HYDROLOGICAL PROCESSES
Hydrol. Process. (2011)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.7971

Lysimeter soil water balance evaluation for an experiment developed in the Southern Brazilian Atlantic Forest region

Rafael Matias Feltrin,* João Batista Dias de Paiva, Eloiza Maria Cauduro Dias de Paiva and Fábio Alex Beling
Department of Sanitary and Environmental Engineering (DESA), Center of Technology (CT), Universidade Federal de Santa Maria (UFSM), Rio Grande do Sul, Brazil

Abstract:

This study aims at monitoring the behaviour of the rainfall, runoff, drainage, soil water storage, and evapotranspiration variables involved in the water balance measured by lysimeter data. The evaluation of the water balance considered different time scales, where the components were monitored daily and in 10-day accumulated period intervals. The results demonstrated that in wet periods the soil water content was greater at a depth of 10 cm, whereas in the dry periods a greater concentration was observed at 70 cm depth. At the depth of 30 cm, the lowest values of soil water content were observed for both wet and dry periods. The results, obtained through the use of tensiometers and time domain reflectometry installed internally and externally to the lysimeter, were very close, which was more noticeable during the periods of lower water loss by the soil. The water balance, calculated from the lysimeter data, demonstrated that 70% of the total rainfall was lost by the process of evapotranspiration. The drainage accounted for 27·5% of the precipitated water, highlighting the fact that this component should not be disregarded in the water balance calculation. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS water balance; lysimeter; tensiometers; soil water storage; evapotranspiration

Received 24 May 2010; Accepted 2 December 2010

INTRODUCTION

The water balance of hydrographic basins usually aims to estimate the evapotranspiration based on the data of rainfall, evapotranspiration, superficial and sub-superficial runoffs, and sometimes disregards the soil water storage. It is in this context that the lysimetric determination becomes an important tool for hydrologic studies, allowing the qualification of the hydrologic variables involved in the water balance, especially those related to the soil water dynamics, which are variables that are not easily measured. Thus, results obtained from lysimetric data are used in the application and calibration of mathematic models, resulting in more accurate results. For this reason, research about the determination of the soil moisture content and the behaviour of other variables involved in the water balance take on great importance and are the subject of many studies.

The use of lysimeters was first reported in France in 1688, where La Hire used lead containers filled with soil and observed the water loss under two soil coverage conditions (Aboukhaled *et al.*, 1982). At that time, the studies were focused on the quantification and qualification of percolating water with no measurement of superficial runoffs, soil water storage, or any evaluation of evapotranspiration. It was only in about 1900 that the studies to determine data for evapotranspiration started, first in 1906 in Germany and then in 1923 in the United States. According to Grebet and Cuenca (1991), Thornthwaite was the first researcher to use this equipment to measure evapotranspiration in field conditions. In Brazil, the first reports about the use of lysimeters are from the 1950s when Camargo (1962) used drainage lysimeters in the determination of potential evapotranspiration in the state of São Paulo.

Field studies using lysimeters represent an accurate tool in the determination of the water balance components in the soil–plant–atmosphere system, representing the real field conditions (Loos *et al.*, 2007). The authors also stated that evapotranspiration is one of the most critical variables in the water balance and it presents the major impacts on the water loss of the system. Moreover, Gee and Hillel (1988) showed that lysimeters are usually better for evaluating the water balance when compared with methods that use soil water sensors, such as micrometeorological and water balance models, as the uncertainties in the drainage quantification are current.

This study aimed at monitoring and quantifying the behaviour of the hydrologic variables involved in the water balance (rainfall, superficial runoff, drainage, soil water storage, and evapotranspiration) by the use of a drainage lysimeter installed in a small experimental hydrographic basin, characteristic of the Atlantic Forest Biome in Southern Brazil. The main importance of this

* Correspondence to: Rafael Matias Feltrin, Department of Sanitary and Environmental Engineering (DESA), Center of Technology (CT), Universidade Federal de Santa Maria (UFSM), Av. Roraima 1000, CEP: 97-105.900, Santa Maria, RS, Brazil. E-mail: agrofeltrin@gmail.com

study is related to the fact that the adopted methodology allows the acquisition of information about the behaviour of water balance components and can be applied to other basins. Hence the study contributes to database acquisition and maintenance for future development.

MATERIALS AND METHODS

This work is included in a larger study, involving a network of research institutions, composed of the Federal University of Santa Maria (UFSM), the Federal University of Rio Grande do Sul (FAURGS), Regional Foundation University of Blumenau (FURB), and the Federal University of Parana (UFPR). The research network (called the Matasul Project) aims at obtaining a general understanding and representation of hydrosedimentological processes at different spatiotemporal scales in the Atlantic Forest biome, in Southern Brazil.

Experimental area

The study was carried out in an experimental basin in Southern Brazil, in the city of Santa Maria, RS (coordinates 29°37′49·7″S and 53°48′39·8″W, 205-m high in relation to sea level). The Vacacaí Mirim River, whose sources are located in this region, is an important effluent of the public reservoir which provides 40% of the supply for the city of Santa Maria (Figure 1). The region's climate, according to the Köppen classification system, is labelled as sub-tropical Cfa, characterized by the occurrence of rainfalls during all months of the year with no significant quantitative difference between the rainiest and the driest month. The annual total rainfall varies from 1700 to 1800 mm, with an average frequency of 113 rainy days a year. The average annual air relative humidity is 82% and the average annual temperature is 19·3 °C, the maximum average temperature in the hottest month (January) is 9·3 °C and in the coldest month (July) is 9·3 °C (Moreno, 1961). The soil of the region, according to the Brazilian soil classification system (EMBRAPA, 1999), is classified as an association of Lithic Eutrophic Neosol with a sandy texture. The vegetation in the lysimeter is a low gramineous (*Paspalum notatum*), native to the region. The vegetational coverage in the lysimeter neighborhood is native forest characteristic of the Atlantic Forest biome. The components involved in the water balance were monitored during the months of January to June 2009.

Lysimeter installation

To monitor the hydrologic variables involved in this study, a drainage lysimeter made of acrylic plates of 1·5 in. thick, glued and screwed together was used (Figure 2). The main advantage of this equipment is the use of undisturbed soil blocks taken from the lysimeter installation site, preserving its original physical characteristics and thus assuring that the flux and transportation conditions are the closest to the original natural conditions, which is a very relevant factor in water balance studies (Meissner and Seyfarth, 2004). Further details about the building, installation, and maintenance of the lysimeter may be found in Feltrin and Paiva (2009).

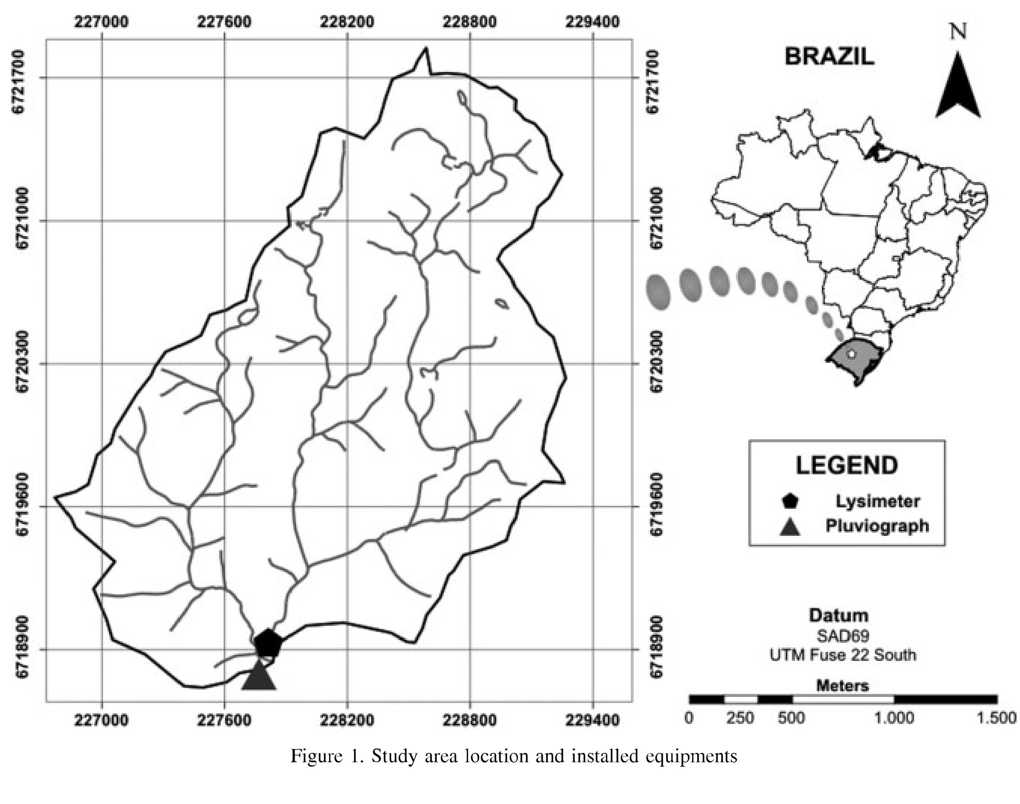

Figure 1. Study area location and installed equipments

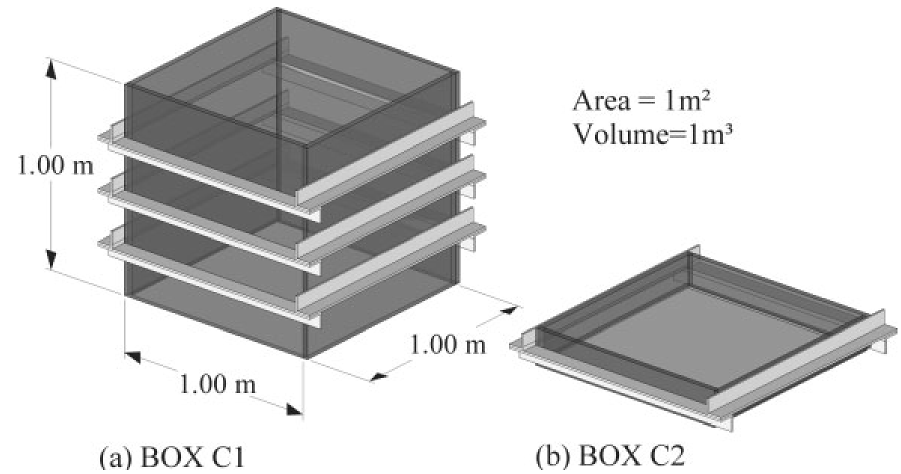

Figure 2. Drainage lysimeter: (a) Box C-1: box to collect the soil sample and (b) Box C-2: base of the lysimeter

Determination of the soil physical-hydric parameters

Undisturbed soil samples were collected from the neighbouring soil at depths of 10, 30, and 70 cm and physical-hydric soil parameters were analysed. From these analyses were determined the bulk density, soil porosity, granulometry, and texture class of the soil inside the lysimeter. The soil water retention curve, for each of the sampled depths, was determined in a laboratory using the Richards method described by Klute (1986). For determining the field capacity (FC) and permanent wilting point (PWP), the soil water matric potential was taken to be −10 and −1500 kPa, respectively, and the available water content (AWC) was equal to the difference between the soil water contents for these values. The curve adjustment was performed by the Van Genuchten (1980) equation (Equation (1)):

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha\psi_m)^n\right]^b} \tag{1}$$

where θ is the volumetric soil water content (cm^3/cm^3), θ_r the residual values of the soil water content (cm^3/cm^3), θ_s the saturation values of the soil water content (cm^3/cm^3), α, n, and b the empirical coefficients, and Ψ_m the soil water matric potential measured in the field (kPa).

The soil water matric potential was obtained using tensiometers with a vacuum gauge installed inside the lysimeter at depths of 10, 30, and 70 cm. The soil water content outside the lysimeter was monitored using the technique of time domain reflectometry (TDR), using TRIME-FM TDR equipment whose characteristics are described by IMKO (2006). The TDR equipment probe was installed at a depth of 30 cm and the readings recorded by the TDR were then compared with the results obtained by the tensiometer installed at the same depth, inside the lysimeter. The tensiometer and the TDR readings were carried out every day at 8:00 AM.

According to the TDR manufacturer, the software installed in the equipment uses the Topp *et al.* (1980) universal equation to quantify the soil water volumetric content depending on the dielectric function. Regarding the equipment calibration, Jacobsen and Schjonning (1993) showed that variables such as soil density, soil texture, and organic matter, among others, should be included to cover a larger range of soils with different characteristics. Nevertheless, Topp *et al.* (1980) state that the environmental soil characteristics such as texture, density, structure, salt content, and temperature do not affect the measurement of water content when using the TDR which makes the calibration in different soil types unnecessary. Zegelin *et al.* (1992) and Roth *et al.* (1990) assure that the Topp *et al.* (1980) equation represents a good adjustment for soils with thick texture, working better for sandy soils like the one which is the subject of this study; however, it does not have a good performance in fine-textured soils like in the argillaceous.

For the calculation of the water storage in soil, the soil inside the lysimeter was divided into layers according to the depths: 0–20, 20–40, and 50–90 cm. Thus, the value of the soil water storage was obtained for each of the considered layers, also integrating the soil water content read in the tensiometer for the soil layer in which it was installed. The total soil water storage was determined by the sum of the storage in each of the considered layers (Equation (2)):

$$A = \int_0^L \theta \mathrm{d}z \cong \sum \theta \Delta z = \theta L \tag{2}$$

where A represents the storage (mm), θ the volumetric soil water content (cm^3/cm^3), and L the considered soil depth (mm).

Thus, the soil water storage variation profile was determined by the difference between the values of the soil water content obtained in the final and initial time of each considered period (daily period), using Equation (3):

$$\Delta A = A_{(f)} - A_{(i)} \tag{3}$$

where ΔA is the soil water storage variation (mm), $A_{(f)}$ the final soil water storage (mm), and $A_{(i)}$ the initial soil water storage (mm).

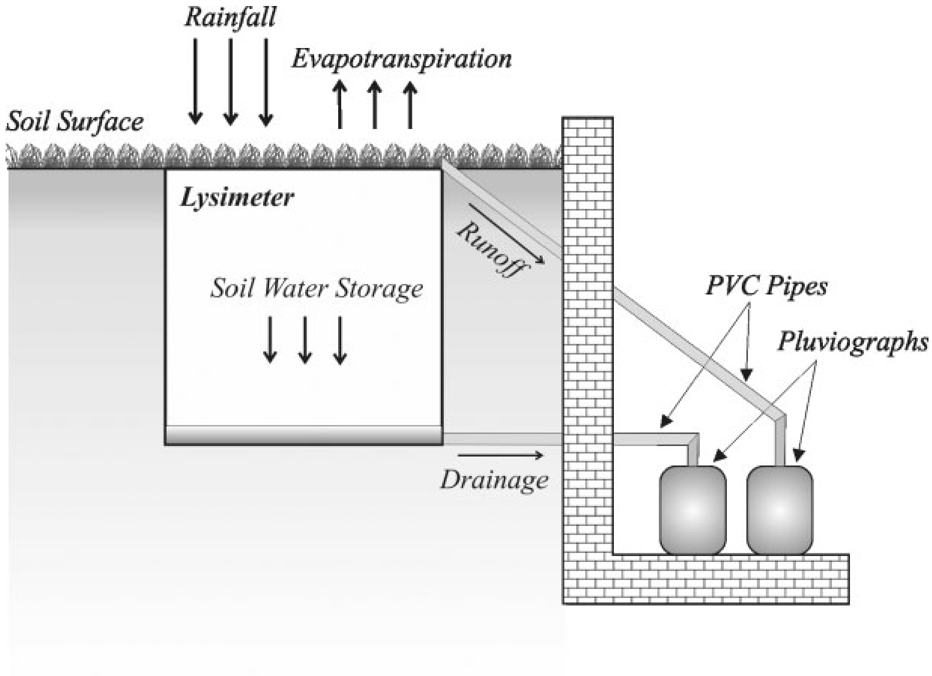

Figure 3. Schematic representation of the controlled variables in lysimeter

Table I. Soil-physical parameters for the different considered depths

Depth (cm)	Bulk density (g/cm^3)	Porosity (%)			Granulometry (%)			Texure class
		Macro	Micro	Total	Sand	Silte	Clay	
10	1·44	22·43	21·53	43·96	88·5	6·5	5·0	Sand
30	1·37	28·52	18·15	46·67	90·6	3·1	6·3	Sand
70	1·41	24·53	21	45·53	87·0	5·5	7·3	Loam Sand

Monitoring of rainfall, superficial runoff, and drainage, and water balance calculation

The rainfall was monitored using an electronic tipping bucket pluviograph installed at 1·5 m high in relation to soil level and 20 m from the lysimeter. The superficial runoff and the drainage were monitored using the same type of electronic pluviographs connected to the lysimeter through PVC pipes (Figure 3). These variables were monitored at 1-min intervals and the values stored in data loggers.

The water balance was calculated daily and in 10-day periods by applying the mass continuity equation and the evapotranspiration was obtained by the difference between the soil water inputs and outputs (Equation (4)):

$$\mathrm{ET} = P - D - \mathrm{ES} \pm \Delta A \qquad (4)$$

where ET is the evapotranspiration (mm), P the rainfall (mm), D the drainage (mm), ES the superficial runoff (mm), and ΔA the soil water storage variation (mm).

RESULTS AND DISCUSSION

Volumetric soil-water content

Results from the granulometric analysis of the samples collected at the site of the lysimeter installations are shown in Table I. The soil presents sand percentages that are over 80% of the total in all considered depths. Where the sand granulometry showed a thicker texture tending to a greater drainage, we expected the soil water storage and content to be lower as the sand fraction increased.

After analysing the physical soil parameters, shown in Table I, we could observe that the 30 cm depth presented the greatest total porosity. This depth range also presented the highest macroporous percentage and lowest microporous percentage when compared with the other considered depths. This result justifies the lower soil density observed at this depth due to the sand percentage found. The same fact explains why the field capacity and the permanent wilting point, which are shown in Table II, are lower at this depth, meaning less AWC, as can be observed in the soil water retention curves shown in Figure 4.

By analysing the soil water content obtained from the daily measurements (Figure 5), we could observe that it

Table II. Soil-hydraulic parameters for the different considered depths

Depth (cm)	Empirical coefficient			FC	PWP	AWC
	α	b	n	(cm³/cm³)		
10	1·189	0·428	7·868	0·178	0·087	0·092
30	1·193	0·474	5·921	0·139	0·054	0·085
70	0·823	0·414	3·547	0·164	0·061	0·103

FC, field capacity; PWP, permanent wilting point; AWC, available water content.

was higher at the 10 cm depth, followed by the 70 and 30 cm depths, respectively. In the dry periods, the higher soil water content was observed at the 70 cm depth, followed by the 10 and 30 cm depths, respectively. Both the wet and the dry periods showed the lower soil water volumetric content at the 30 cm depth, reinforcing what was cited above. The greatest soil water content variations occurred at the 10 and 30 cm depths because these are the most superficial soil layers and are more exposed to environmental actions, where most of the plant roots systems are located. The 70 cm depth presented the least variations, being practically constant throughout the whole period.

Figure 6 illustrates the soil water content dynamics measured at 30 cm depth using tensiometer and TDR, inside and outside the lysimeter. The readings from the tensiometer and TDR had a similar behaviour, becoming closer with the reduction of the soil water content. It was also possible to verify that the storage readings recorded with TDR were more stable and did not present as many oscillations as in the tensiometer readings. In the period between February and early May the soil water content recorded by the tensiometer was higher than the one registered using TDR. In this period there was a gradual decrease of the rainfall and, consequently, a reduction in the soil water storage. From the beginning of May,

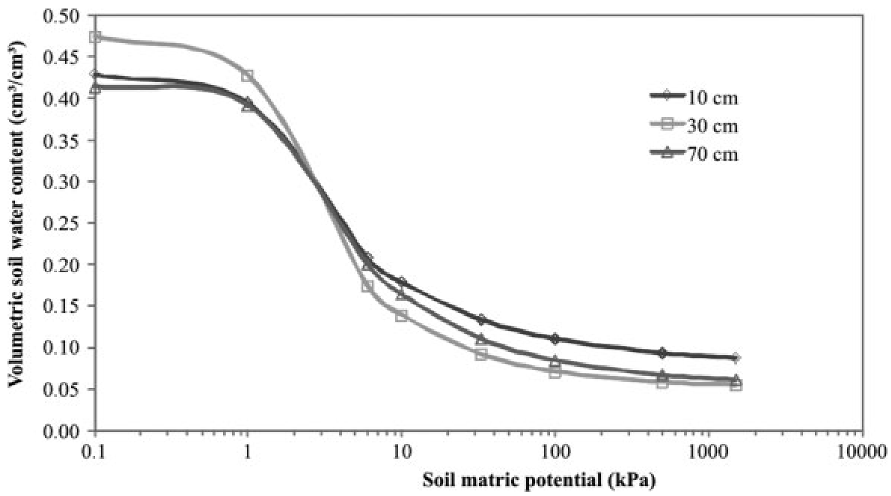

Figure 4. Soil water retention curves for different analysed depths

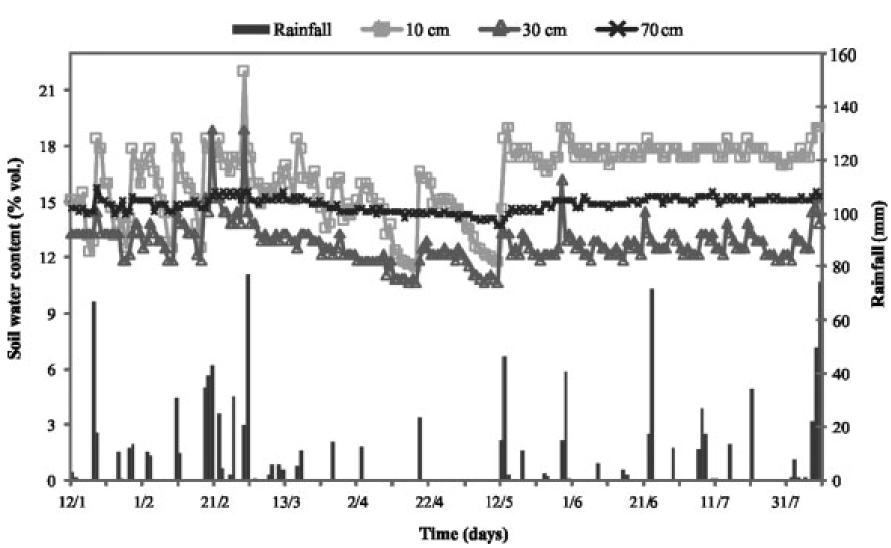

Figure 5. Soil water content inside the lysimeter for different analysed depths

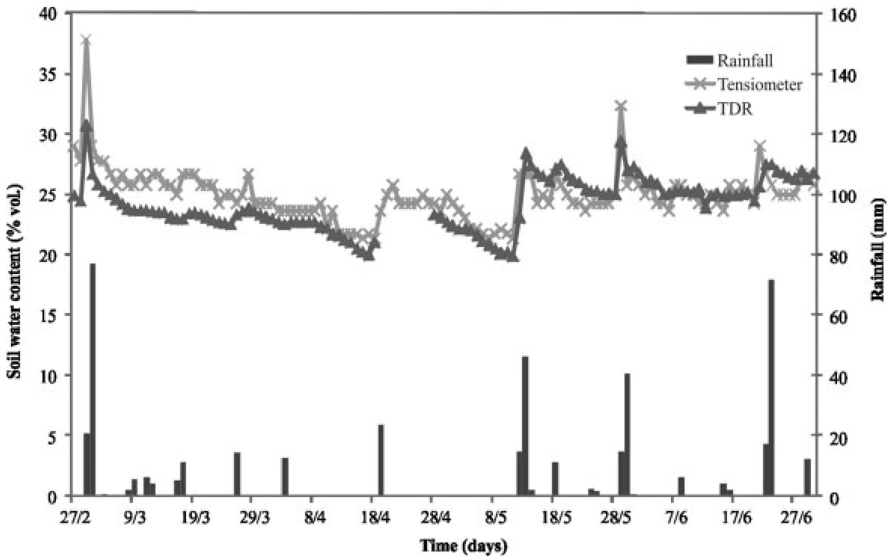

Figure 6. Soil water content measured using TDR and tensiometer

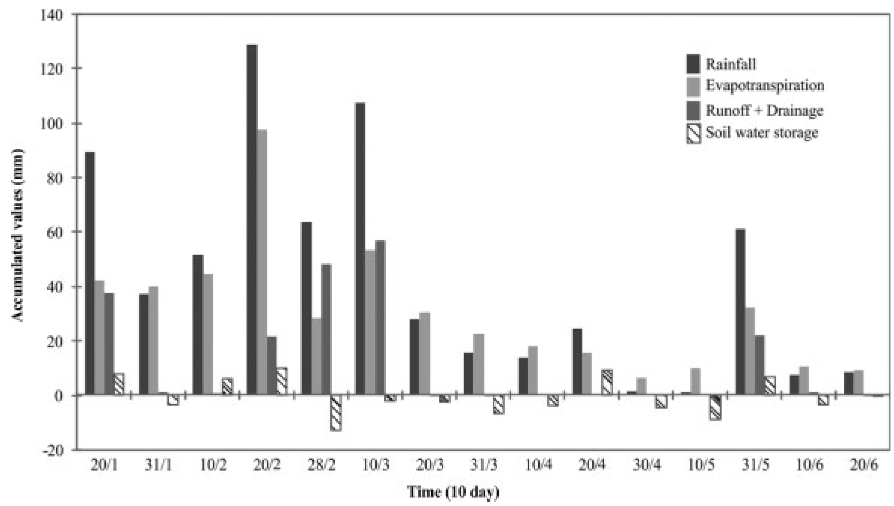

Figure 7. Water balance components accumulated for 10-day period

we observed that soil water content values recorded by the tensiometer and TDR became closer. This period corresponds to a time where temperatures are lower, with fewer sunlight hours, and with climatic conditions that support a lower evapotranspiration rate. Similar results were reported by Silva and Gervásio (1999); Lacerda *et al.* (2005) and Tommaselli and Bachi (2001).

Water balance

Figures 7 and 8 show the soil water component behaviour accumulated in the 10-day period and daily periods, respectively. The total rainfall accumulated during the study period was of 637·6 mm. From this total, 446·32 mm were lost due to evapotranspiration which corresponds to 70% of the total rainfall. The soil water storage varied between 113·28 and 159·63 mm. The drainage represented 27·5% of the total rainfall, showing this is a water balance component that should not be disregarded. The superficial runoff contributed to only 2·5% of the soil water losses. Peruchi (2009) obtained similar results working with drainage lysimeters in the state of São Paulo. The drainage fluxes are considered the most difficult ones to determine and thus are not taken into consideration in many studies. Stone *et al.* (1973); Vachaud *et al.* (1985) and Reichardt *et al.* (1979) declare that the drainage is a water balance component that cannot be disregarded because it may represent 30% or more of the total value especially when performed in tropical weather regions.

The major rainfall concentrations occurred in the subperiods of 20 January, 20 February, and 10 March (summer) with 89·4, 128·6, and 107·4 mm of rainfall, respectively. While analysing the behaviour of the water balance variables for these periods, it is clear that the evapotranspiration varies according to soil water availability, with an increase in its numbers according

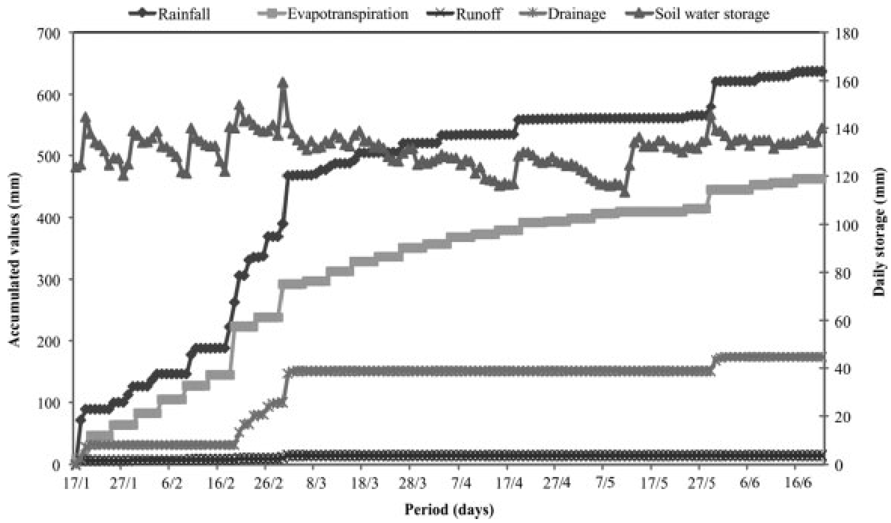

Figure 8. Water balance components accumulated for all period

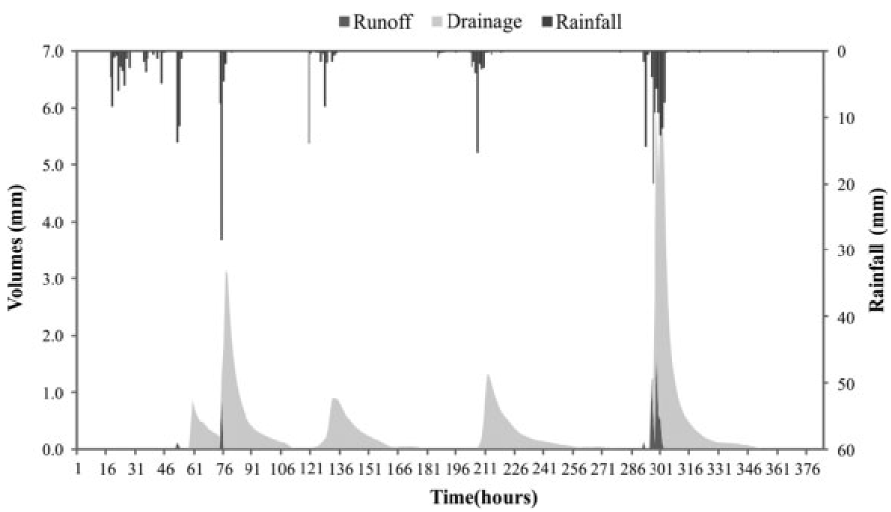

Figure 9. Runoff and soil water drainage between 18 February 2009 and 5 March 2009

to the water availability. In the beginning of May (end of summer/beginning of winter), we could notice a decrease in the rainfall, which reduces the soil water inputs and outputs. This fact, along with the influence of characteristic regional climate factors (low temperatures and fewer sunlight hours) resulted in a remission of the mean daily evapotranspiration.

Figure 9 shows the superficial runoff and soil water drainage behaviour related to the rainfall function in the period between 18 February 2009 and 5 March 2009. The interval illustrated here coincides with the event with the greatest time duration observed and the most representative of the water balance variable behaviour at the study site. It was possible to observe that the superficial runoff is extremely small when compared to the drainage and its occurrence depends much more on the rainfall intensity than on the total rainfall. In the case of drainage, we can verify that it follows the rainfall tendency, varying according to the rainfall volume. Thus, as expected concentrated rainfall with a greater intensity produces more superficial runoff, while a less intense, well-distributed rainfall has a greater capacity to infiltrate and, consequently, produce soil water drainage.

CONCLUSION

The results obtained with the use of lysimeters are important sources of physical soil characteristics and water storage data. Thus, they may allow validation of mathematical models that simulate hydrologic processes and improvement of soil water flow description. Moreover, detailed knowledge of the behaviour of these water balance components can be used for agricultural purposes, as an indicator of water availability and deficiencies in a region serving as a basis for agroclimatic zoning, sizing of reservoirs, and flood forecasting.

In this study, results from the physical soil analysis demonstrated that the analysed soil has sandy texture at all considered depths. At 30 cm depth was observed a greater proportion of macroporosity in relation to microporosity which leads to a reduction in the soil water content at this depth.

The major soil water content variations occurred at the superficial soil layers showing the evapotranspiration effect on soil water losses. The deeper soil layer showed an almost null variation on the soil water volumetric content.

The soil water storage, determined using tensiometer and TDR, to the 30 cm depth showed a similar behaviour, becoming closer as the soil water content decreased. The soil water storage recorded using the TDR proved to be more stable, presenting fewer oscillations than in the readings using the tensiometer.

Most of the rainfall water on soil was lost through a process of evapotranspiration followed by soil infiltration and drainage. The soil water losses by drainage represent a considerable portion, highlighting the importance of this component in soil water balance studies especially in soils with a sandy texture. The superficial runoff, on the other hand, did not contribute significantly to the calculation of the soil water inputs and outputs. A rainfall with higher intensity caused a runoff, while a well-distributed rainfall of minor intensity produced the soil water infiltration and drainage.

Although the findings are precise, they are useful to extrapolate to larger areas with similar soil and land use characteristics, in this case, the hydrologic basin where they are included, serving as a reference for the appliance of hydrologic models that estimate the soil water volumetric content from the rainfall data. However, due to the limitations of just one lysimeter to represent a whole basin, cautions in the extrapolation of results must always be obeyed.

ACKNOWLEDGEMENTS

The authors thank MCT/FINEP/CT-HYDRO-CNPq for the financial resources and scholarships provided for the research network named 'Representative and experimental basins in the Atlantic forest biome in Southern Brazil (PROJECT MATASUL)', and Federal University of Santa Maria Civil Engineering Graduate Program.

REFERENCES

Aboukhaled A, Alfaro A, Smith M. 1982.. *Lysimeters. FAO Irrigation and Drainage Paper (FAO)*. FAO: Rome (Italy); 73.

Camargo AP. 1962. Contribuição para a determinação da evapotranspiração potencial no Estado de São Paulo. *Bragantia, Campinas* **21**: 163–203.

EMBRAPA. 1999. Centro Nacional de Pesquisa de Solos. Sistema brasileiro de classificação de solos. Brasília, DF: Embrapa Produção de Informação; Rio de Janeiro: Embrapa Solos; 412.

Feltrin RM, Paiva JBD. 2009. Instalação e avaliação de um lisímetro volumétrico utilizado no balanço hídrico em uma bacia experimental no sul do Brasil. XVIII Simpósio Brasileiro de Recursos Hídricos. Novembro de 2009, Campo Grande, Mato Grosso do Sul. Anais em CD-Rom.

Gee GW, Hillel D. 1988. Ground water recharge in arid regions Review and critique of estimation methods. *Hydrological Processes* **2**: 255–266.

Grebet P, Cuenca R. 1991.. History of lysimeter design of environmental disturbances. In *Lysimeter for Evapotranspiration and Environmental Measuring*, Allen RG, Howell TA, Pruitt WO, *et al.* (eds.) American Society of Civil Engineers: New York; 10–18.

IMKO. 2006. TRIME-FM User Manual. IMKO Micromodultechnik GmbH; Germany. Available at http://www.imko.de. Accessed 14 January 2009.

Jacobsen OH, Schjonning P. 1993. A laboratory calibration of time domain reflectometry for soil water measurement including effects of bulk density and texture. *Journal of Hydrology* **151**: 147–157.

Klute A. 1986. Water retention: Laboratory methods. In *Methods of Soil and Analysis, Part 1*, *Agronomy Monograph 9*, 2nd edn, Klute A (ed.). ASA and SSSA: Madison, WI; 635–662.

Lacerda RD, Guerra HOC, Barros Júnior G, Cavalcanti MLF, Barros AD. 2005. Avaliação de um TDR para determinação do conteúdo de água do solo. *Revista de Biologia e Ciências da Terra, Brasil* **5**(1): 1–12.

Loos C, Gayler S, Priesack E. 2007. Assessment of water balance simulations for large-scale weighing lysimeters. *Journal of Hydrology* **335**: 259–270.

Meissner R, Seyfarth M. 2004. Measuring water and solute balance with new lysimeter techniques. *Paper presented at the 3rd Australian and New Zealand Soil Science Conference*. Sydney, December 2004.

Moreno JA. 1961. *Clima do Rio Grande do Sul*. Secretaria da Agricultura: Porto Alegre; 42.

Peruchi F. 2009. Evapotranspiração real a partir de medidas lisimétricas e sob diferentes condições de disponibilidade hídrica. Dissertação (Mestrado em Hidráulica e Saneamento. Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos. 141f.

Reichardt K, Libardi PL, Saunders LCU, Cadimaz A. 1979. Dinâmica da água em solo cultivado com milho. *Revista Brasileira de Ciência do Solo, Campinas* **3**(1): 1–5.

Roth K, Schulin R, Fluhler H, Attinger W. 1990. Calibration of time domain reflectometry for water content measurement using a composite dielectric approach. *Water Resources Research* **26**(10): 2267–2273.

Silva EL, Gervásio ES. 1999. Uso do instrumento TDR para determinação do teor de água em diferentes camadas de um Latossolo Roxo distrófico. *Revista Brasileira de Engenharia Agrícola e Ambiental, Campina Grande* **3**(3): 417–420.

Stone LR, Horton ML, Olson TC. 1973.. Water loss from an irrigated sorghum field. I. Water Flux within and below the Root Zone. *Agronomy Journal* **65**: 492–495.

Tommaselli JTG, Bachi OO S. 2001. Calibração de um equipamento de TDR para medida de umidade de solos. *Pesquisa Agropecuária Brasileira, Brasília* **36**(9): 1145–1154.

Topp GC, Davis JL, Annan AP. 1980. Electromagnetic determination of soil water content: measurement in a coaxial transmission lines. *Water Resources Research, Washington* **16**: 574–582.

Vachaud G, Passerat D, Silans A, Balabanis P, Vauclin M. 1985. Temporal stability of spatially measured soil water probability density function. *Soil Science Society of American Journal* **49**: 822–828.

Van Genuchten MT. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of American Journal, Madison* **44**(5): 892–898.

Zegelin SJ, White I, Russell GF. 1992. A critique of the time domain reflectometry technique for determining soil-water content. In *Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice,* Topp GC, Reynolds WD, Green RE (eds). Soil Science Society of America: Madison, WI, SSSA Spec. Publ. 30; 187–208.

