Determining Soil Stage-one Evaporation using Heat Pulse Probe Measurements

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Introduction

Heat pulse probe (HPP) methods exhibit great potential for estimating soil subsurface evaporation based on an energy balance approach (Heitman et al., 2008). The HPP measures soil temperature and thermal properties within a fine grid below the soil surface. Evaporation can be determined from the calculated sensible heat flux and heat storage change within the thin surface layers of the soil profile.

A shortcoming of the existing HPP methods is that evaporation occurring from the soil surface down to the midpoint of the two top needles (i.e., the undetectable zone) is not sensed (Sakai et al., 2011). Our objective was to look for an approach for estimating the evaporation occurring within the undetectable zone focusing on surface evaporation which constitutes a large amount of water lost.

Theory

Heat flow equation is considered as follows:

$$C\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(-\lambda\frac{\partial T}{\partial z} + Lq_v\right) \qquad (1)$$

where T is temperature, t time, z soil depth, C soil heat capacity, λ thermal conductivity, q_v water vapor flux, and L latent heat of vaporization.

During stage-one evaporation, vaporization occurs at the soil surface. Here, we assume a very thin soil surface layer with the thickness of δ (much thinner than needles spacing, Δz), within which vaporization happens. Evaporation then can be determined as:

$$LE = \frac{\partial(Lq_v)}{\partial z}\delta = \lambda\frac{\partial^2 T}{\partial z^2}\delta + C\frac{\partial T}{\partial t}\delta \qquad (2)$$

Numerical simulations (e.g. Figure 8 of Sakai et al., 2011) revealed that the last term of Eq. (2) is negligible Therefore, we may write:

$$LE = \lambda\delta\frac{\partial^2 T}{\partial z^2} \qquad (3)$$

$$\frac{\partial T}{\partial z} = \frac{L}{\lambda}q_v + \text{cons.} \qquad (4)$$

Along the vaporization layer, q_v is changed from zero (at the bottom edge of the layer) to its maximum value at the surface. Assuming that this change is linear, Eq. (4) leads to a binomial temperature profile along the vaporization layer:

$$T = az^2 + bz + c \qquad (5)$$

with a, b, and c as unknown coefficients.

Finding a, b, and c gives the opportunity to calculate evaporation with Eq. (3). In this way, shape of the temperature profile within the vaporization layer is important. Here, we assume two general cases (Fig. 1): A) temperature through the vaporization layer is always decreasing, and B) temperature profile has a local minimum somewhere in the vaporization layer.
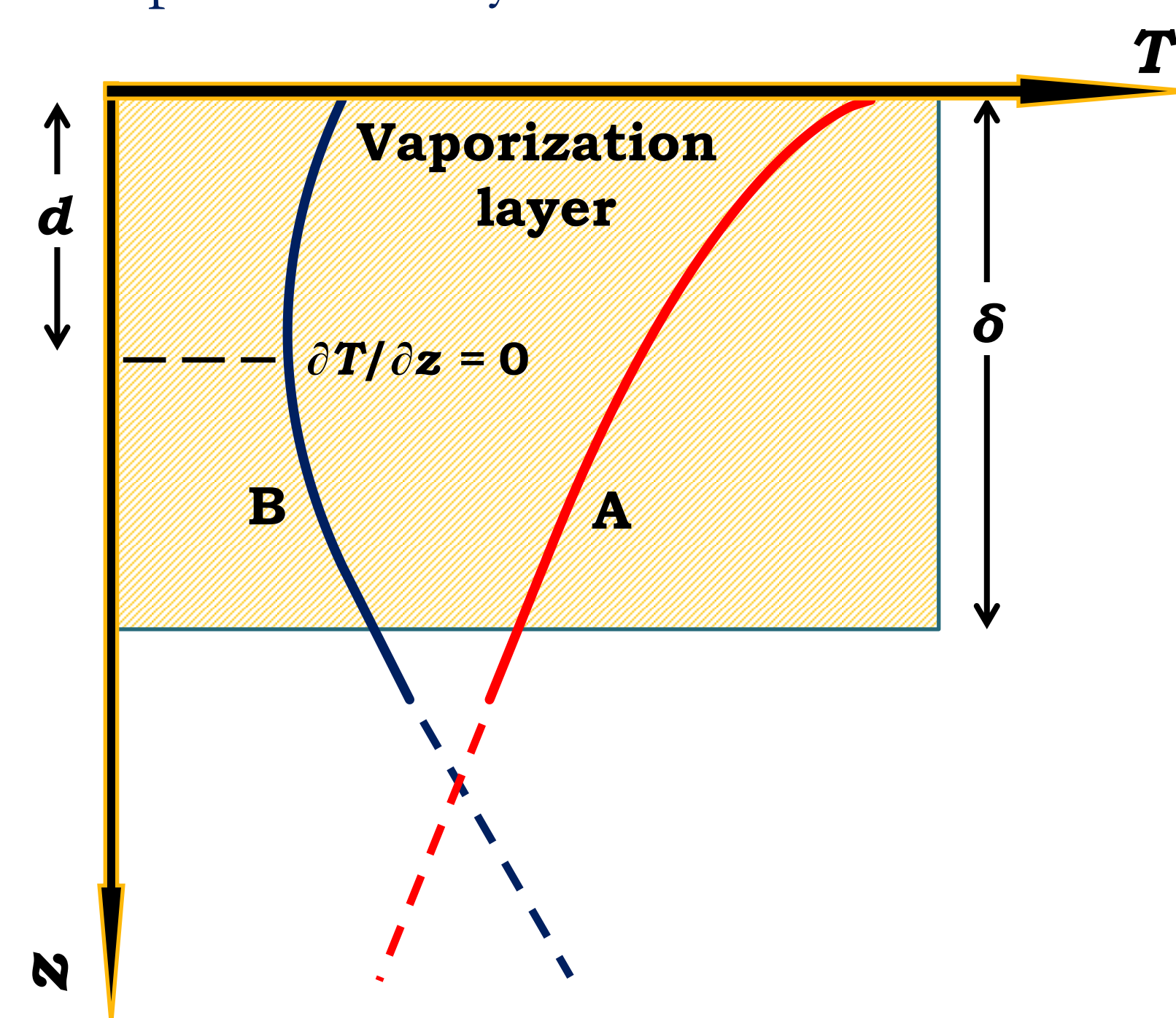

Fig. 1. Two general cases of temperature profile within the vaporization layer.

Case A happens when atmospheric radiation is large enough to provide the energy of vaporization. In this case, based on Eq. (4), temperature below the vaporization layer linearly decreases with depth. Case B is commonly met when the radiation is low (e.g. in laboratories) and vaporization occurs by consuming the internal energy of soil. In this case, temperature below the vaporization layer linearly increases with depth. While case A remains as a question, we now handle case B using HPP measurements. The following relationships hold:

$$T(0) = T_1, \left.\frac{dT}{dz}\right|_{z=d} = 0, \left.\frac{dT}{dz}\right|_{z=2d} = \frac{T_2 - T_1}{\Delta z - 2d} \qquad (6)$$

where T_1 and T_2 are temperature readings of the HPP at the surface and a sub-surface depth, respectively, Δz is HPP spacing (i.e. z corresponding to T_2), and d is the depth at which the temperature depression happens.

Substituting Eq. (6) in Eq. (5) yields:

$$a = \frac{T_2 - T_1}{2d(\Delta z - 2d)} \qquad (7)$$

Combining (3), (5), and (7) results in:

$$LE = \lambda\delta\frac{T_2 - T_1}{d(\Delta z - 2d)} \qquad (8)$$

It is assumed that below the depth of $z = 2d$, the temperature profile takes a linear shape. Based on Eq. (4), it means that most of vaporization occurs between $z = 0$ and $z = 2d$ or in other words $\delta \approx 2d$. Then, having $2d << \Delta z$, Eq. (8) gives the following simple formula for calculating evaporation using HPP measurements:

$$LE = 2\lambda\frac{T_2 - T_1}{\Delta z} \qquad (9)$$

Experimental

A stage-one evaporation experiment was conducted under laboratory conditions. A column (with 15 cm diameter and 15 cm height) was filled with a fine sandy soil. A Penta-needle HPP was installed at the surface down to 12 mm. The HPP was rotated by 27^0 giving a vertical spacing of 3 mm. The column was connected to a Marriott bottle to keep it saturated during the experiment. While the radiation was negligible in the lab, wind speed was uniformly generated using a fan. Two levels of wind speed (0.9 and 1.9 m/s) were periodically applied every 12 hours. HPP measurements including temperature and thermal properties were obtained and used to calculate stage-one evaporation using Eq. (9). Evaporation rate was also measured by weighing the Marriott bottle using a load cell.

Results and Discussion

Evaporation calculations using HPP and water balance are shown in Fig. 2. A reasonable agreement is seen which verifies developed theory and the capability of Eq. (9) for determining stage-one evaporation. Spacing seems not to be critical in application of Eq. (9), where calculations using 3-mm spacing and 12-mm spacing are similar.
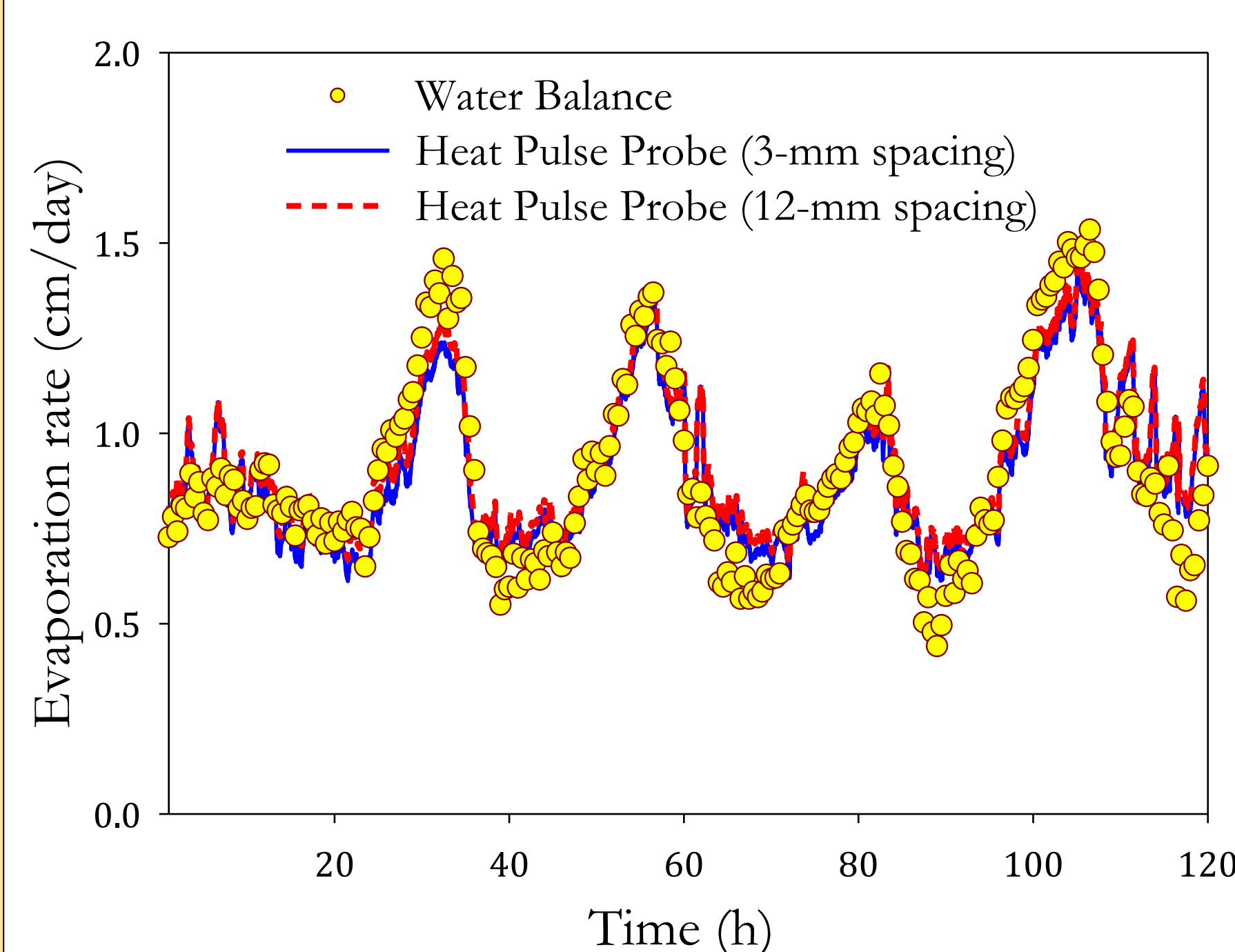

Fig. 2. Evaporation calculations using heat pulse probe measurements, Eq. (9), and water balance.

Although Eq. (9) is only valid for a low-radiation case, it gives the idea that evaporation rate is highly correlated to the heat flux at the surface, $G = \lambda\Delta T/\Delta z$. To follow this idea, we performed another experiment having two levels of radiation (generated by heat lamps) periodically every 12 hours. Fig. 3 shows the results obtained, where HPP calculations follows an empirical findings of $LE = 1.4G$, suggesting that stage-one evaporation can be determined as a constant times soil surface heat flux.
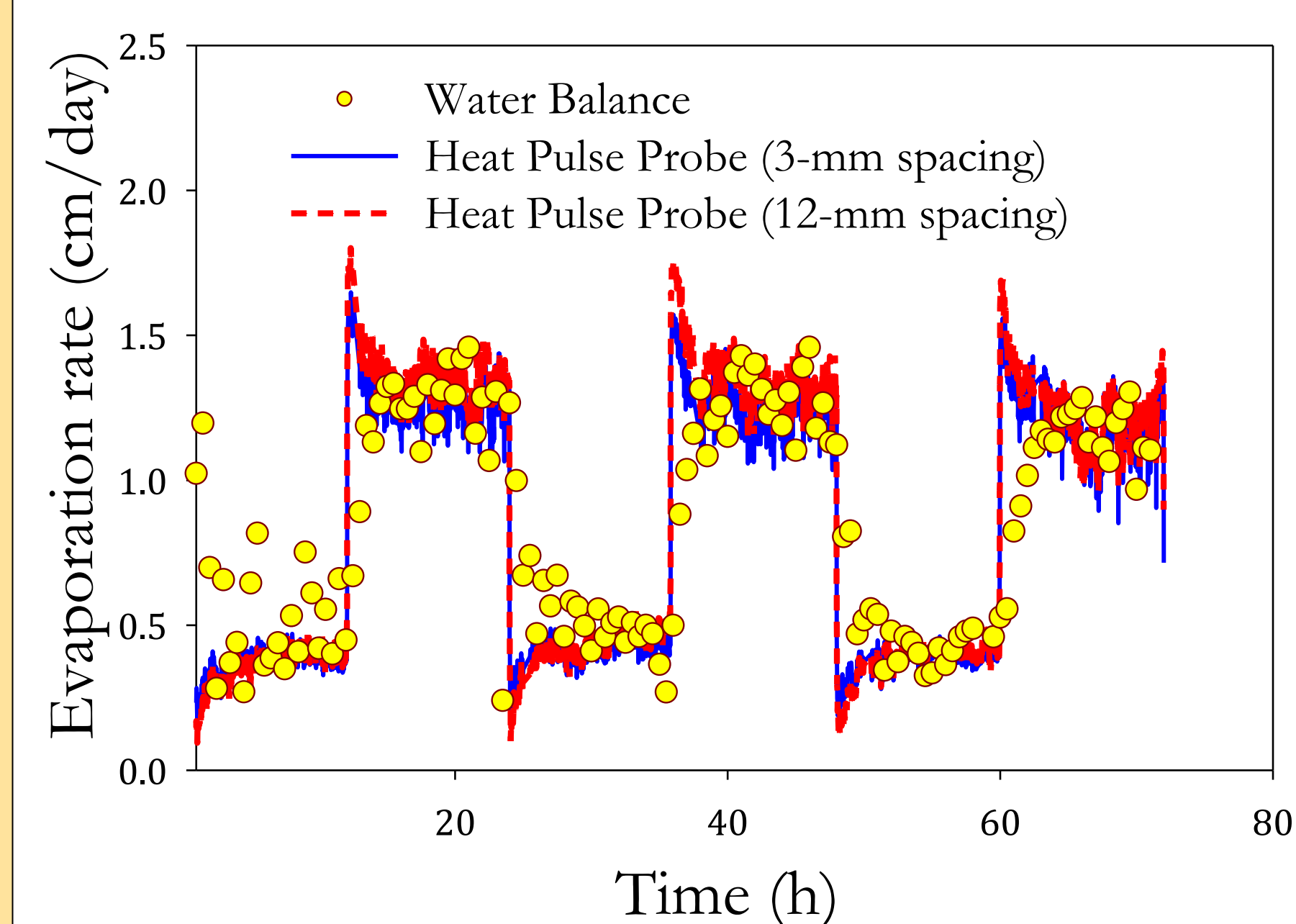

Fig. 3. Evaporation calculations using heat pulse probe measurements, $LE = 1.4G$, and water balance.

Conclusions

For the case of a low-radiation condition, Eq. (9) was derived to calculate stage-one evaporation using HPP measurements and validated using experimental data. Experimental studies also suggest that stage-one evaporation under high-radiation condition can be determined as a constant times soil surface heat flux.

Acknowledgement

References

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