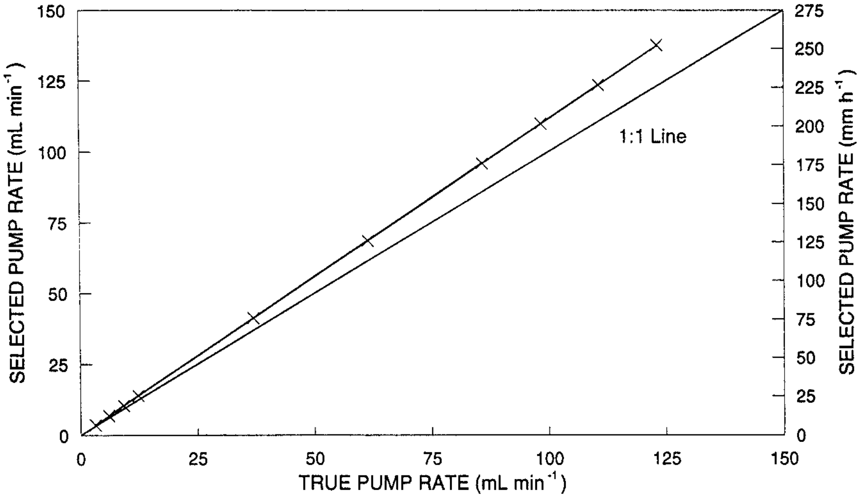

FIG. 3. Typical pump calibration results for 10 selected pump rates equivalent to rainfall rates between 6 and 254 mm h^{-1} [20.3-cm-diameter (8 in.) rain gauge].

A LOTUS 1-2-3 macro, RAINMAC, was written to analyze and display the results of pump and rain gauge calibrations. The macro performs regression analyses to obtain the fitted parameters of slope and intercept and also R^2 values for the pump and rain gauge calibrations. A third developed BASIC program, RAINCOR, performs three functions: 1) correction of field data, 2) graphical display of rainfall data, and 3) integration of corrected rainfall data. For a particular rain gauge, field rainfall data containing bucket tip time records are used to compute corrected rainfall intensities based on the dynamic rain gauge calibration results generated in RAINCAL. The corrected data can be displayed as rainfall intensity versus time (beginning and ending times chosen by the user to assist in isolating a selected precipitation event). The corrected rainfall data can then be integrated using specified time intervals (e.g., 15-min integration times) to obtain actual rainfall amounts. Field data correction and integration results can be saved to disk for later reference.

3. Calibration experiments

Two calibration experiments were done to assess the performance of the automated dynamic calibration system. All calibrations were conducted at room temperature (20°–22°C). In experiment 1, five types of TBRs[2] were calibrated using 10 rainfall intensities ranging from 6 to 240 mm h^{-1} (calculated using true pump rate values). Rain gauge diameters were 15.2, 20.3, and 30.5 cm (6, 8, and 12 in.), with resolutions ranging from 0.1 to 1.0 mm. Five replicate calibrations were performed for each rain gauge except for the Novalnyx rain gauge. In experiment 2, a single calibration was performed on 14 20.3-cm-diameter (8 in.) TBRs of a single type[3] using the same rainfall intensities as in experiment 1. Pump calibrations were performed prior to each rain gauge calibration using target volumes of 500 mL (experiment 1) and 100 mL (experiment 2) for each of the 10 rates. A smaller target volume was used in experiment 2 to reduce calibration time because results from experiment 1 showed that R^2 values were identical for both target volumes.

Pump calibration curves of selected versus true pump rate for experiments 1 and 2 were linear ($R^2 \geq 0.99$) for all replications and had slope values ranging from 1.0 to 1.2. However, true pump rates typically averaged about 5% to 10% less than the selected rate and this error increased with rate (Fig. 3). This discrepancy was attributed to various causes, including friction within the tubing walls, elevation difference between tubing inlet and outlet, and deformation of the tubing within the pumphead. A gradual decline of pump delivery performance over time was observed, which was indicated by the daily increase in slope of the pump calibration curve during these experiments. Replacement of pump tubing every 2 to 3 weeks was required to restore pump performance.

A rain gauge was calibrated immediately following each pump calibration using the same true pump rates and selecting 10 discarded and 150 retained tips. Figure 4 shows a typical measured rain gauge rate versus true pump rate curve and depicts the magnitude of under-

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[2] Sierra Misco Environmental, Ltd, models 2500-8 in. and 2500-12 in., Victoria, BC, Canada; NovaLynx Corp., model 260-201/2501-MM, Grass Valley, CA; Campbell Scientific, Inc., 6-in. diameter (no model number), Logan, UT; Qualimetrics, Inc., model 6011-B, Sacramento, CA.

[3] Qualimetrics, Inc., model 6011-B, Sacramento, CA.

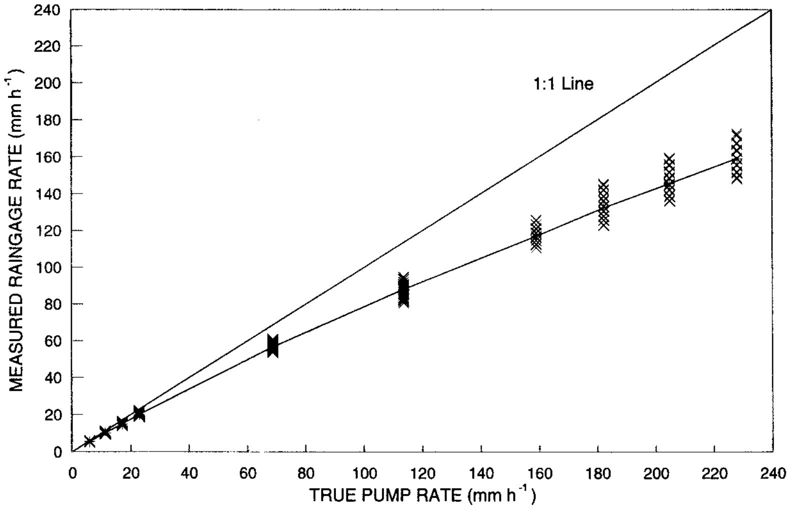

FIG. 4. Departure of measured rain gauge rate from true pump rate along 1:1 line illustrating underestimation of rainfall common with tipping-bucket rain gauges.

estimation errors common with tipping-bucket rain gauges. The difference between measured rain gauge rate and true pump rate increased nonlinearly as the true pump rate increased. All five gauges that were tested demonstrated this behavior and measured rain gauge rates showed a significant departure from the 1:1 line (Fig. 4), ranging from 5% to 29% as the measured rain gauge rate increased from 6 to 240 mm h^{-1}. The scatter of the data points also increased with increasing measured rain gauge rate due to the rain gauge's inability to accurately and consistently measure high flow rates.

Figure 5 compares the average underestimation errors for the five types of rain gauges tested at true pump rates ranging from 6 to 240 mm h^{-1}. Errors from 5% to 15% occurred at true pump rates less than 50 mm h^{-1} and increased to a maximum of 10% to 29% at true pump rates greater than 150 mm h^{-1}. The magnitude of these errors varied from one rain gauge type to the next. Evaporation effects during rain gauge calibration were insignificant at the flow rates used and did not contribute to underestimation errors. Similar results were obtained by Houghton (1985), who compared nine types of TBRs and found that underestimation errors increased in direct proportion to the rainfall intensity. Average underestimation errors also increased with decreasing resolution (independent of rain gauge diameter). This may be explained by the faster bucket motion experienced by the lower-resolution rain gauges, which can contribute to water loss at high rainfall rates. Here, R^2 values were greater than 0.98, and slope values ranged from 381 to

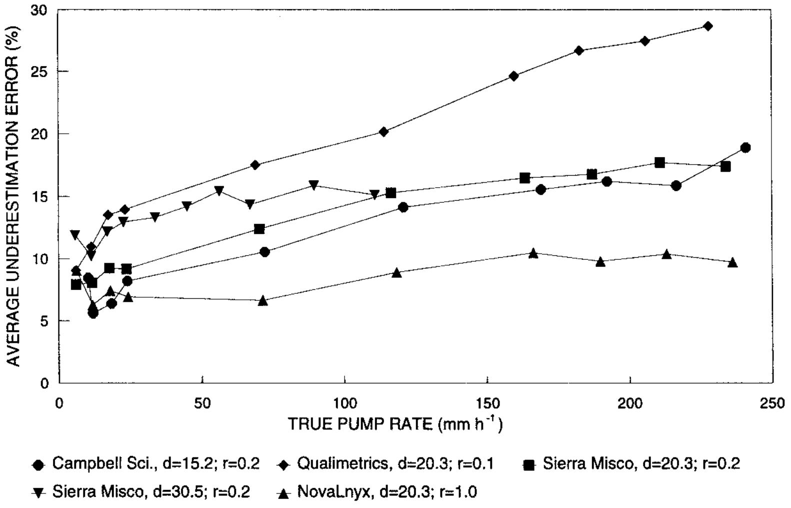

FIG. 5. Average underestimation error for five types of tipping bucket rain gauges using 10 true pump rates equivalent to rainfall rates ranging from 6 to 240 mm h^{-1}. Rain gauge diameters *d* are in centimeters and resolutions *r* are in millimeters.

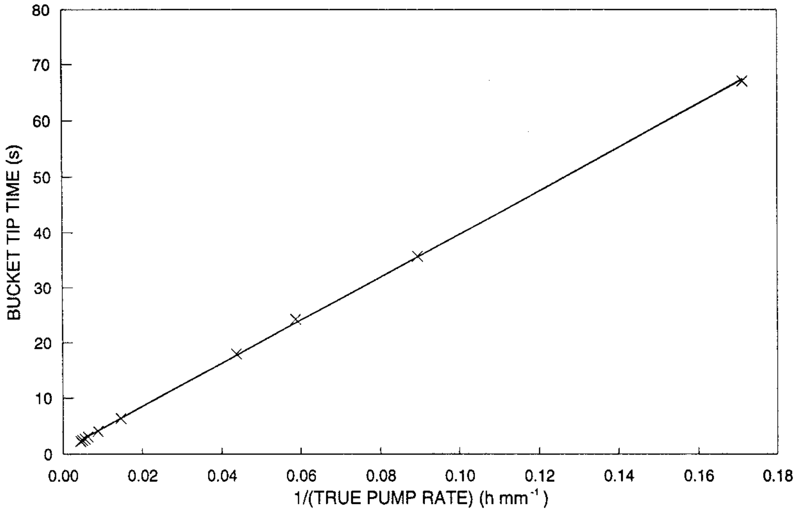

FIG. 6. Rain gauge calibration results showing linear relation between bucket tip time and (true pump rate)$^{-1}$.

3965 s mm h^{-1} for rain gauge calibrations in experiment 1. Slope value was also proportional with rain gauge resolution (i.e., doubling the rain gauge resolution doubled the slope) and was consistent within replicate calibrations.

In experiment 2, 14 identical Qualimetrics' rain gauges (20.3-cm diameter, 0.1-mm resolution) were calibrated. Calibration data for the 14 rain gauges were very similar, as indicated by slope values lying within 14% of each other and ranged from about 367 to 417 s mm h^{-1}. Here, R^2 values were greater than 0.98 in all cases.

4. Field data correction

Field data containing bucket tip time records were processed using the BASIC program RAINCOR. Correction was achieved by comparing bucket tip time records from field data to the dynamic calibration curve for the rain gauge. The calibration curve consists of the linear relationship ($R^2 = 0.99$) between bucket tip time and (true pump rate)$^{-1}$ (Fig. 6) from which slope and intercept values were computed according to the simple straight-line relationship

$$t = mx + b, \tag{2}$$

where t is the bucket tip time (s), m is the slope (s mm h^{-1}), x is the reciprocal of the true pump rate (h mm^{-1}), and b is the y-axis intercept (s). Field rainfall data obtained from a Qualimetrics' rain gauge (20.3-cm diameter, 0.1-mm resolution) that was returned to the laboratory for recalibration was used to demonstrate the field data correction procedure. The field data are for a storm at the crest of Yucca Mountain, Nevada, during which rainfall intensities exceeded 400 mm h^{-1}. For rainfall rates less than 50 mm h^{-1}, corrected and uncorrected data are nearly identical (Fig. 7) and are in agreement with the results of other researchers (Alena et al. 1990; Marselek 1981; Calder and Kidd 1978). For rainfall rates greater than 50 mm h^{-1} discrepancies between uncorrected and corrected data become significant; corrected values can be as much as 45% larger than uncorrected values at rainfall rates exceeding 250 mm h^{-1}.

5. Summary

Tipping-bucket rain gauges suffer from serious nonlinear underestimation errors when rainfall rates exceed 50 mm h^{-1} and can result in significantly lower rainfall totals. Dynamic calibration of TBRs has proven to be an effective method for minimizing these errors. A new automated dynamic calibration system has been developed to calibrate TBRs with minimal effort. The system consists of a programmable pump, datalogger, digital balance, and computer.

The performance of the system was tested using five types of TBRs and showed that, in all cases, rainfall underestimation errors of up to 29% occurred using rainfall rates between 6 and 240 mm h^{-1}. Correction of these errors began by performing a pump calibration followed by a rain gauge calibration. Pump calibration curves were linear in all instances ($R^2 = 0.99$), and slope values were consistently between 1.0 and 1.2. Rain gauge calibration curves, consisting of bucket tip time versus the reciprocal of the true pump rate, were also linear ($R^2 = 0.99$). Slope values were consistent between rain gauge replications as well as between rain gauges of different types, ranging from 367 to 3965 s mm h^{-1}, and correlated well with rain gauge resolution (i.e., doubling the rain gauge resolution also doubled the slope). Corrected rainfall amounts were computed from field data containing bucket tip time records using a developed software program and the rain gauge calibration results. Complete calibration of a TBR at 10 rainfall rates rang-

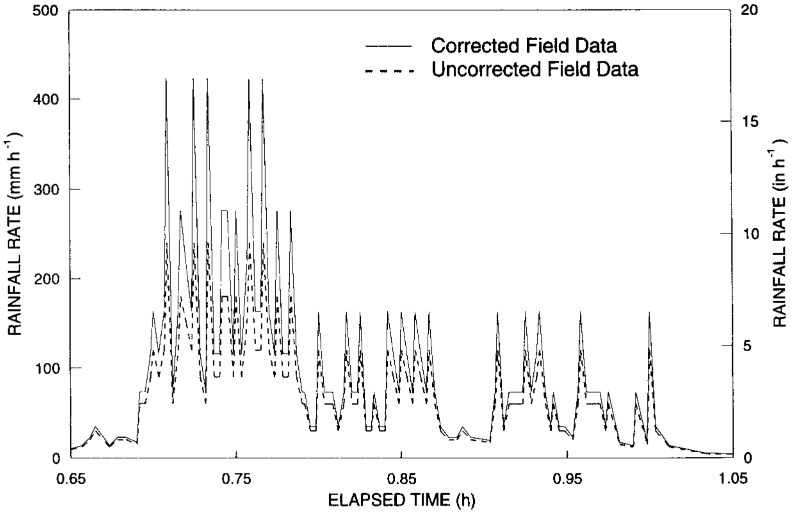

FIG. 7. Effect of applying dynamic rain gauge calibration results to uncorrected field data for a high-intensity storm at the crest of Yucca Mountain, Nevada.

ing from 6 to 240 mm h^{-1} can typically be achieved in about 8 h. The system is now in routine use to calibrate rain gauges in a large precipitation collection network at Yucca Mountain, Nevada. Similar systems could also be developed using other available laboratory equipment and software packages.

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