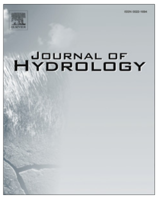
Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



Research papers

Spatial extrapolation of lysimeter results using thermal infrared imaging

B.R. Voortman [a,*], F.C. Bosveld [b], R.P. Bartholomeus [a], J.P.M. Witte [a,c]

[a] KWR Watercycle Research Institute, P.O. Box 1072, 3430 BB Nieuwegein, The Netherlands
[b] Royal Netherlands Meteorological Institute, Utrechtseweg 297, 3731 GA De Bilt, The Netherlands
[c] VU University, Institute of Ecological Science, Department of Systems Ecology, de Boelelaan 1085, 1081 HV Amsterdam, The Netherlands

ARTICLE INFO

Article history:
Received 27 January 2016
Received in revised form 28 September 2016
Accepted 30 September 2016
Available online xxxx
This manuscript was handled by Tim R. McVicar, Editor-in-Chief, with the assistance of Di Long, Associate Editor

Keywords:
Evaporation
Lysimeter
Thermal imaging
Remote sensing
Surface temperature
3T model

ABSTRACT

Measuring evaporation (E) with lysimeters is costly and prone to numerous errors. By comparing the energy balance and the remotely sensed surface temperature of lysimeters with those of the undisturbed surroundings, we were able to assess the representativeness of lysimeter measurements and to quantify differences in evaporation caused by spatial variations in soil moisture content. We used an algorithm (the so called 3T model) to spatially extrapolate the measured E of a reference lysimeter based on differences in surface temperature, net radiation and soil heat flux. We tested the performance of the 3T model on measurements with multiple lysimeters (47.5 cm inner diameter) and micro lysimeters (19.2 cm inner diameter) installed in bare sand, moss and natural dry grass. We developed different scaling procedures using in situ measurements and remotely sensed surface temperatures to derive spatially distributed estimates of R_n and G and explored the physical soundness of the 3T model. Scaling of R_n and G considerably improved the performance of the 3T model for the bare sand and moss experiments (Nash-Sutcliffe efficiency (*NSE*) increasing from 0.45 to 0.89 and from 0.81 to 0.94, respectively). For the grass surface, the scaling procedures resulted in a poorer performance of the 3T model (*NSE* decreasing from 0.74 to 0.70), which was attributed to effects of shading and the difficulty to correct for differences in emissivity between dead and living biomass. The 3T model is physically unsound if the field scale average air temperature, measured at an arbitrarily chosen reference height, is used as input to the model. The proposed measurement system is relatively cheap, since it uses a zero tension (freely draining) lysimeter which results are extrapolated by the 3T model to the unaffected surroundings. The system is promising for bridging the gap between ground observations and satellite based estimates of E.

1. Introduction

Accurate estimates of actual evaporation (E, here defined as the sum of plant transpiration, soil evaporation, and evaporation from canopy interception) are required for the sustainable and cost effective management of water resources. Because E is a relatively large component of the water balance in most regions of the world (Zhang et al., 2016), small errors in E represent rather large volumes of water. E is usually estimated with soil-vegetation atmosphere transfer (SVAT) models or techniques using satellite imagery. Validating estimates of E remains challenging (Kalma et al., 2008), since collecting the ground truth is usually costly and prone to numerous errors (e.g. caused by the construction of lysimeters (Cameron et al., 1992; Corwin, 2000; Howell et al., 1991; Saffigna et al., 1977; Till and McCabe, 1976) or the indirect nature of eddy covariance measurements that appear to be inconsistent with the conservation of energy (Foken, 2008; Twine et al., 2000; Wilson et al., 2002)) and because of the mismatch in the spatial resolution between estimates and measurements (Kustas et al., 2004; Li et al., 2008; Liu et al., in press).

Precision weighing lysimeters generate data of E at a high precision in the order of 0.01–0.05 mm and are regarded as the most accurate measurement technique (typical error between 5 and 15% (Allen et al., 2011)). However, lysimeter systems require substantial experimental care as equipment malfunctioning or improper environmental conditions can lead to measurement errors of 40–100% (Allen et al., 2011, 1991; Howell, 2004). One of the main challenges in lysimeter systems is to keep the moisture content inside the lysimeter equal to its surroundings. This requires e.g. a sophisticated drainage system with a pressure plate and vacuum pump to imitate drainage and capillary rise of the surroundings and a system to prevent wall flow (Cameron et al., 1992; Corwin, 2000; Saffigna et al., 1977; Till and McCabe, 1976). If lysimeter measurement errors remain undetected, these errors will propagate into models to estimate E, e.g. by calibrating crop factors. In

---

* Corresponding author.
E-mail address: bernard.voortman@kwrwater.nl (B.R. Voortman).

http://dx.doi.org/10.1016/j.jhydrol.2016.09.064
0022-1694/© 2016 Elsevier B.V. All rights reserved.

general, the representativeness of lysimeter measurements for field scale E will increase with increasing surface area and depth of the lysimeter because with increasing dimensions, the lysimeter is less affected by its boundaries, and by heterogeneities in soil hydraulic properties and micro climate (Allen et al., 1991). However, since such systems are expensive, scientist often choose for more economical solutions and optimize between lysimeter dimensions and costs (Allen and Fisher, 1990; Payero and Irmak, 2008).

In this paper we present a method to assess the representativeness of lysimeter measurements with the aid of thermal imaging. Instead of investing in large lysimeters or putting effort in duplicating environmental conditions, we invested in monitoring the surface temperature of relatively small, zero tension (freely draining) lysimeters with a thermal infrared camera to detect and compensate deviations in E between the lysimeters and the undisturbed vegetation of their surrounding area. The algorithm to detect and correct deviations in E is based on the three temperatures model (3T model) developed by Qiu et al. (1996a). The 3T model compares the energy balance of a reference surface (subscript r) with that of a surface under study (subscript i):

$$LE_{\mathrm{i}} = R_{\mathrm{n,i}} - G_{\mathrm{i}} - (R_{\mathrm{n,r}} - G_{\mathrm{r}} - LE_{\mathrm{r}})\frac{T_{\mathrm{s,i}} - T_{\mathrm{a}}}{T_{\mathrm{s,r}} - T_{\mathrm{a}}}, \qquad (1)$$

where LE is the latent heat flux (W m^{-2}, positive during evaporation), L is the latent heat of vaporization (J kg^{-1}), E is the evaporative flux (kg m^{-2} s^{-1}), R_{n} is the net radiation (W m^{-2}), G is the soil heat flux (W m^{-2}), T_{s} is the radiometric surface temperature (K) and T_{a} is the air temperature at a certain height above surface (K). Eq. (1) is based on the assumption that the aerodynamic resistance of the reference surface ($r_{\mathrm{a,r}}$) is equal to the aerodynamic resistance of the environment under study ($r_{\mathrm{a,i}}$). Note that the term within the brackets in Eq. (1) is the sensible heat flux of the reference surface (H_{r}, W m^{-2}) which is multiplied by the three temperatures ratio to derive the sensible heat flux of the environment under study (H_{i}, W m^{-2}). In former applications of the 3T model, reference surfaces without a latent heat flux were used, e.g. imitation leaves (Qiu et al., 1996a, 1996b) or a dry bare soil (Qiu et al., 1998; Qiu and Zhao, 2010). In those cases LE_{r} falls out of Eq. (1). Because it is difficult to keep a reference surface dry for a prolonged period, while maintaining similar surface characteristics as the environment under study, we propose to use a lysimeter as reference surface and use the 3T model to estimate E of the undisturbed soil and vegetation outside the lysimeter.

Although the 3T model seems relatively straightforward, there are several issues which need to be addressed if the model is applied to the scale of a lysimeter surface. One of the challenges is to measure or estimate R_{n} and G for the relatively small lysimeter surface (in our case 47.5 cm inner diameter and 50 cm deep), because the surface area viewed by R_{n} sensors is commonly much larger than the lysimeter surface. Similarly, installation of soil heat flux plates could be too destructive for the relatively small lysimeters. Furthermore, multiple measurements of R_{n} and G increase the cost of the measurement systems. Therefore, models are required using spatial patterns in surface temperature to derive distributed estimates of R_{n} and G.

The aim of this study is to assess the performance of the 3T model applied to lysimeters and to review different processes that affect this performance. We give guidelines, based on field measurements, on the required detail and complexity in estimating R_{n} and G for the 3T model (Section 3.1), address how emissivity and shading may affect its results (Section 4.1), and explore the physical soundness of the 3T model (Sections 4.2 and 4.3). We present an improved methodology which could provide accurate estimates of E for relatively large areas (>25 m^2, limited by the area viewed by a thermal camera) without the struggle of controlling the lysimeter moisture content with pressure plates and vacuum pumps or preventing wall flow.

2. Materials and methods

2.1. Field experiments

We conducted three field experiments during the summer of 2013 in plots of approximately 50 m^2 of bare sand, moss (primarily *Campylopus introflex*) and dry grass (*Agrostis vinealis*) situated in a nature reserve on an elevated sandy soil (an ice-pushed ridge, elevated 30–50 m above the surrounding landscape) in the center of The Netherlands (52.14° latitude, 5.31° longitude). The three plots were situated close to each other with a maximum distance of 40 m. Multiple lysimeters were installed in each plot (Fig. 1). In both, the bare sand and the moss plot, one lysimeter (47.5 cm inner diameter and 50 cm deep) was installed with an automated weighing system (measurement resolution of 10 g, i.e. 0.06 mm water) and ten micro-lysimeters (19.2 cm inner diameter and 8 cm deep) were installed which were weighted by hand (measurement resolution of 0.2 g, i.e. 0.007 mm water) in the morning and evening during 4 consecutive dry days (August-27-2013 until August-30-2013 and August-20-2013 until August-23-2013 for the bare sand and moss experiments, respectively). In the grass plot, three automated lysimeters (47.5 cm inner diameter and 50 cm deep) were installed for which data was recorded from June-1-2013 until July-14-2013 and from July-26-2013 until August-4-2013. During the grass experiment, meteorological conditions were moderately dry for Dutch conditions with cumulatively 104 mm of rain and on average 18 °C air temperature (at 1.5 m height, including day and night). The bare sand and moss experiments were performed under dry conditions (i.e. no rain) and on average 16 °C air temperature. A description of the automated lysimeters is presented in Voortman et al. (2015). The micro-lysimeters were made from PVC and were equipped with an aluminum base plate to promote the thermal conduction with the underlying soil.

For every plot, one automated lysimeter was used as reference surface, while the others served to evaluate the performance of the 3T model (Fig. 2). The moisture content of the lysimeters that served for validation was manipulated during the experiments to create a difference in evaporation rate. This was achieved by adding water or by covering the lysimeters with a shelter to allow the surface to dry out for a prolonged period. Manipulations are summarized in Table 1.

The lysimeters were monitored with thermal infrared cameras (Flir SC645; manufacturer specifications, spectral range: 7.5–13 µm, thermal sensitivity: <0.05 °C at +30 °C, resolution: 640 × 480 pixels) installed in an environmental enclosure at 3.50, 2.90 and 5.85 m height from the bare sand, moss and grass surfaces respectively. This camera setup resulted in approximately 4800, 9700 and 2350 pixels inside the reference lysimeters for the bare sand, moss and grass experiments respectively. All surfaces were monitored from the north side of the plots under an angle of 30° from the vertical. The apparent radiometric surface temperature was corrected for the reflected downwelling longwave radiation from the atmosphere, the surface emissivity and for the transmission and emission of the environmental enclosure window. Atmospheric effects were neglected, since the path between the sensor and the object was not longer than 10 m. Thermal images were recorded on the 30 min mark between 6:00 and 18:00 coordinated universal time.

The net radiation (R_{n}) is defined as:

$$R_{\mathrm{n}} = R_{\mathrm{ns}} + R_{\mathrm{nl}} = (1-\alpha)R_{\mathrm{s}\downarrow} + \left(R_{\mathrm{l}\downarrow} - R_{\mathrm{l},total\uparrow}\right), \qquad (2)$$

Please cite this article in press as: Voortman, B.R., et al. Spatial extrapolation of lysimeter results using thermal infrared imaging. J. Hydrol. (2016), http://dx.doi.org/10.1016/j.jhydrol.2016.09.064