J. Jpn. Soc. Soil Phys.
土壌の物理性
No. 163, p.41 ～ 52 (2026)

若手特集
論　文
Original Paper

Development and evaluation of a lower-boundary-controlled weighing lysimeter: measuring evaporation under field conditions

Fadhil NOOR[1], Leon NAKAYAMA[2], Masaru SAKAI[3] and Ieyasu TOKUMOTO[2]

Abstract: Accurate field measurement of evaporation requires weighing lysimeters that reproduce realistic hydraulic boundary conditions while operating reliably with minimal maintenance. This is particularly challenging in coastal reclaimed fields, where shallow and rapidly fluctuating groundwater and desalinization practices can drive the soil profile toward near saturation, limiting the performance of conventional equilibrium tension lysimeters that rely on vacuum regulation. We developed a Lower-Boundary-Controlled Weighing Lysimeter (LBC-WL) that regulates the lower boundary through bidirectional water exchange using a bidirectional tubing (peristaltic) pumping system and operates autonomously with a compact solar panel power supply. The system consists of a weighing inner cylinder whose base contains porous ceramic cups embedded in a silica sand layer and connected to an external water tank. A datalogger continuously compares the bottom pressure head inside the lysimeter (h_b) with an external reference head measured outside (h_{out}) and actuates the pump to maintain h_b within a prescribed tolerance band around h_{out}, with a short waiting time after each pumping action to improve stability.

Laboratory single-step and multi-step tests demonstrated that the pumping system maintained h_b close to prescribed targets over both relatively dry and near-saturated ranges while conserving mass balance between the lysimeter and the tank, consistent with the water retention behavior of the silica sand. Greenhouse tests confirmed continuous operation under solar panel power and showed that widening the tolerance band under near-saturated conditions reduced excessive pump cycling. Field deployment during desalinization in a coastal reclaimed area maintained lower boundary control (typically $h_b = h_{out} \pm 10$ to ± 15 cm, depending on wetness) and enabled evaporation to be quantified at 10-min resolution during the subsequent drying period. These results indicate that the LBC-WL provides a robust platform for studying evaporation and water balance processes in managed fields with shallow groundwater.

Key Words: weighing lysimeter, shallow groundwater, coastal reclaimed field

1. Introduction

Evaporation and evapotranspiration (ET) are key components of the water balance in agricultural systems, particularly in regions where shallow groundwater and salinity management strongly influence soil moisture dynamics. In coastal reclamation areas, farmers often rely on flooding or drip leaching to remove salts from the root zone; during the subsequent drying period, evaporation becomes a primary driver of soil-water availability and salt redistribution (Ishikawa et al., 2022; Tokumoto et al., 2023). To analyze these coupled processes, researchers require instruments that can reproduce field-like hydraulic boundary conditions while resolving evaporation at a temporal resolution sufficient to capture diurnal cycles and short-term responses to atmospheric forcing.

Weighing lysimeters provide direct estimates of water fluxes such as ET and seepage by continuously measuring mass changes of an isolated soil column, and they have been used widely for crop water-use and evaporation studies (Marek et al., 1988; Liu et al., 2002). In addition to their accuracy, weighing lysimeters are increasingly used as ground truth references for evaluating other ET measurement approaches, provided that their fluxes are representative of the surrounding field and the soil water balance is properly closed (Evett et al., 2012). Recent developments in sensors, datalogging, and low-cost control platforms have further promoted “smart” lysimeter systems that aim to improve reliability and reduce labor requirements (Sagar et al., 2022; Dong and Hansen, 2023).

[1]The United Graduate School of Agricultural Sciences, Kagoshima University, 21-24, 1 Korimoto, Kagoshima 890-8580, Japan.
[2]Faculty of Agriculture, Saga University, 1 Honjo, Saga 840-8502, Japan. Corresponding author: 徳本 家康, 佐賀大学.
[3]Graduate School of Bioresources, Mie University, 1577 Kurima-machiya, Tsu, 514-8507, Japan.
2026 年 1 月 19 日受稿 2026 年 5 月 31 日受理

A persistent challenge in lysimetry is that the internal hydraulic state can deviate from that of the surrounding soil when boundary conditions, especially the lower boundary, are not represented adequately. Lysimeters are widely used because they provide one of the most direct approaches to quantify actual evapotranspiration under field conditions (Rana and Katerji, 2000). However, with a seepage-face lower boundary (as opposed to a unit-gradient "free-drainage" boundary), drainage occurs only when the soil at the lysimeter base becomes saturated, and upward inflow (capillary rise) from deeper soil or groundwater is excluded because the hydraulic connection from below is lost (Groh et al., 2016). Such boundary mismatches can lead to artifacts (e.g., unrealistic drainage or perched saturation), and they can also affect interpretations of solute transport and leaching because lysimeter-derived transport estimates may be sensitive to the lower boundary condition imposed (Flury et al., 1999; Singh et al., 2018). To reduce these artifacts, equilibrium-tension lysimeters and related approaches have been developed to match the pressure head at the lysimeter bottom to that of the surrounding undisturbed soil (Brye et al., 1999).

In many practical implementations, tension control is achieved by regulating suction or by active water exchange at the lysimeter bottom. For instance, state-of-the-art mini lysimeter systems can use bidirectional pumping based on internal and external tensiometer comparisons to minimize pressure head differences and thereby enforce hydraulic continuity, enabling both unsaturated seepage and equivalent capillary rise (Ruth et al., 2018). Smart field lysimeters (SFLs) have also been applied to quantify actual ET under field conditions (Doležal et al., 2018). Despite these advances, stable lower boundary control remains difficult under wet to near-saturated conditions, where small water transfers can produce large pressure-head changes and highly sensitive feedback responses. Moreover, long-term field deployment requires autonomous operation under power constraints, robust protection against overflow during intense infiltration events, and and low maintenance; these factors can limit the practicality of suction-based regulation and can introduce measurement errors in automated tension-control systems (Morari, 2006).

To address these limitations, we developed a Lower-Boundary-Controlled Weighing Lysimeter (LBC-WL) that regulates the lower boundary condition through bidirectional water exchange using porous ceramic cups and a bidirectional tubing (peristaltic) pumping system, rather than vacuum-based control. The control algorithm continuously compares the bottom pressure head inside the lysimeter (h_b) with an external reference head measured in the surrounding soil (h_{out}) and maintains h_b within a prescribed tolerance band around h_{out}. A short waiting time after each pumping action is incorporated to allow hydraulic equilibration and to suppress excessive cycling, improving stability particularly under wet conditions. The system further includes overflow protection based on tank mass monitoring and is designed for fully autonomous field operation using a solar panel-battery system.

The objectives of this study were to (i) validate the pressure-control performance and water balance behavior of the bidirectional pumping system in laboratory single-step and multi-step tests, (ii) evaluate autonomous operation and practical control band settings under near-saturated conditions in a greenhouse, and (iii) demonstrate robust field operation in a coastal reclaimed agricultural area during desalinization and quantify evaporation during the subsequent drying period at 10-min temporal resolution.

2. Materials and Methods

2.1 Overview of the LBC-WL system

Figure 1 shows the configuration of the Lower-Boundary-Controlled Weighing Lysimeter (LBC-WL). It consists of an inner stainless-steel cylinder (30 cm i.d. $\times$ 50 cm height) seated within an outer stainless steel containment unit (60 cm diameter $\times$ 70 cm height). The inner cylinder was designed to be portable and installable in the field while still accommodating a soil depth representative of the effective rooting zone under the target cropping/management conditions. In addition, this size keeps the total mass within the operating range of the precision balance required for continuous weighing. The base of the inner cylinder (30 cm i.d. $\times$ 5 cm thickness) is equipped with two porous ceramic cups (50 mm diameter; air-entry value $\approx$ 80 kPa) and a tensiometer (Model ML-2400AET, Mole, Inc.), all embedded in uniformly packed silica sand (Silica sand No. 9, Featherfield Co., Ltd.) serving as a filter layer. According to the product specifications, this material consists of very fine, powder-like particles with a median particle diameter of approximately 0.05 mm. No. 9 is among the finest silica sand grades and has a very fine, silt-like texture rather than the texture of ordinary coarse sand. Its saturated hydraulic conductivity was 123 cm d^{-1}, providing sufficient permeability for drainage while maintaining hydraulic contact with the soil material placed above it. Because the hydraulic properties of the soil material and the silica-sand layer may differ, a hydraulic discontinuity and a possible capillary-barrier effect at their interface cannot be completely excluded under unsaturated conditions. This potential effect was therefore considered when interpreting pressure-head and drainage

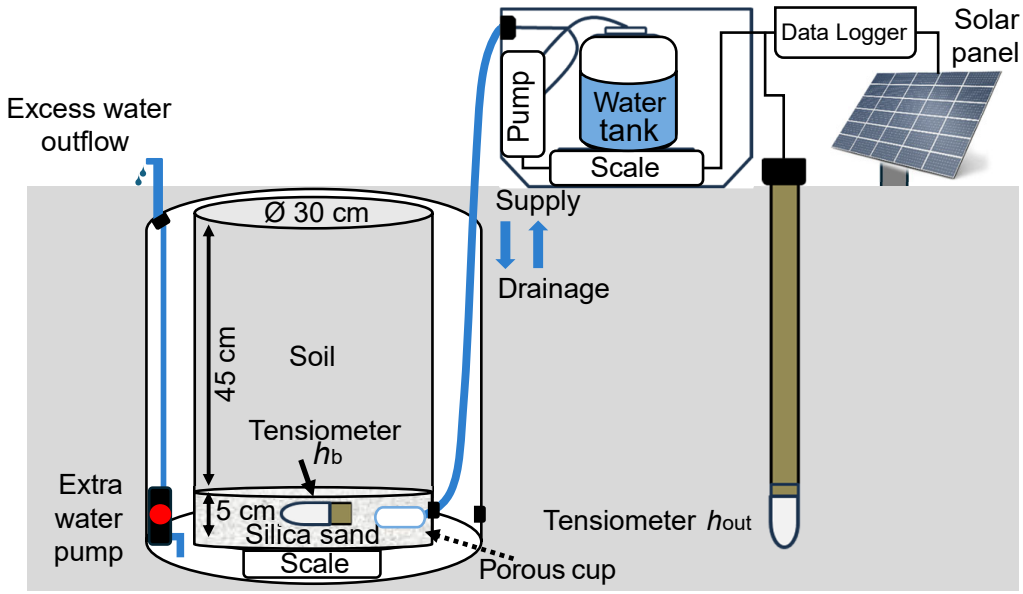


Fig. 1 Schematic figure of the Lower-Boundary-Controlled Weighing Lysimeter (LBC-WL) with the bidirectional supply–drainage pumping system.

responses near the lower boundary.

The silica-sand layer was introduced to provide uniform hydraulic contact between the repacked soil and the porous ceramic cups/tensiometer, thereby stabilizing bidirectional water exchange at the lysimeter base. The entire inner cylinder is placed on a precision electronic balance with a measurement resolution of 28 g, enabling continuous mass monitoring and thus functioning as a weighing lysimeter.

The ceramic cups are hydraulically connected to a bidirectional peristaltic tubing pump system, consisting of two tubing pumps (Model: WPX1-S4.8DM2-WT6, Welco Co., Ltd.) connected via flexible tubing, allowing controlled water injection or extraction at the lysimeter base. The outer cylinder shields the inner system from surface water intrusion during heavy rainfall and protects against rising groundwater. A soil moisture sensor (EC-5, Meter Group), vertically installed at the bottom of the outer cylinder to detect water level, and an outer drainage pump (model iL280p, Rule Industries) were used to remove excess water.

All sensors and pumps are autonomously operated using a CR1000X datalogger (Campbell Scientific). h_b and h_{out} are continuously monitored using tensiometers at the same depth. Water is transferred between the lysimeter and the external tank as necessary to maintain h_b within a prescribed tolerance band around h_{out}, thereby maintaining consistent hydraulic conditions across the lysimeter boundary.

Power for autonomous field operation is provided by two independent solar-supported 12-V battery systems: one for the core control system (bidirectional pump, datalogger, balance, tensiometers) and another for the outer drainage system.

2.2 Bottom-Boundary Control with a Bidirectional Pumping System

The LBC-WL maintains hydraulic continuity at its base using a bidirectional pumping system (Fig. 2). Unlike conventional equilibrium tension lysimeters (e.g., Brye et al., 1999), which often rely on vacuum-based regulation, this system uses automated water transfer between the lysimeter base and an external tank.

2.2.1. Control logic

The CR1000X datalogger compares h_b and h_{out} at fixed

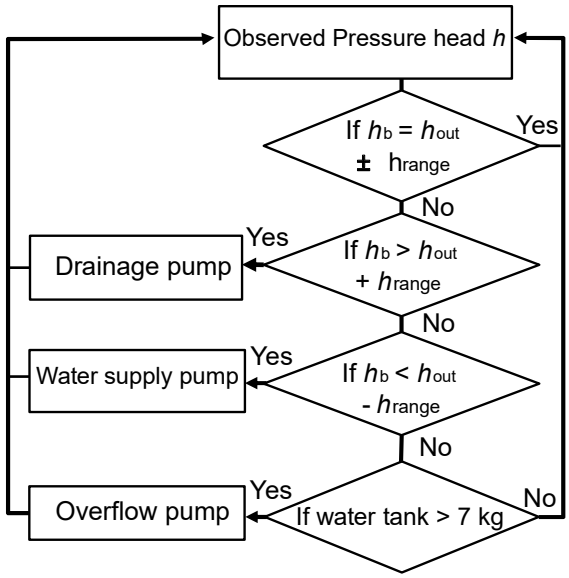


Fig. 2 Flow chart of the lower-boundary control algorithm used in the LBC-WL.

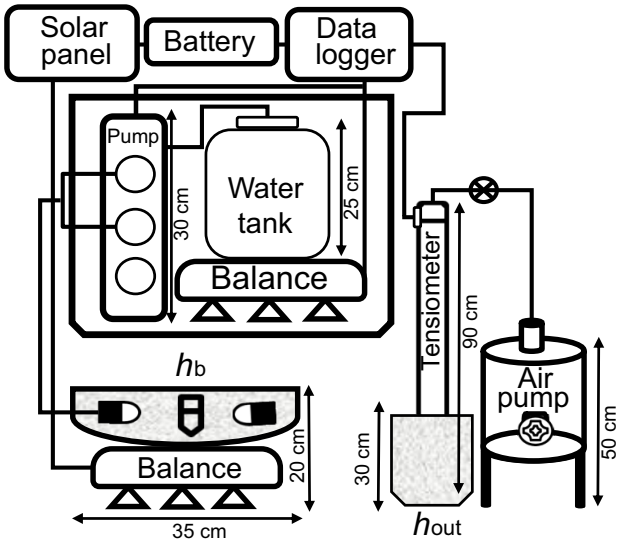


Fig. 3 Schematic figure of the laboratory setup for pressure-regulation tests using only the lower lysimeter assembly.

time intervals. When $|h_b - h_{out}|$ is within a prescribed tolerance ($\pm h_{range}$), the system remains idle. If h_b exceeds h_{out} by more than h_{range}, the bidirectional pump operates in drainage mode to lower h_b. Conversely, if h_b is below $h_{out} - h_{range}$, the pump operates in supply mode to increase h_b.

Based on the greenhouse evaluation (Section 3.2), h_{range} was set to $\pm$10 cm under relatively dry conditions ($h_{out} < -20$ cm) and widened to $\pm$15 cm under wetter, near-saturated conditions ($h_{out} \geq -20$ cm) to reduce excessive pump cycling while maintaining stable control. A 10-s waiting time was applied after each pumping action to reduce immediate repeated actuation and to allow partial relaxation of pressure transients, thereby suppressing overly frequent control cycling within the specified tolerance band rather than implying complete hydraulic equilibration.

2.2.2. Overflow protection

The external water tank used for supplying and receiving water at the lysimeter base is mounted on a load cell that continuously monitors its mass. When the tank mass exceeds 7 kg ($\approx$ 7 L) due to prolonged infiltration events or intense rainfall, an overflow pump is automatically activated. This pump discharges excess water to a drainage outlet until the tank mass is reduced to 3 kg, thereby preventing overflow. This safeguard protects the system from overflow-related malfunctions and retains sufficient water in the tank to enable continued lower-boundary control after rainfall events.

2.3 Validation of the pumping system

To evaluate the performance of the supply–drainage control system, pressure-regulation experiments were conducted in a temperature-controlled laboratory (25°C) using only the lower lysimeter assembly. In this experiment, the system was powered by a direct electrical supply, without the use of a solar panel and battery (Fig. 3). The base section of the inner cylinder was filled with uniformly packed silica sand. Two porous ceramic cups and a tensiometer were embedded in the sand and connected via flexible tubing to the bidirectional pump system and an aboveground water tank. The sand surface was exposed to the atmosphere to impose an atmospheric upper boundary condition, allowing evaporation. An external tensiometer, coupled to a separate pressure-regulation unit, enabled imposition of prescribed h_{out}.

A single-step control test examined whether h_b could be regulated within $\pm$10 cm of h_{out} under two fixed conditions: $h_{out} = -120$ cm (field-capacity equivalent, pF = 2.0) and $h_{out} = -20$ cm (shallow groundwater equivalent). Pressure heads were logged over a 4-h period to evaluate control accuracy.

A multi-step control test characterized dynamic response under repeated changes in h_{out}. Two sequences were defined: Case 1 (h_{out} alternated between -60 and -120 cm) and Case 2 (h_{out} alternated between -20 and -60 cm), with 2-h intervals. h_b response and corresponding mass changes of the lysimeter and water tank were recorded to quantify pump performance under dynamic loading.

2.4 Power supply performance test

To verify autonomous operation using solar power (Fig. 3), a power supply test was conducted in a glass greenhouse in June 2024. This test examined whether a 20-W solar panel and a 12-V, 35-Ah battery could sustain continuous operation under quasi-saturated conditions near-saturated conditions. A soil-filled reference pot equipped with an external tensiometer provided a stable h_{out}. The system maintained h_b near h_{out} by activating the bidirectional pump according to the protocol described above.

The CR1000X datalogger recorded h_b and h_{out} every 10 s and logged each pump activation (frequency and duration). Environmental variables, including air temperature (shielded thermistor, TandD Corp.), solar radiation (pyranometer), and battery voltage were recorded hourly to ensure system reliability. Hourly solar radiation data for Saga City were also retrieved from the Japan Meteorological Agency (accessed July 2025).

2.5 Field deployment of the LBC-WL

Field testing was conducted at an agricultural site in the Yokoshima Reclamation Area (32°50'49.9" N, 130°34'06.4" E), Kumamoto, Japan. This site is protected from the Ariake Sea by coastal levees. The soil was clas-

sified as sandy clay. Average values for saturated hydraulic conductivity (K_s) and dry bulk density (ρ_b), based on undisturbed core samples from surface and subsurface layers, were 5 cm d^{-1} and 1.1 g cm^{-3}, respectively.

2.5.1 Installation and Experimental Setup

At the research field site (Fig. 4), a hole matching the dimensions of the lysimeter's outer casing was excavated, and the casing was installed with its lower edge level. After packing silica sand into the base of the inner cylinder (30 cm i.d. ; 5 cm thickness), the inner cylinder (30 cm i.d. $\times$ 45 cm height) was filled with air-dried soil passed through a 2 mm sieve. The soil was uniformly repacked to a dry bulk density of 1.1 g cm^{-3}, representative of the field conditions, by placing and compacting the soil in $\sim$ 10 cm lifts. The cylinder, once filled, was carefully placed into the casing using a pulley system. As shown in Fig. 1, the lysimeter was connected to the bidirectional pump and other components. The box housing the bidirectional pump and control components was installed above ground to prevent groundwater ingress at the site. Electronic balances were placed beneath both the inner cylinder and the water tank to measure their respective weights. Tensiometers were installed both inside and outside the cylinder to measure the h_b and h_{out} at a depth of 47.5 cm, respectively (Fig. 1). Additionally, a well was installed adjacent to the lysimeter to monitor groundwater depth using a water level sensor. Precipitation was measured with a rain gauge near the greenhouse, and solar radiation and air temperature were recorded by sensors (ATMOS41, Meter Group, Inc.) at the field site in mid-August. During the short-term monitoring period, the soil surface inside the lysimeter and in its immediate vicinity was kept bare (non-vegetated) to quantify evaporation under bare-soil conditions.

The tensiometer installed inside the inner cylinder measures pressure head in the bottom filter medium (silica sand), which provides the hydraulic connection between the lysimeter base and the external reference point. Although monitoring soil water content within the lysimeter profile would further strengthen the interpretation of internal moisture dynamics, the soil-moisture sensor record during the target period was not usable because of unstable readings. Additionally, soil temperature monitoring would be valuable for assessing potential thermal effects of water exchange, but the temperature record was also not usable due to data-logging/communication failures. To reduce radiative heating, the lysimeter surroundings and the upper part of the installation were covered with sandbags and rice-straw bags as insulation. Accordingly, this study focuses on boundary-head control (h_b versus h_{out}) and mass-balance-based evaporation estimates, and improved in-profile moisture and temperature monitoring is left for future work.

2.5.2 Field operation during flood leaching (desalinization period)

In July 2024, prior to the start of continuous measurements, flood leaching was conducted in the greenhouse adjacent to the lysimeter to reduce soil salinity. Leaching water from a nearby agricultural canal was applied to the soil surface for approximately one week (31 July–5 August) to maintain the groundwater depth inside the greenhouse at about 5 cm below the soil surface. During and after this leaching period, the LBC-WL was operated in automatic mode so that h_b was controlled within a prescribed band around h_{out}. A bare soil surface was maintained on and around the lysimeter to quantify evaporation under non-vegetated conditions. All pump operations, pressure heads, and scale readings for both the lysimeter cylinder and the water tank were logged at fixed 10-s intervals. These mass measurements were subsequently used to compute daily evaporation from the lysimeter soil by applying a water balance approach based on the concurrent weight changes of the cylinder and the water tank during the desalinization period. Before operation, the tubing and porous cups were primed to ensure they were completely water-filled. To reduce air entrapment during extended deployment, manual maintenance was performed approximately once per month, including purge/flush cycles to renew water in the tubing and porous components.

3. Results and Discussion

3.1 Laboratory validation of the pumping system

3.1.1 A single-step control test

Figure 5a shows the temporal variation in h_b when the target h_{out} was set to -120 cm using the air pump. Before introducing a waiting time into the control algorithm, h_b fluctuated around h_{out} but did not remain within the target band (-120 ± 10 cm). The maximum h_b was approximately -100 cm, indicating that the pumping system supplied excessive water relative to drainage and thus failed to maintain h_b within the prescribed range. This behavior suggests a rapid hydraulic response of the silica sand near the outlet and a short feedback interval between consecutive pumping actions, which led to overly frequent water supply-drainage cycles in response to small differences between h_b and h_{out}.

After implementing a 10-s waiting time, during which the system temporarily halted both water supply and drainage while monitoring h_b and h_{out}, control performance improved markedly (Fig. 5a). The maximum h_b approached -110 cm, and the amplitude of fluctuations

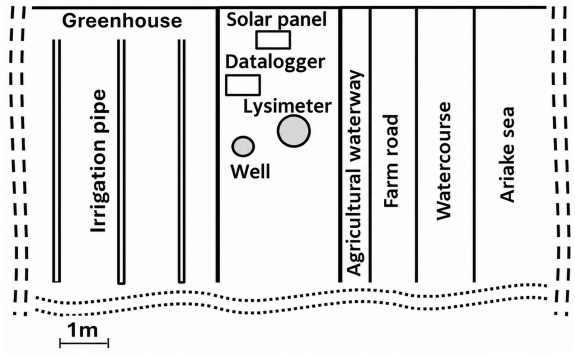


Fig. 4 Location of the LBC-WL installed in the field.

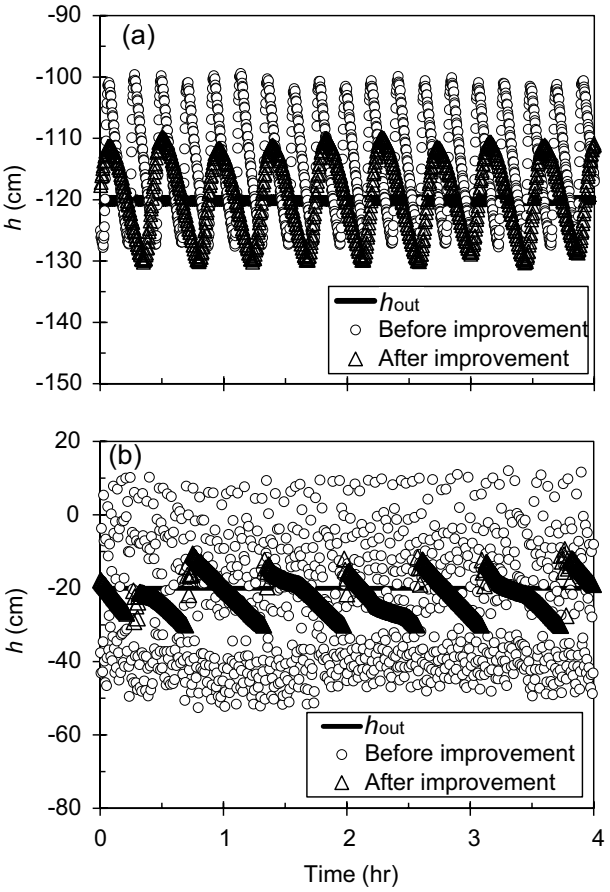


Fig. 5 Time series of the bottom pressure head h_b during single-step control tests in the temperature-controlled laboratory: (a) target $h_{out} = -120$ cm; (b) target $h_{out} = -20$ cm.

around the set pressure head decreased. Although the target value was still not achieved exactly, h_b remained closer to the prescribed range, and the pumping frequency was reduced from roughly 10 to about 5 operations per hour, where one operation was defined as a single pump activation followed by a mandatory 10-s waiting interval, after which the system reevaluated the need for further pumping based on the control flow chart shown in Fig. 2. This reduction is advantageous for long-term field applications because it lowers power consumption and mechanical wear while improving control stability.

Figure 5b presents the single-step control test under comparatively wet conditions, with a target head of -20 cm. Before modification, h_b frequently deviated beyond the ± 10 cm tolerance and the system could not stabilize the pressure around the set value. As the water content of the silica sand approached saturation, its hydraulic conductivity increased sharply; consequently, small pump actions produced large changes in h_b, making the system highly sensitive and difficult to control. After introducing the 10-s waiting time, the fluctuation range of h_b was substantially reduced and the pressure head followed the target more closely, although residual variability remained larger than in the dry case.

Overall, the single-step control test demonstrates that the modified pumping system can approximately reproduce prescribed pressure heads representative of drier (-120 cm) and wetter (-20 cm) conditions at the bottom of the lysimeter. The waiting time improved the stability of the bottom pressure head and reduced the number of pump operations, while the remaining difficulty near saturation is consistent with the strongly nonlinear relationship between water content and hydraulic conductivity in the silica sand.

3.1.2 A multi-step control test

In addition to the single-step test described in Section 3.1.1, a multi-step control test was carried out to examine how the system tracks repeated changes in the prescribed h_{out} under drier and wetter conditions.

Figure 6a shows the results for the drier sequence, in which h_{out} was alternated between -120 and -60 cm. In this case, h_b closely followed the imposed steps with relatively small fluctuations around each set point, demonstrating good tracking performance. The corresponding mass changes of the supply tank and the lysimeter (Fig. 6b) occurred in clear discrete increments of about 10 g per pump event, and the cumulative loss from the tank almost equaled the cumulative gain of the lysimeter, indicating that the water balance between the two reservoirs was well maintained. Between pump events, the 10-s waiting time allowed h_b to relax toward a new equilibrium, so that h_b remained within the control band for most of the dry sequence.

In contrast, Figs. 6c and 6d present the multi-step test under wetter conditions, where the target pressure head was alternated between -60 and -20 cm. The same 10-s pumping and 10-s waiting times were used, and the stepwise changes in lysimeter mass were again on the order of 10 g per event, with the tank and lysimeter masses remaining in close balance. However, control of the higher h_b values was more difficult: h_b exhibited larger short-term fluctuations and slower convergence to the prescribed h_{out},

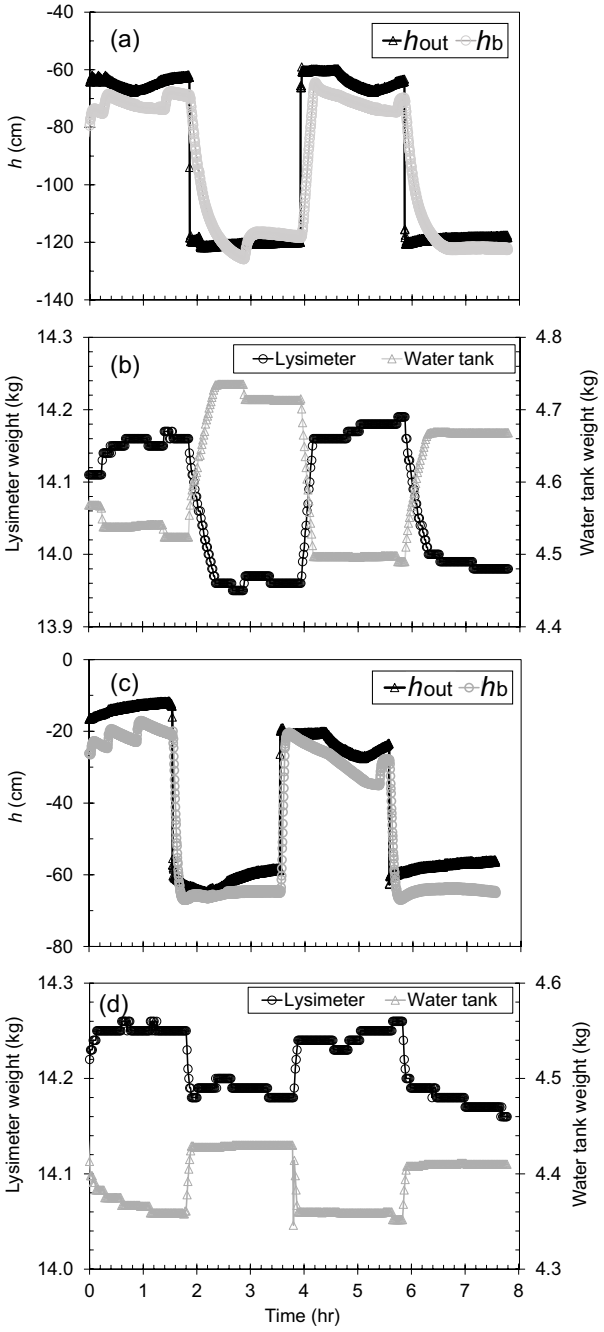


Fig. 6 Multi-step control tests in the temperature-controlled laboratory showing responses of h_b to step changes in h_{out} : (a) dry sequence (h_{out} alternated between -60 and -120 cm); (b) temporal change in weight in the dry sequence; (c) wet sequence (h_{out} alternated between -20 and -60 cm); (d) temporal change in weight in the wet sequence.

and the response became slightly oscillatory in this wetter range, even though the mass balance of the system remained consistent.

The contrasting behavior between the dry and wet sequences can be interpreted from the water retention properties of the silica sand and the fixed water volume moved by each pump event. Figure 7 shows the water retention curve of the silica sand, i.e., the relationship between volumetric water content θ (horizontal axis) and pressure head h (vertical axis), together with the corresponding discrete sensitivity $\Delta h/\Delta\theta$; the inset enlarges the near-saturated range, where the slope becomes much steeper. The volume of silica sand at the lysimeter bottom is approximately 3530 cm^3. During a typical operation of the supply–drainage pump, on the order of 10 g of water are transferred between the tank and the lysimeter, but the actual transfer can be slightly smaller when the tubing is not completely filled. In terms of average water content, this corresponds to a nearly fixed increment of about $\Delta\theta_p \approx 2\times10^{-3}$ cm^3 cm^{-3} per pump event. The resulting change in bottom pressure head can be approximated as $\Delta h_b \approx (\Delta h/\Delta\theta)_{WRC}\Delta\theta_p$, where $(\Delta h/\Delta\theta)_{WRC}$ denotes the slope of the water retention curve at the current state and $\Delta\theta_p$ is the change in θ caused by a single pump operation.

In the drier range around -120 to -60 cm, the slope of the water-retention curve, $S_{wrc}(\theta) = \Delta h/\Delta\theta$, is relatively small (Fig. 7). Therefore, a single pump event that changes water content by $\Delta\theta_p \approx 2\times10^{-3}$ cm^3 cm^{-3} produces only a moderate predicted pressure-head change, $\Delta h_p(\theta) = S_{wrc}(\theta)\Delta\theta_p$. Under these conditions, one or a few pump events, separated by the waiting time, are sufficient to move h_b between quasi-equilibrium levels with limited overshoot (Figs. 6a, 6b). In the wetter range between -60 and -20 cm, the predicted pressure-head change per pump event, $\Delta h_p(\theta) = S_{wrc}(\theta)\Delta\theta_p$, increases sharply (inset in Fig. 7), so the same $\Delta\theta_p$ yields a much larger Δh_p. This amplification explains why control becomes more sensitive, showing pronounced fluctuations around the set point near saturation (Figs. 6c, 6d). Figure 7

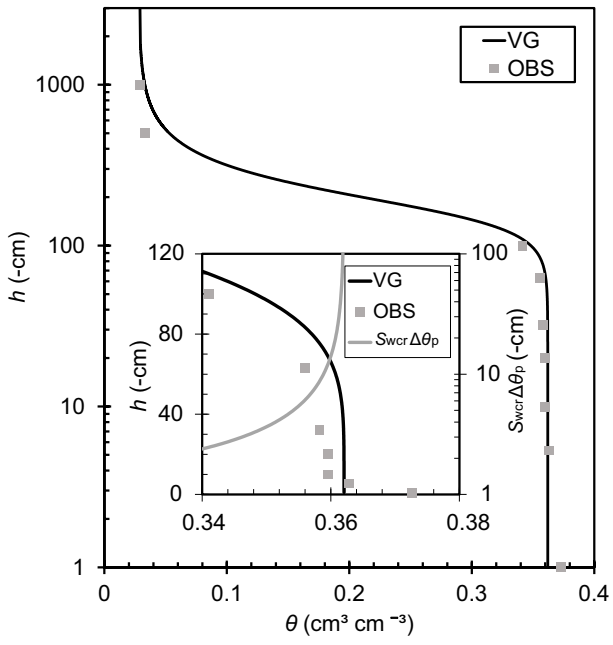


Fig. 7 Water retention curve of the silica sand showing volumetric water content θ versus pressure head h, together with the corresponding sensitivity $\Delta h/\Delta\theta$ (inset near-saturated range).

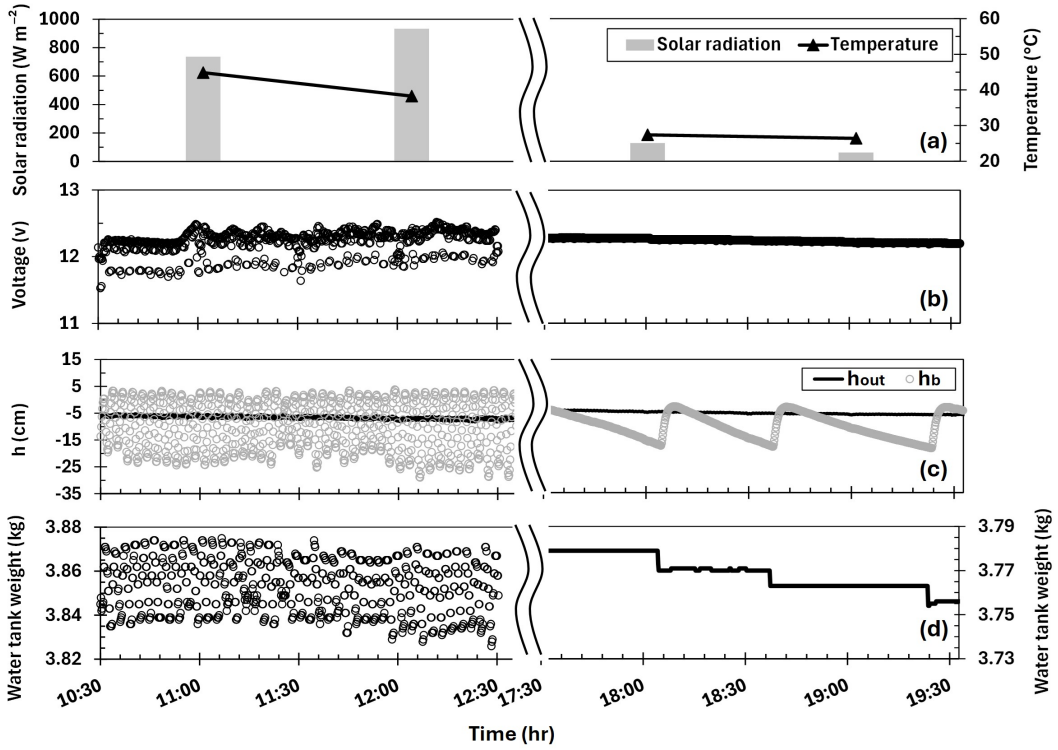


Fig. 8 Greenhouse power-supply test under a constant reference head of $h_{\mathrm{out}} = -5$ cm: (a) air temperature; (b) system voltage; (c) bottom pressure head h_{b}; (d) water-tank mass.

thus links the stability of bottom-boundary control to the $h(\theta)$ relationship of the silica sand by expressing pump actions as small, quantifiable $\Delta\theta_{\mathrm{p}}$ steps and their corresponding predicted Δh_{p}.

3.2 Greenhouse experiment: power-supply performance test

To assess LBC-WL performance under near-saturated conditions and to verify whether the solar power supply is sufficient for continuous operation, a greenhouse experiment was conducted with the outlet pressure head set to $h_{\mathrm{out}} = -5$ cm, representing conditions associated with a transient rise in groundwater level. Figure 8 summarizes the temporal behavior of greenhouse temperature, system voltage, bottom pressure head h_{b}, and the water-tank mass. While greenhouse temperature showed clear diurnal fluctuations (Fig. 8a), the system voltage remained within the operating range throughout the test period (Fig. 8b), indicating that the solar panel–battery system provided sufficient power for autonomous operation under greenhouse conditions. The modified control algorithm described in Section 3.1 (including the 10 s waiting time) was applied in all subsequent experiments.

With the control band initially set to $h_{\mathrm{b}} = h_{\mathrm{out}} \pm 10$ cm, h_{b} exhibited frequent and relatively large short-term fluctuations around the target (Fig. 8c). Because h_{b} could not be maintained within this narrow band under near-saturated conditions, the supply-drainage pump operated almost continuously, which is reflected by rapid and persistent mass changes of the water tank (Fig. 8d). The intensive operation imposed a high instantaneous load during pump start-up, producing brief voltage drops (Fig. 8b).

To reduce pump activity and stabilize pressure control, the control band was widened to $h_{\mathrm{b}} = h_{\mathrm{out}} \pm 15$ cm. Improved control behavior is evident during the post-adjustment period (after approximately 17:30 on the same day). Without any hardware changes, this adjustment markedly improved control performance: h_{b} remained within the wider band and followed the target level without pronounced oscillations (Fig. 8c). Consistent with reduced pump activity, the water-tank mass changed more intermittently (Fig. 8d), and the transient voltage drops became less apparent while the operating voltage remained stable (Fig. 8b). These results support the findings in Section 3.1 that control becomes more sensitive to near saturation. For subsequent field deployment (Section 3.3), we therefore adopted a practical operating rule for the control band: a tighter band of $h_{\mathrm{b}} = h_{\mathrm{out}} \pm 10$ cm was used under drier conditions ($h_{\mathrm{out}} < -20$ cm), whereas a wider band of $h_{\mathrm{b}} = h_{\mathrm{out}} \pm 15$ cm was used under wetter, near-saturated conditions ($h_{\mathrm{out}} \geq -20$ cm) to reduce pump activity while maintaining stable pressure control.

3.3 Field application for evaporation measurement

A field test of the LBC-WL was conducted during a de-

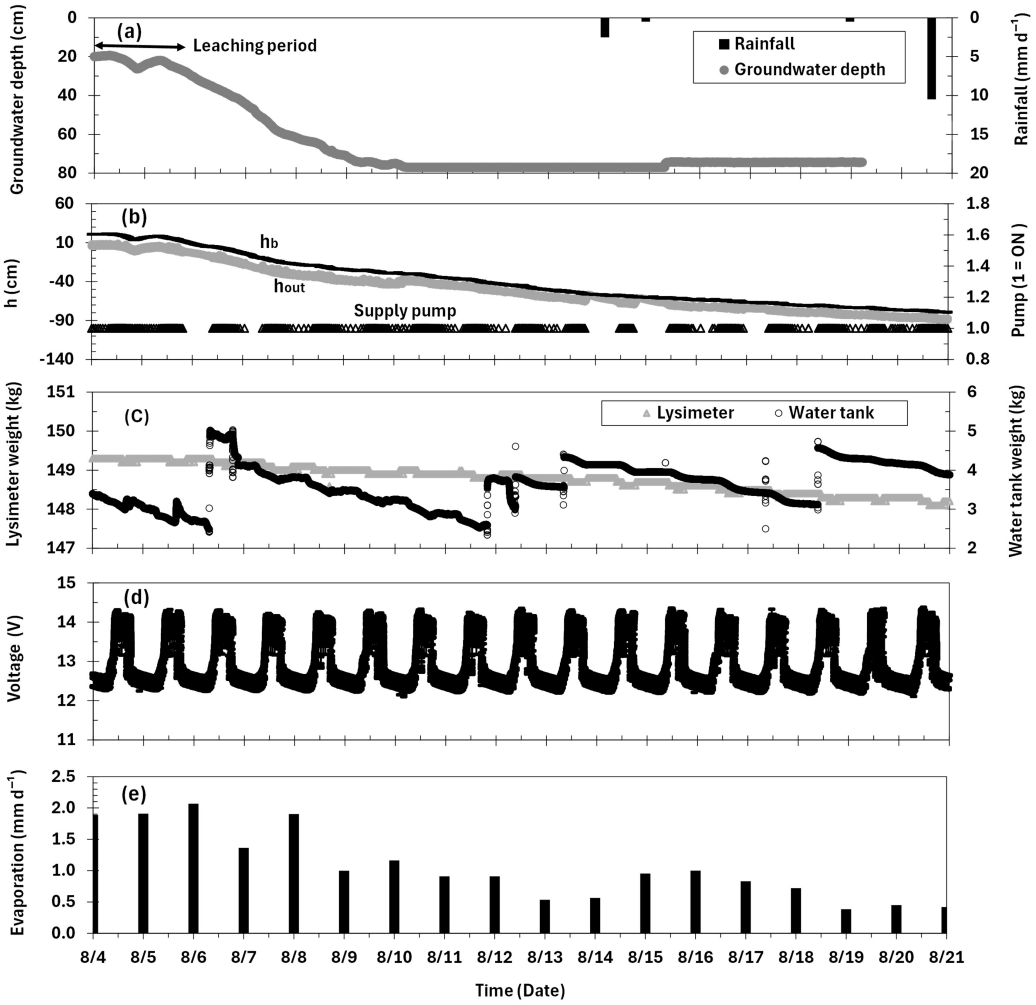


Fig. 9 Field measurements during desalinization and subsequent drying: (a) groundwater level and precipitation; (b) pressure heads (h_b and h_{out}) and pump activations; (c) lysimeter and water-tank masses; (d) system voltage; (e) daily evaporation.

salinization operation using drip irrigation after the crop-growing period. In the absence of rainfall, the groundwater level rose not only inside the greenhouse but also in the surrounding field (Fig. 9a). Leaching-water application induced a pronounced groundwater rise in and around the greenhouse, with groundwater reaching approximately 30 cm below the soil surface in early August. Consistent with this rise, h_{out} measured at a depth of 50 cm outside the lysimeter became positive (up to approximately $+20$ cm; Fig. 9b), indicating saturated conditions at the 50 cm measurement depth and suggesting bottom-up saturation associated with the groundwater rise.

Under these near-saturated boundary conditions, Fig. 9b shows that the LBC-WL maintained lower-boundary control: the bottom pressure head, h_b, tracked h_{out} and remained within the prescribed tolerance band ($h_b = h_{out} \pm$ 10 cm or ± 15 cm, depending on the control-band setting). The pump record indicates frequent supply-direction operations (Fig. 9b), reaching up to about 60 activations per day, to compensate for water losses during the post-leaching period (Fig. 9c). Notably, no drainage-direction operation was observed during the period. This behavior suggests that the transition from near-saturated to drier conditions after leaching was governed primarily by evaporation rather than controlled drainage. Despite this intensive operation, the system voltage remained above 12 V throughout the field test (Fig. 9d), indicating that the solar panel-battery system sustained continuous autonomous control in the field.

Under the wet to near-saturated field conditions examined here, the silica-sand layer was likely to remain hydraulically connected to the surrounding soil, because its air-entry value was approximately -100 cm. This suggests that the layer was unlikely to impose a substantial hydraulic discontinuity at the lysimeter bottom during the present field observation period. Rather, it likely functioned primarily as a filter medium that helped maintain hydraulic contact and stable water exchange at the lower

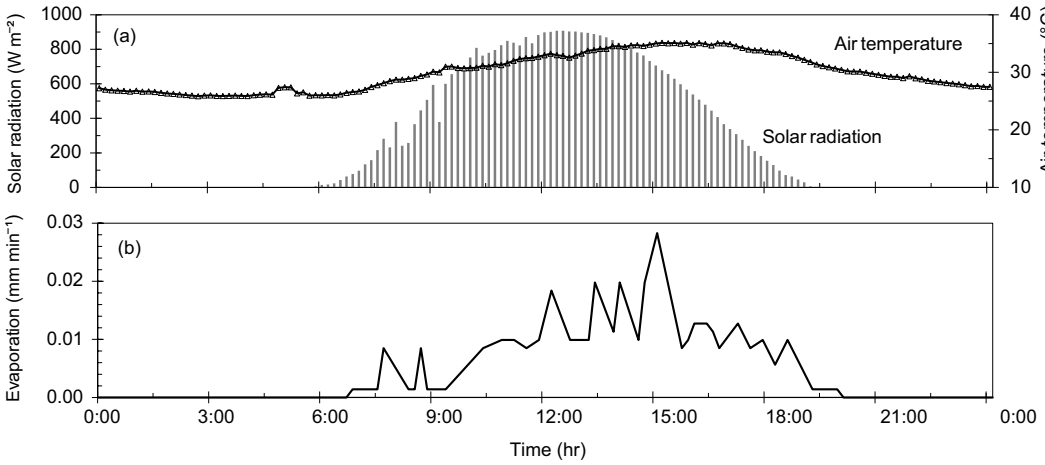


Fig. 10 Diurnal variations on 16 August: (a) solar radiation and air temperature; (b) evaporation at 10-min resolution.

boundary. Further detailed investigation under field conditions is needed to verify whether hydraulic continuity is maintained at the lysimeter bottom, for example through the use of soil-moisture sensors and related measurements.

After the leaching period ended (by 5 August), groundwater depth increased as the water table declined, marking the onset of a drying phase (Fig. 9a). During this post-leaching period, precipitation was absent or negligible (Fig. 9a). In agreement with standard descriptions in soil physics, evaporation from bare soil typically decreases with time as the near-surface soil dries and liquid-phase water supply to the surface becomes progressively less effective (e.g., Jury and Horton, 2004). The daily evaporation derived from the lysimeter records showed a gradual decline after initially reaching approximately 2 mm d^{-1} (Fig. 9e). To examine the sub-daily variability underlying this multi-day decline, Fig. 10 presents a high-temporal-resolution example of evaporation on 16 August, a clear day without rainfall.

Figure 10 illustrates the sub-daily variability of evaporation on 16 August. Air temperature and solar radiation increased after sunrise (Fig. 10a), and the 10-min evaporation-rate record responded accordingly (Fig. 10b): evaporation was essentially zero overnight, became detectable shortly after sunrise (around 06:50), and then increased through the morning with pronounced 10-min scale fluctuations. The evaporation rate reached a maximum of 0.028 mm min^{-1} at around 15:00 and then declined toward evening. Integrating the 10-min series yields a daily cumulative evaporation of 1.00 mm d^{-1}. These results demonstrate that the LBC-WL can resolve the diurnal cycle of evaporation under field conditions at 10-min resolution. The present results provide a proof-of-capability for evaporation quantification with controlled lower-boundary conditions; quantitative validation against an external reference (e.g., Penman–Monteith) will be pursued in future work with fully quality-controlled, collocated meteorological data.

4. Conclusion

We developed a Lower-Boundary-Controlled Weighing Lysimeter (LBC-WL) that regulates the lower boundary condition through bidirectional water exchange using a pumping system, rather than vacuum-based control. The combined laboratory and greenhouse evaluations demonstrated that the pumping system can maintain h_b close to h_{out} over a wide range of wetness conditions. Importantly, the greenhouse test confirmed that a solar panel-battery system can sustain continuous, autonomous operation even under near-saturated conditions, with improved stability and reduced pump activity achieved by an appropriate choice of the control band.

Field deployment in a coastal reclaimed agricultural area provided a stringent test of system robustness under fluctuating shallow groundwater during desalinization. The LBC-WL maintained lower boundary control while enabling evaporation to be quantified during the subsequent drying period, and the 10-min evaporation rate record captured both diurnal dynamics and short-term variability. These results demonstrate that the LBC-WL can be operated reliably in situ with solar-powered autonomy and controlled lower-boundary conditions, supporting its use for field studies of evaporation and water balance processes in managed agricultural systems.

Acknowledgments

This work was supported by JSPS (Grant Numbers 23K05448 and 23H02326). We thank Mr. Yuichiro Uemura of Uemura Farm for assistance with field mainte-

nance. This research was part of the dissertation submitted by the first author in partial fulfilment of a Ph.D. degree. All authors have provided consent for the dissertation submission and the publication of this article.

References

Brye, K.R., Norman, J.M., Bundy, L.G. and Gower, S.T. (1999): An equilibrium tension lysimeter for measuring drainage through soil. Soil Sci. Soc. Am. J., 63: 536–543, doi:10.2136/sssaj1999.03615995006300030016x.

Doležal, F., Hernandez-Gomis, R., Matula, S., Gulamov, M., Miháliková, M. and Khodjaev, S. (2018): Actual evapotranspiration of unirrigated grass in a smart field lysimeter. Vadose Zone J., 17: 170173, doi:10.2136/vzj2017.09.0173.

Dong, Y. and Hansen, H. (2023): Development and design of an affordable field scale weighing lysimeter using a microcontroller system. Smart Agric. Technol., 4: 100147, doi:10.1016/j.atech.2022.100147.

Evett, S.R., Schwartz, R.C., Howell, T.A. and Copeland, K.S. (2012): Can weighing lysimeter ET represent surrounding field ET well enough to test flux station measurements of daily and sub-daily ET? Adv. Water Resour., 50: 79–90, doi:10.1016/j.advwatres.2012.07.023.

Flury, M., Yates, M.V. and Jury, W.A. (1999): Numerical analysis of the effect of the lower boundary condition on solute transport in lysimeters. Soil Sci. Soc. Am. J., 63: 1493–1499, doi:10.2136/sssaj1999.6361493x.

Groh, J., Vanderborght, J., Pütz, T. and Vereecken, H. (2016): How to control the lysimeter bottom boundary to investigate the effect of climate change on soil processes? Vadose Zone J., 15: 2015.08.0113, doi:10.2136/vzj2015.08.0113.

Ishikawa, Y., Noguchi, T., Tasaki, K., Horita, T., Koyama, S. and Tokumoto, I. (2022): Sensing technology education and recovery support of damaged agricultural fields with a soil moisture and salinity sensor network. IEEJ Trans. Fundam. Mater., 142(7): 307–314, doi:10.1541/ieejfms.142.307.

Jury, W.A. and Horton, R. (2004): Soil Physics, 6th ed. John Wiley & Sons, New York.

Liu, C., Zhang, X. and Zhang, Y. (2002): Determination of daily evaporation and evapotranspiration of winter wheat and maize by large-scale weighing lysimeter and micro-lysimeter. Agric. For. Meteorol., 111: 109–120, doi:10.1016/S0168-1923(02)00015-1.

Marek, T.H., Schneider, A.D., Howell, T.A. and Ebeling, L.L. (1988): Design and construction of large weighing monolithic lysimeters. Trans. ASAE, 31(2): 477–484, doi:10.13031/2013.30734.

Morari, F. (2006): Drainage flux measurement and errors associated with automatic tension-controlled suction plates. Soil Sci. Soc. Am. J., 70: 1860–1871, doi:10.2136/sssaj2006.0009.

Rana, G. and Katerji, N. (2000): Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: A review. Eur. J. Agron., 13: 125–153, doi:10.1016/S1161-0301(00)00070-8.

Ruth, C.E., Michel, D., Hirschi, M. and Seneviratne, S.I. (2018): Comparative study of a long-established large weighing lysimeter and a state-of-the-art mini-lysimeter. Vadose Zone J., 17: 170026, doi:10.2136/vzj2017.01.0026.

Sagar, A., Hasan, M., Singh, D.K., Al-Ansari, N., Chakraborty, D., Singh, M.C., Iquebal, M.A., Kumar, A., Malkani, P. and Vishwakarma, D.K. (2022): Development of smart weighing lysimeter for measuring evapotranspiration and developing crop coefficient for greenhouse chrysanthemum. Sensors, 22: 6239, doi:10.3390/s22166239.

Singh, G., Kaur, G., Williard, K., Schoonover, J. and Kang, J. (2018): Monitoring of water and solute transport in the vadose zone: A review. Vadose Zone J., 17: 160058, doi:10.2136/vzj2016.07.0058.

Tokumoto, I., Inoue, K., Koga, N., Noguchi, T. and Ishikawa, Y. (2023): Recovery of a salinized tomato field in a coastal polder after the 2016 Kumamoto Earthquake in Japan. Smart Agric. Technol., 5: 100287, doi:10.1016/j.atech.2023.100287.

This article is an open access article under the terms of the Creative Commons Attribution (CC BY-NC-ND) license (https://creativecommons.org/licenses/by-nc-nd/4.0/).

How to cite this article: NOOR, F., NAKAYAMA, L., SAKAI, M. and TOKUMOTO, I. (2026): Development and evaluation of a lower-boundary-controlled weighing lysimeter: measuring evaporation under field conditions. J. Jpn. Soc. Soil Phys., 163: 41–52, doi:10.34467/jssoilphysics.163.0_41.

要　　旨

沿岸干拓地では，浅い地下水位の急変や除塩管理に伴う土壌の準飽和化により，従来の平衡張力型ライシメータでは下端境界の制御が不安定となる．本研究では，ローラ式チューブポンプによる双方向の給排水と太陽光発電で自律運転可能な下端境界制御型重量式ライシメータ（LBC-WL）を開発した．内筒底部の圧力水頭 h_{b} と，周辺土壌で測定した外部参照水頭 h_{out} を連続的に比較し，h_{b} を h_{out} の所定許容範囲に維持するように制御し，待機時間を導入して安定化を図った．実験室の検証試験により，圃場容水量から準飽和条件までにおける h_{b} の追従性と質量収支の整合を確認し，またガラス温室の試験では許容範囲拡大により過度なポンプの頻繁な作動を抑制できた．沿岸干拓地における除塩期間中の適用試験では，概ね $h_{\mathrm{b}} = h_{\mathrm{out}} \pm 10 \sim \pm 15$ cm を維持し，除塩後の乾燥過程の蒸発量を 10 分分解能で定量できた．LBC-WL は浅い地下水の影響下にある管理農地で蒸発 · 水収支過程の解明に有効である．

キーワード：重量ライシメータ, 浅い地下水位, 沿岸干拓地