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Novel Techniques to Determine Soil Evaporation Rates: Heat Pulse Probe and Automated Microlysimeter

Kashifa Rumana

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NOVEL TECHNIQUES TO DETERMINE SOIL EVAPORATION RATES:

HEAT PULSE PROBE AND AUTOMATED MICROLYSIMETER

by

Kashifa Rumana

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Soil Science

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2015
ABSTRACT

Novel Techniques to Determine Soil Evaporation Rates:
Heat Pulse Probe and Automated Microlysimeter

by

Kashifa Rumana, Master of Science
Utah State University, 2015

Major Professor: Dr. Scott B. Jones
Department: Plants, Soils and Climate

Soil water evaporation is a critical component of both the surface energy balance and the hydrologic cycle, coupling heat and water transfer between land and atmosphere. Bare-soil evaporation and plant-soil-atmospheric interactions are important components of the water balance, especially in semiarid and arid regions. Soil evaporation has been thoroughly studied during the past century, yielding many methods and models. However, none of the methods have adequately addressed the needs for in situ and real-time monitoring of soil evaporation. The objectives of this research project were to track soil water evaporation losses using two different methods: a heat pulse probe (HPP) array and a fully automated microlysimeter (FAML). The HPP consists of a heater needle and five thermistor needles; when rotated to an angle of 27.3° from a vertical orientation, it yielded temperature measurements every 3 mm within the soil profile. On the application of heat input to a resistance wire in the heater needle, the remaining thermistor needles
measured the temperature response at a fixed distance of 6.5 mm from the heater. Results from our study demonstrate application of the sensible heat balance approach that provided reasonable estimates of subsurface evaporation rates. Inconsistencies due to the inability of the HPP to estimate evaporation rates in the near-surface “undetectable zone” are also reported in comparison to actual stage-2 evaporation based on the mass balance method. Additionally, deviations from the prescribed installation angle introduced errors when calculating the temperature gradient; hence, a vertical spacing algorithm was developed to resolve spacing errors. In the third chapter, a fully automated design is discussed based on the microlysimeter concept with the enhancement of an 80 cm deep lysimeter that was mounted on a 10 kg load cell for real-time monitoring of diurnal evaporation rates from bare soil. The comparison with HYDRUS-1D simulation validated the FAML measured instantaneous evaporation rates with slight disparity towards the end of the experiment. Overall, this study shows two feasible methods for estimating real time evaporation rates in situ over prolonged periods with the aid of the HPP or the FAML. These tools can assist researchers with improved assessment of soil evaporation while taking into account proper correction methods.

(90 pages)
PUBLIC ABSTRACT

Novel Techniques to Determine Soil Evaporation Rates:
Heat Pulse Probe and Automated Microlysimeter

Kashifa Rumana

Increase in world population rate has augmented the global water use in municipal, industrial, and agricultural sectors, with renewable water resources changing very little with time. Climate change and variability, degradation of water quality as a result of industrial waste streams, animal manure and waste, application of chemicals, pesticides, pharmaceuticals, heavy metals, etc. have largely influenced the quantity and quality of soil water. Root zone water helps sustain the agricultural industry by providing much of the water needed for irrigation. It is critical to monitor the soil water availability, especially within the plant root zones. The subsurface water tends to flow to the surface in response to environmental interactions such as hot and dry climate, bare surface exposed to sunlight and wind, and soil characteristics, resulting in a significant evaporative loss or depletion from the water balance. While numerous measurement techniques are available to track moisture loss in soil, none of these methods are capable of tracking soil moisture loss instantaneously on a point-scale. The aim of this research project was: 1) to estimate subsurface evaporation rates using a heat pulse probe (HPP) array that measures temperature and determines soil thermal properties in a vertical soil profile on a millimeter depth scale; and 2) to develop a fully automated microlysimeter (FAML), to track moisture losses in situ from the difference in mass changes recorded by
a load cell. In the second chapter of this thesis, near real-time estimates of subsurface evaporation rates were obtained from the on-sensor calculation of soil thermal properties using temperature rise data. The work performed gave an assessment of fine scale determination of subsurface evaporation rate along with the advantages and limitations of the applied HPP design. In the third chapter, the utility of the FAML design was assessed in long-term monitoring of soil evaporation for extended depth in the soil profile. The FAML measurement results were inconsistent with the manual measurements. This led us to perform HYDRUS-1 D numerical simulations. Overall, using proper correction methods, both of these tools have the potential to improve in situ, real-time, and long-term evaporation measurements.
To

Mama and Daddy

And the memory of Nanima
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CHAPTER I

INTRODUCTION

The advent of global climate change, and the world’s population steadily increasing, an improved management of our invaluable water resources has become a critical need (FAO, 1994). Out of 97% of the total earth’s water, only 3% is available as fresh water. Of the available fresh water, 3.8% is found in soil and 0.3% in rivers and lakes, and are recognized as the only direct known water source for daily lives; while the remaining freshwater is in glaciers, snow and ice caps. Soil water, however insignificant the small amount may seem in comparison to earth’s total water content, has a significant impact on food production, and terrestrial ecosystems. Surface soil moisture is a fundamental state variable controlling a wide range of processes occurring at the land-atmosphere interface through evaporation and plant transpiration (Famiglietti et al., 1998; Pielke and Niyogi, 2010). The process of evaporation, transpiration and evapotranspiration plays a crucial role in depleting the usable soil water reserves. Of the three processes, evaporation from bare soil is globally significant, especially in rainfed agriculture of arid and semi-arid regions, as large percentage of soil is kept bare during periods of seed germination and subsequent plant growth. Measurement of increasing or decreasing soil moisture provides better understanding of bare soil evaporation that can help water managers improve the irrigation scheduling using available soil water more productively (Kite, 2000; Mellouli et al., 2000; Zhao et al., 2013).

In general, several direct and indirect methods are available for measuring soil moisture. The gravimetric method is one of the direct methods that involve removing a sample from the soil and then determining the moist and dry weights. This method,
however, entails practical limitations due to the destructive, laborious and time consuming process in sampling, transporting, and repeated weighing. The dielectric methods (Time domain reflectrometry (TDR) and Frequency domain reflectrometry (FDR)) are the most common indirect methods that measure the dielectric constant of the soil water media to estimate the soil volumetric water content (Robinson et al., 2003). The advantage of TDR and FDR is the ability to provide direct readouts of volumetric soil moisture accurately and continuously if used with a data logger. However, high costs of the instruments, susceptibility to good contact within the soil, and the data logger readings in the form of graphs requiring interpretation makes these methods less convenient. A more recent technique to determine soil moisture content especially in large and global scales is with the aid of remote sensing technology. In areas with sparse on-site instrumentation, or areas where obtaining data is difficult, remote sensing proves to be a promising tool to infer soil moisture profiles down to few centimeters. This approach permits collection of information from a distance without any actual contact and provides a spatially comprehensive monitoring. The thermal infra-red technique, largely limited to bare soil conditions, is based on the relationship between the diurnal temperature and soil moisture, and has been successful in measuring the few centimeters of soil moisture. Microwave techniques, both active and passive, have shown a lot of potential in measuring soil moisture; nonetheless, additional research needs to be performed to make this technology operational.

Soil moisture exhibits great spatial as well as temporal variability (Cosh et al., 2004; Famiglietti et al., 1998; Hébrard et al., 2006; Martinez et al., 2008; Western et al.,
2004; Wraith and Or, 2001). Since most of the bare soil evaporation occurs in the top centimeter of the surface, detailed soil moisture profile information at millimeter-scale is needed for some applications such as weather forecast, climate change studies, flood or drought prediction, and irrigation management. Additionally, the integration of in-situ, high resolution point measurements near-surface combined with a range of soil depths can quantify the total evaporation estimates in the vadose zone essential for enhancement and validation of various numerical models.

In an attempt to track bare soil evaporation near shallow-surface, and across a larger depth, the objectives of this research project were two-fold:

1. To employ a heat pulse probe array with an inverse fitting algorithm to estimate subsurface evaporation rates in soil at a millimeter scale, under laboratory conditions.

2. To develop a fully automated microlysimeter capable of in-situ, real-time monitoring of longer soil column mass changes with time; and to evaluate the ability of the fully automated microlysimeter to monitor diurnal evaporation rates from bare soil by comparison with independent measurements and numerical simulations of soil water content and temperature.
References


CHAPTER II
DETERMINATION OF SUBSURFACE EVAPORATION RATES IN SOIL USING A HEAT PULSE PROBE ARRAY

Abstract

A sensible heat balance approach was applied for in-situ determination of subsurface evaporation by means of heat pulse probes (HPP). A heat pulse probe (HPP) array consisting of hexa-needle and penta-needle heat pulse probes facilitated measurements of vertical soil temperatures and estimated thermal properties (i.e., thermal conductivity and thermal diffusivity), as required by the heat balance method to determine subsurface evaporation. Our objective was to employ a heat pulse probe array, under laboratory conditions, for a thorough evaluation of fine-scale measurements of subsurface evaporation rates in soil. The depth-integrated subsurface evaporation rates from the HPP method were compared with the mass balance evaporation estimated under laboratory conditions. The results show that the heat balance approach effectively estimated subsurface evaporation rates for the first individual layer (i.e. 3-9 mm observation grid) with 3.7, 3, and 3.7 mm/d compared with 4.3, 2.8, and 3.2 from mass balance estimates for columns - 1, 2, and 3 at 65 h, 97.5 h, and 85 h. The overlapping of HPP needles due to a shift in installation angle caused the total subsurface evaporation rates to be counted multiple times, resulting in substantial error. Since the vertical spacing along the soil profile is critical in estimating soil heat fluxes, the subsurface evaporation estimates were significantly improved by using the newly developed spacing.
algorithm. In addition to improving vertical spacing error, using a coarser temperature grid (6 mm) minimized overestimation of total subsurface evaporation.

**Introduction**

The fundamental processes that control subsurface evaporation incorporate complex interactions within the soil, and between the soil and atmospheric boundary layer. Soil water evaporation depends on uncertainties in atmospheric demand and liquid-vapor transport mechanisms. These dynamics are complex and make understanding soil water as well as land-atmosphere interactions challenging. Since soil water evaporation is a result of a coupling of soil heat and water fluxes, its quantification continues to be important for soil water surface energy balance and hydrologic studies. Although techniques for measuring surface soil water evaporation for bare soil exist, including Bowen ratio energy balance (Fritschen and Fritschen, 2005), eddy covariance (Meyers and Baldocchi, 2005; Moncrieff et al., 1997), and water balance methods (lysimeter method and soil water depletion method) (Hillel, 1982), none of these methods can determine soil water evaporation locally at the scale of millimeters as a function of depth and time. Prediction of the drying behavior of porous materials is important for agricultural and engineering applications ranging from efficient and optimum water management in surface soil moisture to drying of food and non-food products for various biomedical and pharmaceutical manufacturing processes.

Soil water evaporation is a process of liquid and vapor movement governed by surface boundary conditions and soil transport mechanisms (such as capillarity, gravity
and viscous forces) that control drying with time (Van Brakel, 1980). The changing dynamics at the soil surface and below can result in steep thermal and hydraulic gradients that lead to a three stage soil water evaporation process (Idso et al., 1974; Lemon, 1956).

Stage-1 happens when the soil surface is wet, and evaporation is only energy-input limited, proceeding at a rate proportional to available energy arriving at the soil surface. Stage-2 evaporation represents disruption of saturated hydraulic conductivity to the surface and is limited by water vapor diffusion. Stage-3 is the lowest rate, where the process is limited by the matric forces holding water to the soil particle surfaces. The high, pseudo constant rate stage (stage-1) proceeds until diminishing moisture content near the surface no longer allows water from below to transport sufficiently to keep the surface wet. At a critical surface water content (Keey, 1972), the vaporization plane shifts below the surface; hence, stage 2 is initiated as a consequence of an invasion process dominated by vapor flow, significantly lowering the evaporation rate. The receding drying front leads to reduced temperature gradients and lower drying rates as the evaporation process eventually transitions to stage 3 (Prat, 2002). Grifoll (2013) suggested mechanical dispersion of water vapor in soils contributes to the total vapor transport in the evaporation process under non-isothermal conditions. Numerous studies have assessed the importance of moisture and vapor transport in saturated and unsaturated porous media affecting evaporation processes (Coumans, 2000; Lehmann et al., 2008; Sadeghi et al., 2012; Sadeghi et al., 2014; Scherer, 1990; Schlünder, 1988; Shokri et al., 2009; Van Brakel, 1980). Because soil thermal properties are intimately
linked with soil evaporation processes, there has been considerable interest and research applying thermal measurement techniques for evaluating evaporation.

Quantifying evaporative rates using heat pulse techniques (Campbell et al., 1991) generally requires exploring thermal process properties including sensible heat flux, sensible heat storage, and latent heat of vaporization in the porous medium of interest (Gardner and Hanks, 1966; Mayocchi and Bristow, 1995). The sensible heat balance technique integrates ambient temperature and soil volumetric heat capacity to account for latent heat within the soil profile. Consequently, various heat pulse methods and algorithms have been developed (Endo and Hara, 2007; Ren et al., 2000; Yang and Jones, 2009) and may be employed for soil sensible heat balance calculations. Fine-scale measurements of thermal properties and temperature for multiple depth increments were made by Heitman et al. (2008a, 2008b) to account for changes in sensible heat storage; these measurements were facilitated by heat pulse sensors to determine sensible heat balance that represents evaporation occurring within the soil. The applicability of heat-pulse measurements quantified the location and magnitude of sub-surface soil-water evaporation at multiple depths below the soil. A number of previously employed heat pulse probe (HPP) designs have been used to measure near-surface temperature gradients. The HPP designs have come a long way – progressing from a dual-needle HPP with one heater needle and one temperature sensing needle spaced 6mm apart (Campbell et al., 1991); to a tri-needle HPP with two temperature sensing needles spaced 6 mm apart from the heater needle (Ren et al., 2000); and, finally a penta-needle HPP with 6.5 mm spacing by Yang and Jones (2009). Owing to these varied designs, the numerical modeling
simulations of Sakai et al. (2011) referred to a limitation of the sensible heat balance approach due to an “undetectable zone,” which is a layer extending from the soil surface down to the mid-point of the first paired-temperature observation grid points (e.g., a 3 mm layer for 6 mm thermistor needle spacing). Novel attempts have been made to provide finer needle spacing close to the surface. More recently, Zhang et al. (2012) and Deol et al. (2012) used needles spaced at 0 and 1 mm depth in an attempt to reduce the undetectable zone to 0.5 mm for subsurface evaporation estimates in the shallow soil near the surface.

Although new HPP designs have reduced the undetectable zone by providing finer spacing, it is important to consider the needle effect on measurements. The improved heat pulse probe proposed by Zhang et al. (2012) has 11-vertically-aligned needles leading to a possibility that measurements are influenced by needles below as heat travels through the medium.

There is also a lack of sensors capable of providing instantaneous estimates of thermal properties in soil, where most thermal properties are actually fitted to temperature rise data. Therefore, the main objective of this research was to use an array of heat pulse probes with an inverse model to estimate subsurface evaporation rates in soil. This approach employs a heat pulse probe array comprised of both a hexa-needle heat pulse probe (HHPP) and a penta-needle heat pulse probe (PHPP). An improved inverse method developed by Yang and Jones (2009) for simultaneous estimation of thermal properties was employed.
Theory

Inverse Thermal Parameter Fitting Method

Each PHPP/HHPP employs INV-WATFLX, which is FORTRAN code developed by Yang and Jones (2009), to simultaneously fit thermal diffusivity, thermal conductivity and heat velocities in x- and y-directions from heat pulse temperature traces. The code provides an inverse fitting method by solving the two-dimensional heat equation that combines conductive heat transfer and convective effects in an incompressible porous medium, expressed as:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{C} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - V_x \frac{\partial T}{\partial x} - V_y \frac{\partial T}{\partial y} $$ (1)

where $T$ is temperature, $t$ is time, $C$ is volumetric heat capacity (J m\(^{-3}\)oC\(^{-1}\)), $\lambda$ is thermal conductivity (W m\(^{-1}\)oC\(^{-1}\)), $V_x$ and $V_y$ are two components of the heat velocity, $V$, in x- and y-directions, given by:

$$V_x = J_x \frac{C_w}{C}$$
$$V_y = J_y \frac{C_w}{C}$$ (2)

where $C_w$ is volumetric heat capacity of water, $J_x$ and $J_y$ are the two components of the water flux vector, $J$, in the x- and y- directions – the magnitude of which is obtained from the expression:

$$\|J\| = \sqrt{J_x^2 + J_y^2} = \frac{C}{C_w} \sqrt{V_x^2 + V_y^2}$$ (3)
The resulting analytical solution describes the temperature-time \( T(t) \) relationship assuming an infinite line source in an infinite, homogenous medium derived from Eq. (1), and is written as:

\[
T(x, y, t) = \begin{cases} 
\frac{q'}{4\pi\kappa} \int_0^t s^{-1} \exp \left[ -\frac{(x-V_s s)^2 + (y-V_s s)^2}{4ks} \right] ds; 0 < t \leq t_0 \\
\frac{q'}{4\pi\kappa} \int_{-t_0}^t s^{-1} \exp \left[ -\frac{(x-V_s s)^2 + (y-V_s s)^2}{4ks} \right] ds; t > t_0 
\end{cases}
\] (4)

where \( q' \) is the heat input per unit length per unit time \( (W \, m^{-1}) \), \( t_0 \) the heating duration \( (s) \) and \( \kappa \) is the thermal diffusivity of the system \( (m^2 \, s^{-1}) \). The inverse thermal parameter fitting is obtained from the temperature rise measurements made at thermistor needles surrounding the heater needle. This method minimizes differences between measured and calculated temperatures for four temperature sensing locations using the Gauss-Newton-Levenberg-Marquardt method to optimize the thermal properties – thermal conductivity, and thermal diffusivity. Eight parameters \( (\kappa_1, \lambda_1, \kappa_2, \lambda_2, \kappa_3, \lambda_3, \kappa_4, \text{ and } \lambda_4) \) are estimated from measured \( T(t) \) data input into Eq. (4). Additionally, the insitu calibrated apparent needle spacings are determined from the analytical solution provided by Yang et al. (2013) prior to thermal property optimization in Eq. (4). Subsequently, volumetric heat capacity \( (C) \) is estimated from the ratio of \( \lambda \) and \( \kappa \):

\[
C = \frac{\lambda}{k}
\] (5)

The thermal properties optimized at thermistor needles represent soil properties between the central heater and each thermistor, i.e., for 0-6, 3-6, 6-9 and 6-12 mm layers.
designated as $\lambda_{0.6}$, $\lambda_{3.6}$, $\lambda_{6.9}$, $\lambda_{6.12}$, and $\kappa_{0.6}$, $\kappa_{3.6}$, $\kappa_{6.9}$, $\kappa_{6.12}$ in Fig. 1, respectively. In order to estimate thermal properties, an algorithm is needed. Sakai et al. (2011) used numerical modeling to demonstrate the reduced water content in the near surface due to a receding drying front, which has a proportional effect on the soil thermal conductivity. In order to obtain thermal property estimates for layers where these are not directly determined, depth-weighted harmonic means of soil properties are used. The approach is to assume the $\lambda_{0.6}$ is the harmonic mean of $\lambda_{0.3}$ and $\lambda_{3.6}$ where $\lambda_{0.3}$ is the unknown. However, $\lambda_{0.3}$ is further split to $\lambda_{0.1.5}$ and $\lambda_{1.5.3}$ by assuming a depth-dependent proportional ratio of $\lambda_{0.3}:\lambda_{0.6}$.

**Sensible heat Balance Theory**

The major mechanism that drives evaporation in the presence of energy exchanges between a soil and the atmosphere is the sensible heat flux in the soil. The measure of soil heat storage and latent heat processes are vital for energy balance closure. The change in sensible heat balance storage ($\Delta S$) is introduced by the relation (Heitman et al., 2008a, 2008b):

$$\Delta S = \sum_{i=1}^{N} C_i \frac{t^j_i - T_i^j}{t^j_i - t^j_{i-1}} (z_i - z_{i-1})$$  \hspace{1cm} (6)

where $C$ is the volumetric heat capacity of soil (J m$^{-3}$ °C$^{-1}$), $T$ is the soil temperature (°C), $t$ is time(s), $z$ is the depth in meters ($z = 0$ being at the surface), the subscript $i$ and $j$ are index variables for soil depth increment and time step, respectively. In the case of subsurface evaporation computation, the definition of $\Delta S$ in Eq. (6) can be implemented
in the surface energy balance equation to yield subsurface evaporation rate, \( E \) (m s\(^{-1}\)) and latent heat of vaporization, \( L \) (J m\(^{-3}\); = 2.495\(\times\)10\(^9\) – 2.247\(\times\)10\(^6\) T):

\[
LE = (G_1 - G_2) - \Delta S
\]

where \( G_1 \) and \( G_2 \) are the conduction heat fluxes at upper and lower boundaries of the soil layer, respectively.

**Materials and Methods**

**Heat Pulse Probe Array**

The Penta-needle heat pulse probe (PHPP) consists of a central heater needle with four temperature sensing needles arranged orthogonally around it. The Hexa-needle heat pulse probe (HHPP) provided finer thermistor spacing in the “undetectable zone” with five temperature sensing needles as shown in Fig. 1. The temperature sensing needles were spaced 6.5 mm from the heater (Yang et al., 2013) and were constructed by placing a thermistor (0.46-mm-dia., 10 k\(\Omega\) at 25 \(^\circ\)C) inside a pencil point stainless steel housing of 22 mm length and 1.27 mm outer diameter. Heater needles were constructed by housing two heater resistance wires (79-\(\mu\)m-dia., 205 \(\Omega\) m\(^{-1}\), Nichrome 80 Alloy, Pelican Wire Co., Naples, FL) in two loops inside another pencil point stainless steel housing of 32 mm length and 2.1 mm outer diameter. The total resistance of the completed heater wires was 16 \(\Omega\) each. The thermistor needles and the heater needles were positioned 15 mm and 30 mm from the circuit board into which they were soldered. To provide electrical insulation, water proofing and high thermal conductivity, the heater and
thermistor needles were vacuum-filled with thermally conductive epoxy (RBC-4300, RBC Industries, Inc., Warwick, RI). This low viscosity epoxy was used to facilitate vacuum filling of the needles, which were shut at one end to protect thermistor/heater wires. The wires extending from the heater and thermistor needles were soldered to a high performance embedded system capable of real-time computations. The heater wires connected to the probe circuit board were covered with Urathane (Arathane 5753 A/B (LV), Speciality Polymers & Service Inc., Valencia, CA) to allow heat dissipation after the heater is fired.

The heat pulse probe (HPP) is a high performance system-on-chip embedded design used for real-time computation. The program (firmware) is written to manage the temperature measurements and to determine the thermal properties using an inverse fitting algorithm (Yang and Jones, 2009). We used a HHPP at the surface and a PHPP below in a HPP array to facilitate the shallower spacing in the surface measurements for subsurface evaporation estimates. The HPP array is finally dipped in acrylic conformal coating solution (HumiSeal, Pittsburgh, PA) to provide moisture and environmental protection for printed circuit assembly. A controlled rate of immersion and withdrawal in acrylic conformal coating ensured even deposition of the coating on the HPP array.

**Sand Columns**

Three open top thermally insulated polyvinyl chloride (PVC) columns of 15 cm length and 14.6 cm inner diameter were used for the laboratory subsurface evaporation experiment. A 50-grit wedron sand (Cinder Co., Lindon, UT) was uniformly packed into
the columns (containing HPP arrays) at bulk densities 1.841, 1.855 and 1.816 g/cm$^3$
respectively for each column. The draining water retention characteristics of the sand are
given in Table 4.1 of Heinse (2009). The columns were saturated from the bottom and
disconnected after saturation to facilitate continuous weighing by three low capacity
single point bending beam load cells (model LSP-10, Transducer Techniques, Temecula,
CA) at a resolution of 0.7324 g (0.044 mm). A 225 W heat lamp was suspended 25 cm
above each column surface to provide uniform radiant heating of 450 ±10 W/m$^2$ at the
surface, measured by a pyrgeometer (model CG1, Kipp & Zonen, The Netherlands) as
shown in Fig. 2.

Array Installation

The heat pulse probe array circuit boards were carefully positioned at an
inclination of 27.3° with respect to a horizontal plane and back filled with sand so that the
topmost needle was half buried at the sand surface (see Fig. 2.). Rotating the array at an
angle of 27.3° provided equally spaced (i.e. 3mm) needles within a vertical profile below
the surface. Since the top probe in the array is an HHPP, measurements were also
provided at 1.5 mm below the surface (i.e. 0.75 mm undetectable zone). Soil ambient
temperatures were measured at approximately 0, 1.5, 3, 6, 9, 12, 15, 18, 21, 24, and 27
mm depths in a cycle of 30 min. Soil ambient temperatures were recorded during the first
minute of each cycle, followed by coordinated heat pulse optimization of thermal
properties for the next 12 min. During the optimization process, one heater in each probe
was fired for 8s. With the start of heater firing, the rise in temperature was recorded by
the adjacent thermistor needles for 60s at 1s intervals. Temperature rise data within the microcontroller were used to fit the sand thermal properties using equation (4) and the INV-WATFLX code. Fig. 3 illustrates the temperature rise curves for saturated, intermediate, and dry sand conditions. A datalogger (Model CR1000, Campbell Scientific, Logan, UT), was used to retrieve data from the HPP array via SDI-12 communication.

HPP Calibrations

*Temperature Calibration:* The temperature sensing thermistors in the HPP array needles were calibrated at a known temperature of 0°C in an ice water bath to determine offset values. Temperature values from the needles were measured every 1s and compared with thermocouple type digital thermometer readings (HH82A, Omega Engineering, Stamford, CT) for a given period of time. The measured temperature values were collected through a datalogger and averaged for a short duration to determine offset values for individual needles. The determined offset values of temperature were used to correct measured ambient temperature data for subsurface evaporation calculations.

*In situ Spacing Calibration:* The HPP array was placed in the sand column where measurements were taken to determine the apparent radial distance of each temperature sensing needle from the central heater. We used the zero flux adjusted spacing approach described by Yang et al. (2013) to determine the apparent spacing between the temperature sensing needles and the heater needle. Determining in-situ calibration is critical for thermal property optimization.
Results and Discussion

A laboratory experiment to estimate subsurface evaporation rates with the heat balance method was conducted for 10 days in three thermally insulated columns provided with constant uniform heat input. Here we describe the application of the heat balance method for determining subsurface evaporation rates with comparison to mass balance measurements. Also, the challenges encountered in the evaporation rate estimation process and the methods implemented to improve the results are discussed.

Algorithm to Determine ‘z’ Spacings Relative to the Surface

Correct vertical spacing between HPP needles below the surface is critical for accurate determination of soil heat fluxes and subsurface evaporation rates. Based on the theory described by Sakai et. al. (2011), installing the heat pulse probe array at the 27.3° inclination provides temperature measurements spaced vertically at 3 mm increments. Achieving the precise installation angle is difficult and there is a likelihood of the angle shifting during installation. Errors in installation angle perpetuate to altered vertical needle spacing as demonstrated in the experiments described here, which led us to develop an algorithm for correcting the apparent vertical ‘z’ spacings, which influence the heat flux and subsurface evaporation calculations. In this algorithm, it is assumed that the top needle is hinged at the surface and rest of the array body can swing around the top needle. Using the finite physical needle spacing of 6.5 mm for all four thermistors from the center heater needle, as shown by Yang et al. (2013), the equations to derive vertical ‘z’ spacing as a function of rotation angle are shown in Table 1. Shifts in the installation
angle ($\theta=27.3^\circ$) causes the subsurface needle positions to vary in depth, thus increasing or decreasing the length of the assumed layer.

As the soil surface dries, the evaporation rate decreases continuously with time. This declining evaporation rate leads to a smaller magnitude of soil heat flux for subsequent layers as the drying front recedes below the surface. Prior to the spacing corrections, the subsurface layers exhibited larger heat flux estimates than the surface layer. Applying the new spacing correction scheme significantly improved the soil heat flux estimates throughout the sand profile. Fig. 4 illustrates a comparison of the soil heat flux estimates in column-2 for 0-6 mm, and 12-15 mm depths before and after the application of spacing correction method.

**Soil Heat Flux**

Soil heat flux is determined from the temperature gradients and thermal conductivity estimates for respective layers. Fig. 5 shows the soil temperature profile and corresponding thermal conductivity of column-2 for 0-27 mm depth using a 6 mm observation grid for column-2. As described in the theoretical considerations section, HHPP provides a finer grid spacing of 1.5 mm in the undetectable zone, and 3 mm spacing for rest of the profile. However, in the calculations described, a coarser grid spacing of 6 mm is employed. Due to the misaligned installation angle, the new needle orientation considerably reduced the vertical spacing for the temperature sensing needles at the 1.5, 3, 9, 18, and 24 mm layers. Smaller grid spacing gave a narrow distinction in measured temperature and this introduced more errors in the subsurface evaporation
estimates. Since the temperature sensing needles were too close to measure the temperature gradients at finer resolution, a coarser grid of 6 mm was chosen. Subsequently, thermal conductivities from the 6 mm observation grid were employed for soil heat flux estimates.

The shape of the temperature profile remained almost constant along the profile until before 95 h for column-2 with an approximate increase of 7.2 °C from ambient temperature. A comparison of temperature profile at 50 h and 95 h in column-2 (Fig. 5) shows that 0-6 mm depth layer became steeper at 95 h. This change in soil temperature coincided with the declining thermal conductivity for the same layer. The temperature profile became relatively steeper for the 6-12 mm depth at 110 h as compared to 95 h. The soil temperature maintained the same shape after 120 h except for an increase in temperature at all layers, which could be due to the heat storage after the soil dried out.

Each column was examined individually for the heat flux estimate analysis. Duration of heat flux estimates varied depending on the installation angle. Fig. 6 gives a comparison of estimated heat flux for the first layer, i.e. 0-6 mm from all three columns. Computing ‘z’ spacings for columns 1 and 2 indicated larger divergence (k = +20°; Table 1) from the expected installation angle (27.3°) that resulted in wider gaps between the temperature sensing needles. In the case of column-3, a smaller divergence (k = +5°) in installed angle resulted in closer vertical spacing between the temperature sensing needles. Wider gaps led to an increase in length of the measurable subsurface layers whereas the smaller spacing reduced the measurable zone. This distinction in the length of layers within each column led to the differences in time of peak heat flux estimates.
The HPP nearest the surface yielded heat fluxes at 50, 92, and 85 hours for columns- 1, 2, and 3, respectively. It is important to note that irrespective of needle spacing offset in each column, the peak amplitude for the top layer remained constant, 140±10 W/m², for all three columns. Further explanation on heat flux behavior for deeper layers is elaborated for column-2 (Fig. 7). Although heat fluxes appeared at different times, the divergence in trend was similar in all three columns. Hence, column-2 was arbitrarily chosen for explanation.

Fig. 7 demonstrates heat flux density measured at different depths with time in column 2. The heat fluxes were small and varied little during stage-1 evaporation up to 92 hours after which the heat flux for 0-6 mm depth started to peak while the lower depths responded later. This response in heat flux came in effect following the inflection in measured temperature and estimated thermal conductivity (see Fig. 5) as a result of drying front descending below the surface invading the HPP needle zone. Heat flux peaks started to show for 6-12, 12-15, and 15-21 mm depths as the drying front further receded. Heat flux estimates were insignificant for 21-27 mm depth during our experiment period suggesting stage-3 evaporation. Overall, the amplitude and phase relationships with respect to depth are consistent with the expected behavior.

Assessment of Subsurface Evaporation Rates

A high mass balance evaporation rate of 8 mm/d was recorded at the beginning of the experiment when the heat lamp was turned on. The evaporation rate in the initial stage remained nearly constant until approximately 45 h and then the rate falls steeply
below the potential rate (dictated by the external forcing conditions) between 45 to 110 h with rates decreasing from 7.5 to 1.8 mm/d indicating profile-controlled stage-2 evaporation. The application of the HPP method was assessed by comparing mass balance (load cell) measurements with the HPP arrays. An average plot with error bars representing change in mass from the three load cell measurements is shown in Fig. 8 and is compared with the HPP determined subsurface evaporation rates for all layers in each column. Due to the presence of the undetectable zone (Sakai et al., 2011), the HPP does not capture surface evaporation. Hence, the HPP comparison with mass balance method is essentially limited to subsurface evaporation rates. The peak evaporation rates from a summation of all individual layers were 4, 4.5, and 5 mm/d in columns-1, 2, and 3 respectively. Although each column had the same heat load applied at the surface, the estimated subsurface evaporation rates varied in time and amplitude in each column. Initial evaporation rate estimates from HPP’s in columns 2 and 3 were overestimated compared to measured rates by the load cell. This discrepancy is essentially due to the offsets in spacing and temperature gradients that caused significant impact on soil heat fluxes. The HPP method to determine subsurface evaporation rates in individual depth layers is explained in detail for column-2.

Fig. 9 demonstrates subsurface evaporation rates during stage-2 for individual layer depths as the drying front recedes below the surface. Subsurface evaporation rates in column-2 were observed for the 3-9, 9-13.5, 13.5-18, and 18-24 mm depth layers. In addition to the on-board parameter optimization feature of HPP that determined thermal conductivity for 0-6, and 6-12 mm depths, temperatures at 1, 6, and 12 mm depths were
used in Eq. (7) and 0.5 hours was used as the observation time interval to calculate subsurface evaporation rate in the 3-9 mm depth. Each 6 mm soil depth increment exhibited descending peak evaporation rates. In the 3-9 mm soil water evaporation started at 85 hours achieving a maximum evaporation rate of 3 mm/d at 100 h and diminished to near zero by 115 h. Subsequently, soil water evaporation was initiated for 9-13.5 mm depth at 90 h that also peaked to about 3 mm/d at 115 h and then declined to near zero by 125 h. As shown in previous studies (Deol et al., 2012; Heitman et al., 2008b; Sakai et al., 2011; Xiao et al., 2012), shallower depths exhibited larger evaporation rate peaks at earlier times and deeper depths exhibited smaller peaks at later times, even though the superimposed peaks from 3-9, and 9-13.5 mm depths overestimated the total subsurface evaporation during the falling rate stage compared to load cell measurements. The HPP method captured the declining evaporation rates with time for as long as the drying front remained within the HPP needle domain. A wider vapor flow domain caused part of the evaporation to occur below the HPP needle zone that was left unaccounted for.

Examining the deeper layer, i.e. 18-24 mm, indicated highly diminished evaporation rates of 0.5 mm/d. This large reduction in evaporation rates indicate deeper drying front where the vapor flow extended to a larger region (Sadeghi et al., 2014) that moved past the HPP needle domain implying stage-3 evaporation.

In order to understand the importance of spacing offsets on subsurface evaporation estimates, the numerically simulated data from Sakai et al. (2011) was processed for 6 mm observation grid. Fig. 10(a) demonstrates the declining evaporation rates with descending drying front in deeper layers. In order to understand the effect of
new spacing algorithm, ‘z’ spacings derived for one of the column arrays were used in the numerical data to estimate subsurface evaporation rates. Fig. 10(b) shows a significant overlapping for 9-13.5 mm and 13.5-18 mm depths layers with the new ‘z’ spacing values. Also, the peaks for the two layers are shifted in time in comparison to the rates in Fig. 10(a). This comparison is only to show that incorrect spacings have a significant influence on subsurface evaporation estimates. A numerical simulation with the measured data needs to be carried out in order to understand the influence of incorrect spacings that resulted in evaporation being counted multiple times because of the overlapping needles.

The HPP estimated subsurface evaporation, even though overestimated mass balance method, it is worth noting that the direct comparison of subsurface evaporation rates from individual depth layers are more representative than the summation of all layers. Overall, the HPP method yielded good estimates of subsurface evaporation rates at a millimeter scale.

**Conclusion**

The HPP designs described here provide in-situ, high density vertical soil temperature measurements in addition to fitted soil thermal properties by the on-board microprocessor. Results from our study demonstrate application of the sensible heat balance approach, which provided reasonable estimates of subsurface evaporation rates. The maximum subsurface evaporation rate calculated from HPP for the first layer (i.e., 3-9 mm) of column-1 was 3.7 mm/d, and the corresponding load cell estimate was 4.3
mm/d at 65 h. The maximum subsurface evaporation rate calculated from HPP for first layer of column-2 was 3 mm/d, and the corresponding load cell estimate was 2.8 mm/d at 97.5 h. The maximum subsurface evaporation rate calculated from HPP for the first layer of column-3 was 3.7 mm/d, and the corresponding load cell estimate was 3.2 mm/d at 85 h. Deviations from actual stage-2 evaporation based on the mass balance result from the inability of the HPP to estimate evaporation rate in the near-surface undetectable zone. In addition, any deviation from the 27.3 degree installation angle will result in additional error when calculating the temperature gradient. A vertical spacing calibration algorithm was developed based on the rotation of the array about the topmost thermistor needle to reduce this error.

After incorporating the vertical spacing algorithm, soil heat flux estimates were significantly improved, providing a high-resolution evaporation rate estimates. The rate at which the evaporation front descended calculating using the HPP method agreed well with that of the mass balance method. However, the total subsurface evaporation (which is the summation of all individual layers) from the HPP was an overestimate since evaporation rates were counted twice due to the overlapping needles. The effect of overlapping needles on total evaporation rates was studied by implementing the new spacing algorithm on numerically simulated data from Sakai et al. (2011). The results suggest a possibility of overestimation in total subsurface evaporation rates due to overlapping needles. Further studies to simulate the laboratory conditions under a wide range of HPP installed angle can improve our knowledge of subsurface evaporation rates from HPP when the evaporation plane shifts from surface to subsurface.
By resolving the anomalies associated with the vertical spacings and temperature offsets, the HPP method has a potential to determine subsurface evaporation rates on a millimeter-depth scale. A key to obtaining near-real time estimates of on-sensor fitting of thermal properties from temperature rise data is an unprecedented achievement.

References


layered soils derived under steady-state evaporation from a water table. J. Hydrol. 519: 1238-1248.


determination of soil water flux and thermal properties with a penta-needle heat
Table 1. Outline of HPP array installation angle equations used for correction of needle vertical position, ‘z’, from physical needle distance on probe and the predefined installation angle i.e. θ = 27.3°; k represents the angle shift

<table>
<thead>
<tr>
<th>Depth Layer, z (mm)</th>
<th>Correction Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-6</td>
<td>6.5 sin(90-θ+k)</td>
</tr>
<tr>
<td>6-12</td>
<td>6.5 sin(90-θ+k)</td>
</tr>
<tr>
<td>12-15</td>
<td>31.72 sin(27.3+k) – 2*6.5 sin(90-θ+k)</td>
</tr>
<tr>
<td>15-21</td>
<td>6.5 sin(90-θ+k)</td>
</tr>
<tr>
<td>21-27</td>
<td>6.5 sin(90-θ+k)</td>
</tr>
</tbody>
</table>
Fig. 1. Arrangement of Heat Pulse Probes (HPP) array showing the vertical needle spacing when the array is rotated 27.3 degrees from a horizontal position. All 11 needles contain thermistors and the two long needles also contain heater wires. The upper three needles are spaced at 1.5 mm increments vertically.
Fig. 2. Experimental set-up of the 2-HPP array buried in a sand column with the inset photo showing the top-view of column with the half buried surface needle.
Fig. 3. Mean temperature $T(t)$ rise curves measured at four thermistors (1, 2, 3, and 4) for 3 different water contents during the drying process.
Fig. 4. The soil heat flux estimates compared before and after the ‘z’ spacing correction algorithm was applied for the 0-6 mm and 12-15 mm needles in column-2.
Fig. 5. Temporal snapshots of temperature (left) and thermal conductivity (right) in soil profile starting from surface down to depths of 6, 12, 15, 21, and 27 mm below the surface in column-2
Fig. 6. Soil heat flux computed between 0-6 mm for comparison in all three sand columns.
Fig. 7. Soil heat flux density determined within different depths as a function of time and diminishing water contents for column-2. Note the distinct transitions between evaporation stages-1, -2 and -3.
Fig. 8. Layer-based summation of subsurface evaporation rates (see Fig. 7) from each HPP array compared with 3-load cell average measurements showing periodic standard deviation.
Fig. 9. Diminishing evaporation rates in each layer as the drying front descends in column-2
Fig. 10. Comparison of subsurface evaporation rates from numerically simulated data from Sakai et al. (2011) by changing ‘z’ spacings in the calculations:
(a) Before, and (b) after the application of new spacing algorithm
CHAPTER III
A FULLY AUTOMATED MICROLYSIMETER FOR PROLONGED MONITORING
OF SOIL EVAPORATION

Abstract
The ability to accurately measure soil evaporation is of significance for a wide range of disciplines interested in management of the soil hydrologic regime. Applications are found in agricultural, environmental, meteorological, ecological and industrial sectors spanning from point- to watershed-scales and beyond. The objective of this study was to develop and evaluate a fully automated microlysimeter (FAML) for prolonged, in situ and real-time monitoring of diurnal evaporation rates from bare soil. The evaporation measuring capabilities of an 80-cm long FAML and effects of point-scale measurement in Millville silt loam soil were studied. Evaporation rates determined with the FAML favorably compared with measurements conducted using a down-hole capacitance-based sensor array over a 12- day period with a deviation of < 2 mm. After this, the measurements diverged due to a limited near-surface response volume of the sensor. The FAML measurements were also evaluated against HYDRUS-1D numerical simulations to validate the extension of the measurement period due to the application of longer soil columns. Estimates of numerically simulated evaporation rates agreed well with the measured evaporation rates from the FAML exhibiting a RMSE of 2.449. Also, the temperature dynamics of measured and simulated data at different depths validated the FAML measured cumulative water losses. Hence, the FAML response showed promise
for extending the ‘operational life’, likely to be a function of forcing conditions and column depth.

Introduction

In the Intermountain West of the United States the availability of water is mainly determined by spring runoff, which is a result of the melting snow pack. A number of studies (Barnett et al., 2004; Gillies et al., 2012; Wang et al., 2010; Wang et al., 2014) indicate a large-scale warming trend in the West, which could lead to reduction in mountain snowpack and cause earlier spring runoff. The prospect of earlier spring runoff as a result of anticipated climate change poses a great challenge to water resources managers. Hence, with limited available fresh water for irrigation, improved tools for tracking soil evaporation losses are needed; especially in arid and semi-arid regions. Numerous measurement techniques and models have been developed over the past century to study soil evaporation. Among the water balance approaches, lysimeters are widely used in field studies for measuring point-scale evaporation from soils and crops. Although large lysimeters (with surface areas > 2 m$^2$) provide a standard for measuring evaporation rates, the prohibitive costs for installation and maintenance limit their applicability. A potential alternative for large lysimeters is a microlysimeter (ML) composed of an extracted column of undisturbed soil sealed at the bottom to ensure mass changes in the ML are solely due to soil evaporation.

Previous studies revealed problems with MLs due to thermal properties of selected ML materials and the limited length of soil columns used (Boast and Robertson,
Boast and Robertson (1982) emphasized the length dependency factor of MLs, which affects the amount of energy absorption and transfer along or through walls and through the bottom of the ML column. Owing to this factor, they demonstrated that water evaporated faster from shorter MLs and that longer columns behaved as if they were infinitely long and more comparable with the surrounding soil. Further studies on the effects of ML length by Evett et al. (1995) suggested that at least 30 cm length is required for continuous evaporation measurements over 9 days at a particular site. Walker (1983) indicated that the wall material affects the accuracy of MLs, and it is important to maintain the rate of heat conduction (i.e., thermal conductivity) into or out of the MLs similar to the rate of heat conduction in the surrounding soil. He stated that in order to reduce excessive heat conduction into or out of the soil core, it is important that the wall material is less thermally conductive than the surrounding soil. Hence, Walker (1983) suggested the use of polyvinyl chloride (PVC) over steel or aluminum. Following the work of Walker (1983), a wide combination of materials for the column walls and bottom have been tested to date, which include plastic column-metal bottom, plastic column-plastic bottom and metal column-metal bottom (Evett et al., 1995; Lascano and van Bavel, 1986; Todd et al., 1991). More recently, Evett et al. (1995) verified the effects of using both steel and PVC for column wall and bottom materials, under field conditions. Their results indicated that steel walls underestimated evaporation rates, largely due to the conduction of heat out of the core during daytime and into the core during nighttime. In the case of PVC wall material, this effect was not dominant although the column exhibited a higher temperature than the surrounding soil.
It was explained that trapping heat at the column bottom could be prevented by using capping material that exhibits higher thermal conductivity than the soil below.

Besides the geometrical dimensions and the wall materials of MLs, bulk density is another important factor to be considered when extracting soil cores. Several methods for core extraction are documented in literature (Grossman and Reinsch, 2002), among which, the core method is more applicable to agricultural and organic soils. Hollinger and Isard (1989) described the use of a highly specialized device to extract undisturbed, plastic-encased soil cores with a Hydraulic Giddings Probe. Plastic encasing of soil cores was first used by Robertson et al. (1974) and Mielke (1973) during the sampling process to minimize core fracture. Hollinger and Isard (1989) also showed that the clear plastic allowed observation of the length of the soil column during the sampling process and determination of the degree of compaction.

The core method also facilitates extraction of soil for volumetric water content measurements. However, this method is less suitable if frequent soil core extractions are necessary for water content determination along the soil profile. Recently, down-hole electromagnetic (EM) sensors have been more widely used in soil research. Advantages of EM sensors are their non-destructive nature, fast response time, high resolution measurements at shorter intervals (e.g., 10 cm), and robustness at the field-scale (Paltineanu and Starr, 1997; Starr and Paltineanu, 1998a, 1998b). However, Paltineanu and Starr (1997) suggested the need for careful calibration of sensors in order to get accurate volumetric water content ($\theta_v$) measurements for specific soil types.
To characterize variations in the soil drying front depth, hydrological models serve as aids for accurately assessing soil water evaporation. Hydrus1-D is a one-dimensional numerical code that solves the Richard’s equation using linear finite element schemes (Simunek et al., 2005). The model allows estimation of actual evaporation rates based on soil water content and meteorological data. Previous studies (Assouline et al., 2013; Grifoll, 2013; Saito and Šimůnek, 2009; Saito et al., 2006; Šimůnek et al., 2008) have evaluated the use of numerical simulations to predict coupled liquid water, water vapor, and heat transport at spatial and temporal scales.

Soil evaporation has been extensively studied during the past century. However, none of the applied methods have adequately addressed the need for long-term, in-situ and real time monitoring of soil evaporation. The objectives of this paper were to: (1) develop a functional fully automated microlysimeter (FAML) capable of in-situ real-time monitoring of soil column mass changes with time; and (2) evaluate the FAMLs ability to monitor diurnal evaporation rates from bare soil by comparison with independent measurements and numerical simulations of soil water content and temperature.

Materials and Methods

Field Site

A field experiment was conducted in September 2013 at the Utah State University Agricultural Experiment Station (UAES) – Greenville Research Farm in Logan, Utah (N 41° 45’ 56”; W 111° 48’ 43”; 1382 m elevation). A 15 x 2 m area in a bare field was irrigated for 7 hours prior to instrument installation with MP Rotator 2000 series spray
nozzles (Hunter Industries, San Marcos, CA) spaced at 4.5 meters at an estimated application rate of 0.011 meters per hour. The soil at the measurement site is the Millville series classified as coarse-silty, carbonatic, mesic family of Typic Haploxerolls; a smooth-textured, friable medium-brown to dark-brown silty clay loam, which extends from the top surface to a depth of between 30 cm and 55 cm (SoilSurveyStaff, 2004). Selected physical properties of Millville silt loam are presented in Table 2.

The experimental design included installation of three fully automated microlysimeters (FAMLs – 1, 2, and 3), three manual microlysimeters (MMLs – 1, 2, and 3), an electromagnetic 10-sensor moisture profiling array (EnviroSCAN; Sentek Technologies-Campbell Scientific International, Logan, UT) and E-type thermocouples (Omega Engineering, Inc., Stamford, CT) to record air and soil temperatures (T_air, T_sfc, T_15, T_30, T_40, T_50 and T_80), as shown in Fig. 11.

**Soil Core Extraction and Instrument Installation**

A trailer-mounted hydraulic Giddings probe (Giddings Machine Co., Fort Collins, CO) was used to extract 75 mm diameter soil cores to a depth of 80 cm. Core samples were encased in an acetate liner (Hollinger and Isard, 1989), which was capped at the bottom with a 78 mm diameter steel drying can lid (Soil Moisture Equipment Corp., Santa Barbara, CA). A 100 mm diameter auger was used to enlarge the borehole to accommodate a 100 mm diameter housing for the FAML as illustrated in Fig. 12. The outer protective housing was made of 100 mm diameter, 750 mm long PVC casing. A PVC reducer was attached to the top to transition from 100 mm to 89 mm diameter. The
bottom of the housing was capped with a 100 mm diameter perforated floor drain. The perforated floor drain was used as base for a 10 kg load cell (Model LSP-10, Transducer Techniques, Inc., Temecula, CA) sandwiched between two aluminum plates. The top plate was attached to an 80 mm PVC sewer cap into which Plaster of Paris was injected for stabilization prior to installation of the soil column. The column was centered at the top within the 89 mm PVC reducer.

Subsequently, another set of soil cores were extracted with the Giddings probe for the MMLs and encased in acetate liners. The bottoms of these soil cores were also capped with steel drying can lids and were housed in the soil within 800 mm long PVC casings to facilitate independent periodic weighing of columns. The manual microlysimeters were similar in design to the FAMLs; only without load cells.

The experimental site was irrigated for 7 h to ensure thorough wetting of the soil profile, covered with plastic sheet, and allowed to drain overnight before the installation of three FAMLs, MMLs, an EnviroSCAN sensor array, and thermocouples. For the FAMLs, the soil columns were centered in the PVC casing such that the soil column walls remained isolated from the surrounding soil area. A requirement for accurate evaporation measurements is that the soil column does not touch the outer PVC casing walls. This was verified periodically by centering the PVC reducer around the acetate liner at the top surface. The FAML load cells were field-calibrated three times during the evaporation experiment with standard weights ranging from 5 to 500 g (Fig. 13 shows the load cell calibration results). The mass of the soil columns was continuously monitored and recorded with a resolution of 0.732 g (i.e., 0.146 mm depth of water evaporated) with
a CR5000 data logger (Campbell Scientific, Logan, UT). The load cell contained an internal bridge sensor to compensate for temperature effects. However, additional temperature corrections were made to remove diurnal temperature effects from the measured masses. The cumulative evaporation rate over the time period was estimated from the difference between the two masses divided by the circular cross-sectional area of the soil column. For each mm of water depth about 5 g of water was evaporated from the column.

Manual microlysimeters were weighed twice daily (DOY 249 – DOY 267) at 08:00 AM and between 07:00 – 08:00 PM, and repositioned within the PVC casing. Weighing of manual microlysimeters started on the day after irrigation and continued for 15 days.

Water Content Measurement: EnviroSCAN Sensor

A multi-sensor capacitance probe was used to continuously measure soil water content. To measure volumetric soil water content ($\theta_v$), the EnviroSCAN sensor works on the principle of a capacitance circuit, in which two conductors store charge upon application of an electric potential field. The EnviroSCAN sensor circuitry consists of an oscillator circuit (i.e., an inductor and a capacitor) that oscillates at a frequency determined by the capacitance of the soil (Fares and Polyakov, 2006). Changes in dielectric permittivity of the surrounding media (primarily due to water content variation) modifies the operating frequency of the circuit which varies from ~133 to ~105 MHz (Evett et al., 2006). Scaled frequency is determined in response to bulk dielectric...
permittivity (soil, water, and air) to estimate soil water content. Since the dielectric permittivity of water is high (80.4 - 78.5 at 20-25 °C; (Robinson et al., 2003)) when compared to air and solids (1 – 2.5 at 20-25 °C; (Robinson et al., 2003)), a change in soil water content will govern the capacitance measurements made by the sensor.

The electromagnetic (EM) sensor array used in this experiment consisted of ten capacitors, each comprised of two metal rings (acting as capacitor electrodes) that generate an oscillating electric field which extends into the access tube and surrounding soil. The sensors were spaced in 10 cm intervals, starting at 5, 15, 25, 35, 45, 55, 65, 75, 85, and 95 cm from top of the soil surface. The access tube was a 150 cm long PVC tube with an internal diameter of 70 mm, which holds the sensor array in place with a minimum air gap between the metal rings and the access tube wall.

Calibration of the EnviroSCAN sensor was performed in the laboratory in Millville silt loam soil. Evett et al. (2006) corroborated the need for soil-specific calibration to obtain the coefficients in Equation (1),

\[ \theta_v = A^* (SF)^B + C \]  \hspace{1cm} (1)

where SF is the scaling factor; A, B and C are calibration coefficients determined from laboratory calibration with soil samples of known volumetric water contents. Air dried soil was mixed thoroughly and passed through a 2 mm sieve. For calibration, a known mass of soil was placed in plastic bags and a measured volume of water (\( \theta_v \) ranging from 0 to 0.6) was added to each bag. The access tube of the sensor was centered within a 100
mm diameter PVC sewer casing. Soil mixed with water was poured into the gap between sewer casing and access tube. It was ensured that the soil was tightly packed and in intimate contact with the access tube. Scaled frequency values for soil samples with different volumetric water contents were recorded with a CR1000 datalogger (Campbell Scientific, Logan, UT). Water content calibration coefficients were determined from measured scaled frequency for known water contents using Equation (1).

The EnviroSCAN access tube was installed with a handheld auger. The Giddings probe was used to push the PVC access tube into the auger hole to ensure tight soil contact with the tube. The top end of the sensors rod was sealed with a protective casing. Data were collected for 12 days (DOY 249 – DOY 263; explained later) with measurements made every 30 seconds and averaged over one hour.

Temperature Observations

The effects of diurnal temperature changes on mass loss from FAMLs were studied in the experiment. Chromel-Constantan, E-type thermocouples were used to monitor temperature changes. A thermocouple (T_sfc) was inserted horizontally at the soil surface, while other thermocouples (T_{15}, and T_{30}) were inserted vertically into pilot holes at 15 and 30 cm depths below the soil surface. The thermocouple tip at the soil surface was carefully repacked to ensure that it is not more than a millimeter below the surface. A thermocouple (T_{air}) was mounted in air within a radiation shield at a height of 1 m to record air temperature. Thermocouples (T_{40}, and T_{80}) were installed in the air gap between the PVC casing and acetate liner (Fig. 12) to record the temperature of the air
surrounding the soil core at 40, and 80 cm depth. In addition, one thermocouple ($T_{50}$) was attached to the exterior of the PVC casing to record temperature at the soil-PVC casing interface. All thermocouple tips were coated with water-proof heat shrink tubes to avoid interference from stray voltages within the soil, and were calibrated in ice-water prior to the experiment. Thermocouples were scanned every minute (DOY 249-272) with the Campbell Scientific CR5000 datalogger.

**Meteorological Data**

A meteorological station, operated by the Utah AgWeather Network (AgWxNet) at Greenville farm provided real time weather data. The hourly data corresponding to the experiment period (DOY 249-272) was obtained from the weather station 300 m away from the experimental plot. The reference ET was calculated with the Penman-Monteith combination equation (ASCE-EWRI, 2005).

**Numerical Simulation of Soil Hydrodynamics**

HYDRUS 1-D numerically solves variably saturated water flow and heat transport simultaneously (Saito et al., 2006; Simunek et al., 2005). HYDRUS1-D was used to numerically simulate vertical water content profiles present during soil water evaporation over the experiment period.

In the numerical simulations, a freely draining 100 cm deep soil profile was used with a domain separation at 80 cm to allow separate mass balance calculations. Observations from the 100 cm profile represented measurements from the EM sensor
array while the 80 cm profile represented water content behavior in the FAMLs. The number of used layers (spatial discretization) was 101, with 10 observation nodes starting at \( z = -5 \) cm with spacing of 10 cm. These observation nodes were chosen to compare numerically simulated volumetric water contents with measured values from the EM sensor array at each time step. The initial water content was specified, in simulations for the 100 cm profile, using EM sensor measurements recorded at the start of the experiment. The SWC by van Genuchten (1980) and Ks parameters for Millville silt loam determined by Or and Hanks (1992) (Table 3) and the heat transport parameters for loam determined by Chung and Horton (1987) were used to parameterize HYDRUS 1-D. Measured soil surface temperatures were applied as the upper thermal boundary condition; and measured soil temperature at 80 cm depth was used as the lower thermal boundary condition. Calculations were performed for 23 days from September 6 (DOY 249) to September 28 (DOY 272), 2013.

**Results and Discussion**

**Evaporation Rates from Field Measurements**

The functionality of the FAMLs was evaluated based on comparison with MML measurements and water balance calculations based on the EM sensor array measurements between DOY 249 and 261. The cumulative measured water loss from the FAMLs, MMLs, and EM sensor array during the experiment period is plotted in Fig. 14. The plotted curves represent the mean value of three repetitions for FAML and MML each, and the error bars indicate the standard deviation from the mean. The high-
frequency, real-time measurements with the FAMLs clearly show the diurnal cycles with lower evaporation rates at night and higher rates during day time. The sensitivities of the load cells are evidenced by the mass increase during the precipitation events on DOYs 255-256 and 260-261.

Data analysis started on DOY 249 following instrument installation. The MML measurements diverged from FAML evaporation rates after the first five days as shown in Fig. 14. The 80 cm long soil cores of the MMLs were extracted twice a day to determine the mass loss, except for DOY 255-256 when a rainfall event occurred. After the soil cores were manually weighed, they were repositioned within the PVC casings. In the process of extracting and reinserting the MML soil cores, they underwent slight consolidation. The soil compaction mainly occurred when the soil was wet, which was evidenced by the settlement of the top surface within the acetate liner. This settling of the soil likely caused an increased aerodynamic resistance at the soil-air interface, thereby reducing evaporation rates in the MMLs.

As a second means for comparison, water contents measured with the EM sensor array were converted to cumulative soil water loss considering the change in water content with time for each soil layer. The net cumulative water loss for the 80 cm soil profile was compared with the MML and FAML measurements (Fig. 14). The raw EM sensor water content measurements exhibited sensitivity to temperature fluctuations, which suggested the need for implementation of a temperature correction. A previous study by Wraith and Or (1999) clearly demonstrates changes in dielectric constant and electrical conductivity in response to soil water content and soil temperature fluctuations.
for time domain reflectometry (TDR) measurements. They showed that at low water contents in Millville silt loam, an increase in soil temperature increased the bulk apparent dielectric constant of the soil; hence, overestimating water contents at a higher soil temperature and underestimating at lower soil temperatures. Evett et al. (2006) demonstrated temperature effects on measurements with the EnviroSCAN sensor. They showed that an increase in temperature moderately affected the dielectric constant of soils which in turn affected the water content measurements, suggesting the necessity for soil-specific calibrations that account for temperature fluctuations. Following these studies, the EM sensor array readings were corrected for temperature effects using the soil-specific calibrations (Evett et al., 2006). Fig. 15 depicts EnviroSCAN water content measurements corrected for temperature effects for each layer down to a depth of 100 cm. Water redistribution occurred from the surface down to 30 cm depth and no significant change in $\theta_v$ was observed for all layers below 30 cm. This explains differences in EM sensor array-based early morning evaporation rate estimates in the field soil and the FAML measurements. Moreover, the FAMLs recorded an increase in mass equivalent to 6 mm in the soil columns following precipitation on DOY 255-256, while the EM sensor array measurements yielded a mass increase of only 2 mm. The EnviroSCAN sensor response window was centered at 5 cm below the surface which led to underestimation of surface recharge. Hence, the inability of the EM sensor array to accurately capture precipitation was due to its reduced observation window. This sensor response limited the comparison with the FAMLs after the first rainfall event. Owing to
these variations, only a few days of data was collected following the first precipitation event.

**FAML Measurements Compared with Numerical Simulations**

A comparison of HYDRUS-1D simulated and FAML measured cumulative water losses plotted together with the potential evaporation rate for DOY 249 – 271 is shown in Fig. 16. An improved agreement of evaporation rates was seen between simulated and measured data for 23 days of the experiment period, although a small discrepancy was still observed towards the end (after DOY 264). The larger water loss from the FAMLs, in comparison with the simulations, is most likely due to higher subsoil temperatures in the soil column, which may have induced higher water vapor transport towards the surface during the night time redistribution and early morning evaporation (Assouline et al., 2013). In a previous study by Evett et al. (1995) it was found that for a capped plastic microlysimeter surface temperatures were cooler and below surface temperatures were significantly higher in the lysimeter cores than in the surrounding field soil. With this in mind, our goal was to understand the effects of overall diurnal temperature variation on evaporation rates. Fig. 17 shows variation in temperatures at different depths in the soil core casing and in the surrounding field soil along the 80 cm soil profile over 23 days of the experiment period. Data analysis beginning with DOY 249 shows a decreasing temperature trend for all depths in the soil profile as a result of decreasing air temperature. However, the temperatures below 40-cm depth in soil cores were higher and exhibited damped amplitude, suggesting warmer subsoil within the microlysimeters.
Amplitude changes for 50 and 80 cm depths are insignificant; hence gradual attainment of temperature minima for depths below 40 cm indicates minimal amplitude fluctuations leading to warmer subsurface soil for longer periods of time. It is interesting to note that during the course of weighing the MMLs, water vapor condensation was observed along the acetate liner walls near the surface each morning and the liner appeared dry during evening measurements. Although the MML measurements deviated from the expected results, this observation corroborates the assumption that larger thermal gradients (as recorded by thermocouples) led to water redistribution and vapor condensation during night time leading to higher evaporation rates during early morning from the microlysimeters. Therefore, cooler surface temperature during the nighttime and higher temperature during the daytime caused elevated water redistribution and vapor transport during night time.

The simulated evaporation rates were obtained based on the assumption that the system is at steady-state. This assumption leaves the diffusion of water vapor towards the surface, i.e., as a result of variations in temperature gradients at night, unaccounted for (Grifoll, 2013). Owing to this, simulation results did not track the higher early morning evaporation which led to underestimated evaporation rates towards the end of experiment. The numerical simulations were validated by comparing measured temperature dynamics with the simulated temperatures at different depths within the soil profile. Fig. 18 depicts measured and simulated temperatures for depths of 15 and 80 cm. The amplitude and phase of temperature variations are similar indicating a realistic simulation of heat transport along the soil profile.
Summary and Conclusions

In this study, the applicability and potential limitations of a fully automated microlysimeter (FAML) for measurement of evaporation from bare soil was evaluated. The mass loss from the FAMLs was continuously monitored and recorded, yielding instantaneous evaporation rates. First, the applicability of the FAMLs was compared with measurements from manually operated microlysimeters (MMLs) and an EM sensor array. The net water loss was determined from mass changes with time. The MML based evaporation rates significantly diverged from the other field measurements as a result of a settled soil column surface. The EM sensor array based cumulative water loss showed a similar trend (< 2 mm) to declining water content when compared with FAML measurements. However, the EM sensor array did not capture part of the precipitation following the first rainfall event due to the lack of vertical axial sensitivity and to its limited window response. Hence, the comparison of the FAML and the EM sensor measurements was limited to 12 days.

Second, comparison with HYDRUS-1D numerical simulations validated the FAML measured cumulative water loss until DOY 264. Disparity between the approaches towards the end of the experiment is essentially due to higher thermal gradient in the soil column causing vapor condensation at the surface during nighttime. This led to enhanced evaporation during early morning hours from the moist surface. Although there is no measured data to support condensation occurring at night, the visual observation of water vapor condensation along the acetate liner walls of MML near the surface each morning provides evidence for water redistribution and vapor condensation during the night time.
The FAML is sensitive to any variations in mass, and agrees quite well with the precipitation measured at the nearby weather station. Overall, presented results indicate that the FAML approach has potential for extending the “operational life” of the microlysimeter. The results from the present FAML experiment provide reasonable estimates of in-situ diurnal bare soil evaporation rates. However, further investigation to track the amount of vapor redistribution towards the soil surface will be beneficial for improvement of FAML design.

References


Table 2. Physical properties of Millville Silt Loam (Wraith and Or, 1999)

<table>
<thead>
<tr>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>Bulk Density (Mg/m$^3$)</th>
<th>Surface Area (m$^2$/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>55</td>
<td>16</td>
<td>1.27 – 1.62$^a$</td>
<td>73</td>
</tr>
</tbody>
</table>

$^a$Bulk density range measured at 10 cm intervals within the soil profile down to 80-cm depth.
Table 3. Van Genuchten (1980) SWC parameters and $K_s$ for Millville silt loam soil used to parameterize HYDRUS 1-D

<table>
<thead>
<tr>
<th>$\theta_r$</th>
<th>$\theta_s$</th>
<th>$\alpha$ (1/cm)</th>
<th>$n$</th>
<th>$K_s$ (cm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.045</td>
<td>0.4343</td>
<td>0.02627</td>
<td>1.429</td>
<td>2.506</td>
</tr>
</tbody>
</table>

$\theta_r$ and $\theta_s$ are the residual and saturated water contents, respectively; $\alpha$ and $n$ are the van-Genuchten (1980) empirical SWC parameters.
Fig. 11. Sketch depicting the experimental setup. Three fully automated microlysimeters (FAMLs-1, 2, and 3; solid circles) were randomly arranged with three manual microlysimeters (MMLs-1, 2, and 3; dashed circles). An electromagnetic sensor (EnviroSCAN) was installed within the experimental site to measure water content in the soil profile to 1m depth. Thermocouples were installed to record temperatures: $T_x$ represents thermocouple position below soil surface (shown in Fig. 12) and $T_{air}$ represents air temperature mounted at a height of 1 m.
Fig. 12. Sketch depicting a fully automated microlysimeter (FAML).
Fig. 13. Load cell calibration results representing the mean of three separate field calibrations. The error bars indicate the standard deviation from the mean.
Fig. 14. Measured cumulative water loss from the FAMLs, the MMLs, and EM sensor array during the experiment period. Measurements include a rainfall event that occurred on DOY 255-256.
Fig. 15. Water content measured from an EM sensor array at an interval of 10 cm over 100 cm profile with sensor window centered at 5 cm. No significant change in water content is observed for layers below 30 cm.
Fig. 16. Measured cumulative water loss from the FAMLs (symbol), corresponding HYDRUS 1-D simulated cumulative evaporation (dashed line), and reference ET (dotted line) estimated with the Penman-Monteith equation.
Fig. 17. Measured temperature at different depths – in soil (at <1 cm, 15 cm, and 30 cm), in air gap (at 40 cm, and 80 cm) between soil column and PVC casing of automated microlysimeter, and at soil-PVC interface (50 cm depth), for experiment period (DOY 249-272).
Fig. 18. Measured and simulated soil temperatures at depths 15, and 80 cm.
CHAPTER IV
SUMMARY AND CONCLUSIONS

This study evaluated the accuracy of evaporation rate estimates measured by the heat pulse probe (HPP) under laboratory conditions, and the fully automated microlysimeter (FAML) under field conditions. In the case of HPP method, the near surface soil heat fluxes and subsurface evaporation rates gave good estimates in comparison with the mass balance method. As expected, due to the misaligned installation angle of the HPP array, errors were introduced by overlapping temperature sensing needles. The influence of shifted installation angle was accounted for with the newly developed ‘z’ spacing algorithm. Below the depth of 6 mm, reliable soil heat flux estimates could be obtained with the HPP following the new spacing correction method. The measurements and analysis in this study further identify the inconsistencies recorded in temperature due to the overlapping needles. This resulted in incorrect soil heat fluxes for a finer i.e., 3 mm observation grid. Hence, a coarser observation grid of 6 mm was employed. The on-board optimization of thermal properties from temperature rise measurements gave real-time estimates of thermal conductivity and thermal diffusivity that facilitated the subsurface evaporation estimates at a millimeter-depth scale. Hence, these findings extend the application of HPP in shallow soil surface layer. To obtain accurate measurements of soil heat flux and subsurface evaporation rates, the effect of altered installation angle must be taken into account.

In the case of FAML, the mass loss was continuously monitored and recorded, yielding instantaneous evaporation rates and were compared with measurements from
manual microlysimeter, EM sensor array and HYDRUS-1D numerical simulations. The manual microlysimeter (MML) measurements were compromised after first 5 days in the experiment. The manual handling of the soil core resulted in lowering of the soil surface, hence deviates the estimates from the actual trend. The comparison with EM sensor array gave good estimates of cumulative water loss to declining water content with deviations less than 2 mm. However, this comparison of FAML with EM sensor array lasted only for 12 days. After the first precipitation, EM sensor array accounted only for 2 mm increase in water content whereas the FAML recorded a rise of 6 mm. The EM sensor exhibited a smaller response window which led to deviation from the expected trend. HYDRUS-1D numerical simulations validated the FAML measured cumulative water loss. Disparity between the approaches towards the end of the experiment is essentially due to the higher thermal gradient in the soil column causing vapor condensation on the inside of the acetate liner walls of FAML during nighttime. This possibly led to higher evaporation rates from the FAML during early mornings.

In conclusion, this study shows that it was feasible to estimate evaporation rates in-situ, and in real time for a prolonged period with the aid of HPP (near-surface) and FAML (larger soil depth). Nonetheless, it is desirable to investigate the performance of HPP in estimating evaporation occurring within the soil under natural field conditions. Implementation of fine-scale measurement technique near surface combined with the measurements made from a longer soil profile can provide researchers with improved initial and boundary conditions for various numerical models. Additionally, by taking
proper correction methods into account, the suggested methods can help users decide an applicable method suiting their irrigation and agricultural needs.