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Tipping Bucket Prototype for Automatic Quantification of Surface Runoff Rate in Plots

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ABSTRACT: Quantification of runoff rate is an onerous task with non-automated devices; it requires a lot of manual labor to perform measurements. In this study, an automatic device to quantify the surface runoff rate from plots with a small area was developed and tested. The prototype was based on the tipping bucket technique and built with reused materials. Its performance was tested in the laboratory and a calibration curve was developed to improve measurement accuracy. The device can be used for automatic quantification of surface runoff in small plots, with a flow rate of less than 750×10^3 mm^3 min^{-1}. The device can be built with different dimensions to measure different flow rates. In that case, the error measurements and calibration curve must be recalculated.

Keywords: tipping bucket, Gauge, flow rate, watershed.

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INTRODUCTION

Runoff has been studied for several purposes, mainly to quantify erosion processes and soil and nutrient losses (Panachuki et al., 2011; Oliveira et al., 2013; Costa and Rodrigues, 2015). Surface runoff models and soil water infiltration models (Spohr et al., 2009; Abrantes et al., 2015) have been developed and evaluated.

In scenarios of either natural or simulated rainfall, flow rate from a single channel or a collection of channels needs to be measured to quantify runoff. The total runoff volume (Costa et al., 2013; Costa and Rodrigues, 2015) and the surface runoff rate (Spohr et al., 2009; Oliveira et al., 2013; Lima et al., 2015) are the main variables used to express runoff.

Runoff quantification can be a laborious time-consuming task, especially when the runoff rate is quantified with non-automated devices. In studies on a watershed scale, the runoff discharged into a river changes its water level. This change is detected by a limnigraph and converted into runoff with the aid of a calibration curve (Almeida et al., 2013; Rodrigues et al., 2013). In soil plots, the limnigraph is not an appropriate device, so runoff measurements are usually performed by collecting either all or an aliquot of the outflow at a given time interval, which is then measured using scaled containers (Oliveira et al., 2013; Lima et al., 2015). This runoff measurement strategy cuts down on the need for manual labor by obtaining runoff rates at discrete times, mainly from long rainfall events. Furthermore, an unexperienced researcher can inadvertently introduce many errors when quantifying runoff. Therefore, the use of automated devices to quantify plot outflow can minimize these problems.

The tipping bucket technique is widely used to measure rainfall rate (Fankhauser, 1997). This technique can also be used to measure other flows, as proposed by Edwards et al. (1974) for quantification of surface runoff in plots of up to five hectares. Nevertheless, there is no tipping bucket configured to accurately measure runoff in plots on a square meter scale. Thus, in this study we sought to develop and test an automated tipping bucket to quantify the surface runoff rate from plots with small area.

MATERIALS AND METHODS

The tipping bucket prototype was made at the Soil Physics Laboratory of the Federal University of Santa Maria (UFSM) – Rio Grande do Sul, Brazil. The gauge system was molded from a rectangular metal sheet 120 × 110 mm (Figure 1); its length was 2.75 times its width (110 mm long, 40 mm wide, and 40 mm high). A metal wall was inserted at the center of the gauge (55 mm), separating two sections of equal volume. A fixed metal axis was attached at the gauge center and a stem containing a magnet at the top was attached to one side.

The tipping bucket system was then attached to a metal base composed of two parallel metal sheets (80 mm high and 60 mm wide) and an inverted metal channel (80 mm length, 50 mm wide, and 30 mm high). In construction of the metal base, the plates were secured at one end by the metal channel (Figure 2) and, at the other end, openings were made for coupling the tipping system.

To count the see-saw movements of the tipping system, a Reed Switch magnetic sensor was attached at the top of one of the parallel sheets (Figure 2) so that its position coincided with the magnet fixed on the tipping scale. Thus, when the scale is moved, the magnet (Figure 1) causes excitation in the magnetic sensor (Figure 2) and a pulse of energy is generated and transmitted to the reading and data storage system (CR1000 datalogger, Campbell Scientific, Inc., Logan, UT, USA).

Once the measuring system was assembled, it was attached internally to the lower end of a PVC pipe. A funnel attached to the upper end of the pipe receives and directs the collected water into the gauge. An epoxy resin was used to reduce the funnel outlet opening to a 3.4 mm diameter, improving the direction of water flow into the gauge system and restricting very high volumes. A nylon mesh was attached onto the top of the funnel to prevent the input of coarse material. The fully assembled device is shown in figure 3.

The water volume required to set the gauge system in motion was adjusted after the system had been installed inside the PVC pipe. Due to the capacity of the system, the water volume was adjusted to 15×10^3 mm^3, using the adjusting bolts (Figure 2), for both halves of the gauge. Possible errors include not only those from the adjustment of water volume, but also errors in the readings performed by the device, such as errors

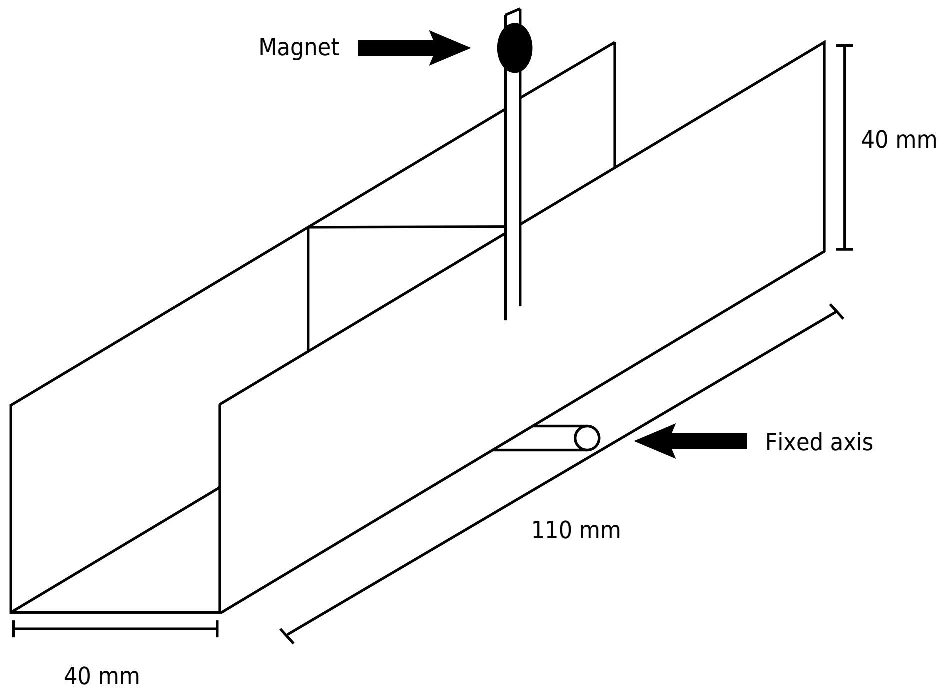

Figure 1. Diagram of the tipping bucket system.

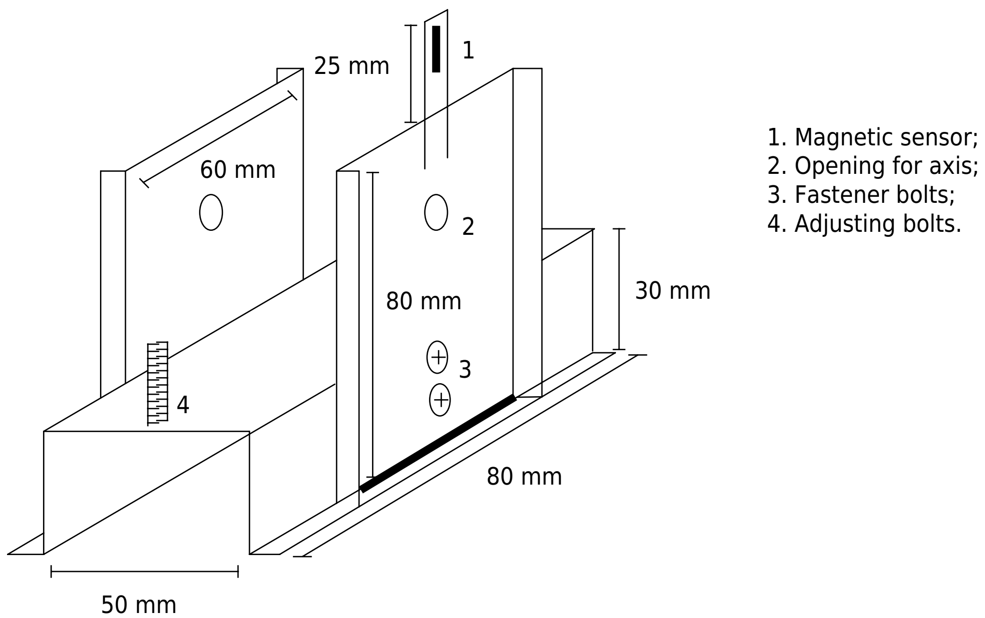

Figure 2. Diagram of the metal base used to support the tipping bucket system.

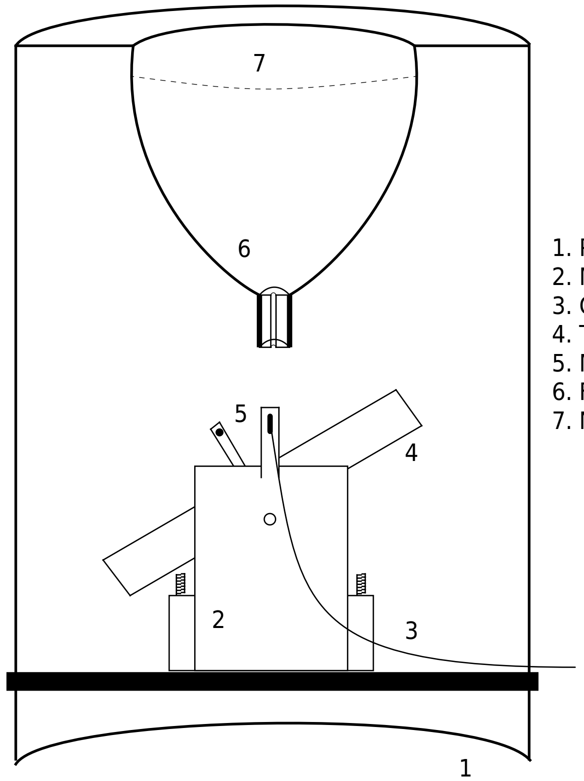

Figure 3. Vertical cross-section of the automatic runoff-measuring device.

arising from the turbulent flow of water within the gauge and the period necessary for the tipping "seesaw" cycle, resulting in larger errors for measurements of larger flows (Edwards et al., 1974). Therefore, Edwards et al. (1974) and Calder and Kidd (1978) suggest a correction in the readings performed by the tipping bucket device.

The need to correct the readings was verified in the laboratory, and a calibration curve was generated by relating the added measured flow rate for each tipping interval (Δt, min) of 1 min to the flow rate estimated by the device for the same interval. For this purpose, nine flow rates in the range of 0.045 to 2.5 $mm^3\ min^{-1}$ were obtained and maintained constant along the Δt interval by means of maintaining the water level inside the funnel constant. As the error from device estimates is dependent on changes in flow rate along the Δt interval and the magnitude of Δt (Edwards et al., 1974), the calibration curve was tested against two Δt (0.16 and 1 min), in which the flow rates randomly varied along the Δt interval.

The performance of the calibration curve at each Δt interval was evaluated by the Nash-Sutcliffe Efficiency (NSE) (Equation 1), which determines the magnitude of the residual variance, indicating how much the added flow rate versus estimated flow deviates from the 1:1 line (Moriasi et al., 2007).

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i^{ad} - Y_i^{est})^2}{\sum_{i=1}^{n} (Y_i^{ad} - Y^{mean})^2} \right] \qquad \text{Eq. 1}$$

in which: n is the number of evaluations; Y_i^{est} is the estimated flow rate by the device; Y_i^{ad} is the added flow rate; and Y^{mean} is the mean of the added flow rate.

The NSE values range between -∞ and 1, with NSE = 1 being the optimal value. Values between zero and 1 are considered indicators of adequate performance, while values below zero represent inadequate performance.

The percentage of bias (PBIAS) (Equation 2) was also used, which shows the trend of the added flow rate to be larger or smaller than the estimated flow rate (Moriasi et al., 2007):

$$PBIAS = \left[\frac{\sum_{i=1}^{n} (Y_i^{ad} - Y_i^{est})(100)}{\sum_{i=1}^{n} (Y_i^{ad})} \right] \quad \text{Eq. 2}$$

The optimal value for PBIAS is zero. Positive values indicate underestimation, and negative values indicate overestimation of estimated flow rate in relation to added flow rate.

Another possible error arises from the fact that 15×10^3 mm^3 of water must be stored so that the gauge starts the water unloading movement. If this volume is not accumulated inside the gauge, the water fraction below 15×10^3 mm^3 will not be quantified, resulting in a resolution error. For that reason, numerical analysis was performed to quantify the importance of resolution error on the measured flow.

RESULTS AND DISCUSSION

From visual analysis of the results, it can be observed that the relation between the measured flow rate and the estimated flow rate by the device with Δt of 1 min departs from the 1:1 line, confirming the need for calibration. The calibration curve was generated by using a quadratic function, which related the added flow rate to the estimated flow rate with a R^2 of 0.99 (Figure 4).

The performance of the quadratic calibration curve generated from Δt of 1 min was considered satisfactory in prediction of the flow rate for Δt of 0.16 and 1 min, according to the NSE and PBIAS coefficients (Table 1). Despite the small variation in NSE and PBIAS, the best calibration curve performance, for both NSE (values close to one) and PBIAS (values close to zero), was observed for Δt of 1 min. Both NSE and PBIAS indicated that there was underestimation (positive values), but the underestimation was less than 3 %.

The calibration curve generated does not take into account the effect of sediment concentration in the water flow. The presence of sediments increases the density of the fluid, requiring a lower volume of fluid to promote the seesaw movement of the gauge, which may cause an overestimation of the error. If necessary, users must check and change the calibration curve when sediments are present in the discharge flow.

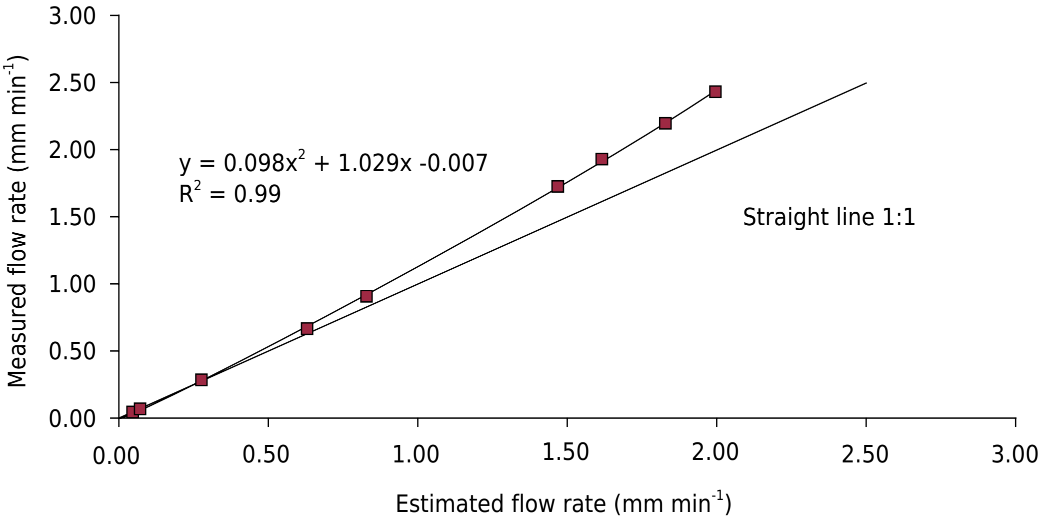

Figure 4. Calibration curve for the device.

Table 1. Performance of the device calibration curve (n=4)

Δt[1]	NSE[2]	PBIAS[3]
min		%
0.166	0.992	2.732
1.000	0.997	2.274

[1] Tipping interval (Δt). [2] Nash-Sutcliffe Efficiency (NSE). [3] Percentage of bias (PBIAS).

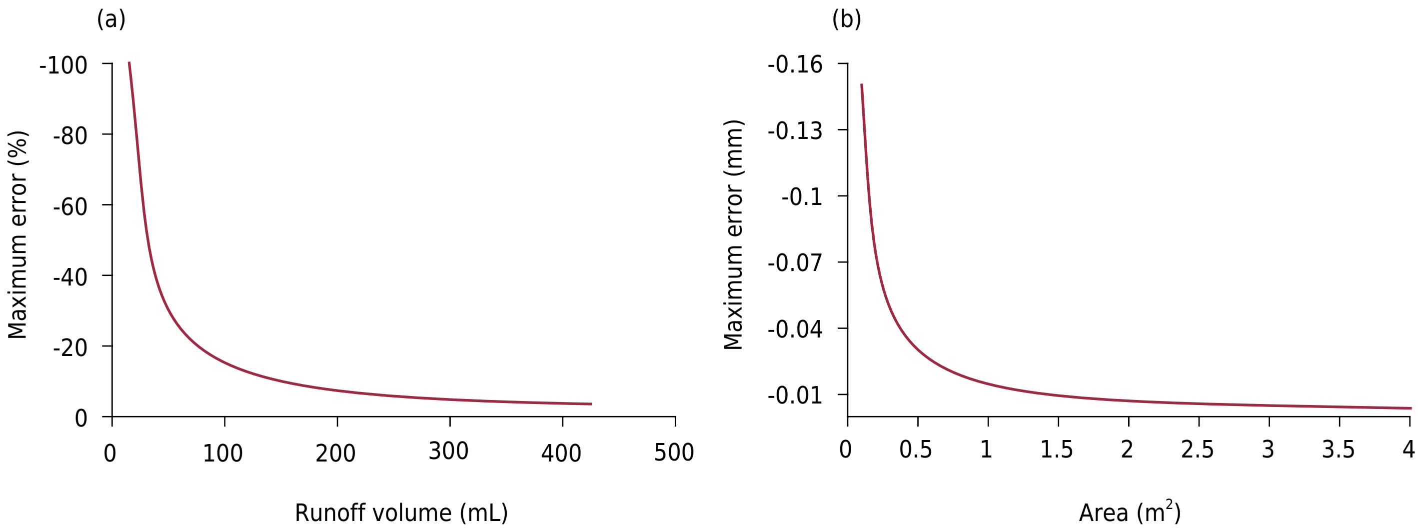

Figure 5. Maximum resolution error by runoff volume (a) and plot area (b). Negative values indicate underestimation of flow rate.

The device resolution error occurs only once during the runoff event and its magnitude is dependent on both the runoff volume and the plot area. In this study, plot means a theoretical surface used for mathematically evaluating the effect of the surface size on water accumulation and resolution error. Smaller runoff volume and smaller plot surface area result in greater participation of the error in the reading, as shown in figures 5a and 5b, respectively. The percent of error increases as runoff volume decreases, because this increases the proportion of the water not unloaded from tipping at the end of discharge flow (if there is not sufficient water accumulated to promote the "seesaw" movement) in relation to total discharge flow. Reduction in plot surface area also decreases total runoff volume; therefore, the effect is the same.

The maximum rate quantified in this study was 750×10^3 mm^3 min^{-1} in measurements performed in the laboratory and with the device described above. Although there is an inverse relation between resolution error and plot area, for good performance of the device, the plot area must have a flow rate of less than 750×10^3 mm^3 min^{-1}. If the flow rate exceeds 750×10^3 mm^3 min^{-1} the device should be built in larger dimensions.

This device is inexpensive and can be easily assembled. Among the materials used, the CR1000 datalogger is the costliest acquisition. However, it may be replaced by another data storage device, without compromising performance.

CONCLUSION

This tipping bucket prototype can be used for automatic quantification of surface runoff in plots with a flow rate of less than 750×10^3 mm^3 min^{-1}.

To obtain satisfactory approximation of real values, a calibration curve must be used.

The dimensions and capacity of the device can be adapted according to the needs of each user; however, the error analysis and the calibration curve must be recalculated.

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