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Construction and calibration of a bar weighing lysimeter

Daiane de Cinque Mariano[1], Rogério Teixeira de Faria[2], Paulo Sérgio Lourenço de Freitas[3*], Bruno Patias Lena[3] and Andre Luiz Johann[4]

[1]*Departamento de Agronomia, Universidade do Estado de Mato Grosso, Tangará da Serra, Mato Grosso, Brazil.* [2]*Departamento de Engenharia Rural, Faculdade de Ciências Agrárias e Veterinárias, Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil.* [3]*Departamento de Agronomia, Universidade Estadual de Maringá, Av. Colombo, 5790, 87020-900, Maringá, Paraná, Brazil.* [4]*Departamento de Engenharia de Biossistemas,* Escola Superior de Agricultura *"Luiz de Queiroz", Universidade Estadual Paulista, Piracicaba, São Paulo, Brazil. *Author for correspondence. E-mail: pslfreitas@uem.br*

ABSTRACT. Generally, standard lysimeters include a lever-load cell scale, which has become expensive compared to new electronic equipment available for experimental purposes. Currently, lysimeters containing weighing bars with up to 4 load cells are economically feasible. This goal of this study was to present the construction and calibration of four weighing lysimeters built using two rectangular tanks, with a surface area of 1.35 m^2 (1 m by 1.35 m) and a depth of 1.5 m, loaded on two weighing bars. Each bar had two high accuracy loading cells connected to a junction box and a datalogger by a coaxial cable. Calibration of each lysimeter was performed after field installation. The results showed a linear response ($R^2 > 0.9999$) of electric signal (mV) to mass increase or decrease (kg) with minimum hysteresis. The mean absolute error of the mass estimate (0.0245 to 0.2844 equivalent-mm) and a Willmott index between the observed and estimated data (d = 1.0000) indicate the high precision of the new equipment. The results allow concluding that the lysimeters in this study are appropriate for estimating evapotranspiration and other components of soil water balance.

Keywords: evapotranspiration, water balance, soil water.

Construção e calibração de lisímetros de barras de pesagem

RESUMO. Nos lisímetros tradicionais, o sistema de pesagem geralmente inclui uma célula de carga acoplada a uma balança com alavancas de redução de massa. O alto do custo da matéria prima e mão-de-obra dessas balanças, associado à grande oferta atual de componentes eletrônicos de coleta de dados de baixo custo, viabilizam a construção de novos equipamentos constituídos de barras de pesagem com até quatro células de carga por lisímetro. Este trabalho teve como objetivos apresentar a construção e a calibração de quatro novos lisímetros constituídos de tanques duplos retangulares, de aproximadamente 1,35 m^2 (1 m por 1,35 m) de superfície e 1,5 m de profundidade, apoiados sobre duas barras de pesagem. Cada barra de pesagem continha duas células de carga de alta acuracidade, ligadas por cabo coaxial a uma caixa de junção e depois a um sistema de aquisição de dados. Calibrações de cada aparelho foram realizadas após a instalação dos equipamentos no campo, resultando em ajuste linear ($R^2 > 0{,}9999$) entre impulso elétrico (mV) e massa (kg), com mínima histerese. O erro absoluto médio da estimativa da massa (0,0245 a 0,2844 equivalente-mm) e o índice de Wilmott entre os valores observados e estimados (d = 1,0000) indicam a alta exatidão das medições do equipamento construído. Com base nos resultados obtidos, concluiu-se que os aparelhos construídos são apropriados para estimativas de evapotranspiração e demais componentes do balanço hídrico.

Palavras-chave: evapotranspiração, balanço hídrico, água no solo.

Introduction

The complexity and difficulty to determine ET (evapotranspiration) in the field have been surpassed by technological advances in the electronic data collection systems that directly or indirectly monitor the different processes involved. Direct measures provide greater reliability and are typically performed by lysimeters; in addition, soil water balance methods are occasionally used (SILVA et al., 2009).

The use of weighing lysimeters in studies on crop water requirements, which can be used to determine ET or calibrate agrometeorological models, is essential for obtaining reliable results (CAMPECHE et al., 2011; SILVA et al., 1999). According to Silva et al. (2005), when properly installed, lysimeters allow accurate measurements of ET, especially if filled with soil similar to the soil layers of the external area.

The weighing lysimeter is fabricated by a box with impermeable walls that is filled with soil and placed in a field with either a bare surface or vegetation cover. A load cell measures the weight variation (VIANA et al., 2003).

The lysimetry technique has been used to accurately measure rainfall, evaporation and drainage (KIRKHAM et al., 1984; MENDONÇA et al., 2003) through the mass variation of a soil block due to the inflow or outflow of water using a load cell that monitors the water dynamics in the cultivated or bare soil (CAMPECHE et al., 2011).

Although precise, evapotranspiration (ET) measurements obtained using the lysimetry technique can also be affected by environmental and design factors such as advection, lysimeter size, soil moisture regime, wall thickness and distance, wall edge height, and differences in the height and density of vegetation inside and outside the lysimeter (CAMPECHE et al., 2011; MIRANDA et al., 1999).

The calibration of lysimeters is important because poor calibrations lead to inconsistent interpretations of ET values, especially when taken over short periods of time (CAMPECHE et al., 2011). According to Faria et al. (2006), the calibration aims to establish a relationship between the electrical output signal of the load cell and mass of the system and to check the linearity and hysteresis of the weighing system.

Campeche et al. (2011), Carvalho et al. (2007) and Faria et al. (2006) have reported high precision lysimeter measurements for standard weights added and removed from the system during calibration. In these studies, the deviations varied between 0.08 and 0.278 for 0.07 mm and 0.42 mm, respectively, with a linear response between the standard weights and readings of load cells; furthermore, the coefficients of determination were above 0.99.

In conventional lysimeters, the weighing system frequently includes a lever-load cell scale to expand the scale used (CAMPECHE et al., 2011; FARIA et al., 2006). In recent years, the cost of this type of scale has increased due to the rise in raw material and labor costs required for construction. Nevertheless, the electronics industry has offered increasingly inexpensive load cells, allowing the construction of new weighing systems to be less expensive than conventional lysimeters by minimizing the metal structure with the use of weighing bars.

The goal of this study is to present an analysis of weighing lysimeters, including their construction and calibration, to determine their ability to measure variations of soil water storage under field conditions.

Material and methods

Construction of lysimeters

Four weighing lysimeters were constructed and installed at excavated pits with rectangular walls in the Experimental Farm of IAPAR, Londrina, Paraná State. Each lysimeter consisted of double rectangular tanks with internal dimensions of 1.35 m^2 (1 m by 1.35 m) for the surface area and 1.5 m for the depth. Fiberglass and resin walls were strengthened with 2-mm steel beams placed at the edges and in the center (Figure 1). The external tank was constructed of walls fabricated of the same material and with surface dimensions of 1.1 m by 1.45 m and a depth of 1.6 m, and it was separated from the internal tank by 5 cm. The internal tank was supported on the smaller side by two 5-mm carbon steel U-shaped weighing bars that measured 0.15 m wide and 0.9 m long. Two load cells (Z6FC3/1T, HBM measurement, São Paulo, São Paulo State) were coupled on one side by steel screws 0.1 mm from the ends of each weighing bar and steel support brackets (Z6FC4 Z6/1T/ZEL, HBM measurement, São Paulo, São Paulo State).

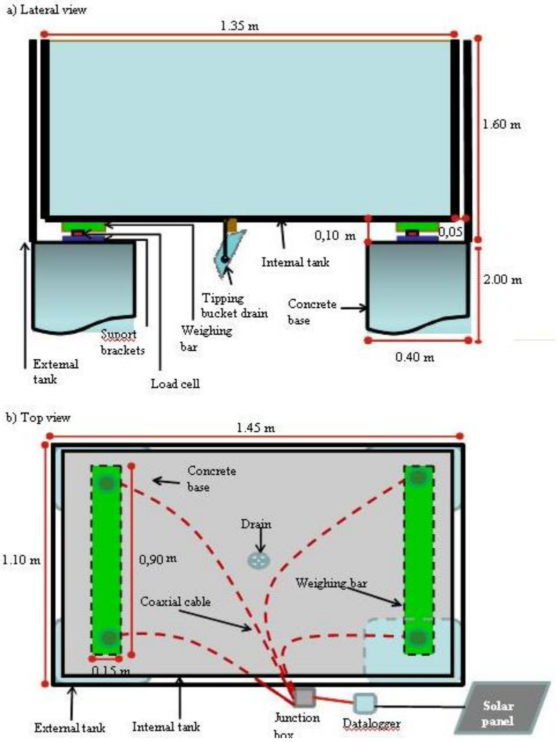

Figure 1. Lysimeter side (a) and top view (b).

At the bottom of the lysimeter pits, four vertical concrete bases of 0.4 x 0.4 x 2 m depth were installed to support the weighing system (Figure 1). The concrete bases supported the two weighing bars, which were leveled using 1 mm-steel sheet shims indicated by load measurements in each cell separately. The external tank was installed and the internal tank was filled as follows: a 5 cm-gravel layer, a 5 cm-sand layer, a geotextile mat (Bidim), Mexichem Brasil, São José dos Campos, São Paulo State, Brazil), and soil was placed at the bottom, which followed a series of five 0.30 m layers previously separated during the pit excavation, while maintaining a slight compression to reproduce the original soil profile.

Each lysimeter was provided with a drainage device consisting of a PVC pipe, 5 cm in length and 12 mm in diameter, to transport the water accumulated in the gravel layer on the bottom of the internal tank to a reservoir that was emptied when its maximum storage capacity of 1.23 mm was reached (Figure 2). This reservoir, called a tipping bucket drain, consisted of a PVC pipe of approximately 0.3 m length and 100 mm diameter with a PVC cap closed bottom and top opening beveled at 45°. The tipping bucket drain was supported by a shaft pierced into holes drilled parallel to the beveled side of the tipping bucket drain, which was placed approximately 1/3 of the distance above the base (Figure 2a). This shaft, built from a PVC rod, 1 cm in diameter and 18 cm in length, was connected with two supports placed approximately 7 cm from the base of a metal structure and fastened to the bottom of the internal tank, which was constructed in the form of a frame with rods measuring 20 cm long, 4 cm wide, and 1 cm thick. To ensure the reservoir was completely filled before tipping (Figure 2b and c), metal rings were glued on the bottom of the reservoir to counterbalance the moment of inertia.

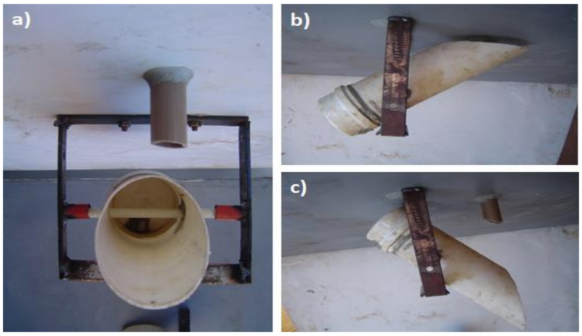

Figure 2. Tipping bucket drain: a) front view, b) side view before drainage and c) after drainage.

The four load cells of the pair of weighing bars at each lysimeter were connected by a coaxial cable with a junction box (4144, Alfa Instrumentos Eletrônicos LTDA, São Paulo, São Paulo State) installed on the soil surface to unify electrical signals resulting from the weighing system. A single coaxial cable was used to conduct electrical signals to the data acquisition system (Datalogger CR10X Campbell Scientific, Logan, USA), which was powered by a 12 V external battery supplied by a solar panel responsible for the power supply in case of outages. Data stored in the datalogger were transferred to a memory module and computer through the program PC208W (Campbell Scientific, Logan, USA).

Each load cell had a capacity of 1 t tensile, a protection degree of IP68 and a connection to the junction boxes by four wires; additionally, six wires were connected, offsetting the temperature effect in the cable between the junction box and the datalogger. According to the manufacturer (HBM measurement, São Paulo, São Paulo State), the sensitivity of the load cells is 2 +/- 0.05% mV. V^{-1} and the accuracy is 0.0180% of the full scale, which is warranted in the temperature range of -10 to +40°C.

The capacity of the reservoirs of the constructed tipping bucket drain was approximately 1.23 mm, with slight variation between devices (± 0.2 mm) due to the constructional features and counterweights used. Those differences were considered by computing the value for each lysimeter instead of the average.

Calibration of the lysimeters

First, the lysimeters' surfaces were covered with plastic to prevent evaporation. Wind effects, which cause oscillations in the lysimeters mass measurements, were minimized by placing windbreakers, made of plastic sheets approximately 1 m high, around each lysimeter. During the calibration period, the wind speed recorded by the IAPAR weather station located adjacent to the experiment varied between 70 and 250 km day, which was similar to or smaller than the usual mean values for the region (210 km day) (IAPAR, 2012).

Based on previous studies (CAMPECHE et al., 2011; FARIA et al., 2006), each lysimeter was calibrated separately. Mass readings were performed every three seconds in response to sequences of voltage measurements by adding and removing mass (sand) contained in sealed plastic bags previously determined by scales to be accurate to 0.01 g. After measuring the mass of the unloaded and covered lysimeter, two sandbags with a mass of 4.72 kg, corresponding to 7 mm, were placed in sequence on the 1.55 m^2 surface area of the lysimeters to reach 70 mm. Afterwards, sandbags with masses of 1.35 kg, corresponding to 1 mm, were added individually until the mass equivalent of 80 mm was reached. Finally, the complete load of 150 mm was achieved by adding ten loads of 7 mm. The unloading sequence from 150 mm was performed with the removal of sand bags from 7 mm to 80 mm and 1 mm to 70 mm; total discharge occurred with the removal of masses equivalent to 7 mm. The loading and unloading operations were repeated four times. Thus, 60 pairs of data per measurement sequence were acquired, with 240 pairs of data over four repetitions, which allowed for the calibration of each lysimeter.

The results were subjected to linear regression analyses that describe the precision of the systems and index of agreement (d), which determines the accuracy (WILLMOTT et al., 1985). The effectiveness of the lysimeter was confirmed by the behavior of the ET measured by the lysimeters and the ET estimated while conducting the cultures.

After calibration, the ability of the lysimeters to measure evapotranspiration was tested on a wheat crop cultivated on the lysimeters, from April to August.

Regression analysis was performed by the software SAEG (UFV, 1997) using data from four iterations. The statistical significance was evaluated by the F test.

Results and discussion

The values of the slope (a) of the regression equation between the weight and voltage for the four lysimeters ranged from 1271 to 1322 mm mV^{-1} (Table 1), which can be caused by the specific characteristics of the electrical strain gauges of each load cell (FARIA et al., 2006). In the current study, slope values were very close, indicating similar characteristics in weighing systems of the lysimeters. The values of the intercept (b) obtained from the regression varied between -2180 and -2015 (Table 1), resulting from the static weight (dead weight) of each set.

The calibration of the lysimeters presented a linear response, satisfactorily describing all cases and with coefficients of determination close to unity. The relationship between the weight and voltage, proven by the absolute error values of the linear regression estimation, ranged from 0.13 to 0.28 mm (Table 1). These results are within the range (0.08 - 0.42 mm) found by Faria et al. (2006), Carvalho et al. (2007) and Campeche et al. (2011). It is worth mentioning that resolutions of the lysimeters can vary depending on their design and construction and differ based on material, size and spatial arrangement for the assessment.

Table 1. Coefficients of determination (r^2) for linear regressions (y = ax + b) between weight (y, equivalent-mm), voltage (x in mV) and mean absolute error of weight estimation (equivalent-mm), which are obtained for the four lysimeters tested and are significant at $a \leq 0.01$ using the F test.

Lysimeter	a	B	R^2	E
1	1322.40	-2179.70	1.00	0.28
2	1303.90	-2117.50	1.00	0.13
3	1270.80	-2021.50	1.00	0.15
4	1272.00	-2015.40	1.00	0.13

The graphic representation of the relationships between the weight variation and voltage of the four lysimeters analyzed (Figure 3) showed the absence of hysteresis, indicating a close relationship in the loading and unloading processes and voltage of the load cell; thus, results obtained from Miranda et al. (1999), Oliveira et al. (2008) and Fernandes et al. (2012) were confirmed. During the lysimeter calibration, Santos et al. (2008) also observed linear responses with negligible hysteresis of ET in the semi-arid Northeastern region.

The low values of the absolute error (Ae), mean square error (MSQ) and mean absolute error (MAE) resulting from the linear regression were satisfactory, which strengthened the accuracy of the evaluated equipment (Table 2). A Wilmott's index of agreement (d) value equal to unity indicated a good aggregation between the estimated and observed values, which resulted in perfect agreement. Santos et al. (2007) studied a diaphragm lysimeter and confirmed its capacity to determine the ETo of citrus seedlings with great accuracy; the coefficient of determination was 0.9975 and the index of agreement (d) was 0.99926.

Table 2. Absolute error (Ae), mean square error (MSQ), mean absolute error (MAE) and Wilmott index (d) resulting from the linear regression between the observed and estimated values.

Lysimeter	Ea	EMQ	EMA	D
1	0.0117	0.1289	0.2844	1.0000
2	0.0334	0.0268	0.0245	1.0000
3	0.0985	0.0424	0.0329	1.0000
4	0.0453	0.0232	0.0259	1.0000

Figure 4 illustrates the simple regression between the weight estimated by the model and weight observed in the experiment and the calculation of the regression parameters (intercept *a*, slope *b*, and correlation *r*). A high linearity of data was verified, and a close relationship occurred between the observed and measured values estimated in the four lysimeters, which gave the lysimeters the ability to adequately detect weight differences with high sensitivity in determining the water balance components in the soil-plant-atmosphere system.

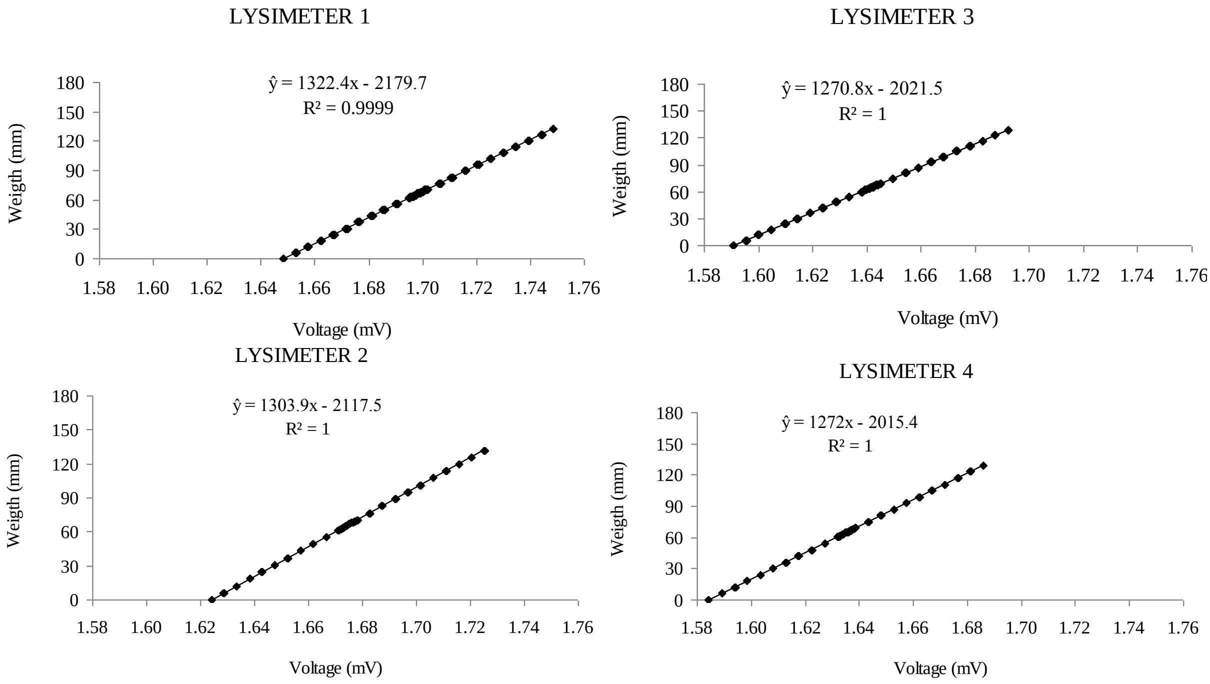

Figure 3. Weight and voltage relationship of the four lysimeters.

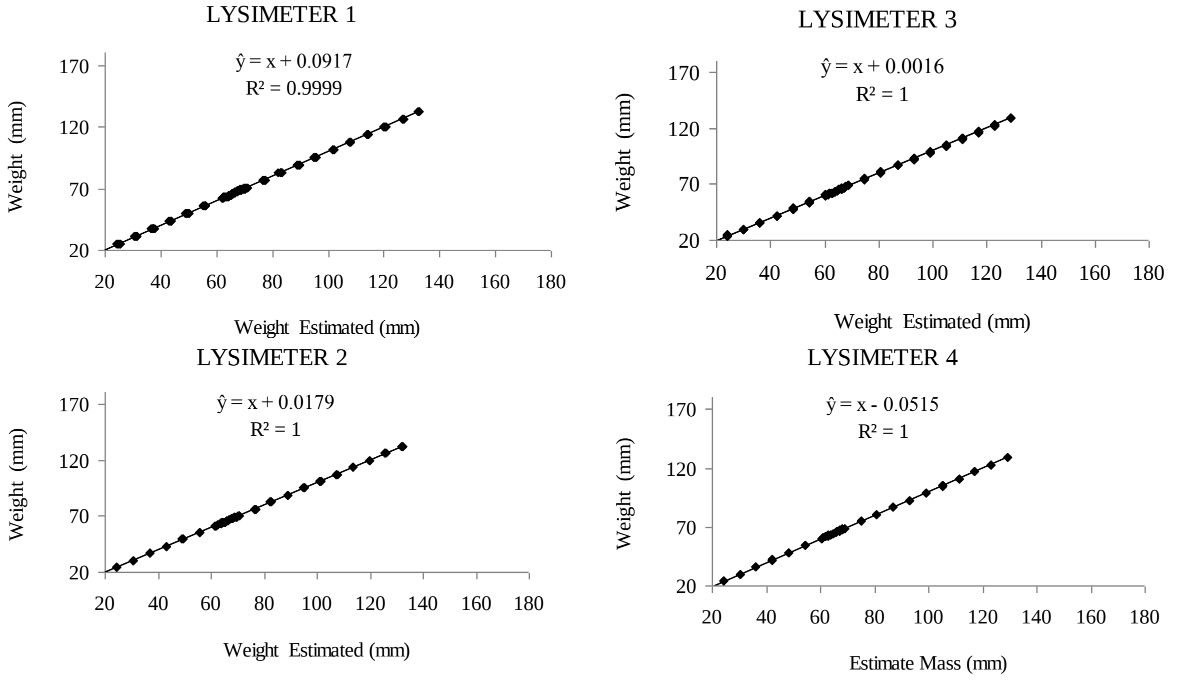

Figure 4. Estimated and observed weighing values as measured in the load cell during loading and unloading cycles and the respective slopes and coefficients of determination for the four lysimeters.

The hydrological component measurements obtained to prove the lysimeters' ability to monitor the water balance components under cultivation were taken over seven days, from May 6 to 12, 2011, when the wheat crop was in booting stage (Figure 5). Thus, the 30-mm irrigation performed on day 6 for approximately 17h resulted in increased water depth stored as approximately 29 mm. From the 8:00h of day 7, and over subsequent days, the stored quantity decreased due to the losses caused by evapotranspiration, demonstrating agreement between the weight variation in the periods of loading and unloading of soil water. Additionally, the equipment's sensitivity to oscillations in soil water storage can be demonstrated by the small peaks observed on days 9 and 12, close to 16h, which were caused by the weight increase/decrease due to the use of a neutron probe to monitor the soil water content (Figure 5). Pereira et al. (2002) observed adequate results of measured and estimated ETo as well as responses to variations of the main meteorological elements that influence the ETo.

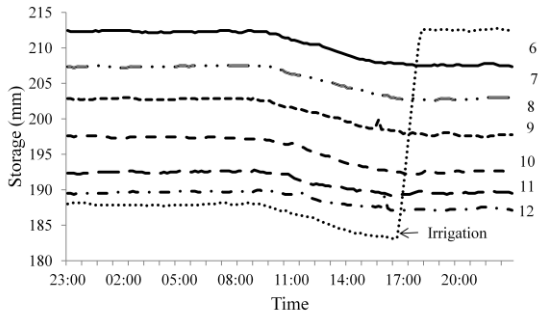

Figure 5. Soil water storage measured by a lysimeter cultivated with wheat from May 6 to 12, 2011.

To show the lysimeters ability of satisfactorily monitor the water balance components, Figure 6 presents hourly ETo and ETc of the wheat crop. ETo was calculated by the Penman-Monteith – FAO method using CLIMA software (FARIA et al., 2003) and ETc was measured in one of the built lysimeters during three days. In that period, there was neither rainfall nor drainage of the lysimeter; hence, the weight variation was caused only by losses of ETc, measured by the weight variation in the lysimeter. The values of ETc followed closely ETo through the three day period, with daily totals of 3.4 and 3.0 mm day, 3.5 and 3.2 mm day, and 3.1 and 3.0 mm day, respectively. Silva et al. (2003).

Likewise, Flumignan and Faria (2009) attained variable values of ET and Kc as a function of the irrigation method (sprinkle, drip irrigation, and non-irrigated), rainfall frequency, atmospheric demand and evolution of leaf area.

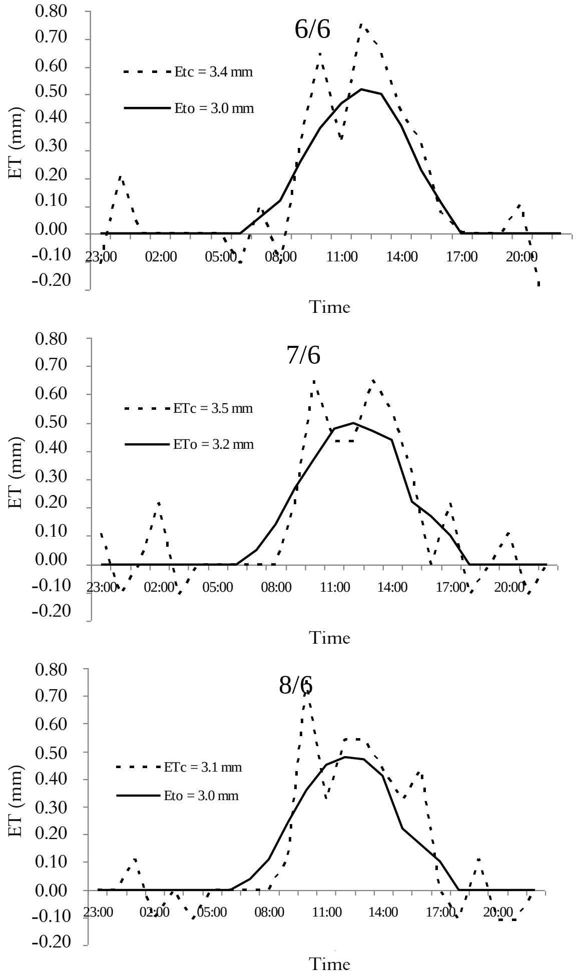

Figure 6. Wheat evapotranspiration (ETc) and reference evapotranspiration (ETo) measured by a lysimeter from Jun 6th to 8th, 2011.

To present the operating conditions of the drainage system, Figure 7a shows the variations of stored water in the lysimeter four days after rainfall (49 mm). Figure 7b shows the resulting drainage curves in the subsequent days. The reductions in the stored water depth were most likely due to the drainage, especially on the day after rainfall. The successive and gradual increases in values of accumulated drainage were due to the tipping of the amount stored in the drainage device installed at the bottom of the lysimeter. As observed in Figure 7b, the drained weight at each event was equal to 1.23 mm, which may have been due to the system.

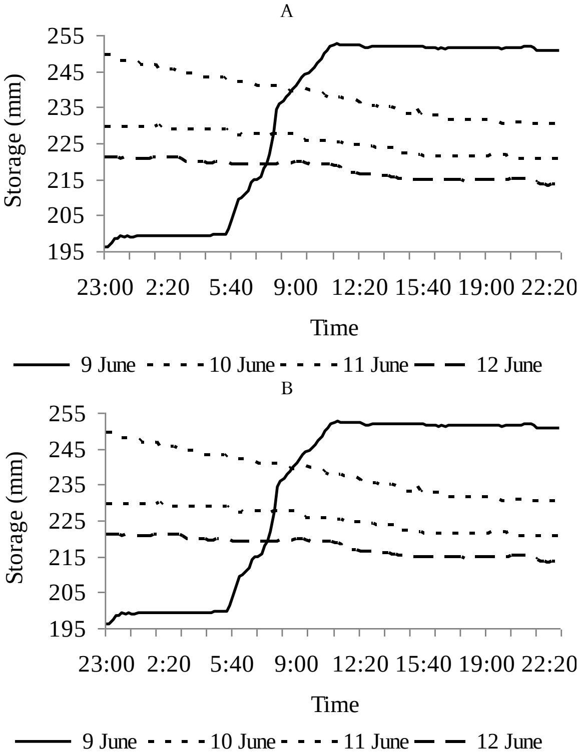

Figure 7. Soil water storage (a) and accumulated drainage (b) measured by a lysimeter cultivated with wheat from June 9 to 12, 2011.

Conclusion

The responses of the lysimeter load cells to applied weights during the calibration process were linear with coefficients of determination close to unity and sensitive to the weight variation equivalent to a water depth of 0.15 mm. Therefore, the weighing lysimeters with bars proved to be suitable for determining estimates of evapotranspiration and other water balance components.

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