Analysis of the Water Balance in a Block of Seven Drainage Lysimeters under Field Conditions

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ABSTRACT

Water Balance (WB) allows for assessing the deficit or excess of water. For this purpose, drainage lysimeters have a mechanism to collect and quantify the amount of water that infiltrates through the soil profile, thus evaluating crop evapotranspiration. This study describes the design, construction, and calibration of a block of 7 drainage lysimeters. The lysimeters were designed with a width of 1.97 m, length of 2.49 m, and depth varying from 0.60 m to 1.10 m. For construction, four sequential layers of soil, each 0.2 m thick, were extracted. The concrete resistance of the walls and floors was 210 kg cm^{-2}, and rhizotrons were installed on the inner wall of five of the lysimeters. Calibration included evaluating compaction in the first 3 layers, averaging 2.11, 5.18, and 7.91 kg cm^{-2} respectively. Infiltration ranged from 5.6 to 10.2 mm h^{-1}. The moisture retention curve allowed determining the irrigation volume to reach Field Capacity (FC), plus an additional percentage of FC volume to produce drainage.

Keywords-construction; calibration; field capacity; compaction; drainage; infiltration; evapotranspiration

I. INTRODUCTION

Water is a fundamental resource for agriculture; supplying the appropriate amount is essential for plant health and optimal productivity [1, 2]. Efficient management of water resources through techniques that increase utilization offers a solution to the problem of water scarcity in some areas of the world. Therefore, understanding evapotranspiration (ET) constitutes key information [3]. ET, which combines the processes of evaporation and transpiration in returning surface moisture to the atmosphere, is one of the most important hydrological and meteorological components of the water cycle in nature [3, 4]. Furthermore, mass balance methods such as lysimeters and energy balance methods such as the Bowen ratio can be used to quantify ET in agronomic crop fields or natural vegetation [5].

A lysimeter consists of a container filled with soil and a mechanism for collecting and quantifying the amount of water that infiltrates through the soil profile until draining towards the base [6]. According to [7], when installed correctly, lysimeters allow precise measurements of ET, as long as they are in the same conditions as the soil layers of the surrounding area. Irrigation and precipitation add water to the lysimeter, increasing its mass, while drainage removes water, and together with ET, cause its total mass to decrease [4]. During a specific period of time, the amount of water collected by the drainage system must be subtracted from the mass variation. ET measurements can be affected by environmental and design factors such as advection, lysimeter size, soil moisture regime, wall thickness and distance, wall rim height, and vegetation density [8]. Care must be taken in lysimeter management and data analysis to minimize problems of underestimation or overestimation of crop ET and to avoid reporting inconsistent data [9]. Lysimeter calibration is important; otherwise, if deficient, it can lead to inconsistent interpretations of ET values, especially when taken over short periods of time [4]. In this context, one of the most significant problems in agricultural production in the Ecuadorian highlands is the inadequate management of irrigation water due to a lack of knowledge about the quantity and opportune timing for watering, at different phenological stages of the crop. Therefore, techniques have been proposed to allow for efficient water use, one of which is the drainage lysimeter, to obtain precise information to address this issue. The objective of this study is to present an analysis of the water balance in 7 drainage lysimeters under field conditions, through physical tests and the hydraulic behavior of water in the soil.

II. MATERIALS AND METHODS

The study was conducted at the Tunshi Experimental Station (2756 msnm), 01°45'S, 78°37'W), Polytechnic School of Chimborazo, Riobamba, Ecuador. The soil is loamy clay in texture, with an average temperature of 14.52 °C, average relative humidity of 75.03%, and average annual precipitation of 531 mm [10].

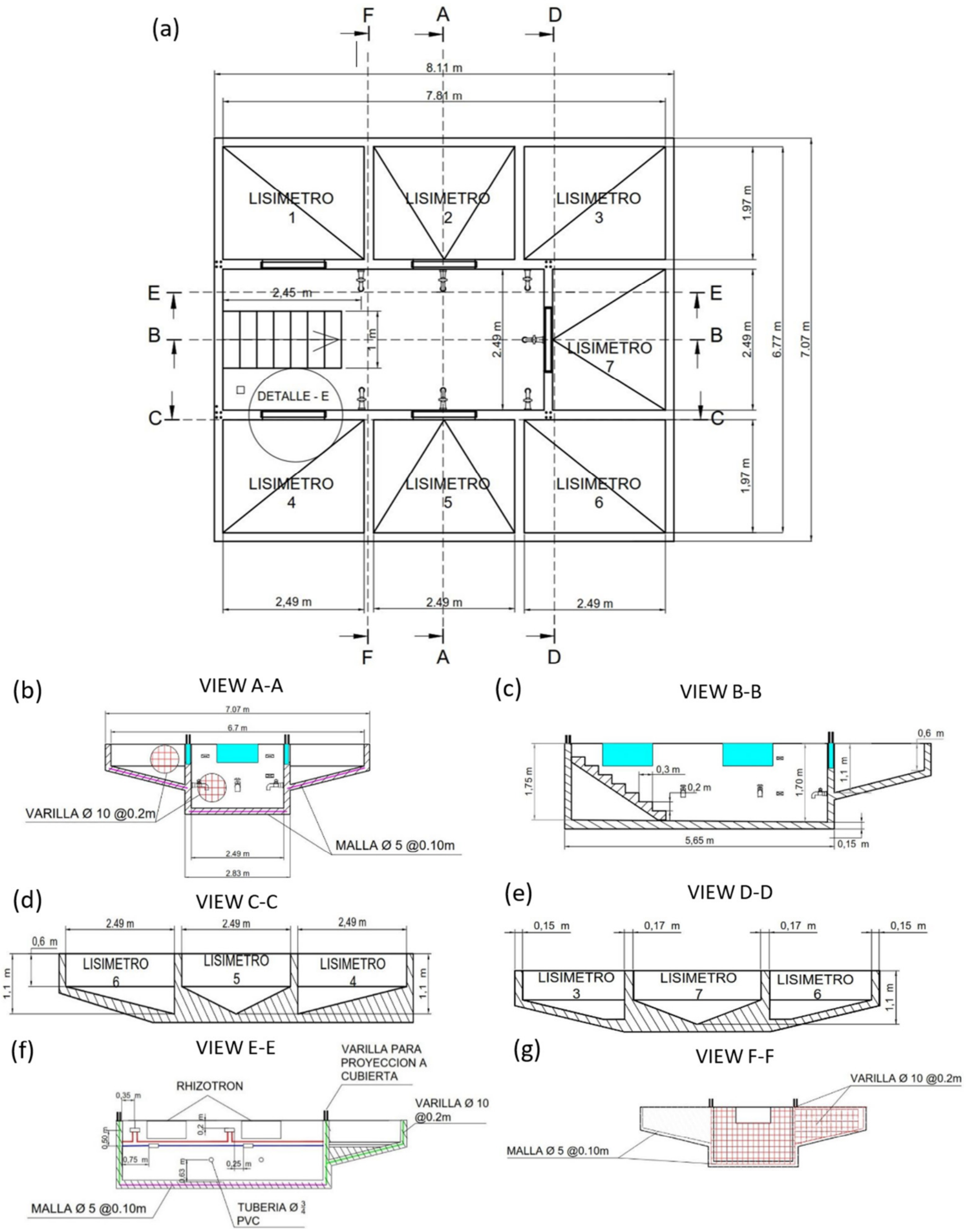

Fig. 1. Design of the block of lysimeters and rhizotrons.

The design of the block of 7 lysimeters was carried out in AutoCAD v. 2015 (Autodesk, USA) at a scale of 1:100 (Figure 1(a)). Each lysimeter, shaped like a hopper, has a width of 1.97 m, length of 2.49 m, an initial depth of 0.60 m, and a final depth of 1.10 m, where a 50 mm pipe was placed for the collection of drained water (Figures 1(b), 1(d), and 2). The external and internal walls of the lysimeter block had a thickness of 0.15 m and 0.17 m, respectively. Access steps to the observation area were also designed (Figures 1(c) and 1(e)).

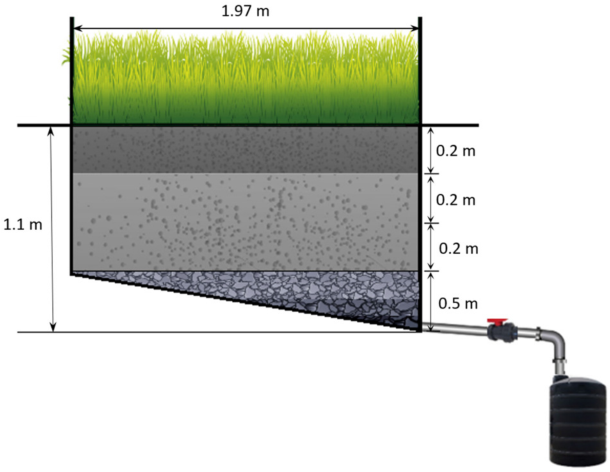

Fig. 2. Characteristics of the lysimeter layers with their drainage system.

Fig. 3. Construction and calibration of the block of 7 drainage lysimeters.

Additionally, rhizotrons were designed in 5 lysimeters (1, 2, 4, 5, and 7), located on the internal wall of the block, with a metal structure of 1.10 m × 0.55 m for the insertion of a tempered glass panel of 10 mm thickness and a geomembrane of 5 μm thickness (Figures 1(a) and 1(f)).

During the construction stage of the block of 7 lysimeters, the area was delimited, and subsequently, 4 sequential layers of soil were extracted at depths of 0 - 0.2 m, 0.2 - 0.4 m, 0.4 - 0.6 m, and 0.6 - 0.8 m in each lysimeter (Figure 3(a)). The base of the lysimeter block and the observation space were constructed using welded mesh and plain concrete. Regarding the internal walls, reinforced mesh, steel reinforcement, and plain concrete were used (Figures 3(b) and (c)). Subsequently, the rhizotrons were installed on the internal wall of the 5 lysimeters, along with electrical conduits for 12 electrical points, and waterproofing was applied to the internal part of the lysimeters (Figure 3(d)). In the first three soil layers of each lysimeter, the compaction was evaluated using an Eijkelkamp 06.01.SA manual penetrometer at 4 equidistant points, and the average was obtained (Figure 3(e)). Then, the infiltration was assessed using a Turf-Tec infiltrometer (Figure 3(f)), and the bulk density was determined using the pit method [11]. The soil moisture retention curve was evaluated at Field Capacity (FC) and Permanent Wilting Point (PWP) in each soil layer. Soil samples were collected for analysis of textural class, pH, macro and micronutrients, organic matter, and electrical conductivity [12]. In the drainage zone of the lysimeters, a metal mesh (0.5 × 0.5 m) with mesh #4 was placed, and the last soil layer (0.6 - 0.8 m) was replaced with gravel. This layer was covered with plastic mesh with mesh #3.

Then, the soil layers were manually placed with their respective degree of compaction (Figure 3(g)). Additionally, ridges were formed, and an irrigation system with a magnetic multiple-jet meter was installed in each lysimeter. Finally, Jet-Fill Model 2725 ARL tensiometers were installed at depths of 0.10, 0.30, and 0.50 m to monitor soil moisture (Figure 3(h)). The gravimetric method was employed to evaluate the soil moisture content in each layer of the lysimeters using (1) [13]:

$$\%\,\mathrm{H} = (\mathrm{PSH} - \mathrm{PSS}) \times \mathrm{PHS}^{-1} \times 100 \qquad (1)$$

where H is the moisture by weight (%), PSH is the weight of the wet sample (g), and PSS is the weight of the dry sample (g).

Subsequently, the irrigation volume to reach FC was determined. The obtained volume was provided with an additional percentage starting from 25, 50, 75, or 100% of the FC volume. This was done with the aim of initiating drainage, based on the equation proposed in [14]:

$$\mathrm{VCC} = (\mathrm{CC} - \%\,\mathrm{H}) \times 200\ \mathrm{mm} \times \mathrm{Dap} \times \mathrm{Al} \qquad (2)$$

where VCC is the volume of water at field capacity (ml), CC is the FC value (%), %H is the moisture percentage of each layer (%), Dap is the bulk density (kg L^{-1}), and Al is the lysimeter area (m^2).

The safety coefficient is calculated by [14]:

$$\mathrm{FC} = \mathrm{VT} \times \mathrm{VCC}^{-1} \times 100 \qquad (3)$$

where FC is the safety coefficient factor, VT is the total applied volume (L), and VCC is the sum of VCC for the 3 layers (L).

From the second irrigation onwards, the volume of water to be irrigated was calculated, which is used to determine the water requirements of the species to be cultivated, as proposed by [14]:

$$Va = ETP \times ND \times Al \times C \quad (4)$$

where Va is the applied volume (ml), ETP is the crop evapotranspiration (mm min^{-1}), ND is the number of days between one irrigation and the next, Al is the lysimeter area (m^2), and C is the safety coefficient (%).

For the calculation of reference evapotranspiration (ETo), lysimeter 7 was selected (Figure 1(a)), where 1.5 kg of ryegrass seed (Lolium multiflorum) was planted. Therefore, two prioritized crops should be established in the remaining 6 lysimeters. For the prioritized crops, crop evapotranspiration (ETc) was evaluated using the equation of beginning of form [14]:

$$ETc = (R - D) \times ND^{-1} \quad (5)$$

where ETc is the crop evapotranspiration (mm day^{-1}), R is the water added by irrigation or precipitation (mm), D is the water drained during the analysis period (mm), ND represents the number of days between one irrigation and the next. The reference evapotranspiration (ETo) was calculated by [14]:

$$ET_o = (R - D) \times ND^{-1} \quad (6)$$

Finally, the crop coefficient (Kc), was calculated by [14]:

$$K_c = ETc \times ETo^{-1} \quad (7)$$

III. RESULTS AND DISCUSSION

The total area used for the lysimeter block was 57.34 m^2, and based on structural requirements, the lysimeter walls were constructed with a thickness of 0.17 m. Additionally, soil extraction and addition were performed, where the soil was separated into layers from 0.20 m to 0.80 m depth. For moisture balance and drainage, layer 4 was replaced with gravel material (2" in diameter), accompanied by a metal mesh at the drainage point of each lysimeter. At the same point, a PVC pipe connected to a 50 mm ball valve on the exterior of each lysimeter was installed. The material used was concrete with a compression strength of f'C = 210 kg cm^{-2}. Additionally, a liquid waterproofing agent (Aquamaster) was applied to the interior of the lysimeters to prevent water retention on the walls. The average compaction records for the layers 0 - 0.2 m, 0.2 - 0.4 m, and 0.4 - 0.6 m were 2.11, 5.18, and 7.91 kg cm^{-2}, respectively (Figure 4). Additionally, the soil horizons present, according to the soil characteristics, were A, A/C, and C/A, respectively.

Regarding horizon A, it exhibited a brown color with subangular and granular blocks, slightly soft consistency, no carbonates, and a diffuse horizon limit. Horizon A/C displayed a brown color with subangular and granular blocks, with soft (dry) consistency, no carbonates, and a diffuse horizon limit. Lastly, horizon C/A showed a brown color with subangular and granular blocks, slightly hard consistency, presence of calcium carbonates ranging from 1 to 3% in punctual concretions, and scarce presence of roots.

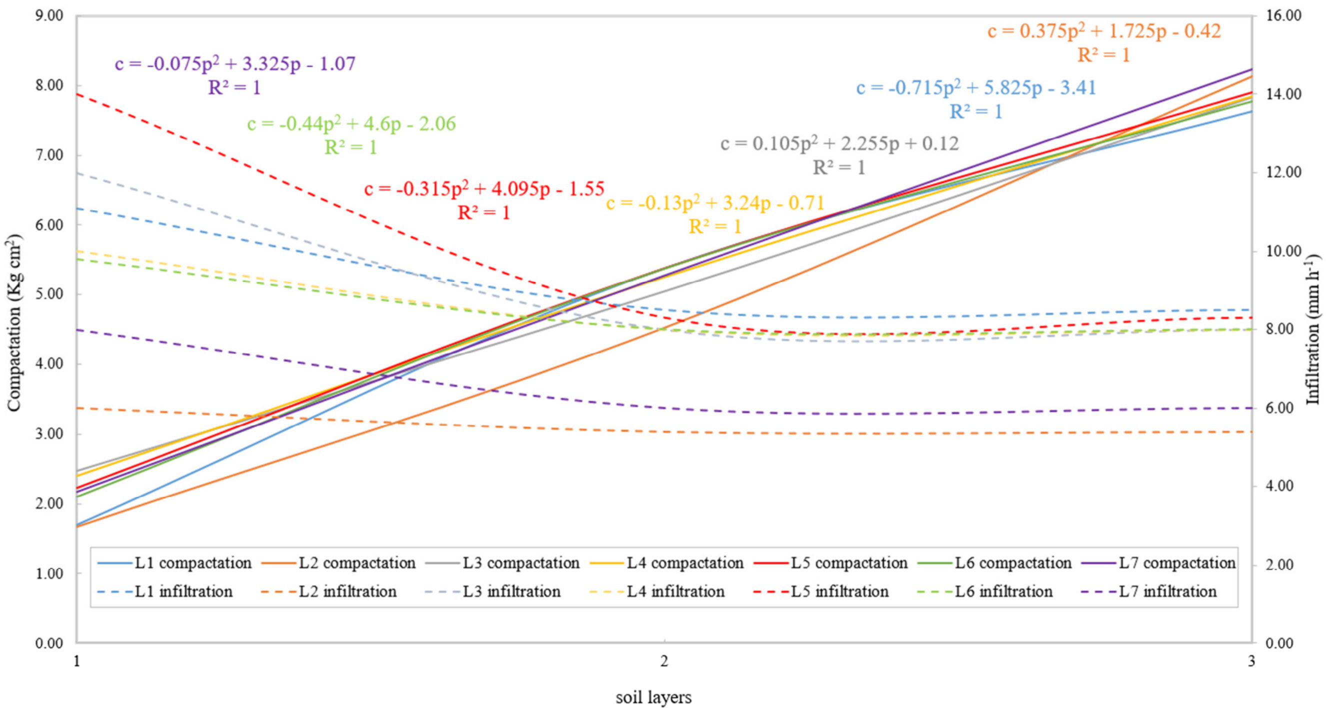

Fig. 4. Soil layer compaction in the block of 7 drainage lysimeters.

Regarding infiltration, the highest record was observed in lysimeter 5 with an average infiltration rate of 10.2 mm h^{-1}, while lysimeter 2 showed the lowest average infiltration rate of 5.6 mm h^{-1} (Figure 5). The volume of water applied to each lysimeter was determined based on the moisture content at field capacity (CC) in each soil layer relative to the present moisture, to induce over-irrigation starting from the minimum percentage. In some cases, such as lysimeters 6 and 7, a higher percentage was required to induce drainage, resulting in the total volume applied, where lysimeter 7 received the highest volume of water (Table I). The relationship of the components in the calibration process of each soil layer with their respective characteristics allowed the identification of variables distinguishing one lysimeter from another. Therefore, lysimeters with the same percentage of over-irrigation were grouped, resulting in significant differences in lysimeters 6 and 7 for the variables of compaction, infiltration rate, and bulk density (Figure 6). For the rest of the lysimeters, there were no significant differences allowing characterization of their calibration.

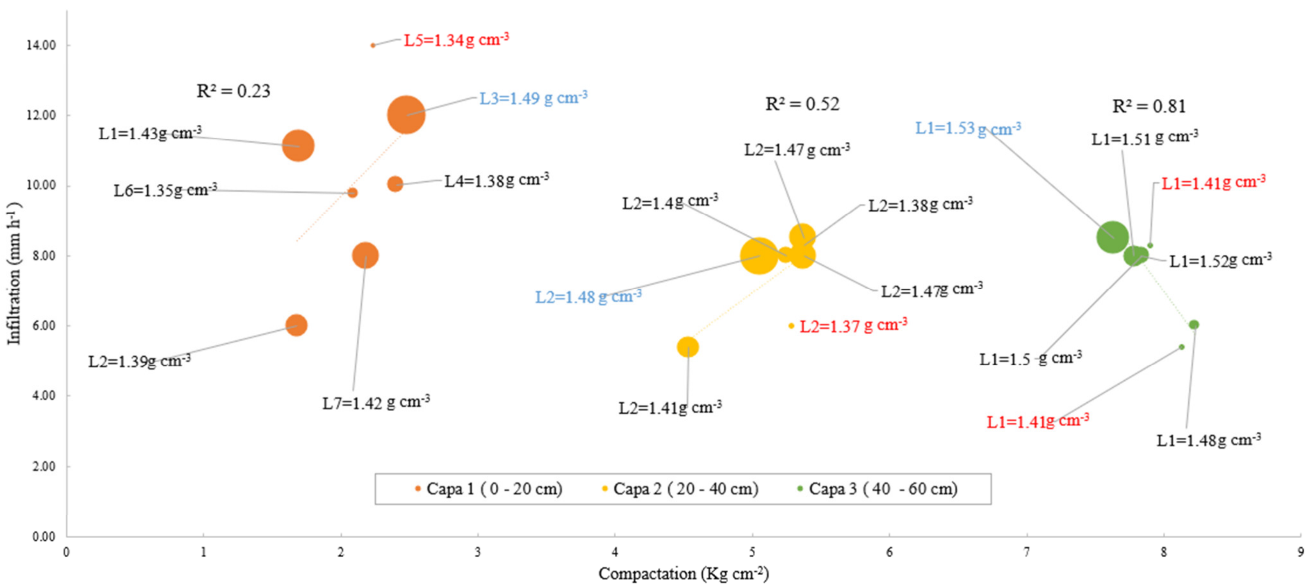

Fig. 5. Infiltration rate in the block of the 7 drainage lysimeters.

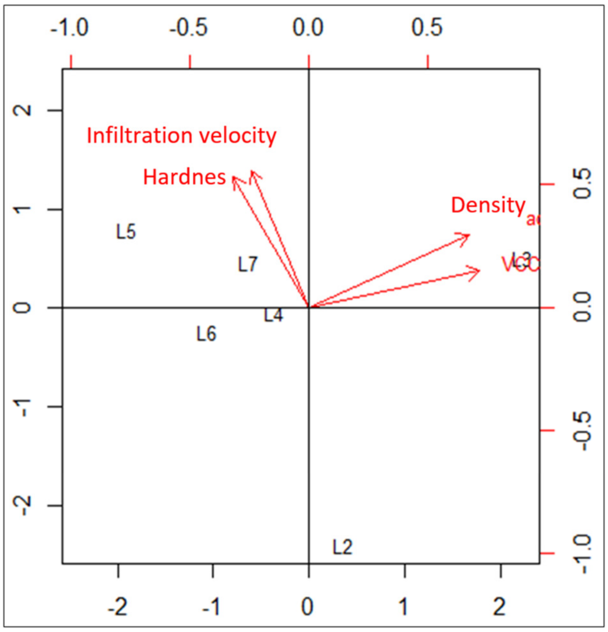

Fig. 6. Principal component analysis of variables for the calibration of the block of 7 drainage lysimeters.

The lysimeter block was designed to simulate natural soil conditions and thus avoid dissipation of vapor due to latent heat and thermal lateral flow between the lysimeter and the surrounding areas, in accordance with the findings of [15]. Through the rhizotrons, the net visibility of root growth of most horticultural species, which do not exceed a root depth greater than 0.5 m, can be observed [16].

The lysimeter block exhibits an acceptable compression strength, correlated with studies indicating a minimum compression strength [17]. Additionally, the waterproofing agent was used to prevent water leakage through the pores of reinforced concrete and thus achieve reliable recording results for accuracy in the amount of water retained and drained in each lysimeter [3, 17]. The compaction assessment was precise to ensure that the lysimeters match the external conditions, otherwise, there would be a moisture and drainage imbalance [16]. Additionally, the degree of compaction (2.11 kg cm^{-2}) falls within the permitted ranges of 0.07 to 2.14 kg cm^{-2} for agricultural soils of medium texture at depths from 0 to 0.20 m [18]. The relationship between soil depth and compaction (correlation exceeding 0.90) indicates that an increase in compaction due to various factors results in a decrease in infiltration rate and restriction of root development [19].

The results of the study confirm what is indicated in research, where the A horizon is superficial, dark in color due to the presence of organic material, allowing for good root development [14]. Additionally, the A/C horizon is a young soil with a discontinuous A horizon and a C horizon that shows traces of sedimentary structure with subangular blocks, with the latter being a lower percentage in the mixed horizon [20]. Lastly, the C/A horizon is a mixture of C and A material, predominantly C horizon, with consolidated elements and subangular blocks [20].

TABLE I. CALIBRATION OF THE DRAINAGE LYSIMETER BLOCK.

Lysimeter	Layer N°	Field Capacity %	PWP %	CAS %	VCC m^3	Over-irrigation %	Over-irrigation m^3	Drainage Coefficient	Total Volume m^3
	1	26.80	10.19	21.74	0.07				
1	2	28.67	10.34	6.25	0.32	25	0.18	0.25	0.89
	3	29.54	9.80	8.33	0.32				
	1	26.80	10.19	18.75	0.11				
2	2	28.67	10.34	9.68	0.26	25	0.16	0.25	0.82
	3	29.54	9.8	8.79	0.29				
	1	26.80	10.19	23.35	0.05				
3	2	28.67	10.34	4.94	0.34	25	0.19	0.25	0.93
	3	29.54	9.80	6.12	0.35				
	1	25.77	9.72	19.66	0.14				
4	2	26.85	9.66	8.97	0.25	25	0.16	0.25	0.80
	3	29.72	9.65	8.33	0.26				
	1	25.77	9.72	18.95	0.14				
5	2	26.85	9.66	9.68	0.23	25	0.16	0.25	0.78
	3	29.72	9.65	7.88	0.25				
	1	25.77	9.72	22.27	0.1				
6	2	26.85	9.66	10.03	0.24	50	0.28	0.5	0.85
	3	29.72	9.65	10.64	0.22				
	1	25.90	9.75	19.91	0.08				
7	2	28.44	9.62	10	0.25	50	0.33	0.5	0.98
	3	31.97	10.63	9.76	0.32				

CAS: soil water content, VCC: volume of water at field capacity.

The infiltration rate is moderately slow, meaning it decreases as the soil compaction level increases. Therefore, in soils of medium texture, the infiltration rate is lower in compacted soils, and in laminar structures, it results in low infiltration [21, 22]. The field capacity varies in relation to the depth from 9.2 to 18.9%, meaning that with every 0.1 m increase in soil depth, it increases within a range of 1.9 to 22% [23]. The soil layers with their physical characteristics made statistical analysis difficult because only one data point per variable could be taken, namely the average of the three layers. This average is not a representative data point due to the potential inconsistency that may exist. Therefore, an approach was made to identify the distinguishing characteristics of one lysimeter from another, in order to determine a variable in which lysimeters with the same percentage of over-irrigation could be grouped [14].

The design of the lysimeter block allows for precise measurement of the impact of climate change on soil and water resources in the studied crops. Its main innovation lies in the ability to be divided into two sub-blocks of three, facilitating the simultaneous analysis of the water requirements of two crops during the same season and enabling the evaluation of reference evapotranspiration in one of them. This structure allows for an accurate characterization of the water balance, providing a solid foundation for the precise calculation of solute balance and the modeling of hydrological processes.

This innovative design becomes a key tool for scaling up the results of small-scale experiments to larger geographical units. It is particularly useful for studying phenomena such as the rapid rise of the water table, prolonged flooding under extreme heat conditions, or the transport of contaminants during heavy rainfall events followed by severe drying of the soil profile, among other natural phenomena.

During implementation, each lysimeter was waterproofed to prevent water loss due to leakage, ensuring precise evaluation. Additionally, the placement of 0.20 m thick layers was carried out with a high degree of precision, supported by the characterization of the soil moisture retention curve and infiltration rate, both of which are key parameters in this drainage lysimeter block [6, 7].

IV. CONCLUSIONS

Through the proposed methodology, the study enabled the development of a protocol for the design, construction, and calibration of a block of 7 drainage lysimeters. Consequently, the design allows for the simulation of natural soil conditions without any restriction on the behavior of crops in the area. Construction requires that the material used meets the resistance limits, so, the type of waterproofing used to prevent leaks is crucial. In calibration, an important aspect is the evaluation of the soil's physical characteristics, where the most representative variables such as compaction, structure, field capacity, and bulk density were considered. As mentioned, the degree of compaction increases with depth, significantly affecting the soil's ability to transmit water throughout the profile. Additionally, field capacity allows for the determination of the maximum limit of water retention, and thus, with the additional percentage, over-irrigation can be generated.

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REFERENCES

[1] R. S. Johnson, L. E. Williams, J. E. Ayars, and T. J. Trout, "Weighing lysimeters aid study of water relations in tree and vine crops," *California Agriculture*, vol. 59, no. 2, pp. 133–136, 2005.

[2] A. N. Laghari, M. A. Soomro, Z. A. Siyal, S. H. Sandilo, and T. A. Soomro, "Water Availability in Snow Dominated Regions under Projected Climatic Variability: A Case Study of Alpine Catchment, Austria," *Engineering, Technology & Applied Science Research*, vol. 8, no. 2, pp. 2704–2708, Apr. 2018, https://doi.org/10.48084/etasr.1831.

[3] R. G. Allen, L. S. Pereira, D. Raes, and M. Smith, *Evapotranspiracion del cultivo Guias para la determinacion de los requerimientos de agua de los cultivos*. Rome, Italy: FAO, 2006.

[4] L. F. M. de S. Campeche, A. O. A. Netto, I. F. Sousa, G. G. Faccioli, V. de P. R. da Silva, and P. V. de Azevedo, "Lisimetro de pesagem de grande porte. Parte I: Desenvolvimento e calibracao," *Revista Brasileira de Engenharia Agrícola e Ambiental*, vol. 15, no. 5, pp. 519–525, 2011.

[5] V. de P. R. da Silva, J. H. B. da Cunha Campos, and P. V. de Azevedo, "Water-use efficiency and evapotranspiration of mango orchard grown in northeastern region of Brazil," *Scientia Horticulturae*, vol. 120, no. 4, pp. 467–472, May 2009, https://doi.org/10.1016/j.scienta.2008.12.005.

[6] D. de C. Mariano, R. T. de Faria, P. S. L. de Freitas, B. P. Lena, and A. L. Johann, "Construction and calibration of a bar weighing lysimeter," *Acta Scientiarum. Agronomy*, vol. 37, no. 3, pp. 271–279, Jul. 2015.

[7] L. D. B. da Silva, M. V. Folegatti, and N. A. Villa Nova, "Evapotranspiracao do capim Tanzania obtida pelo metodo de razao de Bowen e lisimetro de pesagem," *Engenharia Agrícola*, vol. 25, pp. 705–712, Dec. 2005, https://doi.org/10.1590/S0100-69162005000300016.

[8] J. O. Payero and S. Irmak, "Construction, installation, and performance of two repacked weighing lysimeters," *Irrigation Science*, vol. 26, no. 2, pp. 191–202, Jan. 2008, https://doi.org/10.1007/s00271-007-0085-9.

[9] R. G. Allen, L. S. Pereira, T. A. Howell, and M. E. Jensen, "Evapotranspiration information reporting: I. Factors governing measurement accuracy," *Agricultural Water Management*, vol. 98, no. 6, pp. 899–920, Apr. 2011, https://doi.org/10.1016/j.agwat.2010.12.015.

[10] [10] INAMHI, Base de datos climatológicos, no. 52. 2019. [Online]. Available: http://www.serviciometeorologico.gob.ec/docum_institucion/anuarios/meteorologicos/Am_2013.pdf

[11] D. Gabriels and D. Lobo, "Metodos para determinar granulometria y densidad aparente del suelo," *Venesuelos*, vol. 14, no. 1, pp. 37–48, 2006.

[12] *Protocolo de analisis fisico y quimico del suelo*. INIAP, 2015.

[13] I. J. Ekanayake, *Studying drought stress and irrigation requirements of potatoes*. Lima, Peru: CIP, 1989.

[14] O. B. G. Canales, *Manual de uso consuntivo del agua para los principales cultivos de los Andes centrales peruanos*. Lima, Peru: IGP-INCAGRO, 2009.

[15] R. Lopez-Urrea, A. Montoro, F. Manas, P. Lopez-Fuster, and E. Fereres, "Evapotranspiration and crop coefficients from lysimeter measurements of mature 'Tempranillo' wine grapes," *Agricultural Water Management*, vol. 112, pp. 13–20, Sep. 2012, https://doi.org/10.1016/j.agwat.2012.05.009.

[16] M. Silicani, *Diseño, construcción y operación de un lisímetro de bajo costo*. Editorial Académica Española, 2017.

[17] L. Machaca Cari, "Determinación de las necesidades de agua del cultivo haba baby mediante lisímetros de drenaje en la irrigación Majes – Arequipa," M. S. thesis, Universidad Nacional del Altiplano, Puno, Peru, 2011.

[18] L. D. Perez Soto, "Influencia de la maquinaria agricola sobre la variabilidad espacial de la compactacion del suelo. Aplicacion de la metodologia geoestadistica-fractal," Ph.D. dissertation, Technical University of Madrid, Madrid, Spain, 2012.

[19] J. J. Ibanez, "La Compactación del Suelo: Exploración del Suelo por las Raíces II - Un Universo invisible bajo nuestros pies," *Un Universo invisible bajo nuestros pies*, Dec. 25, 2006. https://www.madrimasd.org/blogs/universo/2006/12/25/55938.

[20] R. Santa Laura Leyva, P. Aime Baldoquín, and O. Manuel Reyes, "Propiedades de los suelos en diferentes usos agropecuarios, Las Tunas, Cuba," *Revista de Ciencias Agrícolas*, vol. 35, no. 1, pp. 36-47, Jun. 2018, https://doi.org/10.22267/rcia.183501.81.

[21] J. Denoia, O. Sosa, G. Zerpa, and B. Martin, "Efecto del pisoteo animal sobre la velocidad de infiltracion y sobre otras propiedades fisicas del suelo," *Pastos*, vol. 30, no. 1, pp. 129–141, 2000.

[22] C. R. Alvarez, M. Torres Duggan, E. R. Chamorro, D. D ´Ambrosio, and M. A. Taboada, "Descompactacion de suelos franco limosos en siembra directa: efectos sobre las propiedades edaficas y los cultivos," *Ciencia del suelo*, vol. 27, no. 2, pp. 159–169, Dec. 2009.

[23] C. Zúñiga Espinoza, "Manejo de riego mediante un monitoreo hídrico en tiempo real determinado con la técnica Frequency Domain Reflectometry.," B.Sc. thesis, Universidad de Chile, 2004.