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# Short grass actual evapotranspiration and its dependence on soil water status

Diploma Thesis

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# Declaration

I hereby declare this M.SC. thesis on “Short grass actual evapotranspiration and its dependence on soil water status” is my independent work and effort, carried out under the guidance of my supervisor. All scientific literature and all other information sources used in it have been dully acknowledged in the text and in the list of references in the end of the thesis. As an author of the thesis I declare that, in association with writing it, I did not infringe copyrights of third persons.

Prague,……                                        Signature

## Acknowledgement

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I would like to thank my parents for allowing me the opportunity to carry out this experience of personal and academic growth. Also to my friends and family who despite the distance and time kept supporting me during my two years of studying. And finally to G.C, who made me enjoy my time here and without him things would have never been the same.

# Short grass actual evapotranspiration and its dependence on soil water status

## Summary

A weighable Smart-Field Lysimeter (30 cm diameter, 30 cm depth) located in the experimental field of the Czech University of Life Science in Suchdol, Prague, was used to measure directly the daily actual evapotranspiration (ETa) of a short grass surface, neither artificially irrigated nor fertilized, during a period of two years, 26 April, 2013 to May 1, 2015. The primary data recorded by the lysimeter contain periods of rain or snowfall and also some the noise and gaps. In this project, only daily actual evapotranspiration sums from midnight to midnight were calculated and only for rainless days.

Secondly, using daily meteorological data from the weather station at the experimental site, the reference crop evapotranspiration (ETo) was calculated with the FAO 56 Penman-Monteith method. At last, the calculated actual evapotranspiration from the lysimeter has been contrasted with the reference evapotranspiration and their ratio was related to the soil water content at 5 cm.

The actual evapotranspiration measured with the lysimeter has a seasonal behaviour similar to that of the reference crop evapotranspiration. However, the ratio or the difference of the two does not have a pronounced seasonal behaviour. It is recommended that for continuity of this study, the original Penman-Monteith equation should be applied to estimate the impact of the bulk surface resistance and LAI on ET.

**Key words**: lysimeter, soil water content, actual evapotranspiration, reference crop evapotranspiration, FAO56 Penman-Monteith equation.

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# CHAPTER 1

# 1. INTRODUCTION

Evapotranspiration is one of the most important processes of the hydrological cycle, considering precipitation as the most important. The calculation of actual evapotranspiration (ETa) is not an easy task. However, it is essential for the water management of fields and crops as well for the design of irrigation systems and of catchment water balance calculations. There are different methods that can be used for the estimation of ETa. The large weighing lysimeters have been common instruments used for measuring evapotranspiration, as well as other fluxes of the hydrological cycle. They are considered as ideal devices for accurate and reliable measurements (Shuttleworth, 2012). However, because of their size they require large areas to be installed as well as they are costly instruments. Therefore, with the advances in technology, the usage of high definition small lysimeters has grown as a more reasonable alternative, because of an easier transportation to the studied fields and lower cost (Goss and Ehlers, 2009).

This research has focused on the usage of a small lysimeter for measuring ETa in short grass and to compare it with the reference evapotranspiration crop obtained using FAO56 Penman-Monteith equation. This is the first time when, after the installation of the lysimeter in the experimental field, the data recorded for a longer period have been analysed from a macro perspective, which made it possible to evaluate the advantages and disadvantages of the usage of a small lysimeter.

## 1.2 Objectives of thesis

To estimate actual evapotranspiration (ETa) of non-irrigated, non-fertilised short grass on Chernozem loamy soil in Central Bohemia. The estimation will be based on two years of measurements with a weighing lysimeter, accompanied by other weather and soil water measurements. To compare this ETa with the FAO 56 reference crop evapotranspiration and with the soil water content, in order to contrast the ETa measured with the potential evapotranspiration of the same grass canopy.

## 1.3 Hypothesis

The actual evapotranspiration can be quantitatively related to the potential one if one takes regard of the soil water status and, perhaps, the energy balance of the evaporating surface.

# CHAPTER 2

# 2. REVIEW OF LITERATURE

## 2.1 Theoretical Framework

### 2.1.1 Lysimeter

**History of the Lysimeter**

The usage of the lysimeter dates since 300 years ago. Kohnke and Dreibelbis, two scientists who made an extensive literature survey related to the lysimeter, covering almost tree decades of research until 1939, mentioned over 150 installations and included around 500 references. According to their broad review, most lysimetric investigations in the hydrological field in Europe before the 19th century were related to water percolation through the upper soil and used filled-in lysimeters (Kohnke and Dreibelbis, 1940).

The first to carry out a study using an instrument similar to the actual lysimeter was the French mathematician and meteorologist Phillipe De la Hire in Paris. In 1688, he wanted to find out about the origin of springs. He used three different vessels made out of lead with different depths and filled them with soil. (De la Hire, 1720; according to Kohnke and Deibelbis, 1940) Each lysimeter had in the bottom a pipe set to measure the percolated water from the rainfall and snow. With his experiment he was able to conclude that rainfall did not contribute sufficiently for the flow of natural spring and that plants could avoid water percolation (Goss and Ehlers, 2009).

A hundred years later, taking in account De la Hire’s findings, John Dalton installed in England in 1796 the first lysimeter with run-off provision. He studied the evaporation from land to the atmosphere using the lysimeter and was able to derive the actual evapotranspiration by the changes in soil moisture content (Rodda and Ubertini, 2004).

In 1870, Lawes, Gilbert and Warington developed at Rothamsted, England the first monolith lysimeter, in which the soil inside the vessel was kept undisturbed. This allowed them to recollect information about water drainage in the natural environment (Kohnke and Dreibelbis, 1940).

In Germany, Van Seelhost was the first to install weighting lysimeter in the year 1906 (de Santa Olalla and López, 1992). Later in 1937 at Coshocton, Ohio, the Soil

Conservation Service built 11 lysimeters in which they incorporated different features for a better measurement and recording of water cycle's data. Among their improvements, there were first soil-block lysimeters with automatic weighing devices (Harrold and Dreibelbis, 1958).

Some decades ago the usage of lysimeter by the majority of research and experimental institutions would have been seen as a remote idea. However, with the technology advances, this type of instruments and equipment has gained a new impulse in the agro-meteorological research.

### Lysimeter definition

The word lysimeter derives from the Greek word l*ysis,* which means dissolution or leaching, and *metron,* which means to measure. The lysimeter is a cylindrical container introduced into or filled with soil on which grass or other vegetation can grow (Jones, 1992). Its purpose is to mimic in the closest way possible the natural environment of the soil in order to measure the different inputs and outputs in the hydrological system. This last is understood as a chain of reservoirs, that store water and allow to measure the inputs and outputs during a time period (Hudak, 2004). The lysimeter is a soil column located in the field, with its surface at ground level though which the precipitation water infiltrates and later evaporates back. The weight changes in the soil column are measured, which allows the quantification of the infiltrated water or of the evapotranspiration by means of the weight increase or reduction, respectively, based on the water balance. In the water balance equation the soil volume of interest is seen as a storage reservoir, in which the changes in the soil water content should be equal to difference between the added water and the lost water during the same time period (Hillel, 1982). Predominantly the lysimeter is used for the measurement of actual evapotranspiration (ETa), in most cases, crop evapotranspiration (ETc). If there is no vegetation in the lysimeter, we can measure the bare soil evaporation. This field method can also be used for determination of the percolation rate and volume.

According to Aboukhaled and Alfaro (1982) the weighing lysimeters are considered as the best available equipment to measure accurately the actual evapotranspiration ETa and (if the conditions correspond to the reference crop) the reference crop evapotranspiration ETo and to calibrate various evapotranspiration models.

### Types of Lysimeters

There are different types of lysimeters, which can be classified according to their use, drainage or weighing. The first type measures the evapotranspiration based solely on the difference between the added and drained water amount. (Torbjörn and Odin, 1978) The second type utilises the weight changes in the soil column to estimate the evapotranspiration from the variation of water gains and losses. The weighing lysimeters can be of the mechanical or the hydraulic type, depending on how the soil column weight is determined. The bottom of the soil column in the lysimeter (so-called tension-free lysimeters) can be open to free drainage or a certain soil water tension is maintained there (tension lysimeters), either constant or regulated in accordance with the suction of water in the surrounding native soil at the same depth (tension lysimeter), or a positive pressure is maintained there (either constant or maintained in accordance with the groundwater table depth in the surroundings), in which case we speak about water-table lysimeters (Schwaerzel and Bohl, 2003). On the other hand, the lysimeters can be also classified depending on how the soil column has been collected.  In the monolith lysimeter, the soil inside in the vessel has not been disturbed, which keeps the soil profile in the lysimeter closer to the natural environment, while in the disturbed lysimeter the soil profile is artificial (Mueler and Saparov, 2013).

Sometimes the word “lysimeter” refers to suction cups, plates or wicks installed in the soil for the purpose of taking soil solution samples, without any explicit regard to soil water balance (e.g. Salazar et al., 2014). On a very small spatial scale, especially for the bare soil evaporation and condensation measurements, some researchers used microlysimeters, of which the diameter and the depth was typically few centimetres only (Boast and Robertson, 1980). These measurements have been recently automated (e.g. Ucles et al. 2013).

### 2.1.2 Evapotranspiration Process

The evapotranspiration (ET) is understood as the combination of two intrinsic processes, the ground surface evaporation and the transpiration of the leaves and other organs of vegetation, in which both processes water is being transferred into the atmosphere in form of vapour.

### Evaporation

Evaporation, seen from a pure physical aspect, it is the change from liquid state to gaseous state of water. In hydrology, the evaporation process occurs when the water at a given natural surface is transformed from liquid to gaseous state and, incorporated into the water cycle in the atmosphere as vapour. The process of evapotranspiration requires high amount of energy to transform the state of water from liquid to vapour and to remove the vapour from the evaporating surface (Allen and Pereira, 2006). The evaporation depends on the amount of water present and the available energy (solar radiation), which in turn depends on the region's climate (Davie, 2008). Evaporation can take place from open water surfaces such as lakes, rivers or oceans, or also from bare soil surfaces. This last case is very important to consider for agriculture, because important amounts of water can be depleted from the soil during the preparation of the soil and during the first stages of the growing season. The soil surface may remain largely bare throughout this period. Consequently, the evaporation occurs mainly from the soil and the growth of young plants can be restricted at the stage when they are most vulnerable (Hillel, 1982)

### Transpiration

Transpiration is the principal mechanism of soil-water transfer to the atmosphere when soil surface is covered with vegetation (Hillel, 1982). It is the transport process of water from the soil, through the plant to the phase change in the substomatal cavities (Novak, 2012). The transpiration of water that moves out of the leaves and into the atmosphere is the driving mechanism for the ascent of water from the roots and for the rate which water is taken in through the roots (Ward and Trimble, 2003). First, the water in the soil is taken up by osmosis by the hair roots, after which it travels upwards through the xylem and through the tissue of the leaves. Located in the epidermis of the leaves, the stomata are the plant structures responsible for releasing water vapour from the plant into the atmosphere or retaining it in the plants, working as pores that open and close, regulating the exchange of vapour.

### Evapotranspiration (ET)

Both evaporation and transpiration processes are interdependent and simultaneous, being difficult to measure separately. One process can be predominant over the other depending on the crops development stage, influencing the level in which some factors affect ET. The solar radiation, soil water availability, wind speed, humidity and air temperature are the main weather factors that influence evapotranspiration.

However, some other factors to consider are the crop characteristics and the environmental and management conditions of the soil, such as salinity, use of agrochemicals, soil compaction and the lack of oxygen (Allen et al., 1998).

Evapotranspiration is normally expressed as evapotranspiration rate in units of water depth per unit time, usually in millimeters (mm) per minute, hour, day or year (e.g. mm day$^{-1}$). Alternatively, the evapotranspiration can be express ad the total depth of water lost over (unit or non-unit) period time.

## 2.1.3 Types of Evapotranspiration

### Actual evapotranspiration (ETa)

Actual evapotranspiration (ETa) is the evapotranspiration that actually takes place. It included all possible effects, such as those of soil moisture, land cover heterogeneity, soil surface wetness, water interception on plant surfaces and, of course, the variability of weather conditions (Melesse and Abtew, 2014). ETa can be measured or estimated from ETp or ETo or using the complementary concept (e.g. Morton, 1983) for a specific crop in a specific situation, taking in count that water is limited and the effect of all other factors can be accounted for in some way.

### Potential evapotranspiration (ETp)

According to Penman (1965) the potential evapotranspiration is understood as “the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water.” However, the FAO and the scientific community because of its ambiguity have discouraged the usage of this term. Hence, the term reference crop evapotranspiration (ETo) is preferred. There are also other potential evapotranspiration concepts, such as those by Thonwaite (1948) and Morton (1983).

### Reference Crop Evapotranspiration (ETo)

Reference crop evapotranspiration or reference evapotranspiration is understood as the evaporation rate from a reference surface, which is covered by hypothetical reference vegetation in optimal conditions. According to Allen et al. (1998), the reference crop is assumed to have a height of 0.12 m, a fixed surface resistance (rs) of 70 sec m-1 and an albedo (α) of 0.23, which resembles green grass of uniform height, actively growing and adequately watered. This concept is generally more accepted than the potential evapotranspiration because it defines in quantitative terms a specific type of grass as the reference crop (Irmal et al., 2014). More specifically, the assumed optimal conditions are optimal water and nutrient supply and absence of stress by any pest or disease. These well-defined characteristics make it easier to measure the evaporation demand of the atmosphere independently from the crop and soil characteristics and management practices (Allen et al., 1998). Therefore, meteorological data of a specific location at a particular time can be used to calculate ETo. They include solar radiation, relative humidity, wind speed and temperature. The FAO56 Penman-Monteith method, which is based on the reference crop instead of grass (Jensen et al., 1990), mainly because it has deep roots and therefore does not suffer from water stress often.

## 2.1.4 Determining Evapotranspiration

### Soil water balance

The soil water balance is based on the law of conservation of mass, assuming that water's mass cannot come from nothing or disappear into nothing. Hence changes in soil water content are equal to the amount of water inflow minus the amount of water outflow.

Evapotranspiration can be determined by calculating the amount of water inputs and outputs in a volume soil during a specific period of time. The precipitation, irrigation, capillary rise and surface or subsurface run on are considered as the inflows, contrary to surface and subsurface runoff, evapotranspiration and deep percolation which are considered as looses. If all other fluxes are known, then the evapotranspiration (ET) can be inferred from the changes in the soil water content. The interaction between soil water storage and evapotranspiration is an important component of vadose zone hydrology (Hillel, 1982).

### Soil water balance equation:

$ET = I + P - RO - DP + CR \pm \Delta SW$ (1)

where:
ET: evapotranspiration
I: irrigation
P: precipitation
RO: runoff minus run on
DP: deep percolation
CR: capillary rise
$\Delta$SW: the change in soil water content (positive in the case of increase).

All terms in this equation are expressed in the same units, e.g. mm per unit time or mm per period. Some fluxes can be neglected in some cases, such as run on and runoff, deep percolation and capillary rise. The soil water balance method can be principally used for ET estimation for any period and under the use of lysimeter.

### Energy balance equation for an evaporating urface

The energy balance equation is based on the law of conservation of energy, assuming that energy cannot be created or destroyed; it can only be transformed. On that account, the amount of energy entering a surface that has no thermal capacity must be equal to the energy exiting the surface during the same time period. This balance allows us to estimate the latent heat flux (carried by evapotranspiration), if all other energy fluxes are known. The following energy balance equation for an evaporating surface includes only the main four components of the balance, excluding others like the energy for photosynthesis or the advection (the net horizontal transfer of heat and water vapour by the wind):

$$R_n - G - \lambda ET - H = 0 \quad (2)$$

where Rn is the net radiation flux [MJ m-2 d-1],G is the soil heat flux [MJ m-2d-1], λET is latent heat flux [MJ m-2 d-1] and H is the sensible heat [MJ m-2 d-1] that heats up the air.

According to Hillel (1982), the solar radiation is the major driver of the energy balance, of which greatest portion is absorbed by the surface, conducting soil heat flux (G). From the absorbed solar energy, the largest part is used by the evaporation of water into the atmosphere (the latent heat flux), as long as there is enough water near to the surface. Therefore the evapotranspiration depends highly on the amount of available energy. However, if the surface is dry, the largest portion of the absorbed solar energy goes back to the atmosphere as the sensible heat (H).

**Penman Equation**

Penman (1948) developed an equation for estimating the evaporation for open water surfaces using climatological records (Allen et al., 1998). Combining the energy balance and an aerodynamic formula, he developed the following equation:

$$\lambda E = \frac{[\Delta(R_n - G)] + (\gamma E_a)}{(\Delta + \lambda)} \quad (3)$$

where:

λE= latent heat flux [MJ m-2 d-1],

Δ= slope of the saturated vapour pressure curve [kPa °C-1],

Rn = net radiation flux (MJ m-2 d-1],

G = sensible heat flux into the soil [MJ m-2d-1],

γ = psychrometric constant [kPa °C-1],

Ea = vapour transport of flux due to wind speed and saturation deficit [mm d-1].

**Penman-Monteith Equation**

The Penman equation was adapted by Monteith (1965) for the bare soil and cropped surfaces, taking in count specific parameters of these surfaces, such as by surface resistance and roughness. The resulting equation is known as the Penman-Monteith equation, which may be expressed for daily values as:

$$\lambda ET_o = \frac{\Delta(R_n - G) + [86,400\,\frac{\rho_a C_p (e_{s^\circ} - e_a)}{r_{av}}}{\Delta + \gamma(1 + \frac{r_s}{r_{av}})} \qquad (4)$$

where:

R*n:* net radiation [MJ m-2 day-1],

G: soil heat flux [MJ m-2 day-1],

(es - ea): vapour pressure deficit of the air [kPa],

ρa: the mean air density at constant pressure

cp: specific heat of the air

Δ: slope of the saturation vapour pressure temperature relationship [kPa °C-1]

γ: psychrometric constant [kPa °C-1]

rs: (bulk) surface resistances

ra: aerodynamic resistances

**FAO 56 Penman-Monteith method**

By simplifying the terms containing latent heat of vaporization, air density, and aerodynamic resistance in the Penman-Monteith equation (equation 5) and adopting a constant value 70 s $m^{-1}$ for the surface resistance, the FAO 56 Penman-Monteith method was formulated and established in 1990 as the standard method for determining ETo (Allen et al., 1998). This method is based on the hypothetical reference crop similar to short grass characteristics of which have been described above. However, it is possible to calculate other crops' evapotranspiration with the used of ETo and the appropriate crop coefficients. The reference crop evapotranspiration can be estimated by simplified methods, even when some weather data are missing. The FAO 56 Penman-Monteith equation for the daily scale is defined as follows:

$$\lambda ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad (5)$$

where:
ETo: reference evapotranspiration [mm day-1],
Rn: net radiation at the crop surface [MJ m-2 day-1],
G: soil heat flux density [MJ m-2 day-1], (neglected for daily calculations, being too small compared to Rn)
T: air temperature at 2 m height [°C],
u2: wind speed at 2 m height [m s-1],
es: saturation vapour pressure [kPa],
ea: actual vapour pressure [kPa],
es - ea: saturation vapour pressure deficit [kPa],
Δ: slope vapour pressure curve [kPa °C-1],
γ: psychrometric constant [kPa °C-1].

### 2.1.5 Meteorological requirements for the FAO 56 Penman-Monteith method

Several types of data are required for the calculation of the ETo with the FAO 56 Penman-Monteith equation, such as the location’s altitude above the sea level in meters (m), the latitude of the location in radians and the serial number of the particular day within the calendar year (so-called Julian day), additionally to the average air temperature, humidity, radiation and wind speed for the calculated period of time. Allen et al. (1998) published a guideline, in which all the steps for arriving to ETo calculation are described in detail:

**Air temperature**

$$T_{mean} = \frac{T_{\max} + T_{\min}}{2} \qquad (6)$$

where:

T mean: mean daily air temperature [°C],

T max: maximum daily air temperature [°C],

T min: minimum daily air temperature [°C].

**Slope of saturation vapour pressure curve (Δ):**

$$\Delta = \frac{4098[0.6108\exp(\frac{17.27 * Tmean}{Tmean + 237.3})]}{(Tmean + 237.3)^{2}} \quad (7)$$

where:

Δ: slope of saturation vapour pressure curve.

T mean : mean daily air temperature, [ºC] (Eq. 6),

exp = 2.7183 (base of natural logarithm).

**Psychrometric constant (γ)**

The psychometric constant is calculated this way:

$$\gamma = \frac{C_p P}{\varepsilon\lambda} = 0.000665P \quad (8)$$

where:

γ: psychrometric constant [kPa °C-1],

*P:* atmospheric pressure [kPa],

λ: latent heat of vaporization, 2.45, [MJ kg-1],

cp: specific heat at constant pressure, 1.013x10-3[MJ kg-1 °C-1].

**Saturated vapour pressure (es)**

The saturated vapour pressure is expressed in kilopascals (kPa) and it is obtained as the mean of maximum and minimum daily saturated vapour pressures:

$$e_s = \frac{e(T\max) + e(T\min)}{2} \quad (9)$$

$$e(T\max) = 0.6108\exp\left[\frac{17.27T_{\max}}{T_{\max} + 237.3}\right] \quad (10)$$

$$e(T\min) = 0.6108\exp\left[\frac{17.27T_{\min}}{T_{\min} + 237.3}\right] \quad (11)$$

where:

T max: maximum daily air temperature [ºC].

T min: minimum daily air temperature [ºC].

**Actual vapour pressure (e**a)

The actual vapour pressure (kPa) is derived using the maximum (RH max) and minimum (RH min) daily relative humidity:

$$e_a = \frac{e(T\max)\left[\frac{RH\max}{100}\right] + e(T\max)\left[\frac{RH\min}{100}\right]}{2} \quad (12)$$

where:

ea : actual vapour pressure [kPa],

e (): saturation vapour pressure at daily minimum temperature [kPa],

e (): saturation vapour pressure at daily maximum temperature [kPa], RH max: maximum relative humidity [%],

RH min: minimum relative humidity [%].

### Inverse squared relative distance Earth-Sun (dr)

Julian day (J) is needed for the inverse relative distance Earth-Sun

$$dr = 1 + 0.033\cos\left[\frac{2\pi}{365}J\right] \quad (13)$$

where:

dr: inverse squared relative distance Earth-Sun,

J: Julian day.

### Solar declination (δ)

Julian day (J) is also needed for the solar declination calculation:

$$\delta = 0.409\sin\left[\frac{2\pi}{365}J - 1.39\right] \quad (14)$$

where:

δ: solar declination [radians], i.e. the angle between the equatorial plane and the Sun-Earth connecting line,

J: Julian day.

### Sunset hour angle (ωs)

Using the latitude in radians and the solar declination, the sunset hour is obtained:

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \quad (15)$$

where:

ωs: sunset hour angle [radians],

φ: latitude [radians],

δ: solar declination [radians].

### Extra-terrestrial radiation (Ra)

The extra-terrestrial radiation hitting a unit horizontal surface outside the Earth’s atmosphere is obtained as:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [(\omega_s \sin\varphi \sin\delta) + (\cos\varphi \cos\delta \omega_s)] \quad (16)$$

where:

Ra: extra-terrestrial radiation [MJ m-2 day-1],

Gsc: solar constant = 0.0820 [MJ m-2 min-1]

dr: inverse squared relative distance Earth-Sun,

ωs: sunset hour angle [radians],

δ: solar declination [radians].

### Net shortwave radiation (Rns)

$$R_{ns} = (1 - \alpha) R_s \quad (17)$$

where:

Rns: net shortwave radiation, [MJ m-2 day-1],

α: albedo coefficient (0.23 for the hypothetical grass reference crop), Rs : the incoming solar radiation [MJ m-2 day-1], as average daily net radiation obtained from a pyrometer at the weather station for a 24 h period.

**Clear sky solar radiation (Rso)**

$$R_{so} = (0.75 + 2x10^{-5}\ z)R_a \qquad (18)$$

where:

z = elevation above sea level [m],

Ra = extra-terrestrial radiation [MJ m-2 day-1].

**Net long wave solar radiation (Rnl)**

$$Rnl = s\left[\frac{T_{\max} + 273.16)^4 + (T_{\min} + 273.16)^4}{2}\right](0.34 - 0.14\sqrt{e_a})\left[1.35\frac{R_s}{R_{so}} - 0.35\right] \qquad (19)$$

Where:

Rnl: net (outgoing minus incoming) long wave radiation [MJ m-2 day-1],

σ: Stefan-Boltzmann constant [$4.903\times10^{-9}$ MJ K-4 m-2 day-1],

T max: maximum absolute temperature during the 24-hour period [K],

T min: minimum absolute temperature during the 24-hour period [K],

ea: mean daily actual vapour pressure [kPa],

Rs: daily incoming solar radiation [MJ m-2 day-1],

Rso: daily clear sky solar radiation [MJ m-2 day-1].

**Net radiation (Rn)**

The net radiation is obtained as the difference between the incoming net shortwave radiation (Rns) and the outgoing net long wave radiation:

$$R_n = R_{ns} - R_{nl} \quad (21)$$

## 2.6 Overview of previous researches

There have been few results published, involving the usage of high-definition small weighted lysimeters for actual evapotranspiration calculation. In first place, it is important to mention the study of Doležal et al. (2015) that serves as a foundation for this research, giving the first outlook of the functioning of the Smart-Field lysimeter for soil water fluxes measurements.

Another published study has been done by Parisi et al. (2009), who compared for the period of March 2008 and August 2007 the reference crop evapotranspiration computed by Penman-Monteith equation with the daily actual evapotranspiration measured with four mini-lysimeters of 0.25 m2, with minimum weight of 40 kg and maximum of 120 kg. Data were recorded every minute. According to their results, both methods are closer during the two studied months, however there is a slight underestimation of ETo. The most significant differences were during hot summer days, attributed to different reasons: mainly the mini-lysimeter's small dimensions, the disruption created between the lysimeter's border and the field, causing meteorological differences in the ground temperature and the soil water content. Also, the "oasis effect" can affect the lysimeter measurements because of the different soil coverage, where several meteorological factors can generate errors, such as differences in the thermal condition, wind and radiation between the lysimeter and its surrounding (Zenker, 2003). Related to the oasis effect, the study by Wegehenkel and Gerke (2013) compares the actual evapotranspiration measured with 8 grass-covered weighing lysimeters (1 m2 area and 1.5 m depth, four with undisturbed sandy soil column and four undisturbed silty-clay soil monoliths) for a period of tree years (January 1, 1996 to December 31, 1998) with simulated actual evapotranspiration rates using the WOFOST6.0 model. This model calculates the daily potential grass reference evapotranspiration using the modified Penman method. According to their results, there was no limitation in soil water availability for the transpiration rates in the cases where the calculated actual evapotranspiration was higher than the simulated potential evapotranspiration due to the oasis effect.

Furthermore, a meaningful research has been done by Gebler et al. (2013), comparing three ET methods, using the Eddy-Covariance (EC) method, six lysimeters (1 m2 area and 1.5 m depth) and FAO56-Penman Monteith method for the ETo estimation. In their results for one-month period (May 2012), it appears to be a higher monthly sum of the lysimeter Eta in contrast with the reference crop evapotranspiration values. They explain it as a consequence of energy availability and not to soil water content, due to the grass length, being higher than the 12 cm height of the hypothetical grass stated in the FAO 56. As a reaffirmation of this conclusion, Gebler et al. (2015), studied one-year period (2012), arriving to the same explanation about limited energy for the ET process due to harvesting management.

The paper published by Hannes et al., (2015) presents a basic and useful filtering scheme for errors removal in the lysimeter weighing data. This serves as a guideline for obtaining more accurate results, mentioning the importance of keeping a 15-minute resolution. However, it is still a challenge to determine the most adequate method for filtering and correcting lysimeter data.

In the same direction, Schrader et al., (2015) used simulated data derived from real data and real measured data from three lysimeters (1 m2 area and 1 m depth) in Austria and Germany (operated TERENOSoilCan network), to explore a standard procedure for evaluating weight and drainage data for measuring precipitation and evapotranspiration. As a remark, they discredit the usage of meteorological methods for evaluating lysimeter ETa results, due to the frequent calibration problems they suffer. Therefore, they recommend as a better validation strategy to use perfect synthetic calculations from simulated lysimeters. Furthermore, they expose the importance of using filters for data smoothing. However, it is difficult to find the most adequate filter, as well as the length of the moving window, in order to avoid underestimation of ET or the opposite.

# CHAPTER 3

# 3. MATERIALS AND METHODS

## 3.1 Study site and data acquisition

The research was effectuated in the experimental field of the Czech University of Life Science in Prague-Suchdol at the geographical location 50°8'N, 14°23'E and in an altitude of 286 m a.s.l. According to the Czech Hydrometeorological Institute, the annual mean air temperature is 9.6 °C and the mean annual precipitation rate is 587 mm y-1.

The terrain is flat with a soil type of Loamy Haplic Chernozem on loess. The measurements were done inside the A – horizon (0-35 cm). The grass is not being irrigated nor tile-drained; therefore it suffers from water stress most of the time (Doležal et al., 2015).

The meteorological data were collected from the weather station on the spot. Most weather elements were taken from the instruments owned and operated by the Institute of Atmospheric Physics, Czech Academy of Sciences. Few missing data were replaced by the observations made at the weather station of the Department of Agroecology and Biometeorology, Czech University of Life Science at about a kilometer distance. The period processed was from of April 25, 2013 to May 1, 2015.

## 3.2 Materials and methodology

A small weighable lysimeter, operated by the Department of Water Resources, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences, was used for this study. Soil water content and soil water potential were measured in the lysimeter and in its vicinity. Standard weather data (air temperature, air humidity, wind speed and solar radiation) were used for ETo calculation.

All primary data were available at 10 min intervals, but the mass of the lysimeter and the mass of the bottle with percolation water were recorded at 1 min intervals. The daily ETa was calculated from one midnight to the following midnight as specified below for the days without precipitation, because during days with precipitation ETa could be partially or fully overweighed by precipitation. Additionally, the days on which the ETa values obtained were outliers were manually excluded from the data set as detailed below. The meaningful daily ETa values were compared with the reference crop evapotranspiration (ETo) values obtained from weather data by the FAO 56 Penman-Monteith equation.

### 3.2.1 Lysimeter design

The small lysimeter used for this study was the Smart-Field Lysimeter (SFL-300) manufactured by UMS GmbH in München. Its main part is a stainless steel cylinder with 30 cm height and 30 cm diameter with an undisturbed soil monolith inside. The cylinder with the monolith was automatically weighed, with percolation water also automatically weighed and the bottom soil water suction automatically maintained on the natural level. The lysimeter design is depicted in Fig. 1. The cylinder carries a sensor distribution box and six sensor ports at the depths 5, 15 and 25 cm. The sensors in the monolith include three MPS-2 dielectric probes for soil water matrix potential and 5TE sensors (Frequency Domain Response) to measure the volumetric water content, the electrical conductivity and the temperature of the soil.

At the bottom of the lysimeter there is a stainless steel dish with several porous ceramic suction cups immersed in wet silica flower (fine and), which acts as a semi-permeable membrane controlling the suction at the level approximately equal to the matric potential measured by a T8 tensiometer (so-called reference tensiometer) in the native soil at 30 cm depth at the distance about 1 metre from the lysimeter. The air under pressure in the suction cups is measured by the means of a pressure transducer placed in the sensor distribution box, called VTENS (virtual tensiometer).

The lysimeter cylinder is placed on a balance platform that measures the weight of the cylinder with the soil column (monolith) inside, allowing to qualify the amount of water inflow into and outflow from the column for evapotranspiration, precipitation, percolation and capillary rise estimation.

Another element of the lysimeter setup is the Field Box, working as a supply and drainage station for the lysimeter. In here, an automatic vacuum pump and the drain water bottle are found. The pump sucks the percolated water from the lysimeter to the bottle and water is stored in the bottle. There is a balance beneath the drain water bottle that measures its weight and the incoming or exiting water from the lysimeter’s bottom. If the soil in the lysimeter dries up, , it may sucks water back from the water storage bottle, which mimics the capillary rise of water from the (non-existing deeper-lying soil layers. However, this mimicking is not perfect. According to Doležal et al. (2015), when the matric potential of the soil in the bottom part of the lysimeter becomes very low (very negative), the backward suction of water causes the aeration of the silicon flower and the ceramic cups in it. This leads first to short, several hours lasting artefactual peaks in the graphs of the drain bottle weight (around the mid-day of every day) and later to a total break in the function of the vacuum pump. The suction system beneath the lysimeter recovers some time after the end of the dry period, but this also requires that the external reference tensiometer be manually de-aerated..

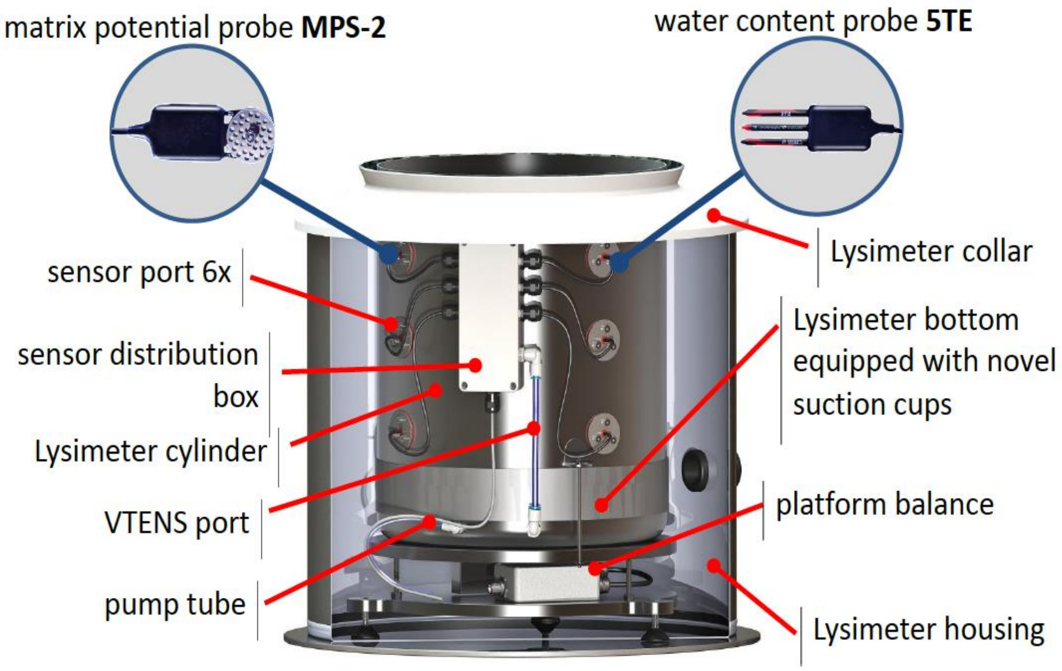


Figure 1: Scheme of small lysimeter (SFL30) design (source: User manual by UMS GmbH, Munich, 2013).

### 3.2.2 Data processing

#### Lysimeter

The primary data obtained from the lysimeter were partially systematised and graphed in order to identify and visualise the gaps due to missing data and to point out the errors, frequently from technical failures in the functioning of the lysimeter. Some small gaps have been filled by interpolation.

The data of the lysimeter mass (LYW) in kg and the storage bottle mass (SWW) in kg were recorded in 1 min time intervals. These data contain considerable noise and need to be smoothed. As this was very time-consuming, we finally decided not to do any smoothing of the primary data but, instead, to used only their midnight points. The midnight values of LYW and SWW were identified, and ascribed to the previous day calendar dates. The difference between the midnight value of (LYW + SWW) at the end of a particular day and the (LYW + SWW) at the beginning of that day (i.e., at the end of the previous day) was then used as an estimate of the daily actual evapotranspiration (ETa) on the particular day. The daily ETa was obtained in kilograms per day (kg/d) and converted to millimeter per day (mm/d). If water had been manually removed from the storage bottle (to prevent its overflow) on a particular day, then the following LYW data were corrected by adding to them the mass of the removed percolation water.

The separation of evaporation from precipitation in the continuous and smoothed 1 minute LYW + SWW data can be usually done by distinguishing the positive weight increments (precipitation) from negative ones (evapotranspiration). In our case we only worked with the daily data and the separation based on the algebraic sign was not possible, as there could be both dry (evapotranspiration) and wet (precipitation) periods during the same day. As the raingauge data are usually not exactly comparable with the lysimeter data, we decided to focus solely on the data for the days without precipitation.

The rainless days (more accurately, the days without precipitation, because in winter there may have been snow precipitation) were primarily selected based on the rain gauge data, but this was no enough. Therefore, the final selection of days to reckon with was effectuated manually, plotting monthly graphs for the (LYW+SWW) one minute data with the midnight values marked by points, as it is illustrated in Figs. 2 and 3) and taking only the daily decrements which looked in the graphs as days without precipitation. As this selection was done manually, some days with very low precipitation sums could have been erroneously defined as rainless.

After obtaining the wider selection of meaningful daily ETa data, the outlier points (rough errors) were identified and removed manually. The daily ETa values, originally negative (decrements of weight) were multiplied by minus unity to make them positive, in order to be more easily compared with the calculated reference crop evapotranspiration (ETo) values as described below. After this change of the algebraic sign, all remaining negative ETa values were also removed.

The cleaned daily Eta series was not continuous; it contained many gaps. At the same time, the Etas values were still very variable from one day to another and did not compare well with the ETo values for the same day or any other data (such as the soil moisture contents). To make the comparisons possible, it was necessary to smooth the daily ETa series further. This was done by:

a) creating a quasi-continuous series of the meaningful daily ETa data, excluding all sorts of gaps,

b) making a mass curve by consecutive summation of this quasi-continuous series,

c) smoothing the mass curve by calculating 7-day moving averages,

d) differentiating the smoothed mass curve in the daily step, taking $(dX/dt)_i \approx X_i - X_{i-1}$, where X are the consecutive points of the mass curve and t is the time,

e) smoothing the differentiated values by calculating 15-day moving averages.

For the purpose of comparison, the daily reference crop evapotranspiration values ETo were smoothed in the same way, creating a quasi-continuous time series for the days for which Eta was meaningful and following the steps a) to e) as above. The daily averages of soil water content measured in the lysimeter at the 5 cm depth were also smoothed for the purpose of comparison with Eta by creating a quasi-continuous series composed of the days for which Eta was meaningful and smoothing it by calculating 15-day moving averages, i.e. carrying out only the steps a) and e) of the above-described procedure.

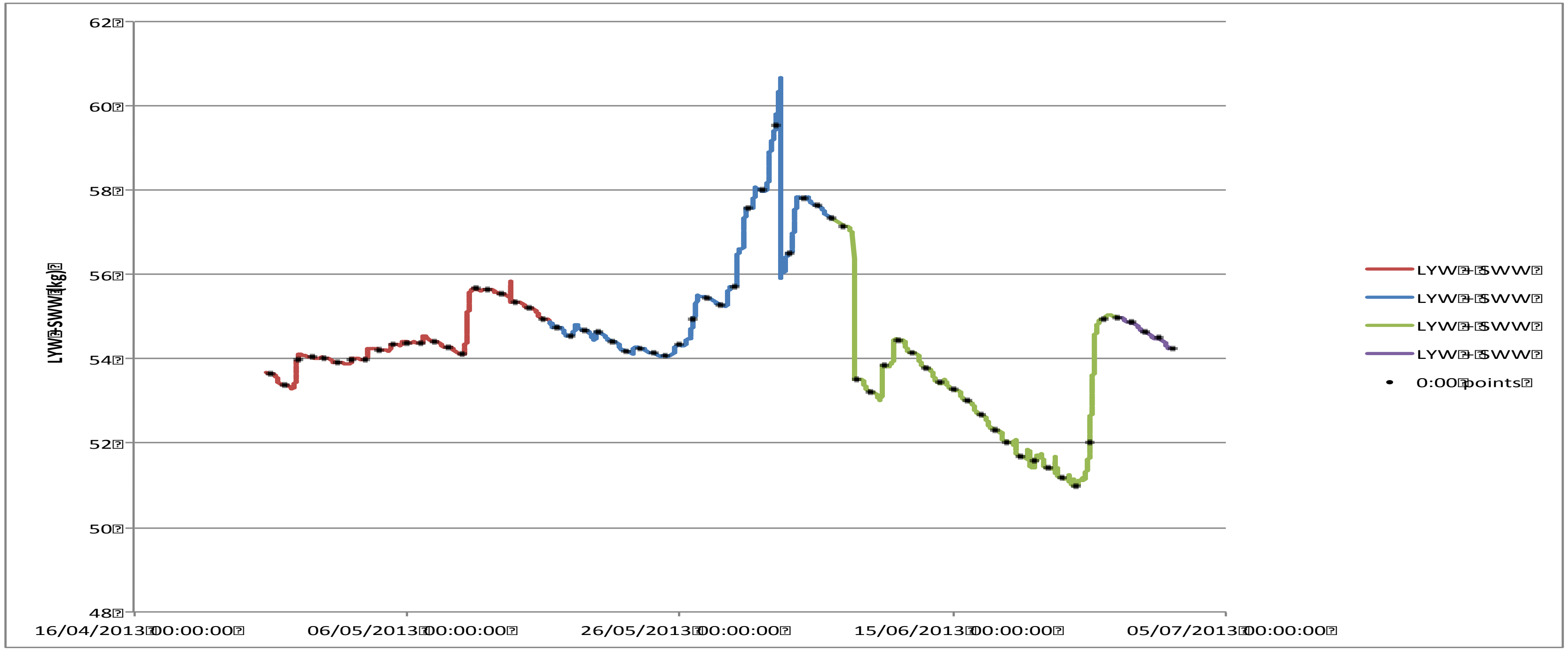


Figure 2. Instantaneous sums of the lysimeter mass LYW and the percolation bottle mass SWW. A partial segment of the one-minute primary data from April 2013 to June 2013. The increments are interpreted as precipitation, the decrements as evapotranspiration. The two sudden large decrements mark manual removals of percolate form the bottle. Black dots mark midnights. Short artefactual mid-day peaks are visible in the driest part of the period in the second half of June.

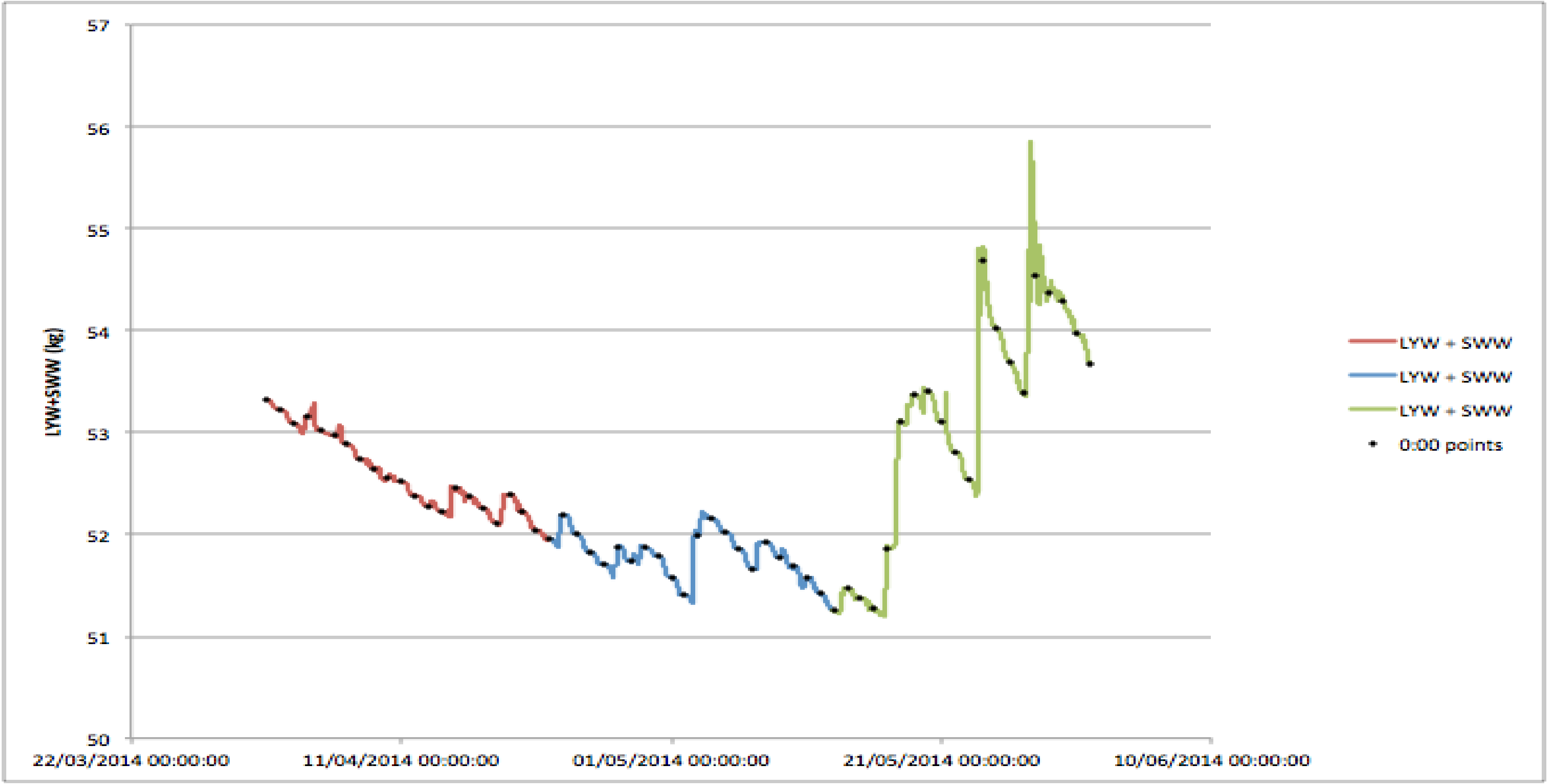


Figure 3. Instantaneous sums of the lysimeter mass LYW and the percolation bottle mass SWW. A partial segment of the one-minute primary data from April 2013 to May 2013. Black dots mark midnights.

### Soil water content

The daily soil water content (Theta05(t)Cor) was measured with the dielectric sensor 5TE (not individually calibrated) in the lysimeter at 5 cm depth. The gaps in data were interpolated linearly. Daily averages were calculated (from midnight to midnight). For the purpose of comparison with the actual evapotranspiration, the soil water content data were smoothed as described above.

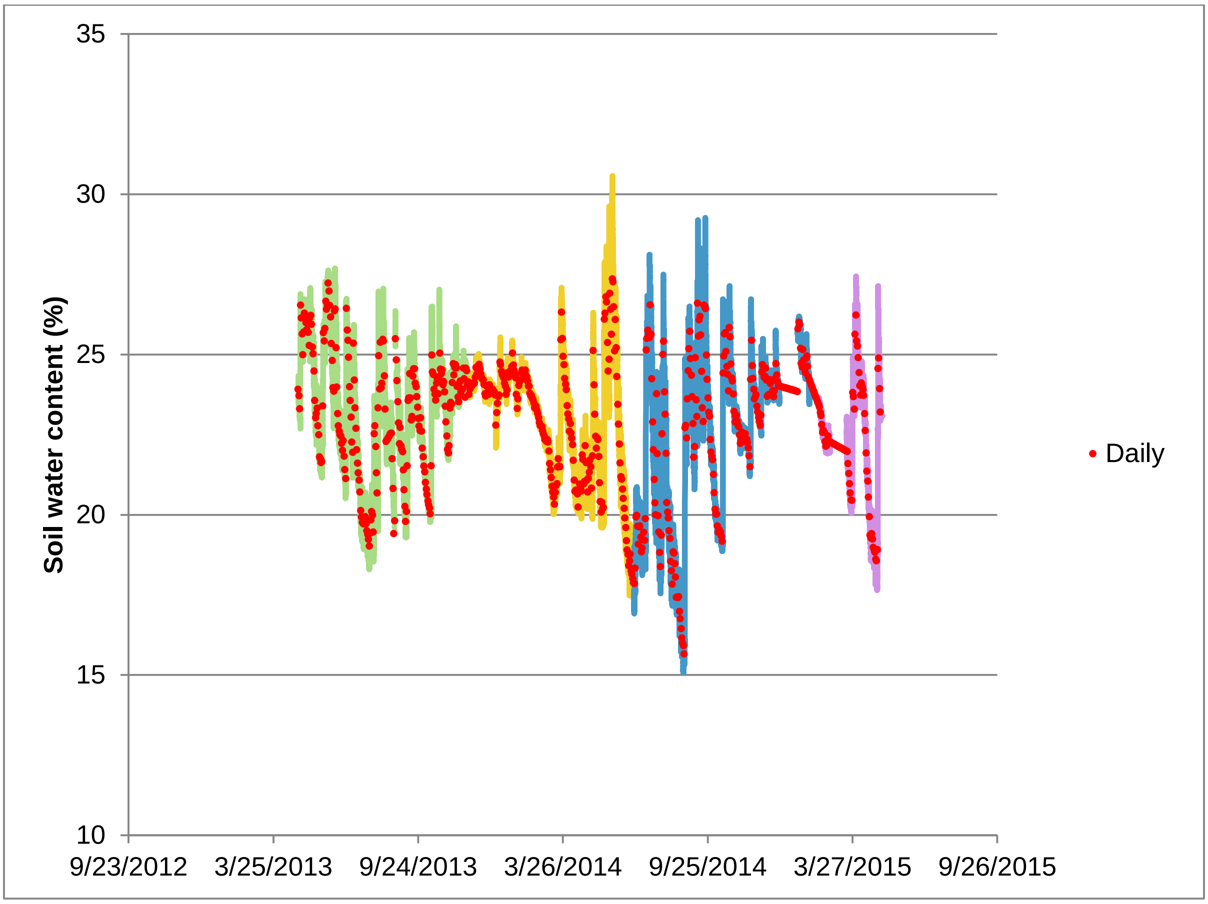


Figure 4. The volumetric soil water content in the lysimeter at 5 cm depth. The American Date Format MDY is used. The graph shows the instantaneous 10-min values and daily averages (red points).

### Short grass reference evapotranspiration

For estimating the reference crop evapotranspiration (ETo), the FAO-56 Penman-Monteith method was implemented, following the extension paper AE459 by Zoratelli et al. (2010), which is based on Allen et al. (1998) and explains the calculation procedure step by step.

The meteorological data used for the ETo estimation from April 2013 to May 2015 were collected from the weather station on the experimental field where the lysimeter was placed. Most weather parameters were taken from the instruments owned and operated by the Institute of Atmospheric Physics, Czech Academy of Sciences. Few missing data points were replaced by the observations made at the weather station of the Department of Agroecology and Biometeorology, Czech University of Life Science at about a kilometer distance.

The data was recorded in 10 min intervals, from which daily sums, maxima and minima, whatever was necessary, were calculated from midnight to midnight for the air temperature at 2 m (ºC), relative humidity at 2 m (%), wind speed at 2 m (m/s) and solar radiation (W/m2).

Average daily Temperature:

The daily minimum and maximum temperature (ºC) at 2 m were used to calculate the average daily temperature (ºC) at 2 m using equation (4). Fig. 4 and Fig 5 illustrate the daily air temperatures for both years.

Average daily relative humidity:

The primary 10-min relative humidity data were corrected by the multiplier 100 /96, because the primary values measured by an electrical sensor were systematically lower than they should be (they virtually never rose above 96 %) After that, the minimum and maximum daily relative humidities were calculated and, from them, the average daily water vapour pressure values as described in the theoretical part of this thesis.

Average daily wind speed:

For the wind speed, the daily averages from midnight to midnight were calculating from primary 10-min instantaneous values measured at 2 m height above the ground.

Average solar radiation:

From the recorded 10-min averages, the midnight to midnight averages were calculated in W/m2 and converted to megajoules per square meter per day as required by the FAO 56 method.

$$R_s\,(\mathrm{MJ\ m^{-2}}\,d^{-1}) = R_s\,(\mathrm{W\ m^{-2}})\ {*}0.0864 \qquad (22)$$

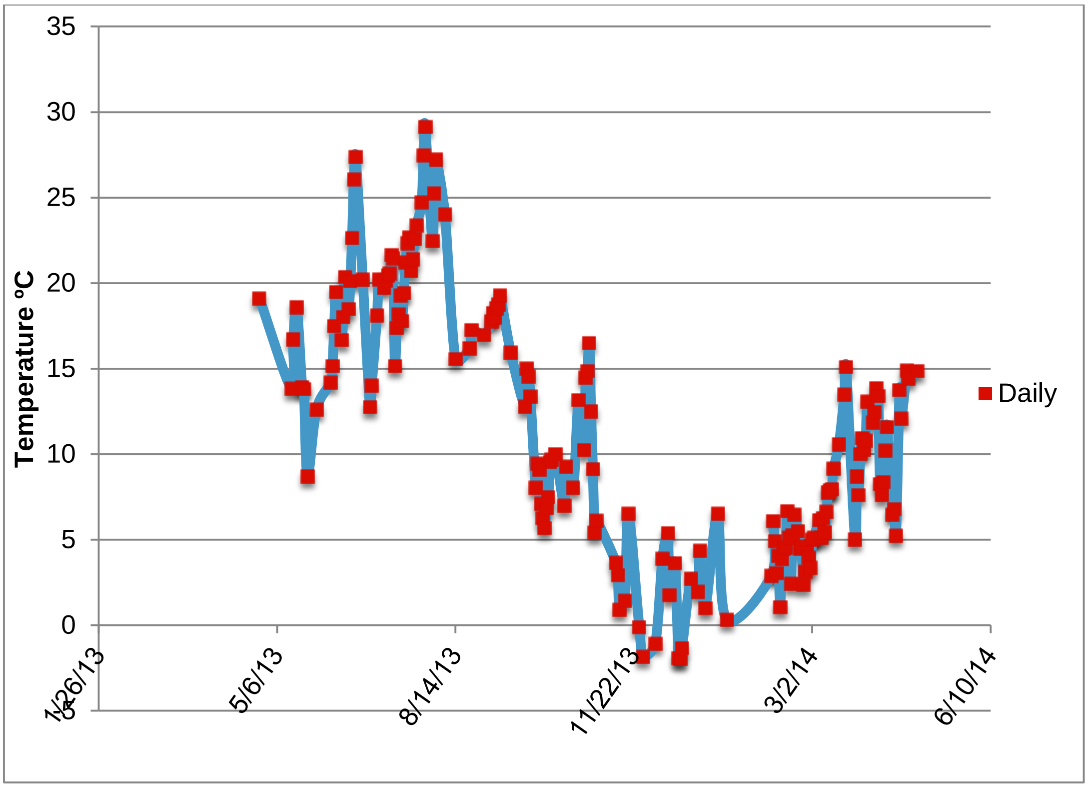


Figure 5. Daily air temperature at 2 m for the rainless days (April 25, 2013 - April 25, 2014) (American Date Format MDY).

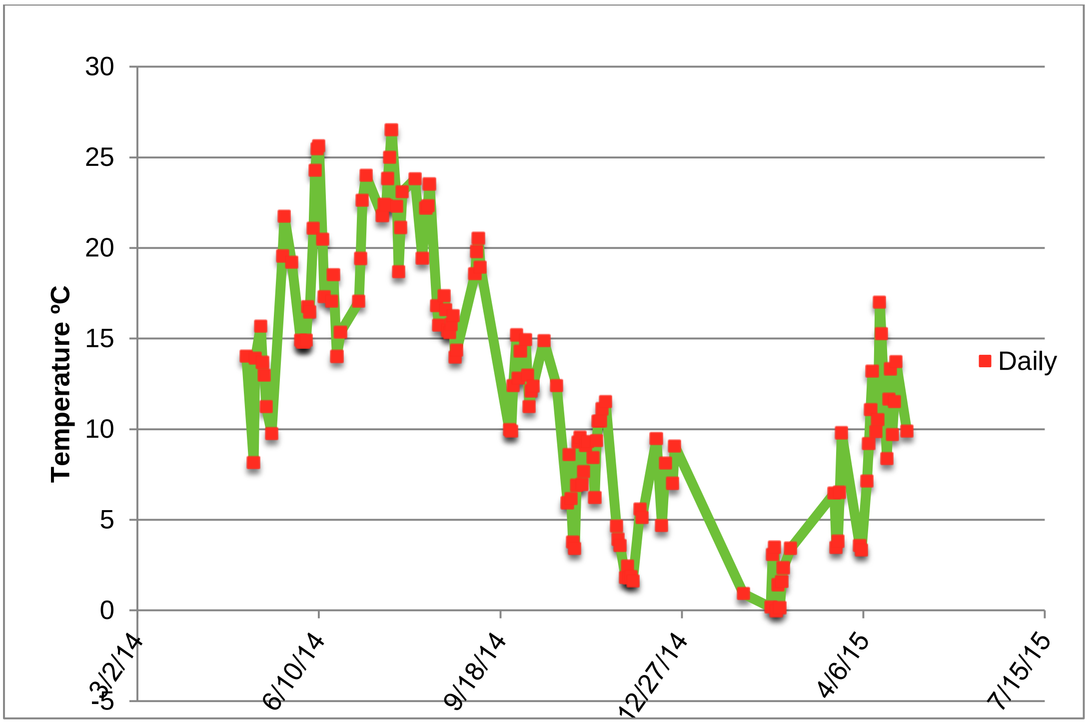


Figure 6. Daily air temperature at 2 m for the rainless days (April 26, 2014 – May 1, 2015) (American Date Format MDY).

All other components required for the FAO 56 Penman-Monteith equation were calculated following the formulas explain in previous sections. Some auxiliary formulas developed by Zotarelli et al. (2010) were used, such as:

Delta Term (DT) (auxiliary calculation for the Radiation Term ETrad)

$$DT = \frac{\Delta}{\Delta + \gamma(1 + 0.34u_2)} \quad (23)$$

where

Δ = slope of saturation vapour curve (Eq. 7),

γ = psychrometric constant [kPa °C-1](Eq. 6),

u2 = wind speed at 2 m above the ground surface [m s-1] .

Psi Term (PT) (auxiliary calculation for the Wind Term ETwind)

$$PT = \frac{\gamma}{\Delta + \gamma(1 + 0.34u_2)} \quad (24)$$

where

Δ = slope of saturation vapour curve (Eq. 9),

γ = psychrometric constant [kPa °C-1], (Eq. 6),

u2 = wind speed at 2 m above the ground surface, m s-1.

Temperature Term (TT) (auxiliary calculation for the Wind Term ETwind)

$$TT = [\frac{900}{T_{mean} + 273}] * u_2 \quad (25)$$

where:

T mean = mean daily air temperature [ºC] (Eq. 8).

u2 = wind speed at 2 m above the ground surface, m s-1.

The radiation term ETrad is then:

$$ET_{rad} = DT\, R_{ng} \qquad (26)$$

where

DT = Delta Term,

Rn = net radiation (MJ m-2 d-1).

The Wind Term ETwind is:

$$ET_{wind} = PT\ \ TT\,(e_s - e_a) \qquad (27)$$

where

PT = Psi Term,

TT = Temperature Term,

es = saturated vapour pressure (kPa),

ea = actual vapour pressure (kPa).

Finally, the reference crop evapotranspiration ETo is:

$$ET_o = ET_{wind} + ET_{rad} \qquad (28)$$

where

ETwind = Wind Term,

ETrad = Radiation Term.

From the obtained continuous series of the daily reference crop evapotranspiration ETo the days on which the actual evapotranspiration was meaningful were selected and made into a quasi-continuous series. This series was then smoothed as described above.

### Actual evapotranspiration compared with reference crop evapotranspiration

The ratio ETa/ ETo was estimated as well as the square differences between the two. The ratio values were then graphically compared and correlated to the average daily solar radiation and the time of the year (Julian day).

# CHAPTER 4

# 4. RESULTS

## 4.1 Results

Fig. 7 shows the daily actual evapotranspiration ETa for the rainless days over the 2-year period of investigation, in which the high evapotranspiration rates are prevailing in summer, while low rates are typical for winter.

The reference crop evapotranspiration ETo, estimated by the FAO56 Penman-Monteith equation, is shown in Fig. 8 for the same rainless days of the 2-year period.

Fig. 9 shows both the actual and the reference evapotranspiration rates plotted together. However, there are some points visible where ETa is reaching or exceeding ETo, especially during the summer period of 2014 and in April 2015. Therefore, , to compare both evapotranspiration rates, the ratios of ETa to ETo were estimated for particular days and are plotted in Fig. 10. A sine function approximation with respect to the day of the year (Julian day) was tried but failed (the results was a horizontal line), because the noise of the data was too large (Fig. 10).

Additionally, mass curves for the quasi-continuous series of Eta and ETo were calculated (Fig. 11) and smoothed with the moving averages for 7 days and for 15 days (the results of the latter smoothing is presented in Fig. 12). Differences between the moving averages for the 7-day and 15-day windows were not high. For that reason the 7-days window was selected as the most adequate.

In order to look for factors that could have influenced the Eta/ETo ratio, in addition to the obvious effect of the actual surface resistance of the evaporating surface, we looked for the linear relation between the ratio and the mean daily solar radiation, illustrated in Fig.13. The graph shows that no such linear relationship between both variables exists.

Another factor that was tested as for its influence on the Eta/ETo ratio was the measured soil water content at 5cm in the lysimeter with the dielectric sensor 5TE. For this comparison, as showed in Fig. 14, the ETo/Eta ratio, in which both the numerator and the denominator were smoothed using a comprehensive a) to e) procedure described above, were related with the 15 days moving averages of the average daily soil water content at 5cm. It is possible to observe in Figs. 14 and 15 that the correlation was poor for autumn and winter 2013, while it was quite reasonable for the remaining parts of the period of investigation there is no good correlation between both variables.

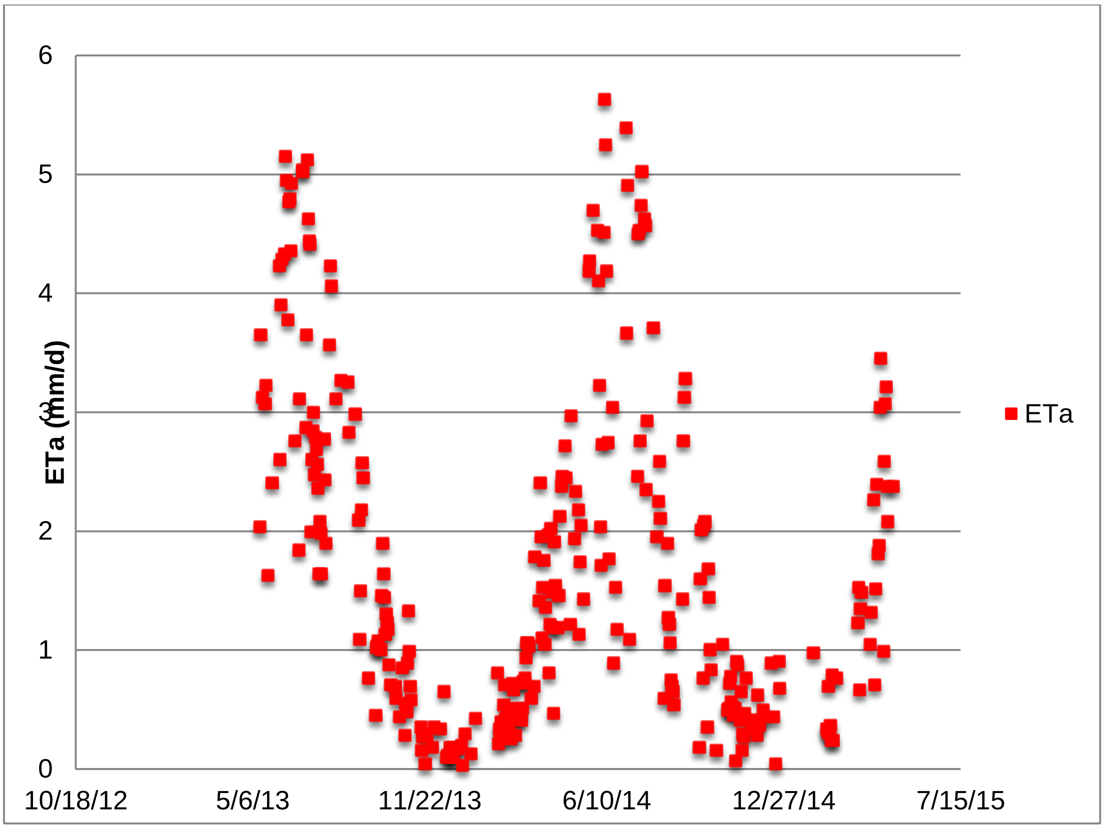


Figure 7. Daily actual evapotranspiration (ETa) for rainless days from April 2013 to April 2015 (American Date Format MDY).

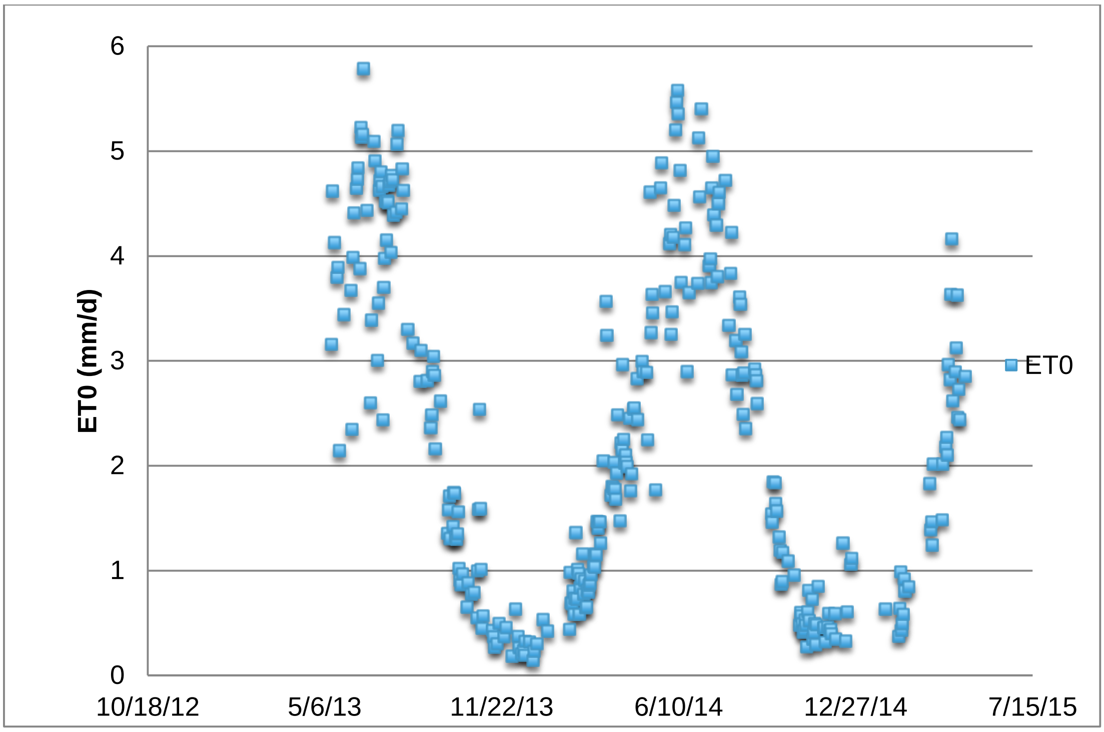


Figure 8. Daily reference crop evapotranspiration (ETo) for rainless days from April 20013 to April 2015 (American Date Format MDY).

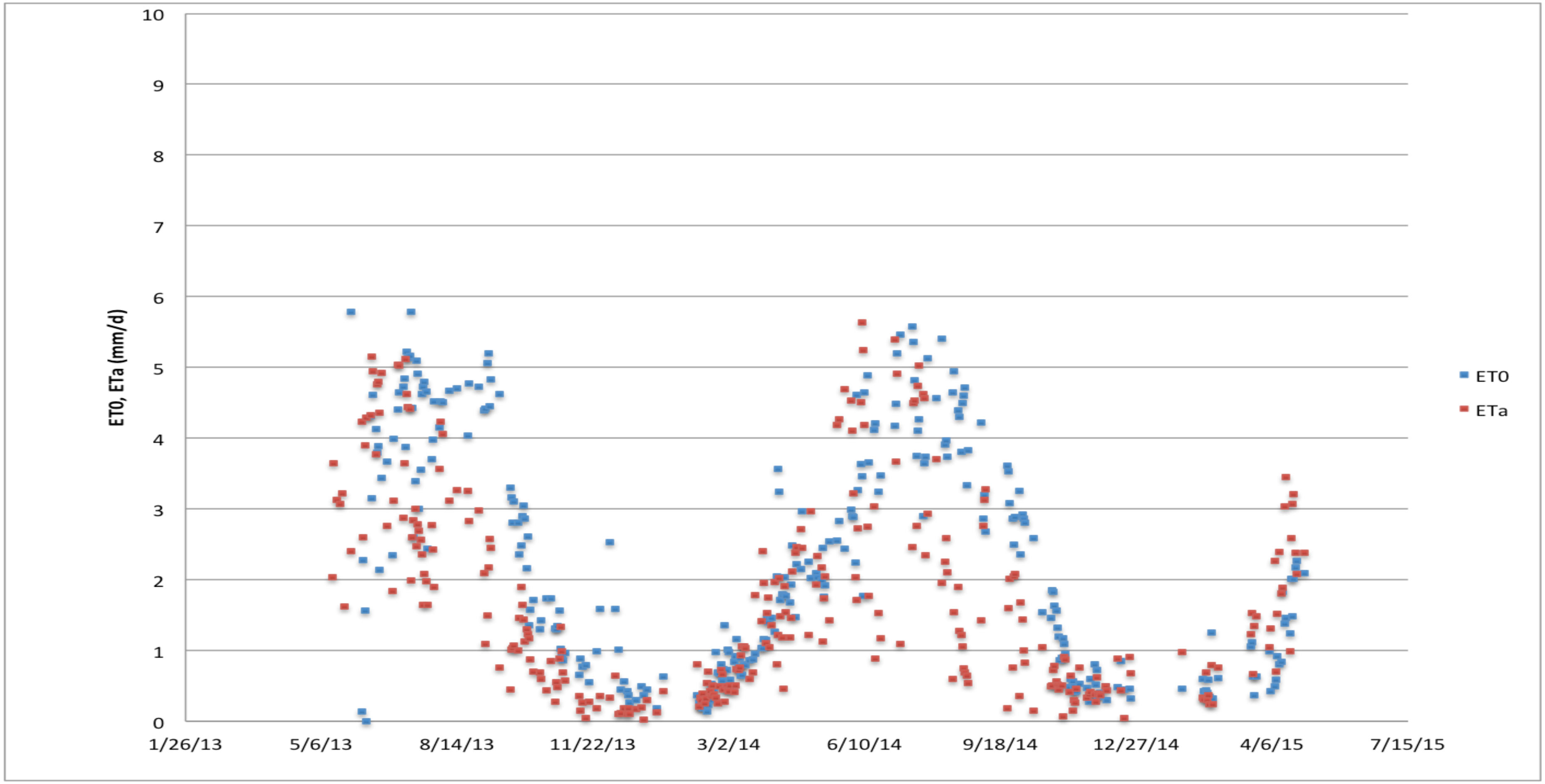


Figure 9. Daily actual evapotranspiration ETa and daily reference crop evapotranspiration ETo from April 25, 2013 to May 1, 2015 (American Date Format MDY).

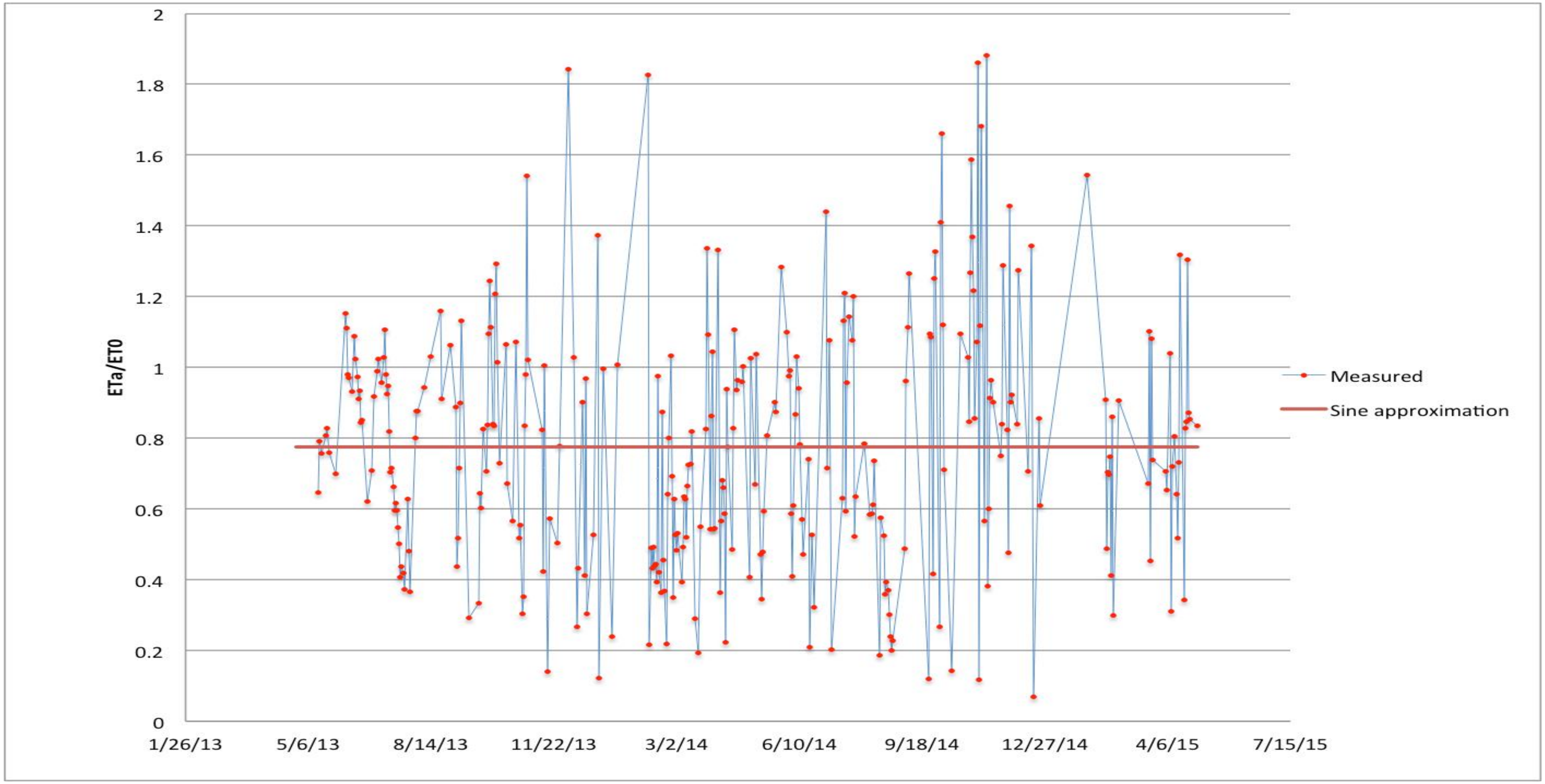


Figure 10. ETa/ETo daily ratios for the two-year period, April 25, 2013 – May 1, 2015 (American Date Format MDY) and an unsuccessful attempt at correlating this ratio to the day of the year (Julian day JD) using the sine function ETa/ET0 = A*SIN(JD/365*2*PI()+B)+C, where JD is the Julian day and A,B,C are constants.

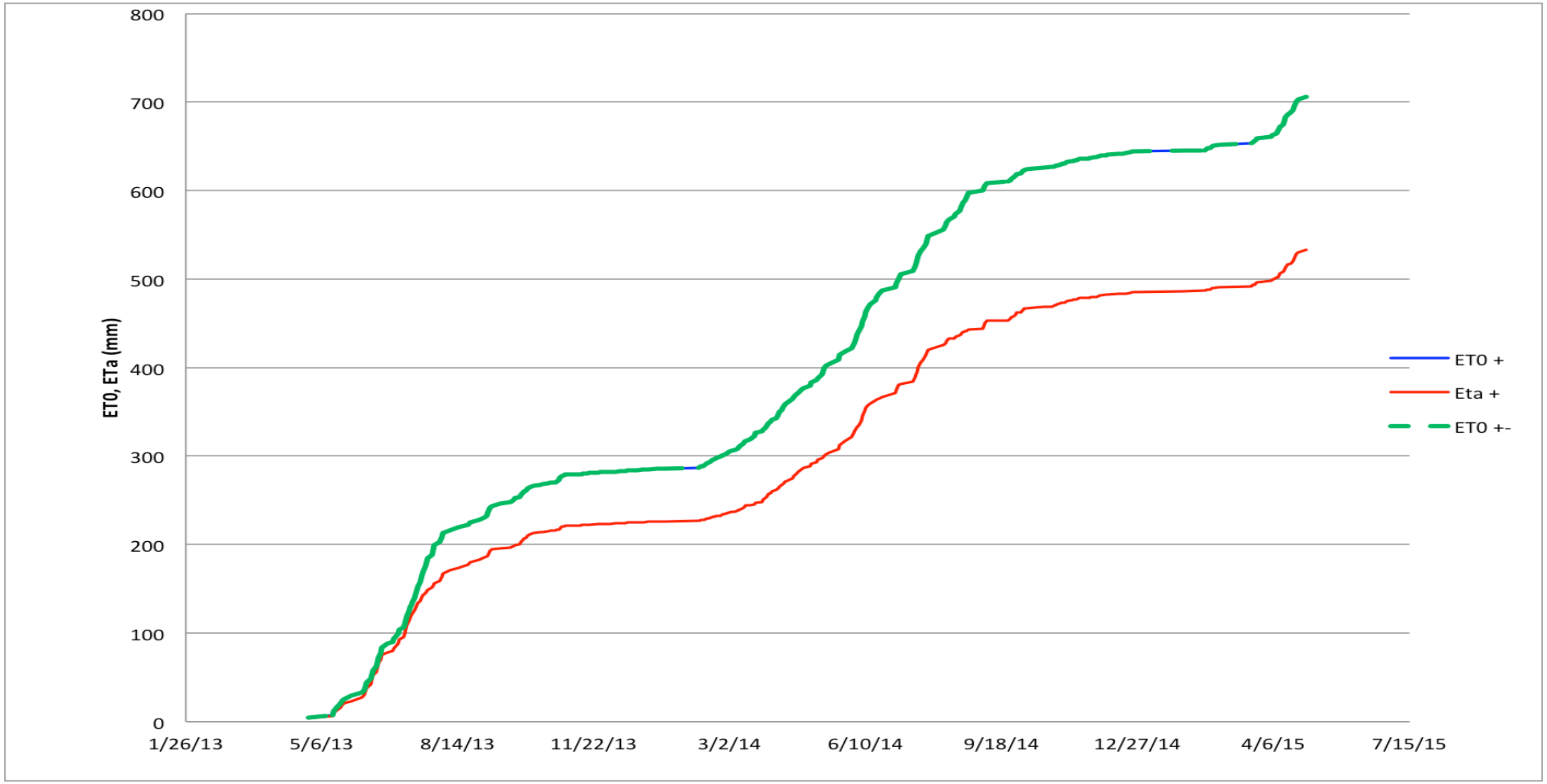


Figure 11. Mass curves of the quasi-continuous daily ETa and ETo series for two-year period April 25, 2013 to May 1, 2015 (American Date Format MDY), unsmoothed.

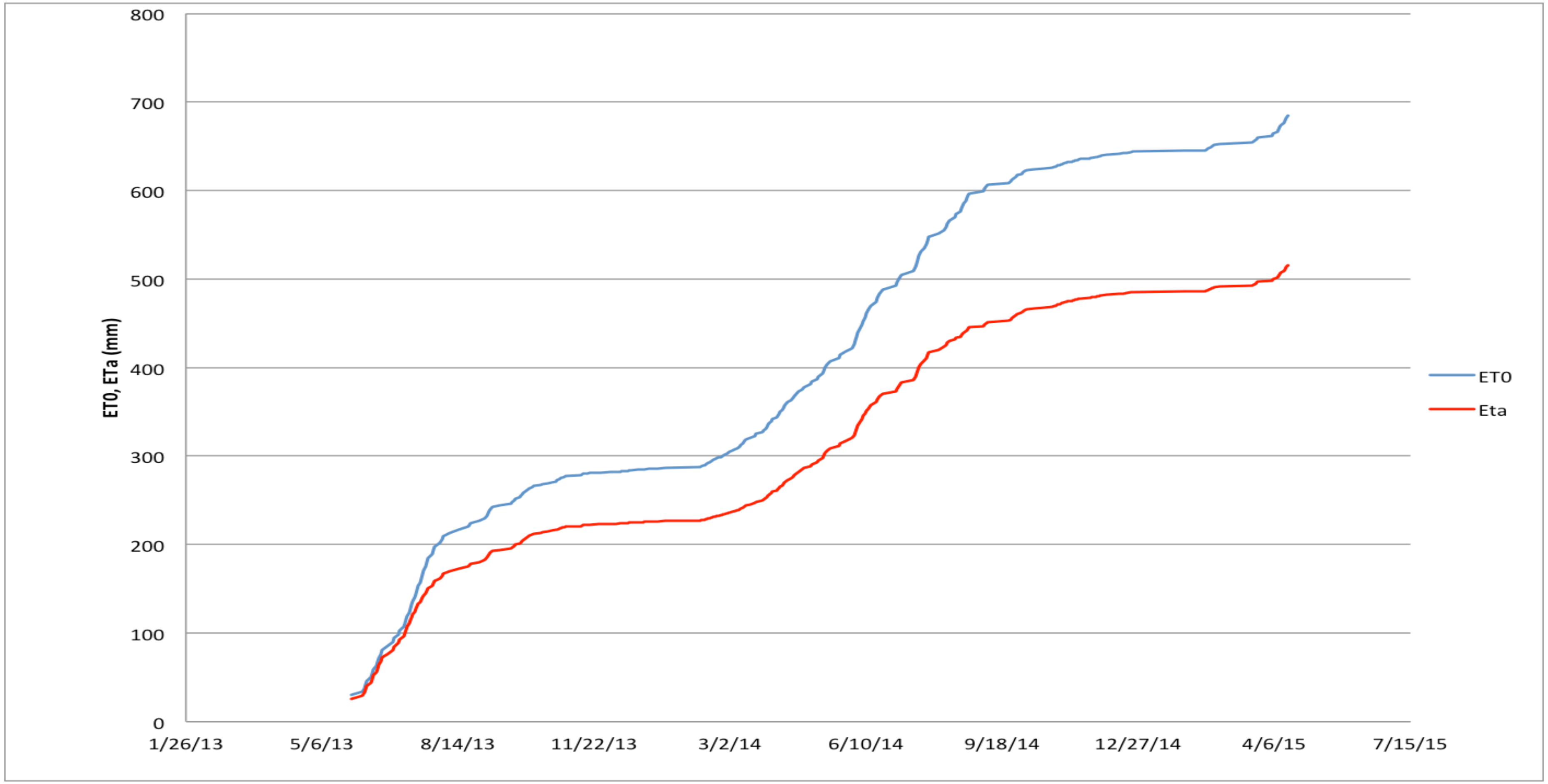


Figure 12. Mass curves of the quasi-continuous daily ETa and ETo series, smoothed using a 15 days moving average, for the two-year period April 25, 2013 to May 1, 2015 (American Date Format MDY).

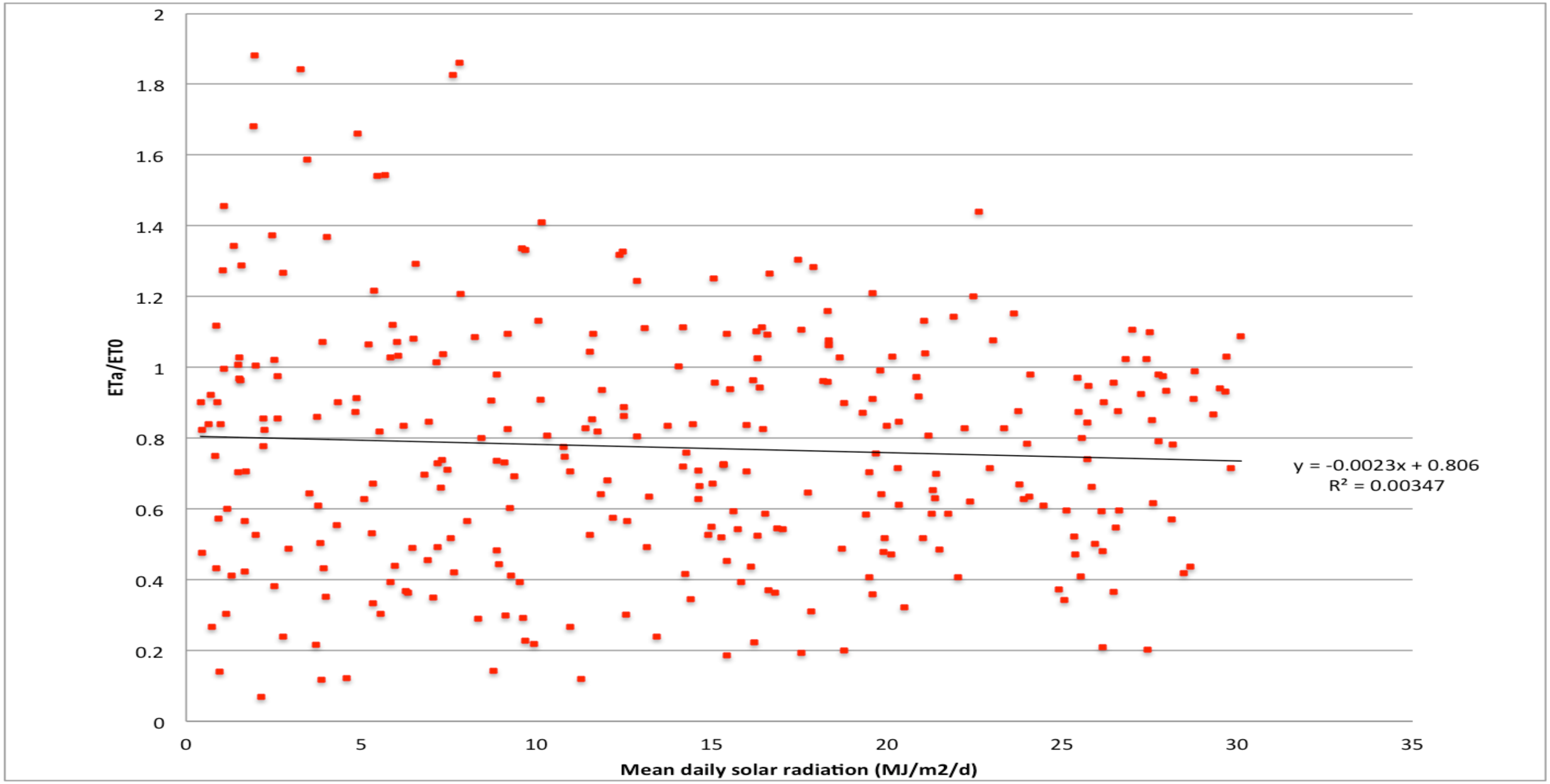


Figure 13. Linear regression of the ETa/ETo ratio with the mean daily solar radiation (MJ/m2/d) for the two-year period April 25, 2013 to May 1, 2015 (American Date Format MDY).

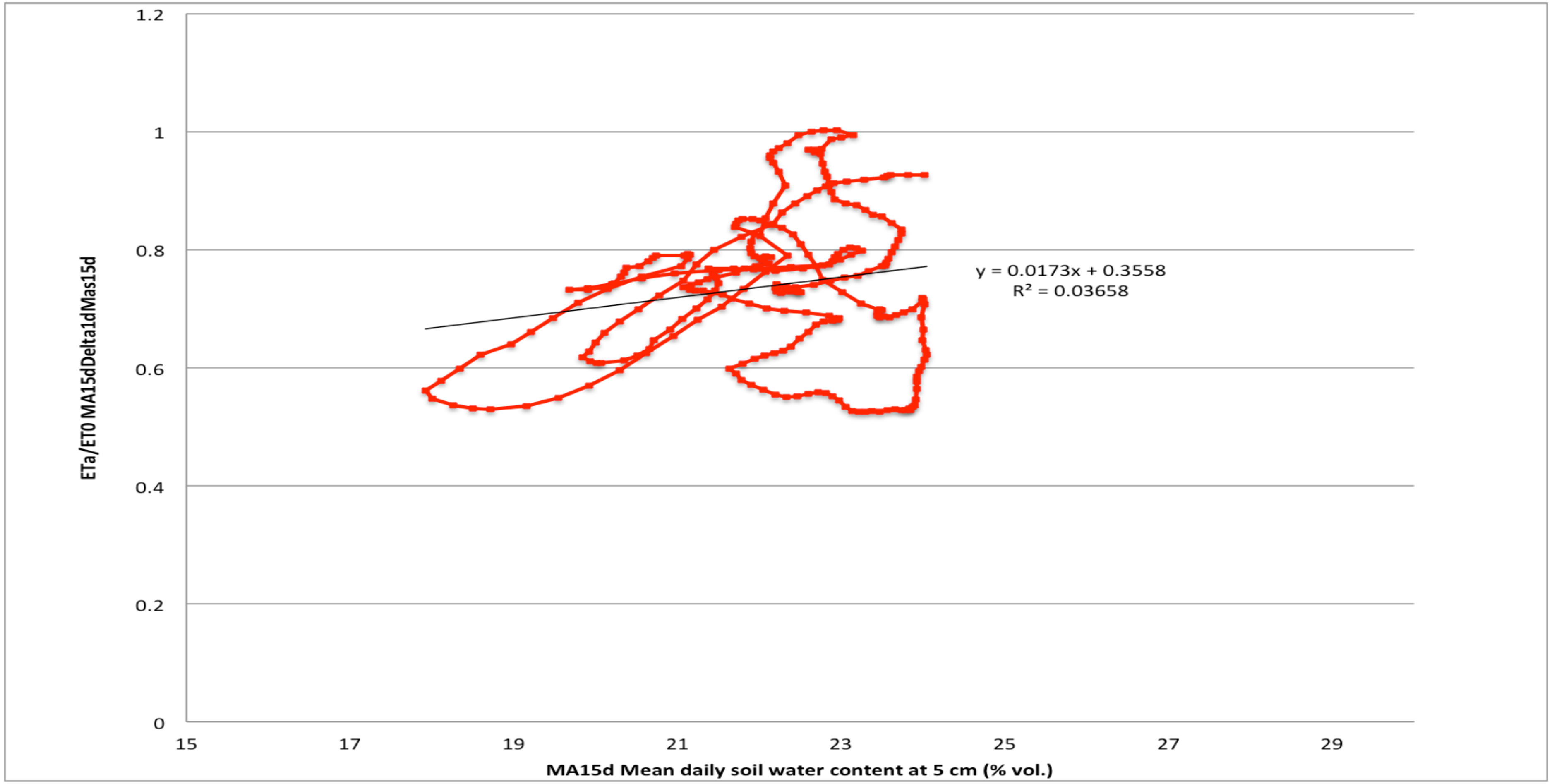


Figure 14. Linear regression of the ETa/ETo ratio (with both the numerator and the denominator comprehensively smoothed) with the15 days moving averages of the soil water content at 5 cm for two-year period April 25, 2013 to May 1, 2015 (American Date Format MDY). The particular points are connected by lines to visualize their temporal sequence.

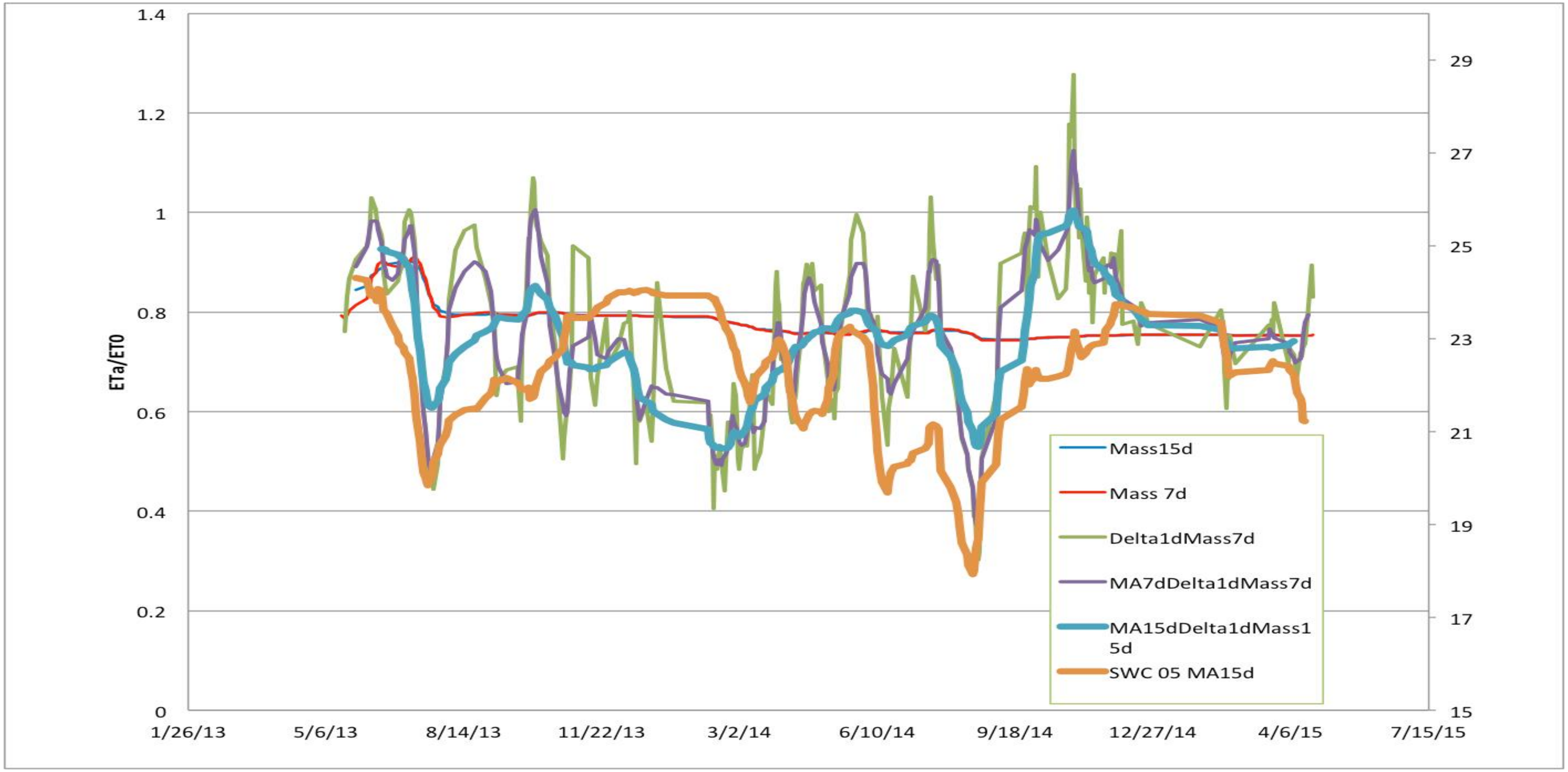


Figure 15. The ETa/ETo ratio as a function of time for the two year-period April 25, 2013 – May 1, 2015 (American Date Format MDY), with ETa and ETo smoothed using several smoothing methods (Mass15d and Mass 7d means mass curves smoothed by 15-day and 7.day moving averages, Delta1d means differentiation in 1-day steps, MA7d and MA15d means 7-day and 15-day moving averages. For contrast, the soil water content in the lysimeter at 5 cm depth (SWC 05) is plotted.

## 4.2 Discussion

Based on the data collected from the Smart-Field lysimeter in the experimental field of the Czech University of Life Science in Prague-Suchdol, the estimations of the actual evapotranspiration were obtained. Also the FAO 56 Penman-Monteith method was used to estimate the reference crop evapotranspiration to be used as a control for measuring the reliability of the ETa estimations obtained by the small lysimeter.

It is not the first time in the scientific community that this instrument is summited to proof by using the reference crop evapotranspiration. Therefore, there are similarities between the results found in this project with those mentioned by studies that precede it.

The lysimeter located in the experimental field can be considered as new, being installed in April 2013. Hence, this project establishes the foundations for next investigations that can be carried out with this device.

Consequently, most of the data collected from the lysimeter data had quite several errors, due to some malfunctioning in the lysimeter readings and the electrical system. One of the reasons was the wrong functioning of the bottom suction maintaining device when the soil was too dry, causing short-term peaks in the percolate collecting bottle mass that can be seen in the graphs. Another reason is that the electrical system stopped working for some time and during that period, when it was needed to replace some parts, the lysimeter was not providing any data.

Some of the rough errors were removed manually while other where interpolated. For the lack of time, some complicated situations were omitted instead of being analysed in detail. Also, because the rainless days were selected manually, some errors could have been introduced due to subjectivity.

About the contrast between ETa and ETo, there is no well-expressed correlation of either their difference or their ratio on the season. The current project draws a similar conclusion as that found in previous literature. We can agree with Parisi et al. (2009) and Wegehenkel and Gerke (2013) about this being a result of the oasis effect. Due to the small dimensions of the lysimeter (being even smaller than the ones used in the cited research papers), which allow to keep higher temperatures and conditions inside the soil column, different to the conditions of the surroundings that the lysimeter is supposed to mimic. According to Samie and de la Villèle (1970) cit. according to Parisi et al (2009), the optimal lysimeter should have an area of 4 m2 and 30 to 40 cm depth. It is important to mention that the grass cover of the soil column in the lysimeter was not in the optimal conditions. It was kept in the same conditions as the surrounding field, no artificially irrigated nor artificially fertilized. The living vegetation coverage of the lysimeter was partial and some parts of it could be regarded bare soil, albeit cover by dead vegetation. Therefore, the soil water content at 5 cm depth could not fully explain the ratio ETa/ETo, which may have rather depended on the water content of the top 1 cm layer of the soil.

These explanations seem more reliable, because based on the comparison with the average daily solar radiation that could have seen as a reason for the differences, we found no correlation.

As for the data processing methods, we can conclude that the most adequate smoothing method was the 15 days moving averages, agreeing with Hannes et al. (2015). However, with more time, it would be recommended to follow the basic filtering scheme constructed in their study.

As part of this study, it was projected to use the water surface evapotranspiration and compare it with the reference crop evapotranspiration. Unfortunately, this was not effectuated, given the advice of the supervisor Prof. Dolezal, due to the short time and because the availability of results of a similar comparison made in a previous MSc. thesis (T.T.H.Dao, 2013: Evaporation from free water surface – measurement, calculation and broader context. M.Sc. Thesis, Department of Water Resources, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences, Prague). This and other elements should be taken in count for future evaluations of these data recorded by the lysimeter in the same period time.

It is important to mention that even if the data collected by the lysimeter had several errors and gaps, it is a very useful device that can give relevant results for the estimation of hydrological fluxes. However, for the ideal functioning of the small lysimeter the optimal conditions and maintenance should be taken care of.

Furthermore, the advantages of this instrument are higher than its disadvantages, given its price, dimensions and easier installation than the large lysimeters.

# CHAPTER 5

# 5. CONCLUSION

**Conclusion**

- It is possible to conclude that the Smart Field Lysimeter can be more useful and affordable for universities and other research stations because of its size and easy installation, compared to traditional large lysimeters.
- Besides the advantages, it is an instrument that requires permanent attention and periodical maintenance, in order to verify its right functioning, even though it is an automatic device, and to avoid error in the data.
- Lysimeters have excellent potential for measuring soil water fluxes. However, there still needs to be more research about their data evaluation in order for them to become indispensable instruments for agro-meteorological and water management researche.
- The actual evapotranspiration measured with the lysimeter has a seasonal behaviour similar to that of the reference crop evapotranspiration. However, the ratio or the difference of the two does not have a pronounced seasonal behaviour.
- A more detailed analysis should be done, in order to obtain more precise results, such as handling with the winter periods where snow has fallen, which can cause negative influence in the weighing data because of the snow weight.
- For better results, the oasis effect should be minimised, by avoiding the conditions leading tor such effect.
- It is recommended that for continuity of this study, the original Penman-Monteith equation should be applied to estimate the impact of the bulk surface resistance and LAI on ET.
- As a follow up of this project, it is recommended to investigate the daily averages measured from noon to noon.

## Bibliography

Aboukhaled, A., Alfaro, J.F., Smith, M. and Food and Agriculture Organization of the United Nations. 1982. Lysimeters. Food and Agriculture Organization of the United Nations.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper, No. 56. FAO. Rome. p. 300. ISBN 92-5-304219-2.

Allen, R. G., Walter I. A., Elliott R. L., Howell T. A., Itenfisu, D., Jensen M. E., Snyder R. L. 2005. The ASCE Standardized Reference Evapotranspiration Equation. American Society of Civil Engineers.

Boast, C.W., Robertson, T.M. 1982. A “Micro-Lysimeter” for determining evaporation from bare soil: description and laboratory evaluation. Soil Sci. Soc. Am. J. 46. 689-696.

De la Hire, P. 1720; cit. according to Kohnke, H., Dreibelbis, F.R. 1940. A survey and Discussion of Lysimeters and a Bibliography on their construction and performance.

Doležal, F., Matula, S., Miháliková, M., Fišák, J., Chala, A. T., Hrkalová., M. 2015. Soil water fluxes measured with a small lysimeter. Acta Hydrologica Slovaca 16 (3): 3-14. ISSN 1335-6291.

Gebler, S., Hendricks-Franssen, H.-J., Pütz, T., Post, H., Schmidt, M., Vereecken, H. 2013. Simultaneous estimation of actual evapotranspiration and precipitation by weighable lysimeters and comparison with eddy covariance and rain gauge measurements. 15. Gumpensteiner Lysimetertagung 2013, 199 – 202. ISBN: 978-3-902559-90-6.

Goss, M.J., Ehlers, W. 2009. The role of lysimeters in the development of our understanding of soil water and nutrient dynamics in ecosystems. Soil Use and Management. Volume 25, Issue 3. 213–223

Hannes, M., Wollschläger, U., Schrader, F., Durner, W., Gebler, S., Pütz, T., Fank, J., von Unold, G., and Vogel, H. J. 2015. Comparison of real evapotranspiration measured by weighing lysimeters with simulations based on the Penman formula and a crop growth model.

Harrold, L.L., Dreibelbis, F. R. 1958. Evaluation of agricultural hydrology by monolith lysimeters, 1944-55. U.S. Dept. of Agriculture Technical Bulletin 1179, p. 166.

Hillel D. 1982. Introduction to Environmental Soil Physics. Academic Press.

Hudak P.F. 2004. Principles of Hydrogeology, Third Edition, p.14. ISBN 9780849330155

Irmak, S., Haman, D.Z. 2014.Evapotranspiration: Potential or Reference? IFAS Extension. Gainesville, University of Florida.

Jensen, M.E., Burman, R.D. and Allen, R.G. 1990. Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice No. 70, Am. Soc. Civil Engr., New York, NY. 332 pp.

Jones, F.E. 1992. Evaporation of Water With Emphasis on Applications and Measurements. Lewis Publications, Michigan.

Kohke H, Dreibelbis F.R, Davidson, J. M. 1940. A survey and Discussion of Lysimeters and a Bibliography on their construction and performance. Washington, D.C. 1-19.

Martín de Santa Olalla F. López P. Calera A. 2005. Water and Agronomy [in Spanish]; Madrid, 164-180.

Melesse, A., Abtew, W., Setegn, S.G. 2014. Nile River Basin: Ecohydrological Challenges, Climate Change and Hydropolitics. Springer, 718 p. 978-3-319-02719-7.

Monteith, J.L. 1965. Evaporation and environment. Symp. Soc. Exp. Biol. 19, 205-224.

Morton, F.I. 1983. Operational estimates of areal evapotranspiration and their significance to the science and practice of hydrology. Journal of Hydrology 66. 1–76

Mueller, L., Saparov, A., Lischeid, G. 2013. Novel Measurement and Assessment Tools for Monitoring and Management of Land and Water Resources in Agricultural Landscapes of Central Asia. Springer Science & Business Media.

Novak, V. 2012. Evapotranspiration in the Soil-Plant-Atmosphere System (Progress in Soil Science).Springer Science & Business Media. ISBN-13: 978-9400738393.

Parisi, S., Mariani, L., Cola, G., Maggiore, T. 2009. Mini-lysimeters evapotranspiration measurements on suburban environment. Italian Journal of Agrometeorology 13-16 (3).

Penman, H.L. 1948. Natural evapotranspiration from open water, bare soil and grass. Proceedings of the Royal Society of London. Series A, 193. 120–146.

Rodda, J.C., Ubertini, L. 2004. The Basis of Civilization--water Science? Publ. 286. IAHS Press, Wallingford, UK, p. 8.

Salazar, O., Vargas, J., Najera, F., Seguel, O., Casanova, M., 2014. Monitoring of nitrate leaching during flush flooding events in a coarse-textured floodplain soil. Agricultural Water Management 146: 218-227.

Schwaerzel, K., Bohl, H. P. 2003. An easily installable groundwater lysimeter to determine water balance components and hydraulic properties of peat soils. Hydrology and Earth System Sciences, 7. 23-32.

Shuttleworth, W.J. 2012. Terrestrial Hydrometeorology, Wiley-Blackwell, p. 448. ISBN: 978-0-470-65937-3.

Thornthwaite, C. W. 1948. An Approach toward a Rational Classification of Climate. Geographical Review, Vol. 38, No. 1. 55-94.

Torbjörn, J., Odin H. 1978. Measurements of evapotranspiration using a dynamic lysimeter. Studia Forestalia Suecica, Nr 146. The Swedish Univeristy of Agricultural Sciences. Umeå. 5-12.

Ucles, O., Villagarcia, L., Canton, Y., Domingo, F. 2013. Microlysimeter station for long term non-rainfall water input and evaporation studies, Agricultural and Forest Meteorology 182: 13-20.

Ward, A D., Trimble, S.W. 2003. Environmental Hydrology. Second Edition. CRC Press. ISBN 9781566706162.

Wegehenkel, M., Gerke H. H. 2013. Comparison of real evapotranspiration measured by weighing lysimeter with simulations based on the Penman formula and a crop growth model. J. Hydrology and Hydromechanics, 61, 2013, 2, 161–172.

Zenker, T. 2003. Evaporation resistances and reference evapotranspiration of grass. Lysimeter studies on the Penman-Monteith Formula in the Berlin area (in German). Dissertation D83 Technical University of Berlin. http://edocs.tu-berlin.de/diss/2003/zenker_ thomas.pdf

Zotarelli, L., Dukes, M.D., Romero, C.C., Kati W. Migliaccio, and Kelly T. Morgan. 2010. AE459: Step by Step Calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method). Agricultural and Biological Engineering Department, UF/IFAS Extension.

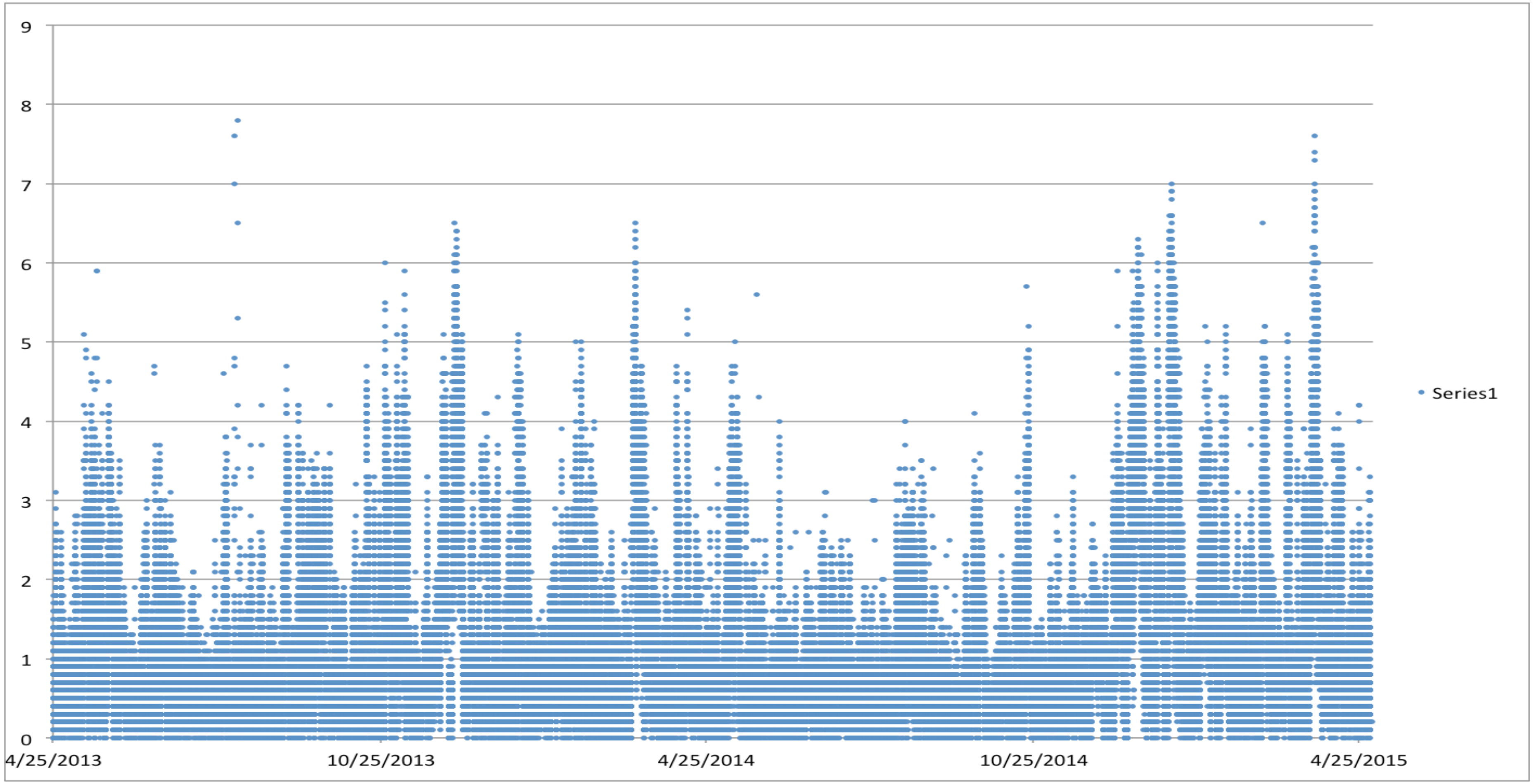
Other sources:

Czech Hydrometeorological Institute. Weather historical data. Consulted on January 27th 2016 from the website: http://portal.chmi.cz/historicka-data/pocasi/zakladni-informace?l=en

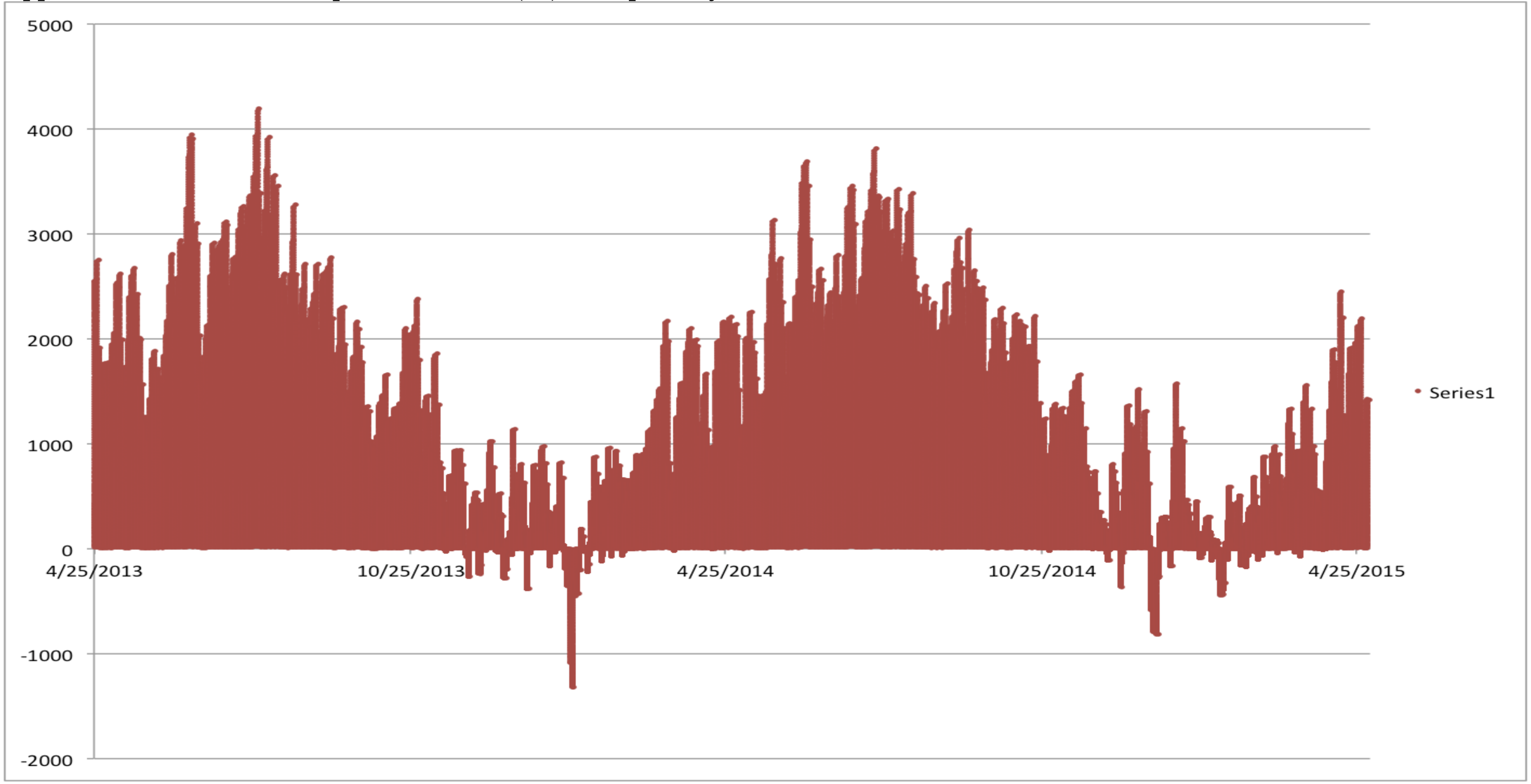
UMS GmbH. SmartField-Lysimeter User Manual. 2013. PDF file from the manufacturer.

# Appendix

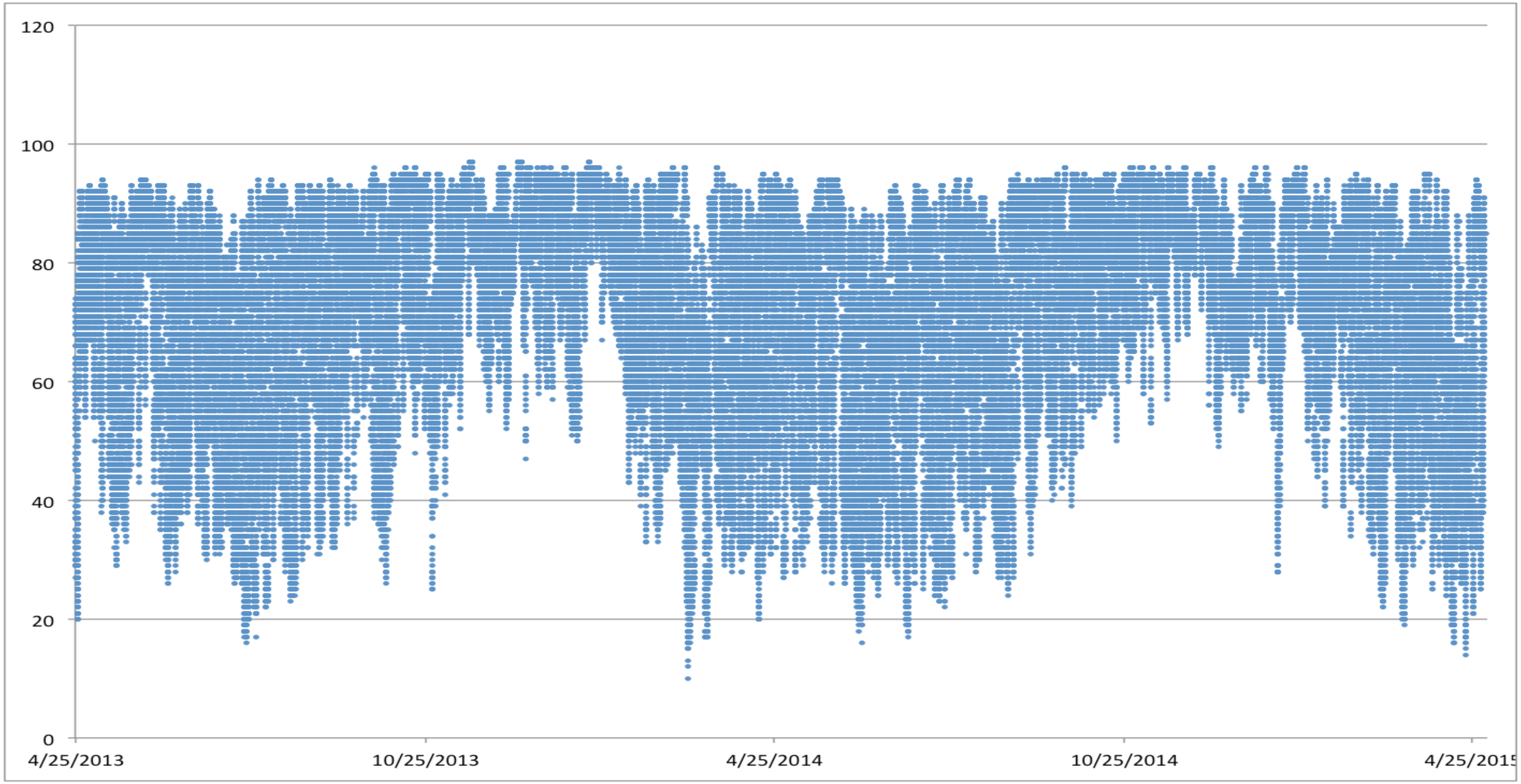
## Appendix 1: Wind speed from primary data.



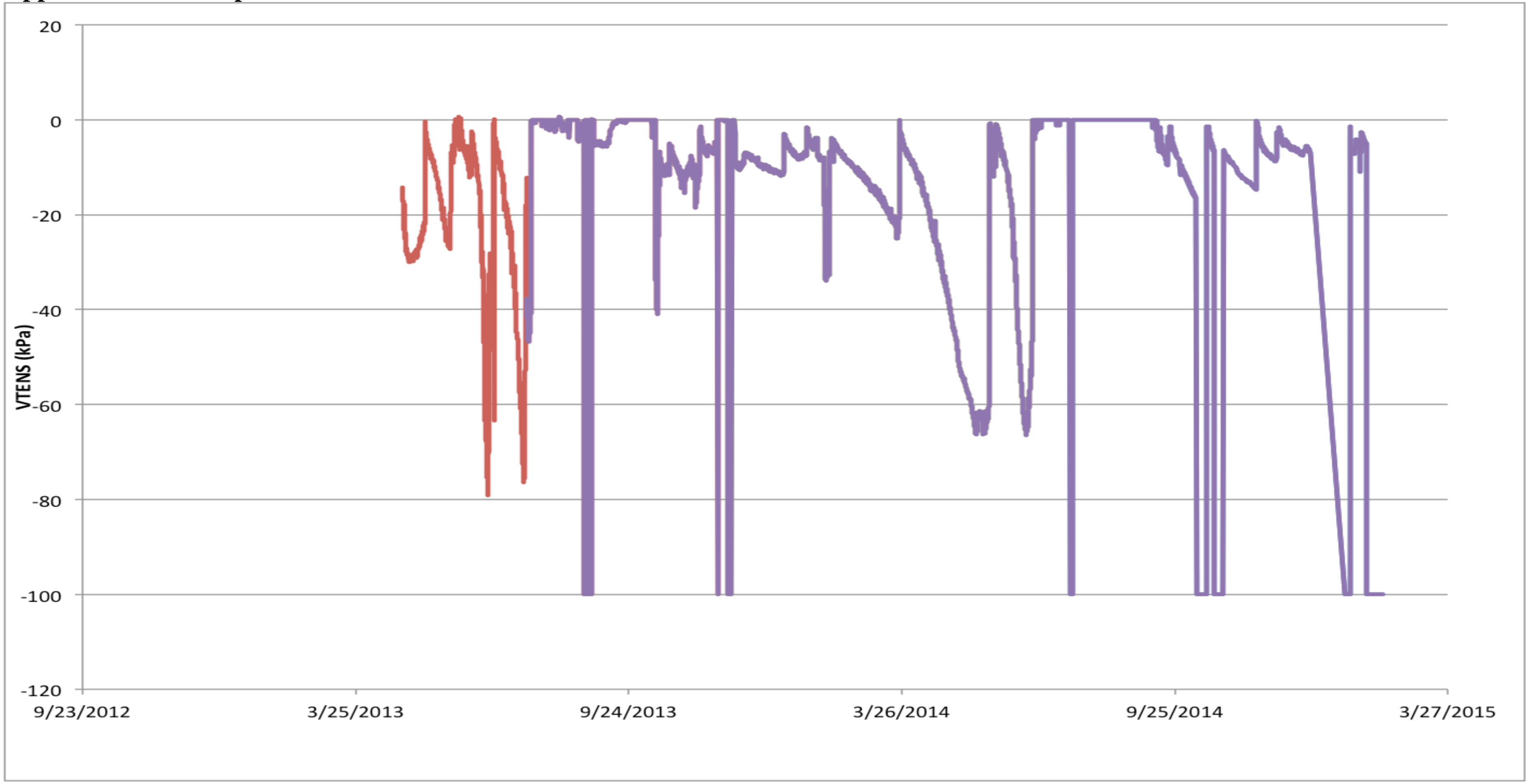
## Appendix 2: Sums of Air temperature at 2 m (°C) from primary data.



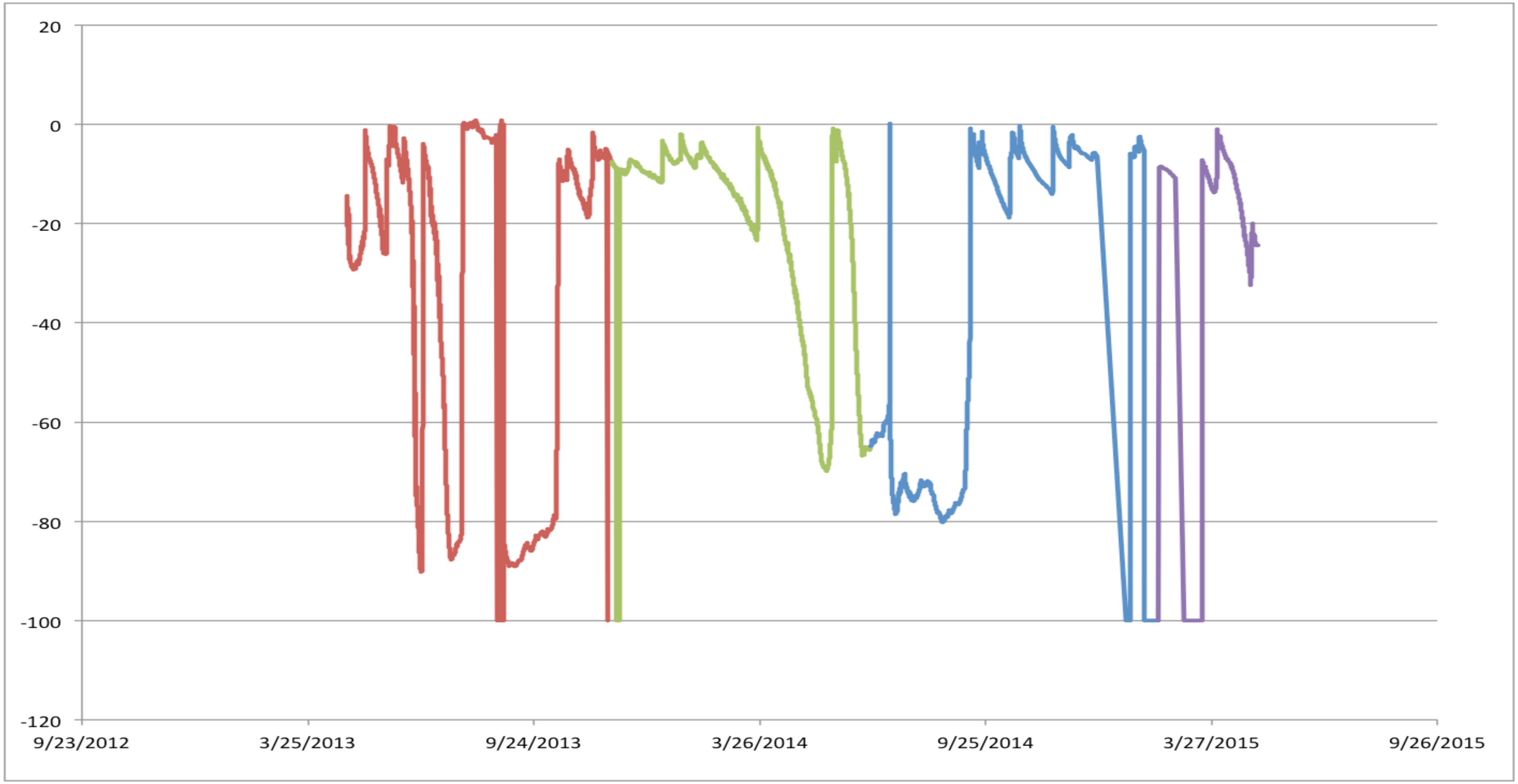
**Appendix 3: Daily relative humidity (%) from primary data.**



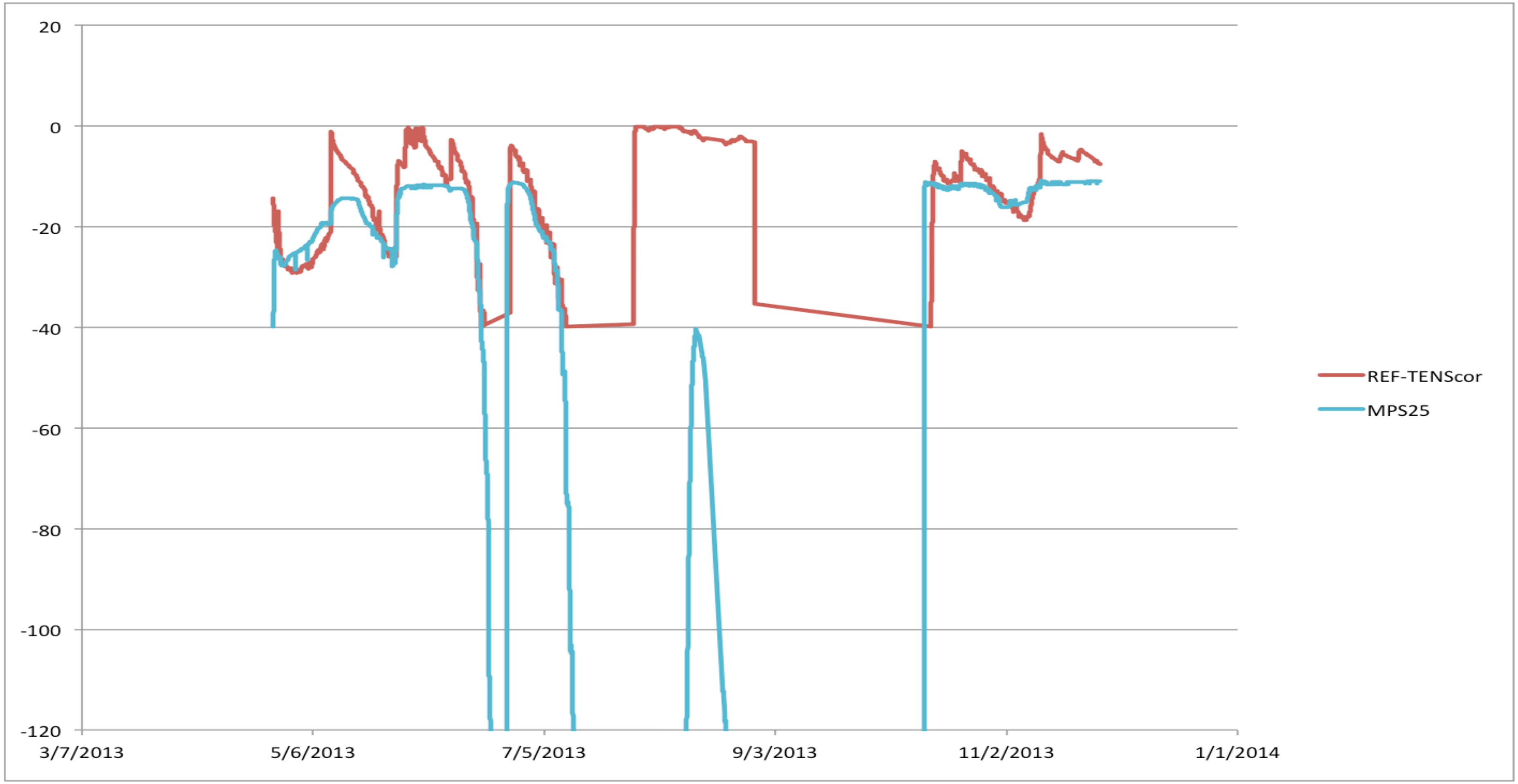
## Appendix 4: Matrix potential measured with the VTENS.



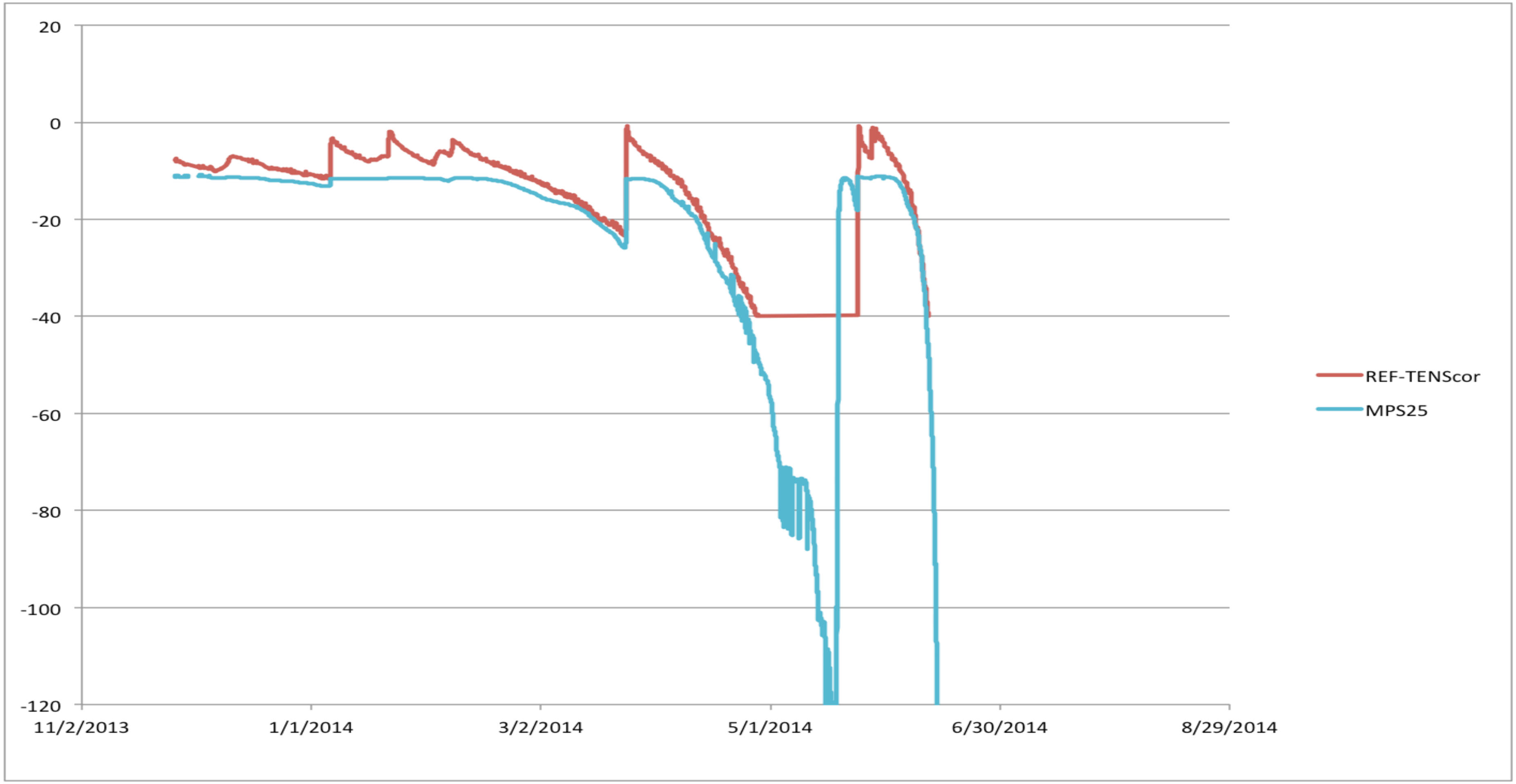
## Appendix 5: Measurements with the Reference Tensiometer.



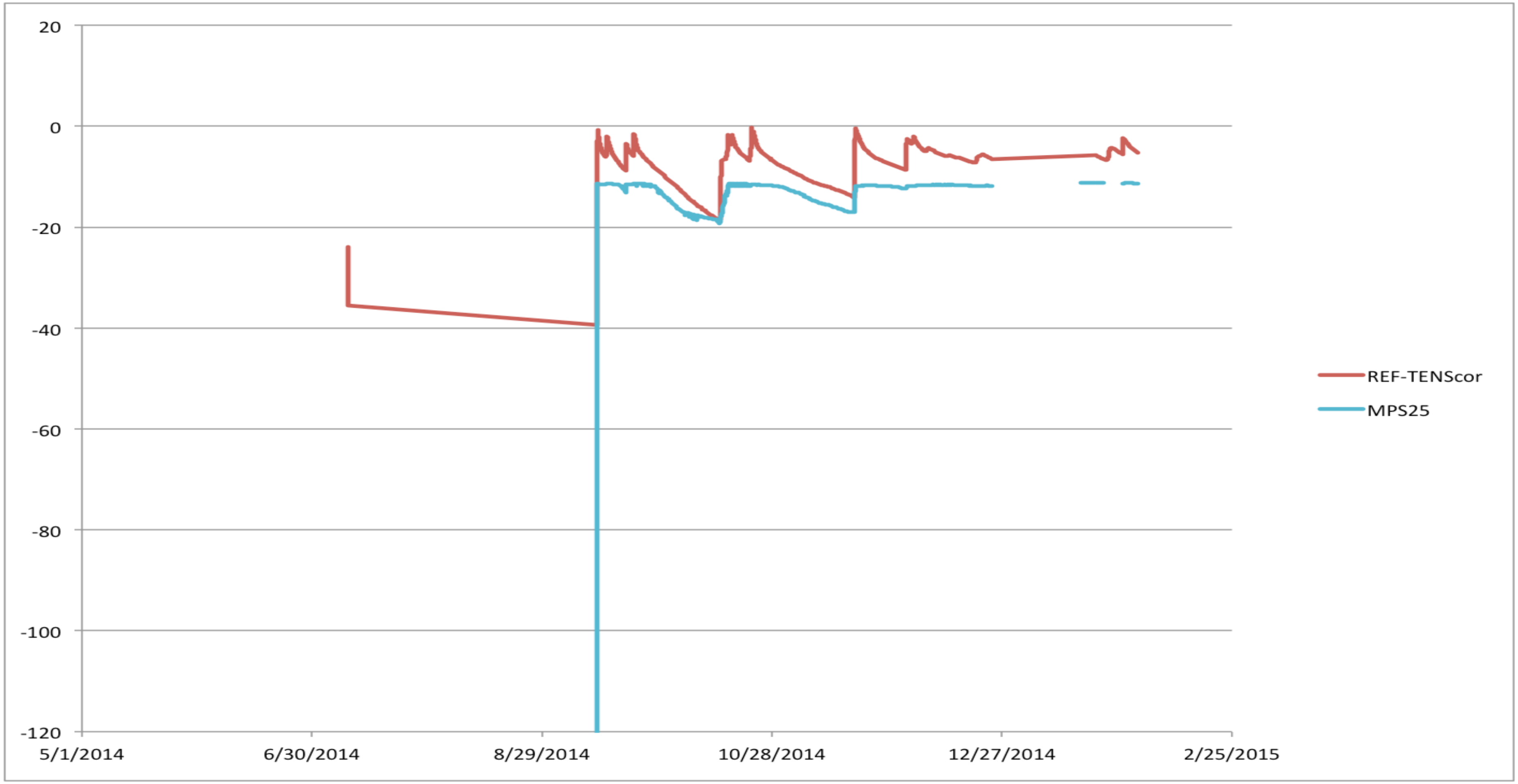
**Appendix 6: Soil water potential with the Ref. Tensiometer and the MPS05 (April 2013-November 2013).**



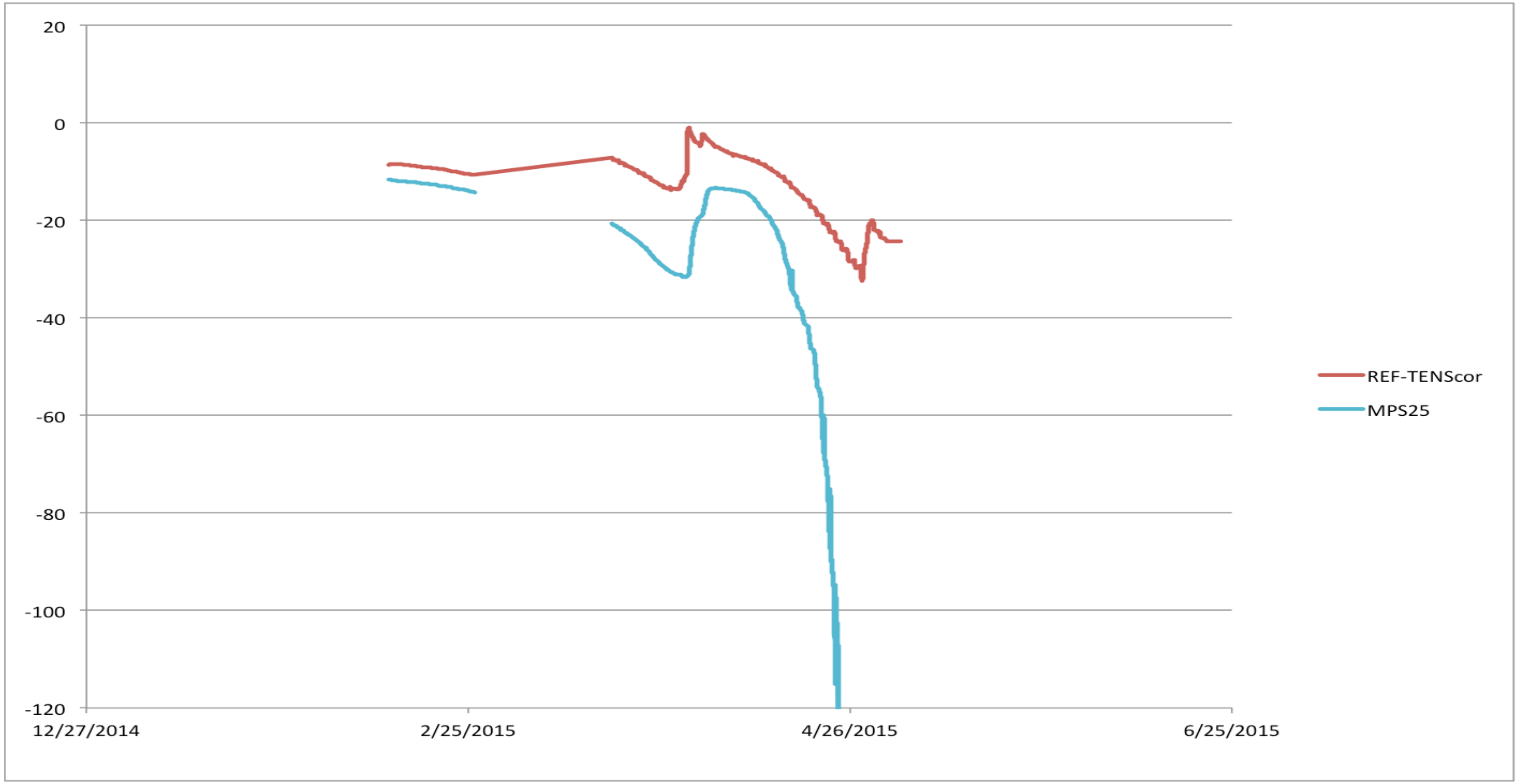
**Appendix 7: Soil water potential with the Ref. Tensiometer and the MPS05 (November 2013-June 2014).**



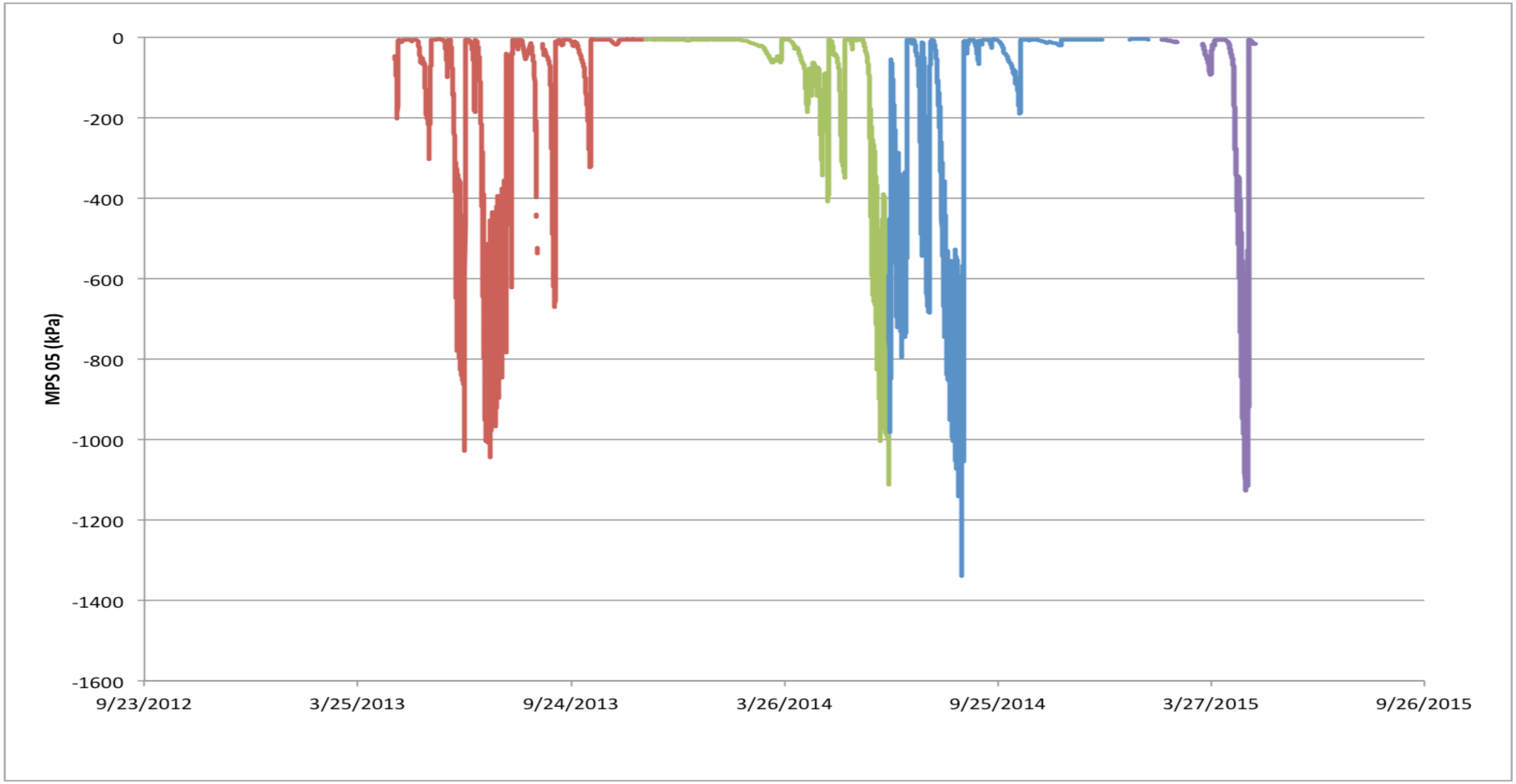
**Appendix 8: Soil water potential with the Ref. Tensiometer and the MPS05 (September 2014-February 2015).**



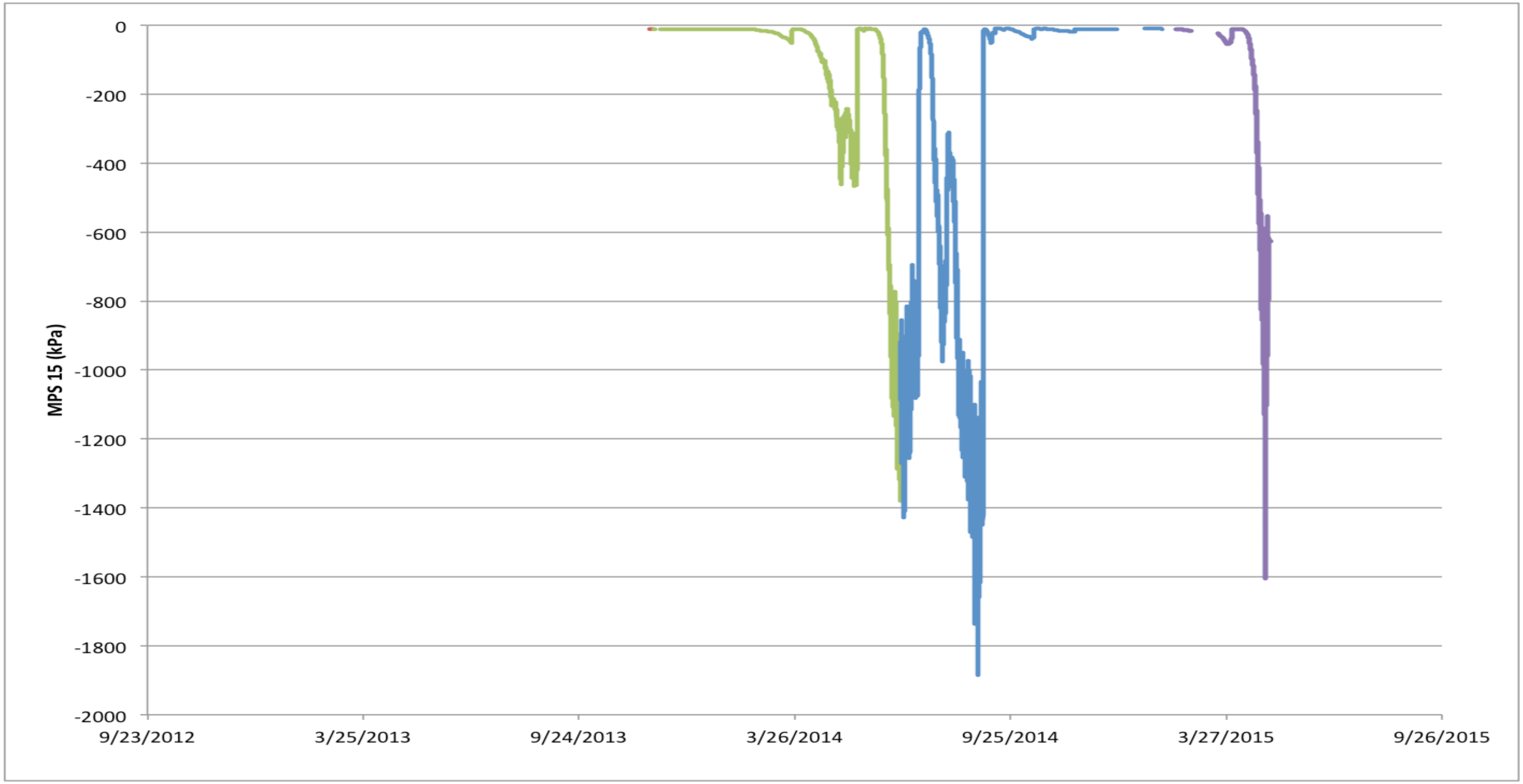
## Appendix 9: Soil water potential with the Ref. Tensiometer and the MPS05 (February 2015-May 2015).



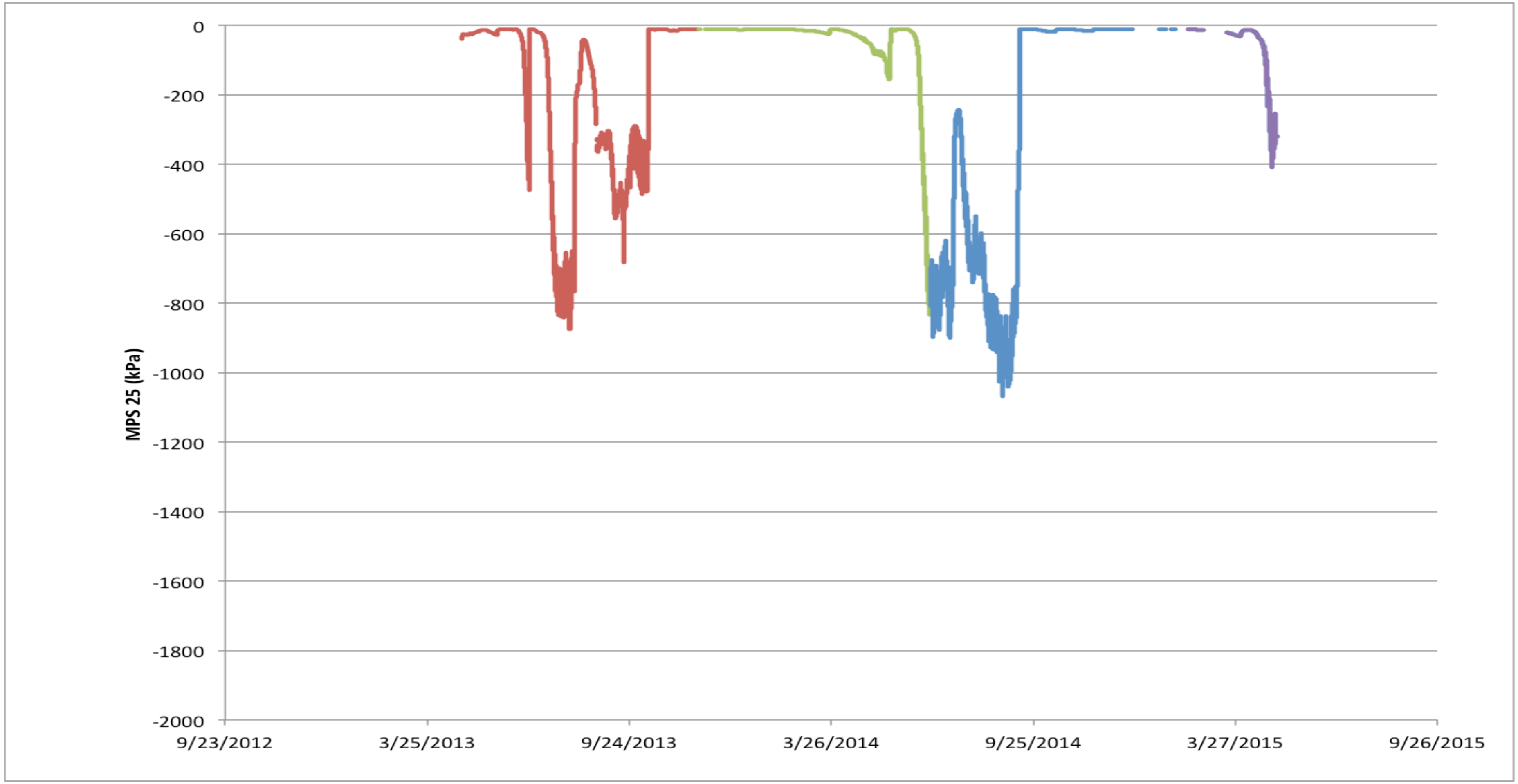
## Appendix 10:  Soil water potential with the MPS at 5 cm.



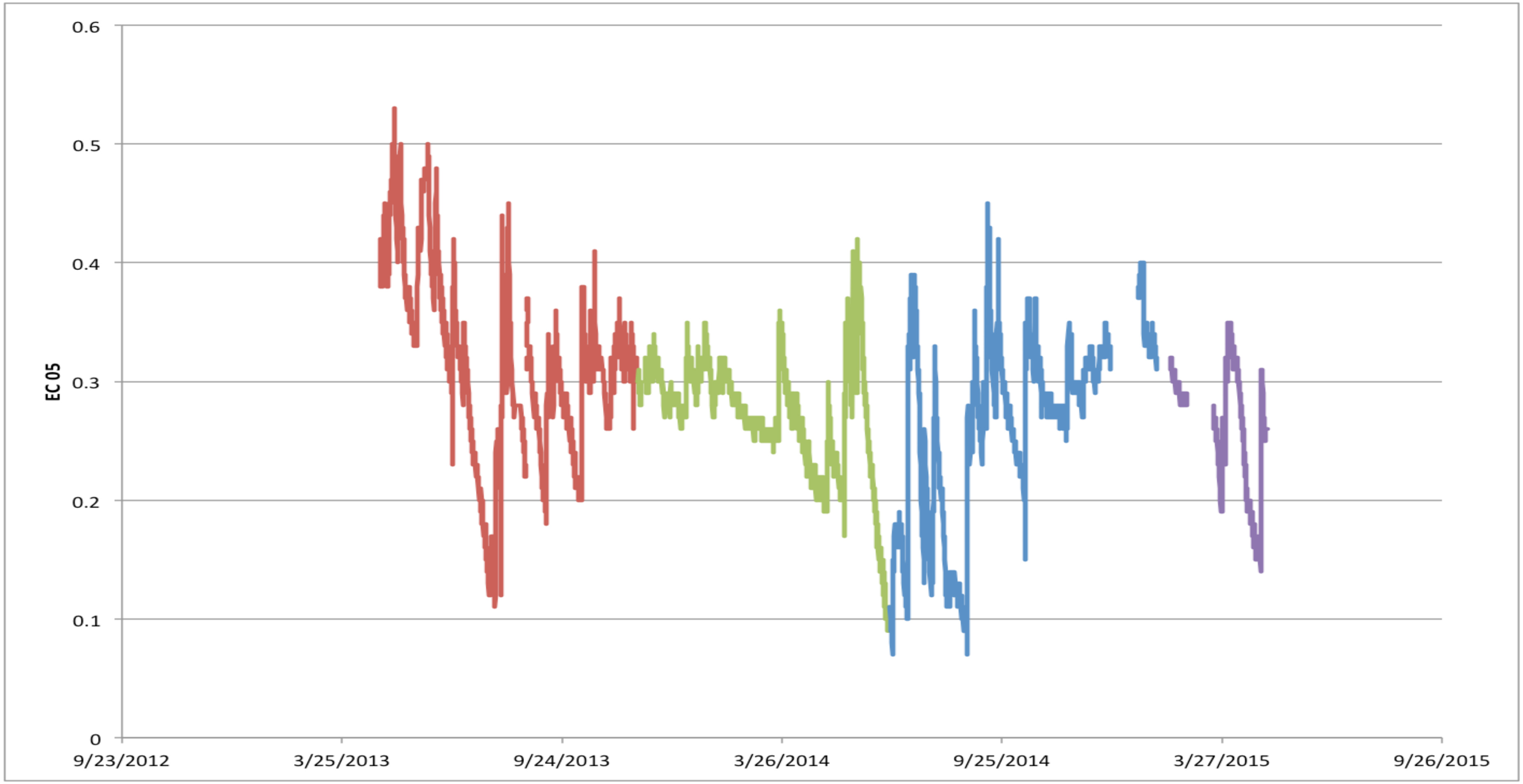
## Appendix 11: Soil water potential with the MPS at 15cm.



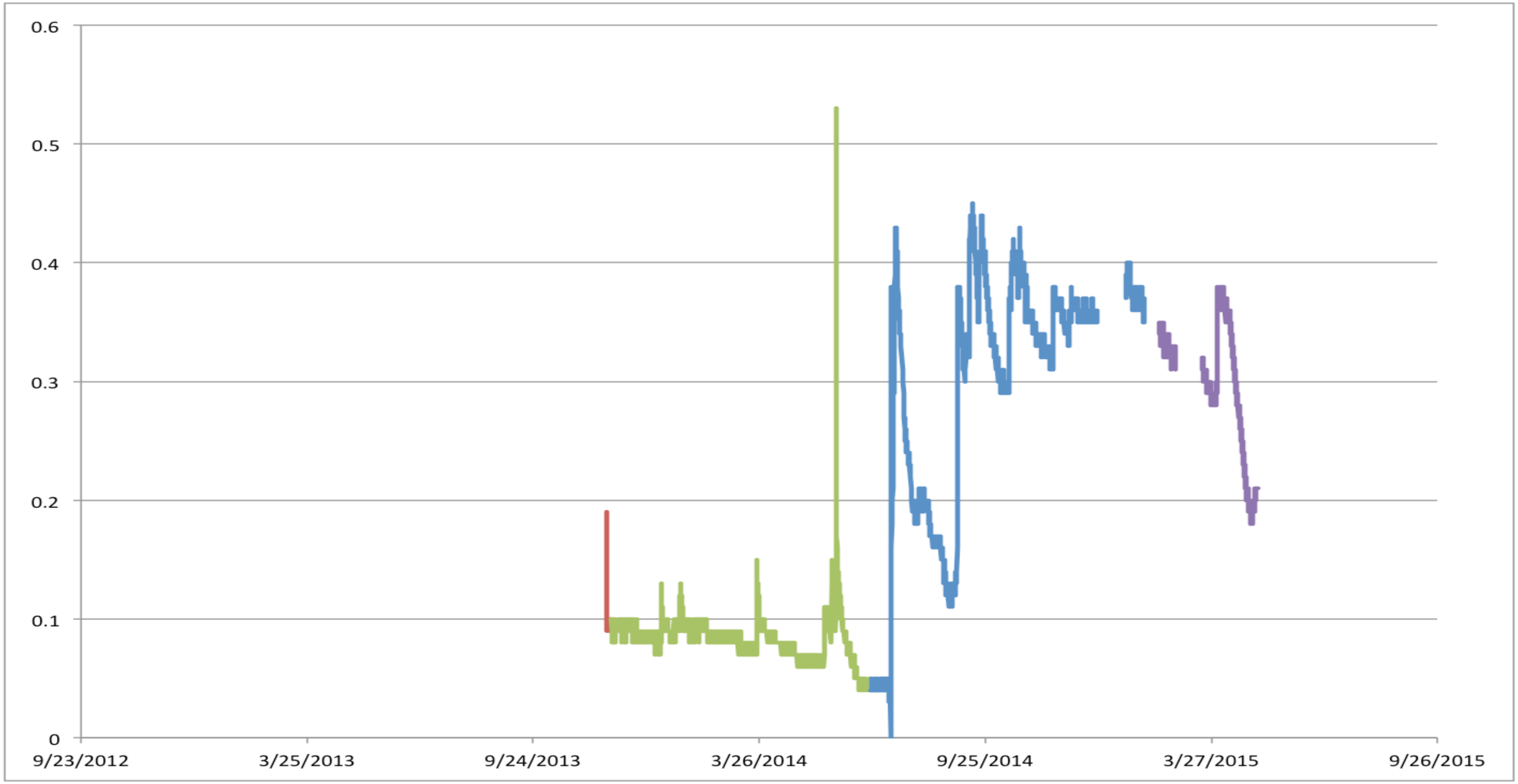
## Appendix 12: Soil water potential with the MPS at 25 cm.



## Appendix 13: Electrical conductivity at 5 cm



## Appendix 14: Electrical conductivity at 15 cm



## Appendix 15: Electrical conductivity at 25 cm.