Surface Evaporation in Arid Regions: Insights From Lysimeter Decadal Record and Global Application of a Surface Evaporation Capacitor (SEC) Model

Peter Lehmann1, Markus Berli2, Jeremy E. Koonce2, and Dani Or1

1ETH Zurich, Soil and Terrestrial Environmental Physics, ETH Zurich, Zurich, Switzerland, 2Division of Hydrologic Sciences, Desert Research Institute, Las Vegas, NV, USA

Abstract Surface evaporation in arid regions determines the fraction of rainfall that remains to support vegetation and recharge. The surface evaporation capacitor approach was used to estimate rainfall partitioning to surface evaporation and leakage into deeper layers. The surface evaporation capacitor estimates a soil-specific surface evaporation depth and critical storage capacitance that defines rainfall events that exceed local capacitance and result in leakage into deeper layers protected from surface evaporation. A decade-long record of hydrologic observations in deep and barren lysimeters near Las Vegas revealed the dominance of a few large rainfall events in generating leakage and increasing interannual soil water storage. The surface evaporation capacitor was used to estimate mean annual surface evaporation and leakage protected from surface evaporation in all arid regions globally. About 13% of arid region rainfall contributes to soil water storage (in the absence of vegetation), similar to 11% found in the lysimeter study.

1. Introduction

Deserts cover about one third of the global land surface, hosting unique ecosystems that are adapted to water limitations. Such regions are characterized by high values of annual potential evapotranspiration ET0 that exceed the annual rainfall P (with aridity index P/ET0 < 0.2 for arid regions) and where most rainfall evaporates locally back to the atmosphere. Evidence shows that while in vegetated arid lands nearly all rainfall evaporates back to atmosphere (Andraski, 1997; Gee et al., 1994; Scanlon et al., 2003, 2005), over barren arid surfaces between 3% and 50% of annual precipitation remains in the soil and potentially percolates deeper into the subsurface (Andraski, 1997; Gee et al., 1994; Scanlon et al., 2006; Wang et al., 2004; Xu et al., 1998). The fraction of rainfall water that percolates into deeper soil layers and become protected from surface evaporation is a complicated function of rainfall patterns, topography, vegetation, and soil texture (Gee et al., 2005; Wythers et al., 1999). Gee et al. (2005) have shown that deep drainage from lysimeters receiving natural rainfall for a decade occurred only from coarse-textured soils but not from fine textured silt loam, highlighting the importance of soil texture and water retention on the onset of deep percolation. In this study, we seek to better quantify the rainfall amounts and soil conditions that give rise to protection of infiltrated water below the reach of surface evaporation in arid regions and discuss if and how this water can be linked to transpiration. The water balance in global arid region will be quantified using a simple and physically based surface evaporation model termed surface evaporation capacitor (SEC) model (Or & Lehmann, 2019). The approach offers a physically based definition of “surface evaporation active” soil depth (soil water in deeper soil layers is largely protected from surface evaporation but could be taken up by plant roots). In addition to soil properties informed representation of surface evaporation, the physics of rainfall infiltration and internal drainage that affect surface evaporation are included, and surface evaporation is estimated directly without invoking information on vegetation essential for estimation of evapotranspiration. The SEC model considers water dynamics within this evaporation-active soil layer only (whose depth is a function of intrinsic soil properties) without discretization of the soil profiles into different layers.

Before we applied the SEC model for arid regions and global scale, we use a decade-long record from deep desert lysimeters (Dijkema et al., 2018) to reveal the processes that control the partitioning of rainfall water in dry areas. The specific objectives of this study were (1) to predict surface evaporation and the partitioning to deep percolation and transpiration for arid regions, (2) to use the SEC formalism to identify soil conditions
and rainfall thresholds for the onset of capacitor leakage and water protection from surface evaporation, and (3) to test the model approach using decadal measurements records from bare soil lysimeter. In section 2 we summarize the key components of the SEC concept, and in section 3 we give an overview of the deep lysimeter facility at DRI (Las Vegas, USA), where soil water dynamics and other variables were measured, and explain data input required to make global estimates for arid regions. The lysimeter results are discussed in section 4 and extended to capacitor leakage flux estimates in arid regions globally in section 5 with a summary in section 6.

2. Modeling Storage Dynamics in Arid Regions Using SEC Concept

The water balance within the lysimeter (see section 3.1) and then for the arid region around the globe was simulated using the SEC approach introduced by Or and Lehmann (2019). In the File S1 in the supporting information the approach is described in more detail; in the main text we just explain the main elements of the SEC required to follow the analysis. The SEC is a 1-D “leaky bucket” of prescribed depth called “characteristic length” $L_C$ that varies with soil texture-dependent soil hydraulic properties. Lehmann et al. (2008) introduced the concept of evaporation characteristic length $L_C$, a soil specific property that marks the deepest reach of capillary forces for pulling water against gravity to supply surface evaporation by direct capillary flow (vapor transport occurs at lower rates driven by other processes). The evaporation characteristic length $L_C$ also marks the critical pressure $h_{cr}$ (with a corresponding water content $\theta_{cr}$) at the surface where capillary flow pathways are interrupted and mark the end of stage-I evaporation (Or et al., 2013). Soil water stored below this critical depth is largely protected from direct surface evaporation, although it may be intercepted by plant roots that extend to larger depths. Additionally, soil water may be lost to the atmosphere at lower and diminishing rates by vapor diffusion between rainfall events during the so-called stage-II evaporation (Or et al., 2013). For simplicity, we assumed homogeneous soil texture within the capacitor layer. For heterogeneous soils with strong textural contrasts the evaporation characteristic length can be adapted as outlined in Shokri et al. (2010).

The SEC is episodically recharged by rainfall events and is subsequently emptied by evaporation (stage-I and stage-II) and by capacitor leakage (into deeper soil layers) at different rates and time scales. Similar to the concept of field capacity (Assouline & Or, 2014), we consider capacitor leakage to occur only when a soil water storage is exceeded, specifically, when mean water content $\theta$ exceeds a critical value $\theta_{cr} = \theta(h_{cr})$. The fluxes of surface evaporation $E$ and capacitor leakage $F$ were estimated at daily time steps, in effect, replacing diurnal variations in evaporation and leakage with a daily mean value. For rainy days, we assumed no surface evaporation (only infiltration and leakage to deeper layers), to obtain a daily mass balance in the surface capacitor according to equations (1a) and (1b) for a dry day (no rainfall):

$$P_{day} = F_{day} + \Delta S_{day} \quad (1a)$$

$$F_{day} + E_{day} = \Delta S_{day} \quad (1b)$$

with precipitation $P_{day}$, capacitor leakage to deeper soil layers $F_{day}$, surface evaporation $E_{day}$, and change in soil water storage of the capacitor $\Delta S_{day}$ (with index “day” highlighting that these are daily values). Following a rainfall event, the infiltrated water is assumed to be evenly distributed across the evaporation capacitor depth without considering details and dynamics of a wetting front. Such instantaneous distribution may lead in some cases to the underestimation of surface evaporation immediately after rainfall due to lower water contents and hydraulic conductivity compared to surfaces remaining wetter in some events and soils. Note that the SEC concept also includes runoff and evaporation from water intercepted by leaves that are marginal for the considered arid region.

We also seek to contrast detailed results obtained with the SEC for evaporation and capacitor leakage at daily time steps with capacitor leakage predictions based on climatic information. Specifically, we consider cumulative monthly rainfall $P_{month}$ events (aggregated from the rainfall record for the location) that may exceed the soil capacity to retain water and could thus trigger capacitor leakage into deeper soil layers at a given location. The SEC predictions and climatic-based $Q$ estimates will be evaluated for arid regions globally using soil and climatic information on potential evapotranspiration $ET_0$ and rainfall $P$. The climatic estimate of monthly capacitor leakage flux $F_{month}$ is obtained for rainy months according to
\[ F_{\text{month}} = P_{\text{month}} - L_C (\theta_{\text{crit}} - \theta_{\text{res}}) \]  

(2)

with local information (soil type based) on \( L_C \) and the soil critical and residual water contents \( \theta_{\text{crit}} \) and \( \theta_{\text{res}} \), respectively.

There are similarities between the SEC approach and the stochastic soil moisture dynamics model of Laio et al. (2001) that was applied to study soil texture effects (Fernandez-Iglesias et al., 2001) and interactions with vegetation (Porporato et al., 2001). As with the SEC model, soil water dynamics within a specific layer is simulated using a stochastic approach. However, while in Laio et al. (2001) the soil depth is prescribed by the root zone depth, in the SEC model the active soil depth is an intrinsic soil property defined by the capillary characteristic length. The water loss from the “active layer” is simpler in the stochastic model (assumed constant evaporation rate independent of soil type for a range of water contents) relative to the estimates by the SEC model.

3. Lysimeter Properties and Climatic Data

3.1. Lysimeter Properties

The water storage dynamics of a desert soil were monitored in large weighing lysimeter facility Scaling Environmental Processes in Heterogeneous Arid Soils near Las Vegas, NV, USA (Chief et al., 2009; Dijkema et al., 2018). The lysimeters with an inner diameter of 2.26 m and depth 3.00 m were filled with local desert soil (93% sand, 5.5% silt, and 1.5% clay). Soil water content, capillary pressure, and soil temperatures were continuously measured at several depths. For this study, we have used water content measurements from depths of 0.10, 0.25, 0.50, 1.00, 2.00, and 2.50 m. Additional information including lysimeter mass, precipitation, radiation, wind velocity, and air temperature and humidity were used to estimate surface evaporation and for model testing. The study uses data collected from October 2008 to 2017 from lysimeter 1 for which hydraulic properties were measured and reported in Dijkema et al. (2018).

We used the soil water characteristic parameters listed in Table 2 of Dijkema et al. (2018) with values: \( \theta_{\text{res}} = 0.07 \text{ m}^3/\text{m}^3 \), \( \theta_{\text{sat}} = 0.292 \text{ m}^3/\text{m}^3 \), \( \alpha = 1.57 \text{ m} \), \( n = 2.57 \), and saturated hydraulic conductivity \( K_{\text{sat}} = 0.48 \text{ m/d} \). The estimated soil evaporation characteristic length for this soil \( L_C \) is 0.57 m (for mean potential evaporation of 5.5 mm/day; see below). A critical water content value \( \theta_{\text{crit}} = 0.13 \text{ m}^3/\text{m}^3 \) defines the threshold for capacitor leakage (and marks the disruption of capillary flow to evaporating surface).

The SEC model was implemented using daily values of observed rainfall \( P_{\text{day}} \) and daily potential evaporation \( ET_0 \) estimated according to Jensen and Haise (1963) as a function of incoming (daily) shortwave radiation \( R_S \) (W/m²) and air temperature \( T \) (°C; Or & Lehmann, 2019):

\[ ET_0 = R_S (0.025T + 0.08) / (L_{\text{heat}} \rho_w) \]

(3)

with latent heat of evaporation \( L_{\text{heat}} \) and water density \( \rho_w \) (to convert energy flux density to equivalent water depth). The estimated annual potential evaporation was about 2,000 mm/year (~5.5 mm/day), considerably higher than mean annual rainfall of about 100 mm/year.

3.2. Global Data for Simulating Capacitor Leakage Flux in Arid Regions

Following the detailed quantification of water balance components in the lysimeter study, we applied the SEC approach globally to arid regions to obtain estimates of how much of the local rainfall becomes protected from surface evaporation (and thus could support vegetation and recharge). Arid and hyperarid regions were defined based on the classical aridity index (the ratio of annual precipitation \( P \) to potential evapotranspiration \( ET_0 \) in the range of 0.03 < \( P/ET_0 \) < 0.20 for arid and \( P/ET_0 < 0.03 \) for hyperarid regions (UNESCO, 1979; Maliva & Missimer, 2012). The classification of arid regions was based on available climatic data in which we linked the CMORPH precipitation data (Joyce et al., 2004) with potential evaporation estimates by the Jensen and Haise (1963) method using incoming shortwave radiation data from CERES EBAF (https://ceres.larc.nasa.gov/) and temperature data provided by the Earth System Research Laboratory (https://www.esrl.noaa.gov/). The hydraulic properties (soil water characteristics and water content-dependent hydraulic conductivity) were estimated locally (for each pixel) using soil textural information from the SoilGrids database (Hengl et al., 2017) and the pedotransfer functions of Tóth et al. (2015). The
soil hydraulic properties also define the (local) soil-specific characteristic length $L_C$ and critical water content $\theta_{crit}$ (equations in File S1 in the supporting information). The computations of global surface evaporation and capacitor leakage $F$ in arid regions were conducted for period 2003–2012 using daily time steps, and at a spatial resolution of 0.25°.

4. Results for Bare Soil Lysimeter Study

4.1. Lysimeter Surface Evaporation Represented by the SEC Model

The results in Figure 1a support the applicability of the simple SEC model in tracking bare soil surface evaporation measurements based on lysimeter mass loss. These results also show a difference between measured cumulative evaporation (930 mm) and cumulative rainfall (1,050 mm) for the decade of about 120 mm that contributed to soil water storage in the lysimeter. Similar to other arid regions (Scanlon et al., 2006; Wang et al., 2004), surface evaporation was considerably lower than the cumulative potential evaporation of 18,000 mm for the decade. The estimated ratio of $E/ET_0 = (930/18,000 mm) \approx 0.05$ from the lysimeter observations is similar to theoretical predictions for arid and hot regions made by Or and Lehmann (2019) and to the 0.075 value reported by Wang et al. (2004) for a desert region in China. We examined another metric for evaluating measured and simulated surface evaporation by classifying the time series into rainfall events followed by dry periods (ending with the next rainfall event) shown in Figure 1b. The results depict strong correspondence between measured and model prediction of per-event surface evaporation (results scattered close to the 1:1 line).

4.2. Measured and Estimated Capacitor Leakage to Deeper Soil Layers

Episodic rainfall events refilled the capacitor layer of the lysimeter with only a few cases in which the infiltrated water leaked into deeper layers (exceeding the critical capacitance of the surface evaporation layer). The SEC assumes that capacitor leakage flux $F$ occurs only when the mean SEC water content exceeds a critical value $\theta_{crit}$ (0.13 m$^3$/m$^3$ for the lysimeter). In Figure 2a we compare the simulated mean water content within the surface evaporation capacitor with the measured water content averaged for all measurement depths that are contained within the capacitor thickness (water content measured at 0.10, 0.25, and 0.50 m depth). The figure shows that simulated and measured water contents are in good agreement. The lysimeter water content remained below the critical water content with no capacitor leakage flux until the end of year 2 as was also confirmed with constant water content values at deeper soil layers (Figure 2b) with no water content increase. In other words, all rainwater during the first two years was retained within the capacitor layer and was subsequently lost to surface evaporation.

Following a large rainfall event after year 2, the critical water content threshold has been exceeded and capacitor leakage into deeper soil layers occurred. Following this leakage event, the measured water content at a depth of 1.0 m has increased (Figure 2b). For rainfall events where the SEC predicted leakage into deeper layers, the measured water content in the 1.0 m depth has increased in agreement with model predictions. For deeper soil layers (depth 2.0 m in Figure 2b), the increase in water content was delayed as expected.

Capacitor leakage events were rare and occurred primarily during three rainfall events similar to lysimeter observations reported by Scanlon et al. (2006) and by Wang et al. (2004). These events correspond to rainfall amounts sufficiently large to fill the capacitor beyond the critical water content; we have used the cumulative rainfall per month $P_{month}$ to evaluate exceedance of the capacitor’s critical storage $L_C(\theta_{crit} - \theta_{res})$ according to equation (2) above. The results in Figure 2c indicate that three (monthly) rainfall values were responsible for increasing soil water storage in the lysimeter for the entire decade. The simple approximation (equation (2)) indicates that these three wet periods during the first five years resulted in capacitor leakage of 93 mm (and 8 mm in year 8).

These values are similar to the measured total increase in storage of 120 mm. In summary, the decadal change in the lysimeter soil water storage is attributed to three rainfall events that induced capacitor leakage flux into deeper layers and protection of soil water from surface evaporation; for the rest of the period, no increase in storage was observed and all the rainfall evaporated back to the atmosphere.
5. Rainfall, Evaporation, and Water Protection From Surface Evaporation in Global Arid Regions

We seek to generalize the insights from the lysimeter and apply the SEC to other arid regions globally. In support for such large leap of scales, we have tested the SEC with reported literature values as presented by Or and Lehmann (2019). Additionally, we have tested the surface resistance terms in the core of the SEC with measurements from several Fluxnet sites across biomes and soil types as reported in Lehmann et al. (2018). The application of a simple approach such as the SEC overlooks many processes that affect soil water dynamics in arid regions such as (i) the effects of biological crusts (Kidron et al., 2003) and potential hydrophobic effects (Siteur et al., 2016) that modify infiltration and enhance surface runoff, (ii) heterogeneity that promotes preferential flow paths (Nimmo et al., 2002), and (iii) complex interactions with (sparse and patchy) vegetation cover (D’Odocrio et al., 2007; Thompson et al., 2008). Consequently, under certain conditions the SEC one-dimensional modeling approach could perform poorly at certain plot-scale conditions. On the other hand, at the scale of 25 × 25-km pixel size for the global application, we expect that the SEC reproduces the salient features affected by local climate and soil properties (as we have seen from the analyses of Or and Lehmann (2019) and Lehmann et al. (2018)).

The results presented in section 4.2 revealed that capacitor leakage flux $F$ to deeper soil layers (where soil water is largely protected from surface evaporation) occurs when infiltrating water increases the average water content within the capacitor above a soil-specific threshold value $\theta_{crit}$. In the following, we estimate capacitor leakage and potential of protection from surface evaporation in arid regions globally. Note that critical water content $\theta_{crit}$ (and the characteristic length $L_C$) are site-specific properties and change spatially as defined by equations given in File S1 in the supporting information.

We present yearly and monthly average values of rainfall, surface evaporation, and capacitor leakage (averaged over a decade) and discuss monthly variations of capacitor leakage and rainfall. The estimated annual values of soil surface evaporation $E$ and capacitor leakage flux $F$ are presented in Figure 3a as a function of mean annual rainfall $P$ (these are averages for the decade of SEC estimates). To compare the SEC simulations of the arid regions with measurements, we plot in Figure 3a the values measured in the lysimeter facility in Nevada.

Note that for Nevada it was possible that the evaporation following a wet year could be higher than the annual rainfall amount (symbols above the 1:1 line in Figure 3a). In addition, we plot in Figure 3a annual values reported by Wang et al. (2004) for lysimeter facility in Shapotou in China ($E$ was determined from Figure 4 and $F$ estimated by $P - E - \Delta S$ with precipitation $P$ and change in storage capacity $\Delta S$ listed in...
Table 3 in Wang et al. (2004). Both data sets (Nevada and Shapotou) are within the band defined by the SEC simulations for the global arid region. Note that for the conditions in Shapotou desert, the estimated $F$ corresponds to the difference between evapotranspiration $ET$ measured from vegetated lysimeters and evaporation $E$ from bare soil lysimeters. This supports the notion that leakage to deeper layers can be used by plants and is subsequently lost by transpiration.

On average, the onset of capacitor leakage flux $F$ for the arid regions requires that mean annual rainfall exceeds 50–150 mm/year after which capacitor leakage (storage of water protected from surface evaporation) increases nearly linearly with mean annual rainfall $P$. This threshold is in agreement with values reported by Scanlon et al. (2006) inferring a threshold of 86 mm for the onset of deep groundwater recharge (we distinguish the capacitor leakage $F$ in this study that could be used by vegetation from deep recharge; see

---

**Figure 2.** Measured and modeled soil water dynamics in the lysimeter using the surface evaporation capacitor (SEC). (a) SEC simulated soil water content within the evaporation active capacitor layer (red) and measured water contents at 0.10, 0.25, and 0.50 m depths averaged for the same SEC depth (blue). The critical water content $\theta_{\text{crit}}$ in the capacitor is marked by dashed gray line. (b) Capacitor leakage events $F$ calculated by the SEC for a 0.57 m soil layer (black vertical lines) and measured changes in water contents at 1.0 and 2.0 m depths (the response is delayed in larger depths). (c) Measured (blue) and estimated (red) soil water storage dynamics attributed to three rainfall events with monthly amounts $P_{\text{month}}$ (black bars) larger than the capacitor storage $L_C (\theta_{\text{crit}} - \theta_{\text{res}})$ with characteristic length $L_C$ and residual water content $\theta_{\text{res}}$.
below). The existence of a rainfall threshold reflects soil surface storage exceedance condition as expressed by equation (2) for the active evaporation capacitor of depth $L_C$. To define an average rainfall threshold, we estimate the rainfall threshold using the average values of $L_C = 0.34$ m and $(\theta_{crit} - \theta_{res}) = 0.20$ m$^3$/m$^3$ as representative for arid regions and obtain an average storage threshold of ~70 mm, in agreement with the deep recharge threshold of Scanlon et al. (2006) and the results in Figure 3a.

The value of soil water storage capacity that must be exceeded to generate capacitor leakage is primarily a function of the soil type. Differences in soil type affecting capacitor leakage amounts in arid regions are shown in Figure 3b focusing on sandy and loamy soils. We express the capacitor leakage as a fraction of annual rainfall amount $F/P$ for the evaluation in Figure 3b. Note that sandy soils occur primarily in hyper-arid regions ($P/ET_0 < 0.03$; 70% of the hyperarid area is overlain by sand) where 9% of mean annual rainfall redistribute and become protected from surface evaporation based on SEC model estimates. For loam, 7% of the annual rainfall are capacitor leakage and for finer textured soils (clay loams and clay) 19% of the annual rainfall redistribute and become protected from surface evaporation based on SEC model estimates.
rainfall leaks to deeper layers. As shown in File S2 in the supporting information, higher values of leakage $F$ from the capacitor for clay are mainly due to higher rainfall amounts in regions with fine-textured soils. Comparing leakage from the soil evaporation capacitor for different soil types with similar rainfall amounts, we find highest leakage values $F$ for coarser textured soils. The estimated capacitor leakage values averaged over arid regions globally were 13% of the annual rainfall and are higher than the groundwater recharge values estimated in Scanlon et al. (2006) in the range from 0.1 to 5% of the annual rainfall for semiarid and arid regions. The difference is attributed to the interception of $F$ by plant roots and subsequent loss as a transpiration $T$ flux.

The lysimeter data of this study (and as reported in Scanlon et al. (2006)) suggest that capacitor leakage events cannot be inferred from climatic mean monthly rainfall values alone, but require information on rainfall variability (i.e., events that exceed critical storage). To test the generality of this hypothesis, we have plotted in the inset of Figure 3b the global capacitor leakage flux values for all sites with a climatic monthly average rainfall of 20 mm as a function of the (climatic) coefficient of variation of rainfall amounts. As shown in inset of Figure 3b (and Figure S3 in the supporting information), similar climatic monthly rainfall amounts may trigger different values of capacitor leakage increasing with rainfall variability. The variation of rainfall is included in the simple “climatic” model presented in equation (2) that was slightly corrected for evaporation during rainy days (subtracting 2 mm of evaporation for rainy days). The capacitor leakage flux estimates using equation (2) are in reasonable agreement with SEC model predictions as shown in Figure S4 in the supporting information. Especially for regions with high-aridity index, soil critical storage exceedance approximation based on the climatic record (equation (2)) tends to underestimate capacitor leakage to deeper layers (relative to estimates based on detailed SEC model). For the average of arid and hyperarid regions, based on equation (2) 10% of rainfall leak from the capacitor (compared to 13% for the detailed SEC simulations). For hyperarid regions with $P/ET_0 < 0.03$, the climatic approximation of capacitor leakage fraction is 2.3%, whereas the SEC model estimates slightly higher values of 2.6% (of annual rainfall).

6. Summary

To quantify amount of rainfall water protected from evaporation by leakage to deeper soil layers in arid regions, we computed the water balance using the SEC model of Or and Lehmann (2019). The SEC is an “active” soil layer from where water can evaporate and leak to deeper soil layers depending on the water content of the capacitor. To understand the processes in arid regions in more detail, we analyzed decadal climate and water balance lysimeter data from barren desert soil in Nevada. Observations show that annually most rainfall water evaporated back to the atmosphere with only three intense rainfall per decade that produced sufficient capacitor leakage into deeper soil layers that increased lysimeter storage in deeper layers as observed by the soil water content sensors. Motivated by these and other lysimeter observations (Scanlon et al., 2006; Wang et al., 2004), we applied the SEC model to estimate characteristics of surface evaporation and capacitor leakage behavior in other arid regions globally. The extension to global scale was also based on tests at intermediate scales of the concept using reported values in the literature (Or & Lehmann, 2019) and Fluxnet surface evaporation estimates of Merlin et al. (2016) with surface evaporation resistance of the SEC as described in Lehmann et al. (2018). The main results of this study based on lysimeter observations and SEC model application suggest the following:

1. 13% of climatic annual rainfall in arid regions redistribute into deeper soil layers below the reach of surface evaporation (similar to the 11% we observed in the lysimeter in Nevada).
2. A rainfall event must exceed a certain threshold to fill the surface evaporation capacitor above a critical water content $\theta_{crit}$ to initiate leakage from capacitor with global average threshold of 70 mm (as compared to 86 mm reported by Scanlon et al. (2006) for deep recharge).
3. Leakage from capacitor is enhanced for regions with higher rainfall variability and propensity of large rainfall events.
4. The estimated capacitor leakage flux values $F$ were similar to transpiration values measured in vegetated desert lysimeters by Wang et al. (2004), supporting the notion that $F$ could be used to estimate or constrain available soil water for plant root uptake in arid regions.

The study provides new insights into surface evaporation from barren soil surfaces in arid regions and the conditions and rainfall events that contribute to recharging plant root zone (increasing soil water storage).
or initiating deep recharge despite the large gap between precipitation and potential evaporation in such regions. Although the focus was on barren surfaces, the results provide upper bounds for evaporation-protected soil water that could support vegetation (noting that the uptake patterns and vegetation density are far more complex than the one-dimensional nature of surface evaporation). Leakage from capacitor and the subsequent protection of infiltrated water from surface evaporation are limited to a few large rainfall events as observed in the lysimeter record and with global application of the SEC model to arid regions. The sensitivity of leakage to rainfall variability (for similar climatic mean) suggest potential changes in future water balance components in arid regions with projected changes in rainfall patterns with climate change.

Acknowledgments
The SEPHAS lysimeter data are based on work supported by the U.S. National Science Foundation under grants IIA-1301726 and EPS-0447416. Data are available at https://figshare.com/articles/AridSoils/7946135/1. We are very grateful for the insightful comments of Ty Peré, Sally Thompson, and two anonymous reviewers.

References
Andraski, B. J. (1997). Soil-water movement under natural-site and waste-site conditions: A multiple-year field study in the Mojave desert, Nevada. Water Resources Research, 33(8), 1901–1916. https://doi.org/10.1029/97WR01502
Assouline, S., & Or, D. (2014). The concept of field capacity revisited: Defining intrinsic static and dynamic criteria for soil internal drainage dynamics. Water Resources Research, 50, 4787–4802. https://doi.org/10.1002/2014WR015475
Chief, K., Young, M. H., Lyles, B. F., Healey, J., Koonce, J., Knight, E., et al. (2009). Scaling environmental processes in heterogeneous arid soils: Construction of large weighing lysimeter facility. Desert Research Institute (p. 370). Las Vegas, NV.
Dijkema, J., Koonce, J. E., Shillito, R. M., Ghezzehei, T. A., Berli, M., van der Ploeg, M. J., & van Genuchten, M. T. (2018). Water distribution in an arid zone soil: Numerical analysis of data from a large weighing lysimeter. Vadose Zone Journal, 17(1). https://doi.org/10.2136/vzj2017.01.0035
D’Odorico, P., Caylor, K., Olin, G. S., & Scanlon, T. M. (2007). On soil moisture–vegetation feedbacks and their possible effects on the dynamics of dryland ecosystems. Journal of Geophysical Research, 112, G04010. https://doi.org/10.1029/2006JG000379
Fernandez-Iglesias, C. P., Porporato, A., Laio, F., & Rodriguez-Iturbe, I. (2001). The ecohydrological role of soil texture in a water-limited ecosystem. Water Resources Research, 37(12), 2863–2872. https://doi.org/10.1029/2000WR000121
Gee, G. W., Keller, J. M., & Ward, A. L. (2005). Measurement and prediction of deep drainage from bare sediments at a semiarid site. Vadose Zone Journal, 4(1), 32–40. https://doi.org/10.2136/vzj2004.1.32
Gee, G. W., Wierringa, P. J., Andraski, B. J., Young, M. H., Fayer, M. J., & Rockhold, M. L. (1994). Variations in water balance and recharge potential at three western desert sites. Soil Science Society of America Journal, 58(1), 63–72. https://doi.org/10.2136/sssaj1994.03615995005800010009x
Heng, T., Mendes de Jesus, J., Heusvelink, G. B. M., Ruiperez Gonzalez, M., Kilhamara, B., Blagotić, A., et al. (2017). SoilGrids250m: Global gridded soil information based on machine learning. PLoS ONE, 12(2), e0169748. https://doi.org/10.1371/journal.pone.0169748
Jensen, M. E., & Haise, H. R. (1963). Estimating evapotranspiration from solar radiation. Proceedings of the American Society of Civil Engineers, Journal of Irrigation and Drainage Division. 89, 15–41.
Joyce, R. J., Janowiak, J. E., Arkin, P. A., & Xie, P. (2004). CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. Journal of Hydrometeorology, 5(3), 487–503. https://doi.org/10.1175/1525-7541(2004)005<0487:CMORPH>2.0.CO;2
Kidron, G. J., Yair, A., Vosshak, A., & Abeličová, A. (2003). Microbiotic crust control of runoff generation on sand dunes in the Negev desert. Water Resources Research, 39(4), 1108. https://doi.org/10.1029/2002WR001561
Laio, F., Porporato, A., Ridolfi, L., & Rodriguez-Iturbe, I. (2001). Plants in water-controlled ecosystems: Active role in hydrologic processes and response to water stress: II. Probabilistic soil moisture dynamics. Advances in Water Resources, 24(7), 707–723. https://doi.org/10.1016/S0309-1708(01)00005-7
Lehmann, P., Assouline, S., & Or, D. (2008). Characteristic lengths affecting evaporative drying of porous media. Physical Review E, 77(5), 056309. https://doi.org/10.1103/PhysRevE.77.056309
Lehmann, P., Merlin, O., Gentine, P., & Or, D. (2018). Soil texture effects on surface resistance to bare-soil evaporation. Geophysical Research Letters, 45(19), 10,398–10,405. https://doi.org/10.1002/2018GL078803
Maliva, R., & Missimer, T. (2012). Arid lands water evaluation and management, Environmental Science and Engineering (Chap. 2). Berlin: Springer-Verlag. https://doi.org/10.1007/978-3-642-92014-3_2
Merlin, O., Stefan, V. G., Amaziri, A., Chanzy, A., Ceschia, E., Er-Raki, S., et al. (2016). Modeling soil evaporation efficiency in a range of soil and atmospheric conditions using a meta-analysis approach. Water Resources Research, 52, 3663–3684. https://doi.org/10.1002/2015WR018233
Nimmo, J. R., Perkins, K. S., Rose, P. E., Rousseau, J. P., Orr, B. R., Twining, B. V., & Anderson, S. R. (2002). Kilometer-scale rapid transport of naphthalene sulfate tracer in the unsaturated zone at the Idaho National Engineering and Environmental Laboratory. Vadose Zone Journal, 1(1), 89–101. https://doi.org/10.2136/vzj2002.8900
Or, D., & Lehmann, P. (2019). Surface evaporative capacity: How soil type and rainfall characteristics affect global-scale surface evaporation. Water Resources Research, 55(1), 519–539. https://doi.org/10.1029/2018WR024050
Or, D., Lehmann, P., Shahraeeni, E., & Shokri, N. (2013). Advances in soil evaporation physics—A review. Vadose Zone Journal, 12(4). https://doi.org/10.2136/vzj2012.0163
Porporato, A., Laio, F., Ridolfi, L., & Rodriguez-Iturbe, I. (2001). Plants in water-controlled ecosystems: Active role in hydrologic processes and response to water stress: III. Vegetation water stress. Advances in Water Resources, 24(7), 725–744. https://doi.org/10.1016/S0309-1708(01)00006-9
Scanlon, B. R., Krese, K., Reedy, R. C., Simunek, J., & Andrusaki, B. J. (2003). Variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing (0–90 kyr): Field measurements, modeling, and uncertainties. Water Resources Research, 39(7), 1179. https://doi.org/10.1029/2002WR001604
Scanlon, B. R., Krese, K. E., Flint, A. L., Flint, L. E., Gaye, C. B., Edmunds, W. M., & Simmers, I. (2006). Global synthesis of groundwater recharge in semiarid and arid regions. Hydrological Processes: An International Journal, 20(15), 3335–3370. https://doi.org/10.1002/hyp.6335
Scanlon, B. R., Levitt, D. G., Reedy, R. C., Krese, K. E., & Sully, M. J. (2005). Ecological controls on water-cycle response to climate variability in deserts. Proceedings of the National Academy of Sciences, 102(17), 6033–6038. https://doi.org/10.1073/pnas.0408571102
Shokri, N., Lehmann, P., & Or, D. (2010). Evaporation from layered porous media. *Journal of Geophysical Research, 115*, B06204. https://doi.org/10.1029/2009JB006743

Siteur, K., Mao, J., Nierop, K. G., Rietkerk, M., Dekker, S. C., & Eppinga, M. B. (2016). Soil water repellency: A potential driver of vegetation dynamics in coastal dunes. *Ecosystems, 19*(7), 1210–1224. https://doi.org/10.1007/s10021-016-9995-9

Thompson, S., Katul, G., & McMahon, S. M. (2008). Role of biomass spread in vegetation pattern formation within arid ecosystems. *Water Resources Research, 44*, W10421. https://doi.org/10.1029/2008WR006916

Tóth, B., Weynants, M., Nemes, A., Maó, A., Bilas, G., & Tóth, G. (2015). New generation of hydraulic pedotransfer functions for Europe. *European Journal of Soil Science, 66*(1), 226–238. https://doi.org/10.1111/ejss.12192

UNESCO, United Nations Educational, Scientific and Cultural Organization (1979). Map of the world distribution of arid regions. MAB Technical Notes No. 7.

Wang, X. P., Brown-Mitic, C. M., Kang, E. S., Zhang, J. G., & Li, X. R. (2004). Evapotranspiration of *Caragana korshinskii* communities in a revegetated desert area: Tengger desert, China. *Hydrological Processes, 18*(17), 3293–3303. https://doi.org/10.1002/hyp.5661

Wythers, K. R., Lauenroth, W. K., & Faruelo, J. M. (1999). Bare-soil evaporation under semiarid field conditions. *Soil Science Society of America Journal, 63*(5), 1341–1349. https://doi.org/10.2136/sssaj1999.6351341x

Xu, X., Zhang, B., Xue, X., & Zhao, M. (1998). Determination of evapotranspiration in the desert area using lysimeters. *Communications in Soil Science and Plant Analysis, 29*(1-2), 1–13. https://doi.org/10.1080/00103629809369924