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Construction and assessment of a hydraulic weighing lysimeter

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Hydraulic weighing lysimeters have been showing good results in evapotranspiration studies. Thus, the aim of this study was to construct, calibrate, and assess a small (0.7 m^3) and low cost hydraulic weighing lysimeter. The lysimeter consists of two containers. The inner container has a circular area of 1 m^2 and volume of 0.7 m^3, while the outer container is constructed with concrete slabs. The inner container is supported by three hydraulic load cells, arranged in the shape of an equilateral triangle. For calibration, standard weights with 1 kg were added and subsequently removed. Calibration results indicated high linearity between mass changes and their readings, with determination coefficient of 0.999. For pressure readings automation, it is necessary to correct temperature-related errors. Wind causes mechanical oscillations in the lysimeter, with subsequent pressure data errors that need to be corrected for proper evaporation measurements, especially in smaller time scales. Comparison between measured ETo and ETo estimated by Penman-Monteith method obtained a coefficient of determination of 0.56.

Key words: Evapotranspiration, calibration, hydraulic load cell, pressure gauge.

INTRODUCTION

Evapotranspiration is an environmental parameter required for crop implantation and management. It expresses the total water amount lost in a system by transpiration and evaporation of water from the soil. Depending on the conditions in which it is obtained, evapotranspiration may represent the site water demand or indicate the water amount that should be returned to the soil to meet crop needs. In regions that have a well-defined dry season, such as the Brazilian Cerrado, for example, there are periods when rainfall is insufficient to meet crop needs. In this case, knowledge of evapotranspiration for irrigation management purposes is indispensable (Valipour and Eslamian, 2014; Valipor, 2014a, 2015a; Khoshravesh et al., 2015).

Many devices and methods can be used to determine evapotranspiration. Among them, lysimeters have been used to directly obtain this variable with extreme reliability. Aboukhaled et al. (1982) considered the weighing lysimeter the best equipment for accurate measurement of evapotranspiration, serving as standard

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methodology to calibrate equations that estimate this variable.

One of the difficulties to use the lysimeter comes from its high cost of construction and installation. In general, it is recommended that the lysimeter surface area should be large enough to maximize the sample area and minimize the effect of the space between the lysimeter and the surrounding soil. Aboukhaled et al. (1982) recommended a minimum size of 4 m^2, while Sarnie and Villele (1970) recommended an area of 2 m^2. Nevertheless, the construction of lysimeters with areas of less than 2 m^2 has become common recently, with relative success. As an example, studies by Lima et al. (2013), Mariano et al. (2015), and Silva (2005), with respective areas of 1.32, 1.52, and 1.038 m^2, can be cited. Wherley et al. (2009) constructed and assessed in field a lysimeter with 0.05 m^2 and total volume of 15 L. Besides reducing construction costs, smaller lysimeters facilitate installation, operation, and maintenance in field.

However, there is concern that smaller lysimeters are subject to a number of problems and limitations among which stand out (Dugas and Bland, 1989; Allen et al., 2011): smaller population of sampled plants; the so-called “bloom effect” where the area of exposed plant canopy exceeds the assumed effective area of the lysimeter; influence of lysimeter’s wall on the thermal regime of the soil and of canopy environment; smaller accuracy and resolution in mass variation measurement.

Dugas and Bland (1989) compared measurements from three lysimeters with surface areas of 0.18, 0.75, and 3.0 m^2. They concluded that no consistent effect of lysimeter size on accuracy was found for the crop tested (sorghum and wheat), although the measurements were made in low temporal resolution (5 to 29 days). Grimmond et al. (1992) tested over short time periods two weighing mini-lysimeters (<0.2 m^2) and compared with evaporative flux measurements obtained using eddy correlation instrumentation from an extensive homogeneous surface. The authors concluded that the mini-lysimeters provided relatively accurate and reliable measurements of latent heat flux. In addition, according the authors, the mini-lysimeters developed can be used for continuous automatic monitoring of evapotranspiration at the resolution of an hour.

Therefore, given the importance of automation and properly measuring ETo, this study aimed to construct, calibrate, and assess a hydraulic weighing lysimeter with 1 m^2 surface, in order to monitor evapotranspiration.

MATERIALS AND METHODS

The experiment was conducted at the Federal University of Mato Grosso, Rondonopolis, MT State Campus, with the following geographical coordinates: 16°28”15’ S, 54°38”08’W and altitude of 284 m.

A hydraulic weighing lysimeter containing two cylindrical containers was constructed. The inner container was constructed with iron plates with 4 mm thickness, 1 m^2 area, and volume of 0.7 m^3. The outer container was constructed with 16 concrete plates with 2 cm thickness, in order to support the surrounding soil. The lysimeter setup consisted of the following components: hydraulic weighing system, drainage system, reading system, and automation system.

For the hydraulic weighing system, three hydraulic load cells were constructed with self-extinguishing hoses made of butyl propylene reinforced nylon, with the following dimensions: 850 mm length and 101.60 mm inner diameter. Hoses had their extremities closed by pressure, using two pairs of galvanized pipes with 0.2 m length. Pipes were transversely drilled to fix screws. A metal connector was coupled in the central part of each of the load cells, in order to couple a polystyrene flexible tube. Flexible tubes of the three load cells were connected through a shutoff valve which, in turn, had an outlet tube connected to the pressure gauge.

Three support bases for the load cells were constructed on the bottom of the outer container. Cells were arranged in the container in the shape of an equilateral triangle, with an angle of 120 degrees between the sides. Bases were made of concrete, with rectangular shape and dimensions of 0.60 × 0.15 × 0.20 m. Bases were carefully leveled to support the hydraulic load cells, so that sealing tubes did not have contact with the soil or the concrete base. Subsequently, a 20 mm thick polyvinyl polychloride film was put on each load cell, in order to isolate the bottom of the inner container from contact with sealing tubes.

For the drainage system, a polyvinyl polychloride tube with 0.2 m diameter and 2.0 m depth was buried alongside the outer container. Inside the inner container, three polyvinyl polychloride tubes with 75 mm diameter, containing a porous clay capsule, were vertically inserted. Porous capsules were connected to the tube receiving the drained water via polyethylene tubes. Accounting of the amount of drained water was made by a folding system used in automatic rain gauges.

The reading system was formed by two independent components: mercury manometer and hydrostatic pressure sensor. The pressure gauge reading mechanism was based on a scale in millimeters. The hydrostatic pressure sensor used was the (PX26-001DV-Omega) model with (-0.007 to +0.007 mV) range, connected to the CR-1000 model (Campbell Scientific, Inc., Logan, USA) data logger.

Inner container filling was first conducted with a 0.1 m layer of gravel. The other layers, added at every 0.1 m, were filled with soil, respecting the order found in the original layers during their removal from the field. For each layer completed, the lysimeter soil received water to approach its natural density. Lysimeter implementation process was completed after coupling an access tube in the center of the lysimeter, in order to conduct soil moisture reading through the humidity probe. In Figures 1 and 2, there is a representation of the hydraulic weighing lysimeter constructive part, with some of its main components.

Load cells optimum volume calculation

In order to determine the optimal water amount for load cells, recommendations by Silva et al. (2003) were followed. This step was carried out in laboratory. Load cells filling was conducted with 13 L of distilled water at rest. Through a control shutoff valve linked to the load cells, equal volumes of 50 ml were released in each step, whose pressure values were observed in the mercury manometer and in the data logger. The procedure was repeated until reading differences were stable and proportional. Recorded values were subsequently correlated with the accumulated withdrawal volume. The optimal water volume for load cells corresponds to the minimum point of the regression curve fitting between manometer readings variation and accumulated water amount.

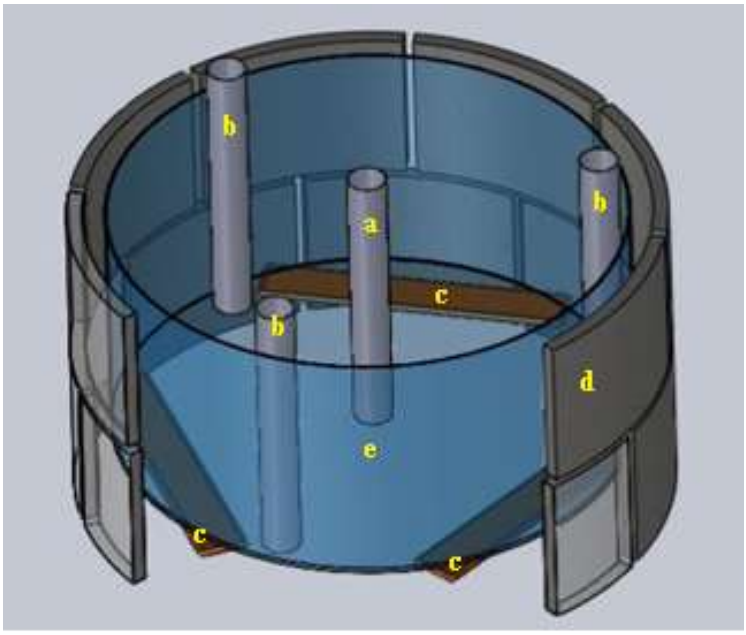

Figure 1. Lysimeter General Representation: (a) humidity probe access tube; (b) drainage pipes; (c) load cells; (d) casing and (e) inner container.

Figure 2. Details of the structure and mounting of the hydraulic lysimeter. (A): hydraulic load cells arranged in an equilateral triangle format and attached to each other by a metal connector. (B): arrangement of hydraulic load cells supported on concrete foundations in the field; (C): mounting the lysimeter in the field, with layer of gravel and the tubes to the drainage system. (D): tipping bucket rain gauge adapted for measuring the water drained.

Lysimeter calibration

This step was carried in field, after the installation of lysimeter. Calibration was divided into two stages. The first step consisted of lysimeter central calibration, gradually adding 1 kg weights until the total weight of 100 kg was reached. Each individual weight was equivalent to a 1 mm water blade. Subsequently, added weights were gradually removed, one by one. At every weight addition or withdrawal, 1 min was waited, in order to stabilize the reading system. In the second step, loads were applied on each load cell and in the vertices of the equilateral triangle formed by load cells. In this step, 36 weights of 1 kg were added and subsequently removed. As in the central calibration, addition and removal of weights in the latter stage occurred gradually, respecting the time required for system stabilization. The purpose of this last step was to verify lysimeter stability.

Temperature effects on data quality

Evapotranspiration data quality in hydraulic lysimeters may be affected by environmental factors that act in the several components of the lysimeter system. Temperature is a major factor, as it influences fluid expansion and contraction in the load cell, in the fluid transmission system and in the reading system. Errors may still occur even in thermal insulation, in an attempt to minimize thermal fluctuation effects (Wangati, 1965).

Thus, in order to correct temperature effects acting on the whole system, pressure transducer readings were correlated with temperature values inside the weather shelter. The analysis was conducted in four days in a row. During this period, the lysimeter surface was sealed to avoid water loss by evapotranspiration, and therefore, pressure variation recorded in the data logger was related to temperature variation.

The measured data of evapotranspiration were compared with simulated data by the Penman-Monteith model. The Penman-Monteith model is usually used as reference in evapotranspiration simulation studies. Thus, it is noteworthy that the construction of the lysimeter is also useful for further evaluation of the various models available to simulate evapotranspiration or even for building empirical models. Examples of studies comparing different models of evaporation can be found in Valipour (2012, 2014b, c, d, 2015b).

RESULTS AND DISCUSSION

Optimum fluid volume in the load cells

Pressure variation registered in the pressure gauge showed tendency to constant readings, with fluid withdrawal in volumes equal of 50 ml. Initially, differences measured in the pressure gauge were higher, gradually decreasing as the contact area between the load cell and the base became practically invariable with subsequent extractions. Taking into account that the optimal water volume for load cells corresponds to the minimum point of the regression curve fitting between manometer readings variation and accumulated water amount, then:

$$\Delta L = 0.0000003Va^2 - 0.0038Va + 12{,}33 \quad (1)$$

where ΔL is the readings variation (mm) and Va is the accumulated volume (ml).

Volume was obtained by the derivative of the following function:

$$\frac{dy}{dx} = 0.0000006Va - 0.0038$$

By solving Equation 2, after the tangent is defined as equal zero (minimum point), the optimum volume of 6333 ml is found.

A similar result was observed by Silva (2005), while using hydraulic weighing lysimeters to determine evapotranspiration and crop coefficients of passion fruit, in which the result reduced hydraulic load cells pressure along with successive 50 ml water decreases. According to Silva (2005), inadequate fluid volume within the load cell does not allow a constant contact area, interfering with pressure responses that are transmitted to the reading system.

Calibration and stability coefficient

In Figure 3, lysimeter central calibration results are shown. It is noted that both mercury manometer and pressure transducer had linear responses between the added or removed weight and the corresponding pressure. In both cases, fitting quality was excellent (R^2>0.999). It was also noted that small hysteresis effect occurred in both measurement systems. Similar results were found by Lima et al. (2013), while calibrating load cells and hydraulic load cells.

Results of calibrations conducted in each load cell and in the vertices are shown in Tables 1 and 2. In general, it was observed that determination coefficients were all above 0.99 for both individual cells and vertices, in both measurement methods. This indicates that the lysimeter is stable, which is extremely important to obtain reliable data. It is important to highlight that equipment balance is due to the fact that the three hydraulic load cells were arranged to form an equilateral triangle. Another important factor is that the water amount used in hydraulic load cells should not make the contact area between the inner container base and the cells cause inconsistent estimates, as mentioned by Silva (2005).

Calibration coefficients (*k*) obtained in the mercury manometer ranged from 3.577 to 4.011 mm with the addition and removal of 1 kg weights (Table 3). For the transducer, this coefficient ranged from 0.982 to 1.169 kg for 1 kg weights added or removed. The central calibration coefficient (*k*), which is the standard used in lysimeters, was of 3.434 mm kg^{-1} for the mercury manometer and of 1.017 kg for the electronic pressure transducer. That is, each 1 kg of added or removed weight in the lysimeter corresponds to 1.017 mm of evapotranspired depth.

Lysimeter stability was determined by the mean of the calibration coefficients of the three hydraulic load cells

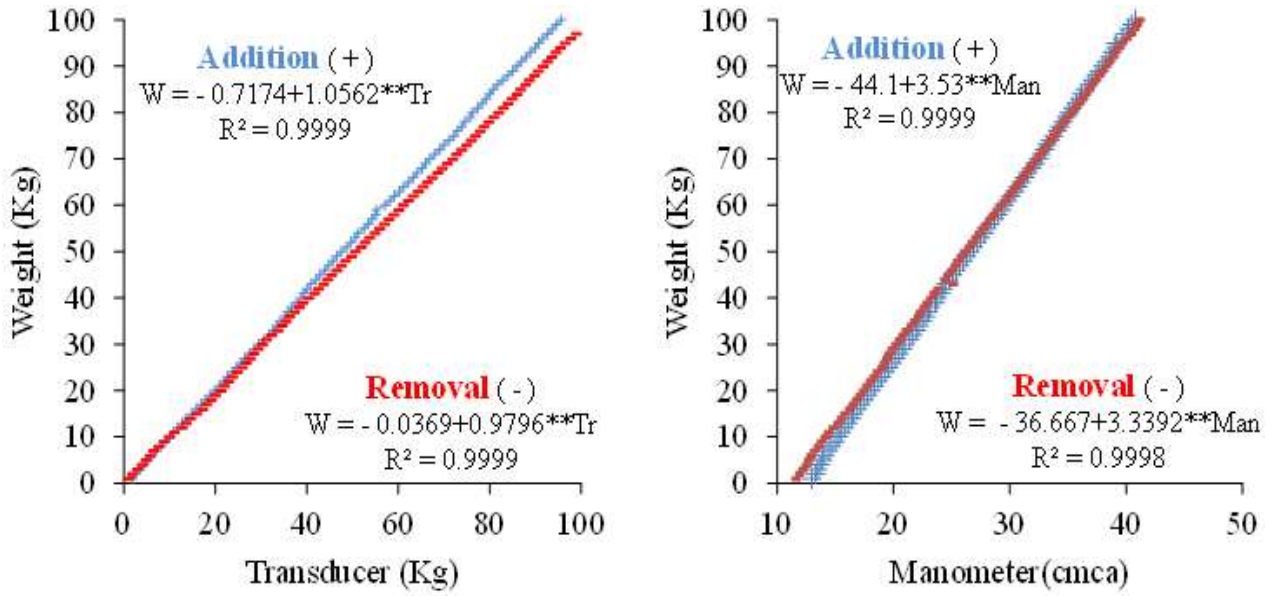

Figure 3. Lysimeter central calibration regression analysis. Readings observed in the transducer (Tr) and in the mercury manometer (Man) were related to the addition (+) and removal (-) of 1 kg weights (M). **Significant at 1% probability.

Table 1. Relationship between weight variation (kg) and pressure (mm) in the mercury manometer and in the pressure transducer, with point load in each of the three hydraulic load cells.

System of measurement	Load cell	Addition		Removal	
		Model**	R^2	Model**	R^2
Manometer	1	Y=30.072+3.522x	0.998	Y=-25.469+3.617x	0.996
Transducer		Y=-23.706+1.061x	0.997	Y=-14.74+0.9021x	0.996
Manometer	2	Y=-30.083+3.712x	0.997	Y=-32.723+3.811x	0.996
Transducer		Y=-17.524+1.150x	0.999	Y=-19.847+1.189x	0.998
Manometer	3	Y=-34.255+3.731x	0.998	Y=-36.188+3.521x	0.997
Transducer		Y=-24.239+1.024x	0.998	Y=-26.586+1.042x	0.997

**Significant at 1% probability.

Table 2. Relationship between weight variation (kg) and pressure (mm) in the mercury manometer and in the pressure transducer, with point load in each of the three vertices of hydraulic load.

System of measurement	Vertex	Addition		Removal	
		Model**	R2	Model**	R^2
Manometer	1	Y= -2.355+3.744x	0.996	Y=-21.213+3.606x	0.995
Transducer		Y=-7.7445+1.098	0.998	Y=-6.540+1.049x	0.996
Manometer	2	Y=-20.628+3.636x	0.999	Y=-20.902+3.519x	0.995
Transducer		Y=-6.051+1.057x	0.999	Y=-5.977+1.034x	0.997
Manometer	3	Y=-23.960+4.4x	0.995	Y=-14.331+3.622x	0.998
Transducer		Y=-3.666+1.124x	0.997	Y=-2.338+1.023x	0.992

**Significant at 1% probability.

Table 3. Calibration coefficients (k) and mean error, with point load in the centers and vertices of hydraulic cells and in the lysimeter center, in mm kg^{-1}.

Posição	Calibration coefficient (*k*)	Calibration coefficient (*k*)
	Manometer	Transducer
cell 1	3.569	0.982
cell 2	3.761	1.169
cell 3	3.626	1.033
vertex 1	3.675	1.074
vertex 2	3.577	1.046
vertex 3	4.011	1.073
Mean	3.703	1.063
Lysimeter center	3.434	1.017
Mean positional error (%)	7.83	4.50

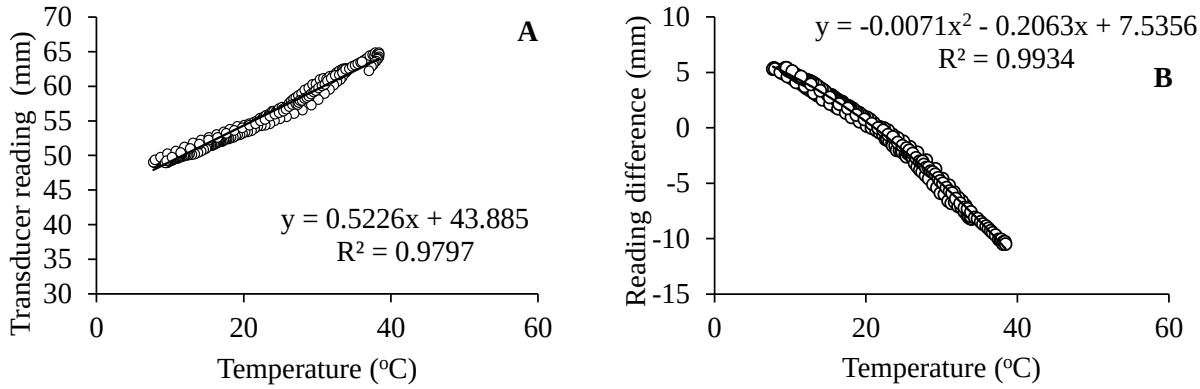

Figure 4. Relationship between pressure data generated by the transducer and the temperature obtained in the data logger (A); differences between original data and standard data, estimated at 20°C. Timescale of 10 min.

and of the three vertices compared to the lysimeter central calibration coefficient. Mean positional errors of 7.83 and 4.50% were observed for the mercury manometer and the transducer, respectively (Table 3). This result confirmed that the lysimeter is stable, especially when used in an automated manner, that is, by readings generated by the transducer in the data logger. Compared to other studies, hydraulic weighing lysimeters constructed by Santos et al. (2008), showed mean errors of up to 3.93 and 1.73%, respectively, using mercury manometer.

It is noteworthy that Black et al. (1968), quoted by Silva et al. (2003), stated that the tolerable error limit is 10%, as tank inclination influences fluid deformity in hydraulic cells, causing lysimeter reading errors. Thus, the mean positional error of 7.83% obtained by pressure gauge reading was lower than the 10% limit.

Temperature influence on lysimeter reading

It is possible to observe correlation between the transducer reading in the data logger and the temperature (Figure 4A). These data were obtained during the four days in which lysimeter surface was sealed to prevent water loss. A linear equation was fitted to the data from this relationship, in order to subsequently obtain a correction factor. The value regarded as reading standard was observed substituting the "x" value by 20°C in the linear equation. The 20°C value was established in accordance to the recommendations of the Instituto Nacional de Metrologia (2011). Figure 4B represents the differences between the amounts recorded over the four days and the standard value. Having with the equation fitted to the data in Figure 4B, temperature values associated with the pressure values generated by the transducer during the period were substituted (Figure 4A). The result represents the value to be corrected to the original data. In Figure 5, original data and corrected data are shown.

It is observed that the correction factor obtained by the methodology was efficient to linearize lysimeter readings under temperature effect, minimizing reading errors.

This correction procedure is important because there

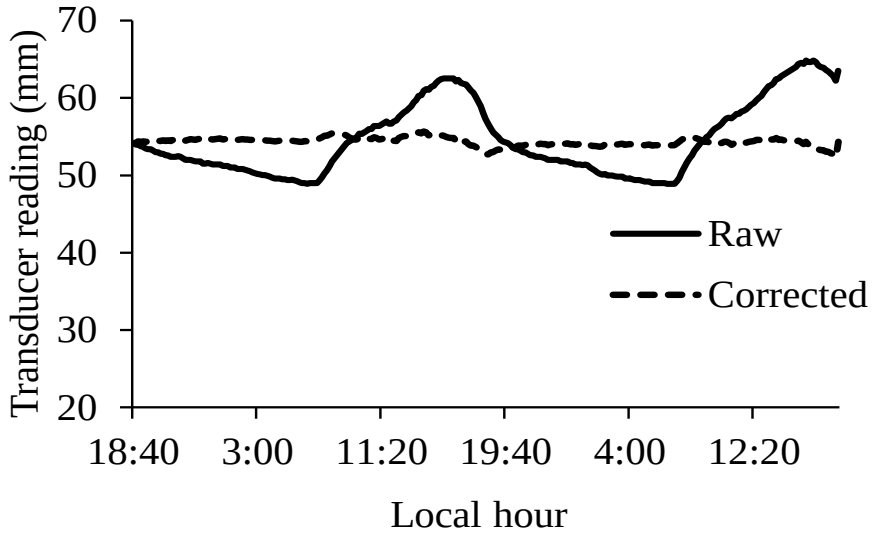

Figure 5. Uncorrected and corrected pressure transducer response (converted to mm) in a timescale of 10 min.

are basically two types of errors related to pressure transducer. One related to the sensor itself and the other related to external factors. So, for example, ambient temperature variations can affect the output signal of the sensor, even in a condition in which there was no variation of the applied pressure. These measurement errors are usually corrected by a compensation to the output signal of the sensor. However, there are additional variations throughout the hydraulic lysimeter measurement system that are transmitted to the pressure transducer. The main error is due to thermal expansion of the water column along the hydraulic system. The magnitude of this expansion is difficult to quantify exactly. However, Wangati (1965) calculated that the fluctuation of the water column due to temperature would be 0.66 mm. Of course, this value is different depending on the weather conditions of the region.

Evapotranspiration assessment

Correlation between measured and estimated evapotranspiration by Penman-Monteith method is as shown in Figure 6. The determination coefficient was of 0.5683, which is a mean value. However, similar results were found by other authors. For example, Medeiros (2002) and Mendonca et al. (2003) obtained determination coefficient values of 0.56 and 0.58, respectively, comparing lysimetric measurements on a daily scale by the Penman-Monteith method.

Among the possible additional sources of errors in lysimetric measurements, wind has an important contribution. It was observed that variations in the measured data occurred over time (Figure 7A). These variations are correlated to the wind speed values throughout the day (Figure 7B). However, wind is a very difficult variable to model and to predict. In addition, it is also very difficult to eliminate its effects on the system. One option would be to smooth the data using means on larger timescales, such as 1 h for example (Figure 8).

Weighing lysimeter reading errors are common (Schrader et al., 2013), especially in mechanical vibrations caused by the wind in high temporal resolution data (Vaughan and Ayars, 2009). Schrader et al. (2013) and Vaughan and Ayars (2009) discussed methods to reduce these errors, such as the application of filters to remove inconsistent data. They also suggested the statistical processing of collected data, in order to smooth noises.

Pressure transducer response during the day varies according to lysimeter water loss dynamics (Figure 9A), in which three variation stages stand out. Initially, it is noted that variation is very small during the night. During this period, there would only be water decrease by evaporative process. Subsequently, there is sharp, near-linear fall, indicating intense water loss to the atmosphere. Again, there is apparent pressure variation stabilization with the beginning of the nocturnal period (Figure 9A).

The tendency described earlier was observed for four sequential days in which there was no water replacement in the soil (Figure 9B). In this case, soil water variation represents the actual evaporation process. It is noted that radiation during those days did not decrease sharply, demonstrating that there was no energy availability reduction. It was observed that the period of increased pressure depletion apparently decreases with each passing day, which is typical of water reduction in the soil.

Finally, it is noteworthy that the lysimeter constructed in

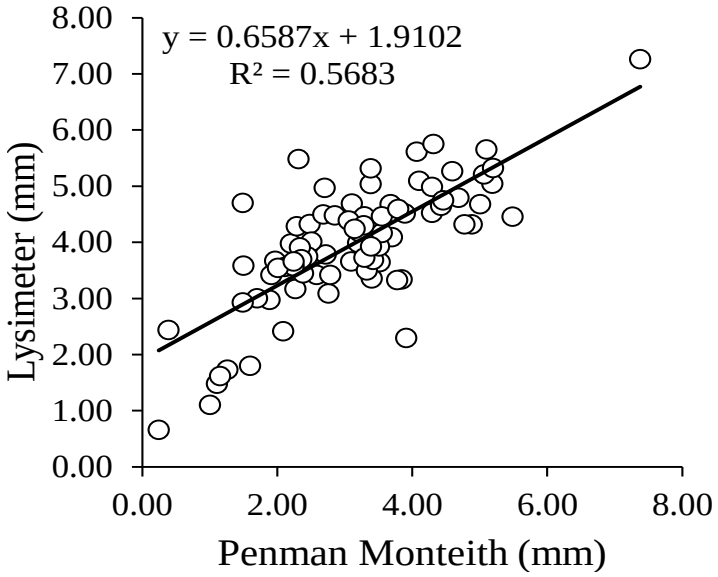

Figure 6. Correlation between ETo daily values measured by the lysimeter and estimated by Penman-Monteith (mm) for the period from 08.01.2013 to 10.31.2013, in the southern region of Mato Grosso, Brazil.

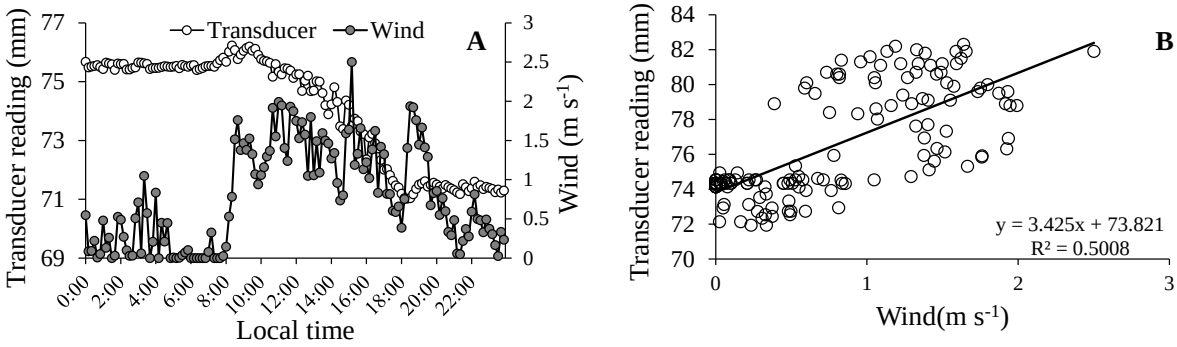

Figure 7. Pressure transducer response (converted to mm) and wind velocity (m s^{-1}) over the day in a timescale of 10 minutes (A); correlation between pressure transducer response (mm) and wind velocity (m s^{-1}) (B).

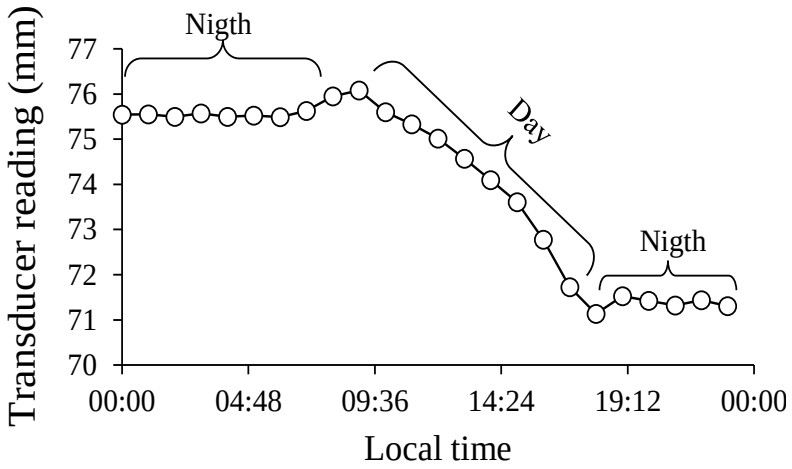

Figure 8. Pressure transducer response time means (converted to mm).

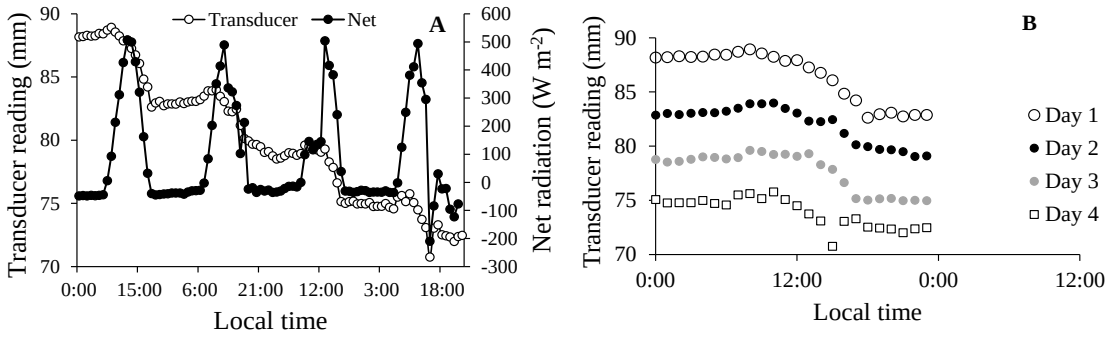

Figure 9. Pressure transducer response (converted to mm) and net radiation (W m^{-2}) time means variation in four sequential days (A); comparison between pressure transducer response (mm) in four sequential days.

this study has relatively small dimensions if compared to those usually described in the literature. The surface area was of 1.0 m^2, with total volume of 0.7 m^3, facilitating lysimeter use not only in the scientific research area, but also in farms or sectors related to the environment.

Conclusions

The hydraulic weighing lysimeter showed highly significant and accurate calibration responses for both central and localized calibrations. Therefore, the construction methodologies described in this study can be used as methodological reference, especially with regard to the disposal of hydraulic load cells in the form of an equilateral triangle.

Lysimetric readings automation with the pressure transducer is efficient and accurate. However, it is necessary to correct reading errors caused by temperature. In addition, mechanical oscillations caused by the wind are important data error sources, especially if smaller timescales are used.

Conflict of Interests

The authors have not declared any conflict of interests.

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