Czech University of Life Sciences Prague

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UNIVERZITA V PRAZE

Diploma Thesis

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Actual and potential evapotranspiration of a grass stand according to small smart field lysimeters

Diploma Thesis

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Declaration

I hereby declare that this M.Sc. thesis on “Actual and potential evapotranspiration of a grass stand according to small smart field lysimeters” is my independent work and effort, carried out under guidance of my supervisors. All scientific literature and other information sources which are used in this thesis 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

I have many people to whom I want to express my sincere appreciations upon completion of my Master's graduate study, research and thesis.

First of all, I would like to thank my academic supervisor Ing. František Doležal, CSc. for giving me great support during his supervision. My thesis project could not have been completed without the mentorship, patience, tolerance, understanding, and friendship with him. Also I want to thank my co-supervisor from my home university Ass.Prof. Alim Pulatov, CSc. who is also my Home University coordinator, for his patience, advices and consultations.

Many thanks to the coordinator of the European Commission Erasmus Mundus program CASIA project, Ewa Wietsma-Lacka, who granted me and gave me opportunity to study at Czech University of Life Sciences Prague (CULS) and be its alumnus.

I would like to express my appreciation to staff members of the Czech University of Life Sciences, Faculty of Agrobiology, Food and Natural Resources. I thank the Department of Water Resources for providing me with a graduate assistantship for the duration of my study at the University.

I want also thank my parents and my friends for their great support during my mobility in Prague.

Summary

Lysimeters are basic instruments for evapotranspiration measurement. This master thesis characterizes the actual evapotranspiration of non-irrigated and unfertilized grass in a warm region of the Czech Republic on a Chernozem loamy soil. A weighing lysimeter SFL-300 (diameter 0.3 m, depth 0.3 m) was used for this purpose. The suction at its bottom was maintained at the same level as in the native soil nearby. 585 rainless days with regular records were selected for the analysis of daily sums. On most days, the lysimeter-measured actual evapotranspiration ETa was smaller than the Penman-Monteith FAO 56 reference crop evapotranspiration ET_0. The FA0 56 procedure was found to be a reasonable estimator of the non-stressed evapotranspiration in a moderately stressed environment. The ET_a/ET_0 ratio and the canopy surface resistance r_s depend on the soil water content and suction measured at 5 cm. This dependence breaks down into a horizontal non-stressed part and declining (for ET_a/ET_0) or inclining (for r_s) water-stressed part. The ratio ET_a/ET_0 is about 85 % and r_s is about 250 s m^{-1} when the grass is not under water stress. The annual curve of the non-stressed crop coefficient has a sine shape. An energy balance criterion suggests that advection of heat is important in winter but not so much in summer. The paper provides parameters of evapotranspiration for a canopy that can be found on many standard weather stations and demonstrates that high-quality research of evapotranspiration of low, dense and shallow-rooting crops is possible with small lysimeters of this type.

Virtually all results were obtained with the newer and more perfect of the two lysimeters available, while the older lysimeter and its problems were discussed only shortly. The older lysimeter can be operated in parallel with the new one, mainly to serve as a check for soil water suction and percolation measurements

A brief overview of some lysimeter research results obtained in Uzbekistan is also provided. The main topic of this research is the effect of shallow groundwater on total water consumption of irrigated and non-irrigated cotton crop. The very shallow fresh groundwater may replace surface irrigation, but there is always a risk of soil salinization and oxygen stress. The lysimeters for this type of research would have to be much deeper (more than 2 m) and its diameter would have to be larger, of the order of 1 m or more, to adequately represent the cotton canopy.

Key words: reference crop, evapotranspiration, weather station, FAO 56 Penman-Monteith equation.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Evapotranspiration is a very important process of Earth's water cycle. It consists of two closely related processes: physical evaporation and transpiration (physiological evaporation). Physical evaporation is a process when water present in the soil or on the surface of soil or plants or in surface water bodies turns from the liquid form (in a generalized sense also from the solid form) to the vapor form and escapes into atmosphere. Transpiration is a process when water from the soil or a water body is absorbed by plant roots, transported through plant tissues and released to the atmosphere from the surface of above-ground plant tissues, mainly leave stomata. The sum of these two processes is referred to as evapotranspiration.

Evapotranspiration plays very significant role in our life. Alkaeed et al. (2006) claim that estimation of evapotranspiration is one of the major hydrological components for determining the water budget and is becoming indispensable for the calculation of a reliable recharge and evaporation rate for the groundwater flow analysis. Therefore, reliable and consistent estimate of evapotranspiration is of great importance for the efficient management of water resources

The proper and precise estimation of evapotranspiration is a fundamental issue in different fields such as food security research, land management systems, pollution detection, nutrient flows. Knowledge on *ET* is fundamental when dealing with water resources management issues, for example, the provision of drinking and irrigation water, industrial water use or water reserve management. These issues go from questions of agricultural and life sustainability to even direct human life support measures for large parts of the globe (Verstraeten et al., 2008).

Understanding water cycle and its components is crucial for various environmental issues, such as drinking water supply, water resource management, groundwater protection, or agricultural water management. The latter, for instance, is concerned with drainage and irrigation with respect to optimal crop production. In this regard, it would be helpful to observe and quantify the processes in the soil-plant-atmosphere system. Furthermore, long-term monitoring of water balance components may provide a database for climate change studies (Nolz, 2013).

1.2 Objective of thesis

The objective is to estimate actual evapotranspiration (*AET*) of non-irrigated, non-fertilised short grass on Chernozem loamy soil in Central Bohemia. The estimation will be based on several years of measurements with two weighing lysimeters, accompanied by other weather and soil water measurements.

1.3 Hypothesis

The actual evapotranspiration measured on the days without precipitation is correlated to the FAO 56 reference crop evapotranspiration and the soil water potential.

CHAPTER 2

LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Lysimeters

Lysimeter is a device for measuring percolation of water through the soil and sampling soil water for chemical analyses but also for determining water use by vegetation. Precision lysimeters for measuring evapotranspiration *(ET)* have developed mainly within the past 50 years. As for their thistory, Kohnke et al. (1940) and Aboukhaled et al. (1982) attributed the first lysimeter for the study of water use to De la Hire in France of the late 17th century. Salisbury and Ross (1969) described a lysimeter study conducted in the Netherlands in early 17th century (probably about 1620) by Van Helmont. Principle advances in *ET* lysimetry have centered on the measurement of the lysimeter mass and vacuum drainage and making the lysimeters deeper to more closely duplicate field conditions. The weighing mechanisms - mechanical, floating, hydraulic, or electronic - can be automated for electronic data recording. Major advances in recording weighing lysimeters have occurred in the past 20 years (Howell et.al., 1991).

According to Aboukhaled et al. (1982), the word lysimeter is derived from the Greek words *lysis,* which means the dissolution or movement and *metron*, which means to measure. The lysimeter is a device, generally a tank or container, to estimate the water movement across a soil surface and/or across the lower boundary of the soil body of which the lysimeter consists. The water use (actual evapotranspiration) can be determined by a balance of water between these two boundaries. Weighing lysimeters determine *ET* directly by the mass balance of water in the soil body as contrasted to non-weighing lysimeters which requires a more comprehensive water volume balance, including precipitation and percolation.

In addition, the term lysimeter may mean any instrument which measures weight changes, especially weight reduction due to evapotranspiration, in a particular volume of soil with or without accompanying vegetation (Johnson et al., 1978).

According to Lanthaler (2004), various types of lysimeters differ from each other in their characteristics:

- size: small (< 0.5 m^2), standard (0.5–1 m^2), large (> 1 m^2)

- weighability: weighable, non-weighable

- soil filling method: disturbed (backfilled) or undisturbed (monolith/monolithic lysimeter)
- whether or not groundwater occurs in them: groundwater lysimeters with a variable or invariable groundwater level; lysimeters without groundwater
- low boundary condition with or without applied vacuum; the vacuum can be constant or variable
- vegetation: bare soil, grassland, arable land, forest
- soil fractions: sandy, silty, clayey soil.

According to the survey by Lanthaler (2004), in Europe there were 117 institutions operate ca. 2930 lysimeters and seepage water samplers (SWS) in 18 countries. 2440 of the total number are lysimeters made by soil blocks in vessels; 84 % of them are non weighable and up to 30 % are monolithically filled. 269 containers are weighable, whereof 46 % are monolithic lysimeters. Two thirds of all lysimeters are used for research on arable land, almost one fourth is used under grassland and only 1 % is implemented in forests. SWS are used to a higher extent in grassland (41 %); 15 % are installed under arable land, and 8 % in forests. The percentage of all vessels used for studies of arable land amounts to 54 % (1590 vessels).

2.2 Evapotranspiration as a process

As already stated in the introduction, evapotranspiration is a sum of two natural processes: evaporation and transpiration. In both processes, water escapes into atmosphere in form of vapor.

Evapotranspiration is one of the component of the water budget (balance) of land surfaces. There are also other components of this water budget, such as precipitation, infiltration and runoff. We can see the water budget components visualized in Figure 1.

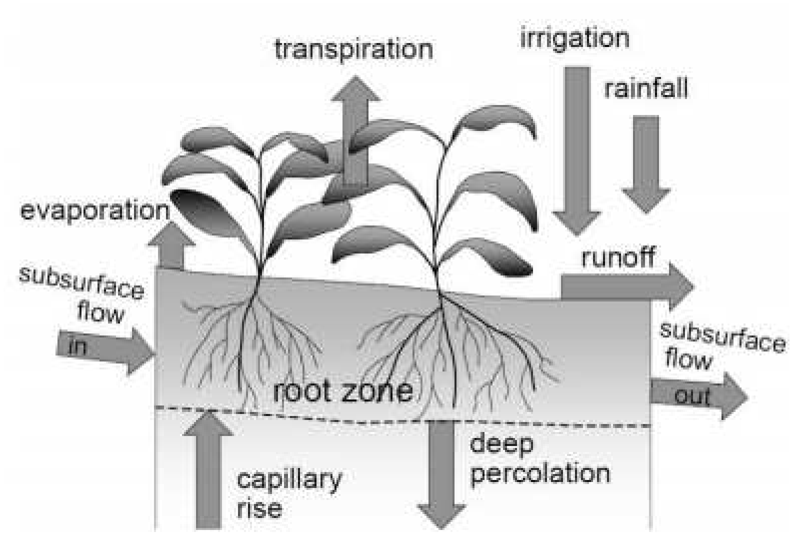


*Figure 1.*Soil water balance of the root zone (Allen et. al. 1998). The balance components are marked with arrows.

Evaporation is the process whereby liquid (or solid) water is converted to water vapor (vaporization) and the vapor is removed from the evaporating surface. Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils, snowpack, ice and wet vegetation (Allen et al., 1998). According to Ziemer (1979), evaporation of water from the soil is controlled by two factors: the availability of energy and the rate of water conduction to the soil surface. As the soil dries, energy availability becomes less important and the rate of soil water conduction becomes more important.

Transpiration is the process of water loss from plants through stomata. Stomata are small openings found on the underside or both sides of leaves that are connected to vascular plant tissues (Figure 1). In most plants, transpiration is controlled by the evaporative demand of the atmosphere, the water availability in the soil and other environmental factors (light, temperature, salts, oxygen, pests etc.). Of the transpired water passing through a plant only 1% is used in the growth process. Transpiration also transports nutrients from the soil into the roots and carries them to the various cells of the plant. It is also used to keep plant tissues from becoming overheated. Some dry environment plants do have the ability to open and close their stomata during the day. This adaptation is necessary to limit the loss of water from plant tissues. Without this adaptation, these plants would not be able to survive under conditions of severe drought. (Pidwirny, 2006).

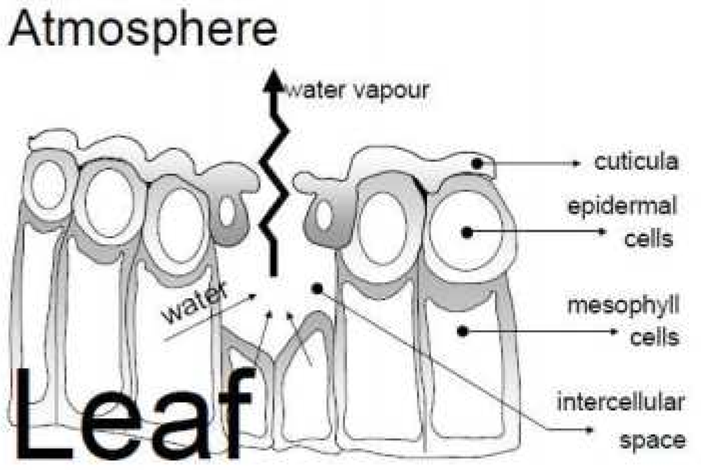


Figure 2: Schematic representation of a plant stoma, the tissues around it and the transpiration process (Allen et. al. 1998)

Transpiration, like evaporation, depends on such weather parameters as the energy supply, vapor pressure gradient and wind. Therefore, radiation, air temperature, air humidity and wind speed should be considered when assessing transpiration. The soil water content and the ability of the soil to conduct water to the roots also determine the transpiration rate, as do waterlogging and soil water salinity. The rate of transpiration is also influenced by crop characteristics, environmental conditions and cultivation practices. Different kinds of plants may have different transpiration rates. Therefore, the crop development, environment and management also should be considered when assessing transpiration (Allen et al., 2006).

Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes. Apart from the water availability in the topsoil, the evaporation from a cropped soil is mainly determined by the fraction of the solar radiation reaching the soil surface. This fraction decreases over the growing period as the crop develops and the crop canopy shades more and more of the ground area. When the crop is small, water is predominately lost by soil evaporation, but once the crop is well developed and completely covers the soil, transpiration becomes the main process.

Evapotranspiration is undoubtedly a very important process and a significant component of the hydrologic budget (balance). Evapotranspiration varies regionally and seasonally; on shorter time scales it varies according to weather conditions. Because of these variabilities, water managers who are responsible for planning and making decisions about allocation of water resources need to have a thorough understanding of the evapotranspiration process and knowledge about its spatial and temporal variability.

2. 3 Types of evapotranspiration

Actual evapotranspiration (*AET*) refers to the actual evaporation of water from an evaporating surface under given atmospheric conditions (Matin and Bourque, 2013). Sometimes it is defined as the quantity of water vapor evaporated from the soil and plants when the ground is at its natural moisture content (WMO, 1992). Actual evapotranspiration is the main path of water loss from both plant and soil surface. The main goal of irrigation is to supply plant with water as needed to obtain optimum yield and quality of a desired plant constituent. This is why on agricultural lands, *AET* measurement and calculation is needful for developing more efficient and sustainable water management techniques as well as for irrigation scheduling of crops (Attarod et al. 2005).

There are direct and indirect methods of estimating actual crop evapotranspiration. One of the direct methods is the application of weighing lysimeters, which provide a mass balance of soil water. Accuracy of *AET* estimation with lysimeters rests on the precision of the weighing instrument and sampling frequency (Rana and Katerji, 2000).

Reference crop evapotranspiration (ET_o) is defined by the Food and Agriculture Organization of the United Nations (FAO) (see Irmak and Haman, 2003) as “the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m (4.72 in), a fixed surface resistance of 70 sec m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground”. Due to this definition, we can say that the reference *ET* is a calculated value based on weather conditions only, while the effect of seasonal changes, type of crop and other factors are eliminated. The most common practice to quantify reference *ET* is through the Penman-Monteith equation calculation, which is recommended by FAO as a universal procedure.

Potential evapotranspiration (*PET*) is defined as the evapotranspiration that would result when there were always adequate water supply available to a fully vegetated surface. This term implies an ideal water supply to the plants. In case water supply to the plant is less than ideal, the deficit can be drawn from the soil moisture storage until about 50 per cent of the available soil water is utilized, without any significant impact on the evapotranspiration rate. With a further increase of the soil moisture deficit, the actual evapotranspiration (*AET*) will become less than *PET* until the wilting point is reached, at which instant the evapotranspiration stops (WMO, 2008).

In the course of history, scientists made different definition of *PET*. Thornthwaite (1948) coined the term “potential evapotranspiration” the same year that Penman (1948) published his approach for calculating evaporation from a short green crop completely shading the ground. Penman (1956) called this process “potential transpiration”. Since then there have been many definitions and redefinitions of the potential evaporation, transpiration or evapotranspiration.

2.4 Factors affecting evapotranspiration

There are many factors that must be mentioned and evaluated during the examining of evapotranspiration. These factors we can divide to several groups, in particular the atmospheric parameters, soil properties, crop characteristics, management and environmental factors.

Atmospheric Factors belong to the most important ones, in particular solar radiation, air temperature, air humidity and wind speed. If temperature increases, the evapotranspiration rate will typically also increase, especially during the growing season. Stronger and longer sunlight and warmer air masses will cause plant cells to open the stomata and supply more energy, which makes more water evaporate into the atmosphere. The relative humidity has an inverse effect on evapotranspiration. For example, higher humidity tends to result in lower evapotranspiration rates because it is easier for water to evapotranspire into dry air than into moist air. Increase in wind speed will result in a higher evapotranspiration rate because it more quickly removes the saturated air from the evaporating surface.

Soil properties, in particular the soil moisture availability to plants are also factors that affect evapotranspiration, because less available soil moisture will result in reduction of evapotranspiration (Truong, 2012).

Crop Characteristics are reflected, for example, in the crop coefficients (Allen et al., 1998) with which the reference crop evapotranspiration (ET_o) must be multiplied to obtain the actual crop evapotranspiration. There are four primary characteristics that are considered when developing a crop evapotranspiration, namely: 1) crop cover density and total leaf area; 2) resistance of foliage epidermis and soil surface to the flow of water vapor; 3) aerodynamic roughness of the crop canopy; and 4) reflectance (albedo) of the crop and soil surface to short wave radiation. The crop coefficients, K_c, were developed for and applied to agricultural situations but can be also developed for and applied to natural vegetation and other conditions, including open water, but in these cases they can have large spatial variability.

During the growing season, K_c varies as the plant develops, because the fraction of ground covered by the vegetation changes, and later the plants age and mature. In addition, K_c can vary according to the wetness of the soil surface, especially when there is little vegetation cover, such that the crop coefficient has a high value when soil is wet and steadily decreases as the soil dries.

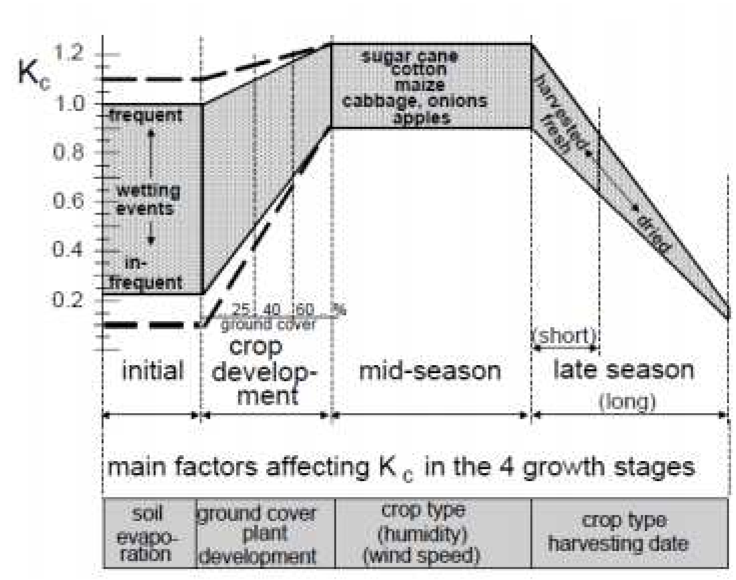


Figure 3: Typical ranges expected in K_c for the four growth stages of annual crops (Allen et. al. 1998)

Figure 3, developed by Allen, illustrates the change in K_c during the life cycle of annual crops during the season. The coefficient depicted in Figure 3 is a result of the so-called single coefficient approach, when the soil evaporation and the plant transpiration are treated together. As illustrated in Figure 3, the crop coefficient can vary substantially throughout the season. In general, at its peak, K_c can be as high as 1.2, while it may be as low as 0.2 during the late season.

2.5 Estimation of evapotranspiration

2.5.1 Penman Equation (1948)

A large number of empirical and semi-empirical methods have been developed for estimation of evapotranspiration based on different climatic variables, among them also the Makkink (1957b, 1959) and the Priestley-Taylor (1972), described below in the Materials and Methods section.. Significantly most important among these methods are those derived from the now well-known Penman equation (Allen et al., 1998) for determining evaporation from open water, grass and bare soil (including what is now called evapotranspiration). The Penman equation is based on a combination of the energy balance and an aerodynamic formula. The result is given as:

$$\lambda E = \frac{[\Delta (R_n - G)] + (\gamma \lambda E_a)}{(\Delta + \gamma)} \tag{1}$$

where:

λE = evaporative latent heat flux (MJ m^{-2} d^{-1}),

Δ = slope of the saturated vapor pressure curve [$\partial e_s/\partial T$, where e_s = saturated vapor pressure (kPa) and T = daily mean temperature (°C)],

R_n = net radiation flux (MJ m^{-2} d^{-1}),

G = sensible heat flux into the soil (MJ $m^{-2} d^{-1}$),

γ = psychrometric constant (kPa °C^{-1})

and E_a = aerodynamic vapor transport term (mm d^{-1}), depending on the mean daily vapor saturation deficit and an empirical function of the mean daily wind speed.

2.5.2 Penman-Monteith equation

Monteith (1965) included the bulk surface resistance term in the Penman equation, which resulted in an equation we call Penman-Monteith's. In terms of daily values it may be written as follows:

$$\lambda ET_0 = \frac{\Delta(R_n - G) + \left[86400\ \frac{\rho_a C_p (e_s - e_a)}{r_{av}}\right]}{\Delta + \gamma\left(1 + \frac{r_s}{r_{av}}\right)} \tag{2}$$

where, in addition to the symbols already defined:

ET = actual evapotranspiration,

ρ_a = air density (kg m^{-3}),

C_p = specific heat of dry air,

e_s = mean saturated vapor pressure (kPa) computed as the mean of the saturated pressures at the daily minimum and the daily maximum air temperature (°C),

r_{av} = bulk surface aerodynamic resistance for water vapor (s m^{-1}),

e_a = mean daily ambient vapor pressure (kPa),

and r_s = the canopy surface resistance (s m^{-1}).

2.5.3 Penman-Monteith equation modified by U.N. Food and Agriculture Organization

In 1998, FAO guidelines titled "*FAO Irrigation and Drainage Paper No. 56*", written by R. Allen, L. Pereira, D. Raes, and M. Smith, were published (Allen et al., 1998). It recommended the Penman-Monteith equation as a universal tool for estimation of the reference crop evapotranpiration ET_0 with the surface resistance r_c replaced by a constant value 70 s m-1) and some other values made also appropriately constant. Later on, this effort was complemented by the action of the American Society of Civil Engineers (ASCE) with the purpose was to achieve consistency and wider acceptance of the FAO *ET* models (Howell and Evett 2006). The principal result was that two equations, one for a short crop (similar to short-cut, cool-season grass) named ET_{os} and another equation for a tall crop (similar to full-cover alfalfa) named ET_{rs}, were developed for daily (24 hr) and hourly time periods. The equation for the short crop coincides with the original FAO 56 equation:

$$ET_o = \frac{0.408\,\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \tag{3}$$

where, in addition to the symbols already defined:

ET_0 = reference crop evapotranspiration rate (mm d^{-1}),

T = mean air temperature (°C),

and u_2 = wind speed (m s^{-1}) at 2 m above the ground.

To use this equation with hourly data the constant value "900" should be divided by 24 (because there are 24 hours in a day) and the R_n and G terms should be expressed in MJ m^{-2} h^{-1}.

2.5.4 Input variables and parameters required for calculation of *ET_o*

For the calculation of ET_0 according to the Penman-Monteith (FAO 56) equation we need meteorological input data, namely air temperature, air relative humidity, solar radiation and wind speed. The other information needed includes the average barometric pressure or the site elevation above sea level, the calendar day (day of year) and the site latitude. The calculation procedure was described in a step-by-step way by Zotarelli et al. (2010). and used, among others, by Hernández Gomis (2016) and by the author of this thesis.

The mean daily temperature is obtained as:

$$T_{mean} = \frac{T_{\max} + T_{\min}}{2} \tag{4}$$

where:

T_{mean} = mean daily air temperature, (°C);
T_{max} = maximum daily air temperature, (°C);
T_{min} = minimum daily air temperature, (°C)

The slope of the saturation vapor pressure curve (Δ) is obtained from the FAO 56 semi-empirical equation into which the mean daily temperature was substituted:

$$\Delta = \frac{4098 \left[0.6108 \exp \left(\frac{17.27\ Tmean}{Tmean + 237.3} \right) \right]}{\left(Tmean + 237.3)^2 \right)} \tag{5}$$

where:

Δ = slope of saturation vapor pressure curve.

T_{mean} = mean daily air temperature, [ºC] (Eq. 4).

The psychrometric constant (γ) is estimated from:

$$\gamma = \frac{C_p P}{\varepsilon \lambda} = 0.000665P \tag{6}$$

where:

γ = psychrometric constant (kPa °C^{-1}),

P = average atmospheric pressure (kPa),

λ = latent heat of vaporization, 2.45 MJ kg^{-1},

c_p = specific heat at constant pressure, 1.013x10^{-3} MJ kg^{-1} °C^{-1}.

The mean daily saturated vapor pressure e_s is obtained as a mean of the maximum and minimum daily saturated vapor pressures:

$$e_s = \frac{e_s(T_{max}) + e_s(T_{min})}{2} \tag{7}$$

$$e_s(T_{max}) = 0.6108 \exp\left[\frac{17.27 T_{max}}{T_{max} + 237.3}\right] \tag{8}$$

$$e_s(T_{min}) = 0.6108 \exp\left[\frac{17.27 T_{min}}{T_{min} + 237.3}\right] \tag{9}$$

where:

e_s = the mean daily saturated vapor pressure (kPa),

T_{max} = maximum daily air temperature (ºC),

T_{min} = minimum daily air temperature (ºC).

The mean daily actual vapor pressure (kPa) is obtained using from the minimum (RH_{min}) and the maximum (RH_{max}) daily relative humidity and the minimum and maximum daily saturated vapor pressure as follows:

$$e_a = \frac{e_s(T_{min})\left[\frac{RH_{max}}{100}\right] + e_s(T_{max})\left[\frac{RH_{\min}}{100}\right]}{2} \tag{10}$$

where:

e_a = actual vapor pressure (kPa),

$e_s(T_{min})$ = saturation vapor pressure at the daily minimum temperature (kPa), Eq. 9,

$e_s(T_{max})$ = saturation vapor pressure at the daily maximum temperature (kPa),

RH_{max} = maximum daily relative humidity (%),

RH_{min} = minimum daily relative humidity (%)

The inverse squared relative distance Earth-Sun is estimated from the day-of-year number J:

$$d_r = 1 + 0.33\cos\left[\frac{2\pi}{365}J\right] \tag{11}$$

where:

d_r = inverse squared relative distance Earth-Sun (unitless),

J = day-of-year number (J=1 for 1st January).

The solar declination δ (the angle between the equatorial plane and the Sun-Earth connecting line) is similarly estimated as:

$$\delta = 0.409\sin\left[\frac{2\pi}{365}J - 1.39\right] \tag{12}$$

where:

δ = solar declination (radians).

The sunset hour angle ω_s can be obtained from the latitude of the place and the solar declination:

$$\omega_s = \arccos\left[-\tan(\varphi)\tan(\delta)\right] \tag{13}$$

where:

ω_s = sunset hour angle (radians),

φ = latitude (radians),

δ = solar declination (radians)

The extra-terrestrial radiation on a horizontal surface R_a can be obtained by the formula:

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r \left[(\omega_s \sin\varphi \sin\delta) + (\cos\varphi \cos\delta \sin\omega_s)\right] \tag{14}$$

where:

R_a = extra-terrestrial radiation (MJ m^{-2} day^{-1}),

G_{sc} = solar constant = 0.0820 (MJ m^{-2} min^{-1})

d_r = inverse squared relative distance Earth-Sun,

ω_s = sunset hour angle (radians),

δ = solar declination (radians).

The net shortwave radiation R_{ns} is estimated as:

$$R_{ns} = (1 - a)R_s \tag{15}$$

where:

R_{ns} = net shortwave radiation, (MJ m^{-2} day^{-1}),

α = albedo, i.e. the shortwave reflection coefficient (0.23 for the hypothetical grass reference crop),

R_s = the incoming solar radiation (MJ m^{-2} day^{-1}), the average daily net radiation obtained from a pyranometer at the weather station for a 24 h period, or estimated from the sunshine duration hours.

The clear-sky solar radiation (R_{so}) is estimated as:

$$R_{so} = \left(0.75 + 2E10^{-5} z\right)R_a \tag{16}$$

where:

z = elevation above sea level (m),

R_a = extra-terrestrial radiation (MJ m^{-2} day^{-1}).

The net long-ave radiation R_{nl} can be estimated as:

$$R_{nl} = \sigma\left[\frac{(T_{\max} + 273.16)^4 + (T_{\min} + 273.16)^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left[1.35\frac{R_s}{R_{so}} - 0.35\right] \tag{17}$$

where:

R_{nl} = net (outgoing minus incoming) long wave radiation (MJ m^{-2} day^{-1}),

σ = Stefan-Boltzmann constant (4.903×10^{-9} MJ K^{-4} m^{-2} day^{-1}),

T_{max} = maximum daily temperature (°C),

T_{min} = minimum daily temperature (°C),

e_a = mean daily actual vapor pressure (kPa),

R_s = daily incoming solar radiation (MJ m^{-2} day^{-1}),

R_{so} = daily clear sky solar radiation (MJ m^{-2} day^{-1})

Finally, the net radiation R_n can be obtained as the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net long wave radiation (R_{nl}):

$$R_n = R_{ns} - R_{nl} \tag{18}$$

2.6 Research in Uzbekistan concerning evapotranspiration and water consumption of cotton crop (mainly based on Akhmedjanov and Akhmedjonov, 2013)

2.6.1 Total water consumption by cotton crop

To calculate the total water consumption of irrigated cotton, any empirical equation characterizing evaporativity can be used, if the coefficients allowing us to convert evaporativity into the actual cotton water consumption can be established. Under "evaporativity" (in Russian: "isparyaemost") one understands the evaporation or evapotranspiration obtained by a standard method and independent of the crop. It is a sort of reference evaporation or reference evapotranspiration.

In order to increase the cotton yields, lysimetric studies were carried out in Uzbekistan to determine specific features of the cotton water regime under conditions of both shallow and deep groundwater table. Appropriate irrigation regimes were.developed on this basis.

The total water consumption by both plant transpiration and soil evaporation can be determined in proportion to the sum of evaporativity or of the vapor pressure deficit over the growing season. The following formulae were proposed:

The Ivanov formula (1970):

$$M = a\sum E \tag{19}$$

where:

M = total water consumption over the growing season (mm),
$E = 0{,}0018(t+25)^2(100-a)$ is the monthly evaporativity (mm/month);

t = average monthly air temperature (^{o}C);

a = average monthly relative humidity (%);

$\sum E$ = sum of evaporativity (mm) over all months of the growing season;

α = coefficient (the recommended value for Central Asia being 0.8)
The Alpatyev formula (1954):

$$M = K\sum D \tag{20}$$

where:

M = total water consumption over of the growing season,

K = the ratio of the total water consumption to the sum of daily vapor saturation deficits, called "biological coefficient", which is and specific for a given crop (0.3 to 1.0 mm/mbar) and must be determined experimentally,

$\sum D$ = the sum of mean daily vapor saturation deficits over the growing season (mbar).

2.6.2 The use of groundwater by cotton crop

The seasonal irrigation depth for cotton (M_1) is determined by balance calculations:

$$M_1 = M - M_p - M_r - M_g \qquad (21)$$

where:

M_1 = seasonal irrigation depth for cotton (mm),

M = total water consumption (by transpiration and soil evaporation) over the growing season (mm),

M_p = exploitable precipitation (mm),

M_r = exploitable soil water storage (mm),

M_g = exploitable water supply from the shallow groundwater table (mm).

The total water consumption by plant transpiration and soil evaporation is proportional to the sum of evaporativity sum or to the sum of daily vapor saturation deficits over the growing season, as explained above.

The seasonal irrigation depth is significantly reduced due to the presence of shallow groundwater. The lysimetric studies at UZNIKhI stations, which followed a unified methodology, established that the rate and height of moisture rise from the groundwater table to the root zone of the soil depend on the soil profile composition, crop and irrigation regime (Kovda, 1972).

The highest rate and height of the capillary rise are characteristic for homogeneous coarse-silty loams. The seasonal water consumption of cotton at the expense of groundwater table as deep as 3 m can be up to 40% of the total water consumption, while the yields in the conditions of the Hungry Steppe can reach more than 4 tons /ha.

The data by Alimov and Rysbekov (1985), reproduced in Table 1 below, demonstrate that the shallow groundwater table may supply up to 80% of the total water consumption. In order to establish the cotton irrigation schedules for shallow groundwater conditions, it is necessary to estimate the groundwater contribution to the active soil layer water balance from the lysimetric observations made under particular conditions (such as those in Table 1).

Table 1. Data of cotton crop experiments (mm).

Experiment stations	Groundwater table at 1 m depth				Groundwater table at 2 m depth			
	M	M_1	M_g	%	M	M_1	M_g	%
Pakhta-Aral	1167	195	912	78.2	599	377	162	27.5
Bukhara	867	490	437	45.2	837	680	115	13.7
Fedchenkov	632	427	138	21.9	410	315	23	5.5
Khorezm	739	433	336	45.5	820	600	219	26.8

See equation (21) for the meaning of the symbols. The percentage is M_g/M.

From Table 2 it is clear that the total water consumption at shallow groundwater (1 m) is by 132 – 681 mm larger than that at deep groundwater (3 m). Chapovskaya (1971) found that the total seasonal water consumption was 1180 mm at the groundwater depth 1.0 m and only 900 mm at the groundwater depth 3.0 m, which is by 280 mm smaller. The corresponding groundwater contributions were 54-64% at the groundwater depth 1.0 m, 34-38% at 1.5 m, 19-22% at 2.0 m and 7-10% at 3.0 m.

Table 2. Total water consumption of cotton crop and its components in the Bukhara Oasis according to different authors.

Water balance terms	N.I. Kurilova			A.Kim			D.M.Katz		
	Depth of groundwater, m								
	1.0	2.0	3.0	1.0	2.0	3.0	1.0	2.0	3.0
Seasonal irrigation depth M_1 mm / % M	667/59	201/16	61/4.5	662/67	252/20	131/11	397/28.6	178/24.4	72/10.2
Groundwater supply M_g mm / % M	219/41	594/84	693/95,4	364/33	573/80	705/89	988/71.4	550/75.6	632/89.8
Total water consumption M, mm	886	795	754	1026	825	836	1385	728	704

See equation (21) for the meaning of the symbols. The percentage is M_g/M.

The investigations reported by Alimov and Rysbekov (1985) showed that a considerable amount of water is spent on total evaporation at shallow groundwater occurrence, up to 1200 mm/season, which is by 250 to 450 mm more than at deep groundwater.

In order to disregard the effect of superfluous soil evaporation when the groundwater table is shallow, Rachinsky (1965) and Soyfer and Soyfer (1971) proposed to determine the contribution of groundwater to the total seasonal water consumption as:

$$m = \left(1 - \frac{E'}{E}\right) \tag{22}$$

where:

m = the groundwater contribution to the total water consumption by the crop (unitless),

E' = the seasonal irrigation depth at a given groundwater depth (mm),

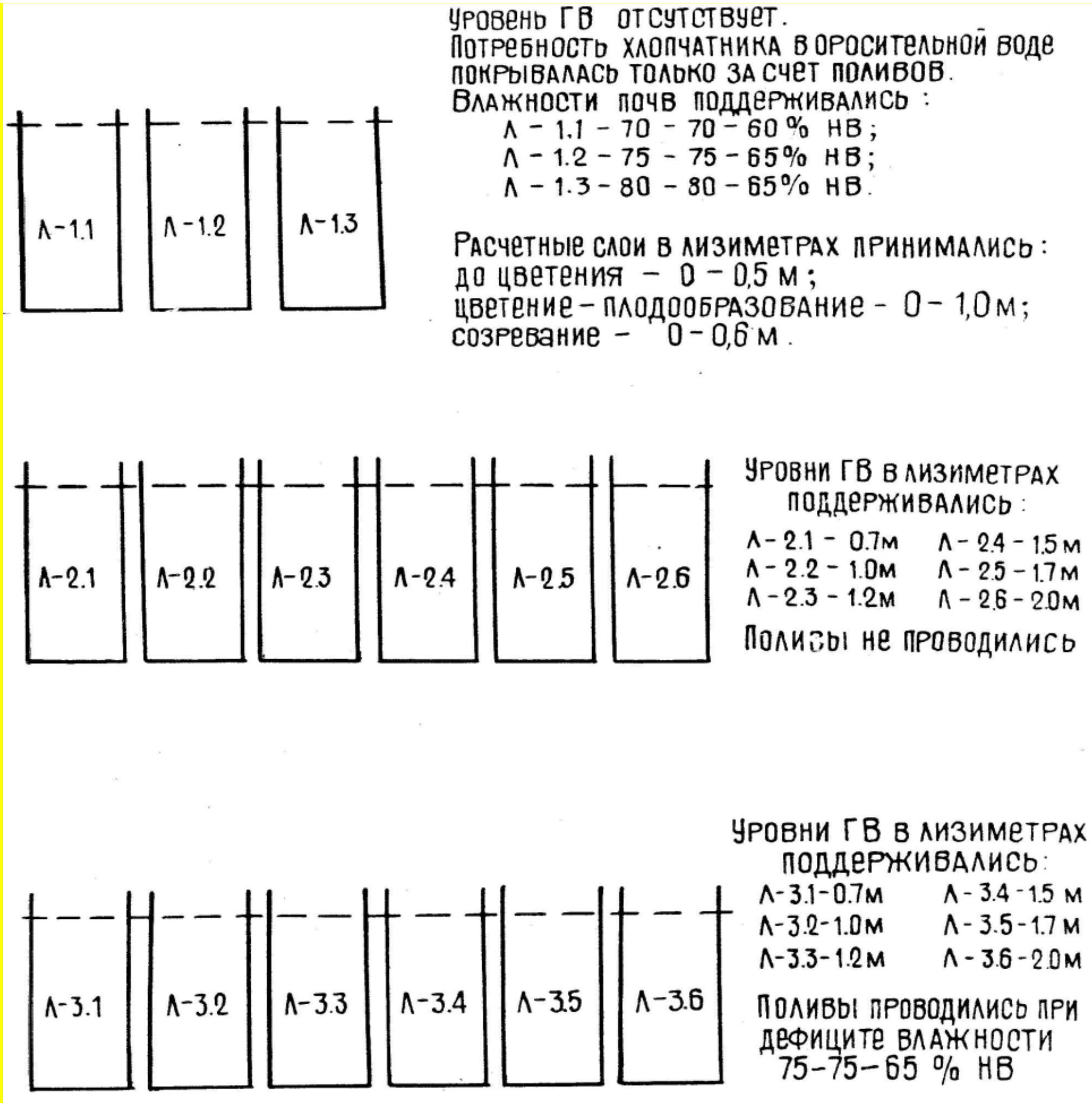
E = the total water consumption at a deep level of groundwater (mm).

Pisarenko and Meshchukova (1983) and Rakhimbayev and Ibragimov (1978) showed that the shallow groundwater table leads to excessive non-productive use of water for soil evaporation and to poor aeration of the root zone. Lowering the water table below the critical depth reduces water loss due to evaporation, salt accumulation in the soil and mineralization of drainage water in the drainage collector network.

2.6.3 Detailed description of a lysimeteric experiment

A lysimetric study was carried out in the Chirchik-Angren Valley in order to develop optimum cotton irrigation schedules for conditions of shallow fresh groundwater. Altogether 15 lysimeters were installed on an experimental site (Fig.4). Three series of experiments were carried out:

Series 1) Groundwater was absent. The cotton demand in water was covered by irrigation from the top, which was differentiated according to the three phases of the growing season: 1) before flowering, 2) between flowering and fruit formation, 3) maturation. The threshold soil water contents at which the irrigation started were (in % of field capacity), respectively: 70 – 70 – 60% in A-1.1, 75 – 75 – 65% in A-1.2. and 80 – 80 – 65% in A-1.3. The depth of irrigation (the same in all three lysimeters) was, respectively, 0.5 m, 1.0 m and 0.6 m for the three growing phases.



Уровень ГВ отсутствует.
Потребность хлопчатника в оросительной воде покрывалась только за счет поливов.
Влажности почв поддерживались:
Л - 1.1 - 70 - 70 - 60 % НВ;
Л - 1.2 - 75 - 75 - 65% НВ;
Л - 1.3 - 80 - 80 - 65% НВ.

Расчетные слои в лизиметрах принимались:
до цветения – 0 – 0,5 м;
цветение – плодообразование - 0 – 1,0 м;
созревание - 0 – 0,6 м.

Уровни ГВ в лизиметрах поддерживались:
Л - 2.1 - 0.7м Л - 2.4 - 1.5м
Л - 2.2 - 1.0м Л - 2.5 - 1.7м
Л - 2.3 - 1.2м Л - 2.6 - 2.0м
Поливы не проводились

Уровни ГВ в лизиметрах поддерживались:
Л-3.1-0.7м Л - 3.4 - 1.5 м
Л-3.2-1.0м Л - 3.5 - 1.7 м
Л-3.3-1.2м Л - 3.6 - 2.0м
Поливы проводились при дефиците влажности 75-75-65 % НВ

Figure 4. Scheme of lysimetric experiments to determine irrigation regimes at various levels of groundwater occurrence

Series 2) Groundwater was maintained in the lysimeters but no other irrigation was made. The cotton crop developed due to the use of groundwater The groundwater table depths maintained in particular lysimeters were, respectively: A-2.1 - 0.7 m; A-2.2 - 1.0 m; A-2.3 - 1.2 m; A-2.4- 1.5 m; A-2.5 - 1.7 m; A-2.6 - 2.0 m.

Series 3) Groundwater table was maintained at the same level as in the second series of experiments. In addition, irrigation from the top took place when the estimated average soil water content of the layer of interest decreased to 75-75-65% field capacity. The thickness of the soil layer of interest was 0.5 m before flowering and 1.0 m after flowering (including the phase of maturation).

The following water balance equation (Aver'yanov, 1966) was used for the calculation of components of the total water consumption under conditions of groundwater recharge:

$$E_w - \left[P + \left(W_1 - W_2\right) + G + M - F\right] = 0 \tag{23}$$

where:

E_w = total water consumption over the calculated period (mm),

P = atmospheric precipitation over the same period (mm),

W_1 = available water content in the root zone at the beginning of the period (mm),

W_2 = available water content in the root zone at the end of the period (mm),

G = inflow of water into the root zone from groundwater (mm),

M = irrigation depth depending on the duration of the period (mm),

F = deep percolation of water beyond the root zone (mm).

The total water consumption was determined for particular phases of cotton crop development for each lysimeter of each series as the sum of the volumes of water supplied in order to maintain the required soil water content and the volumes needed to replenish the groundwater used.

The contribution of groundwater to water consumption of cotton crop was determined for the lysimeters of the second and third series from the volume of water supplied to maintain the groundwater table.

The necessary volumes of water supplied to the lysimeter from the top in order to maintain the soil water content in the root zone at the threshold levels prescribed, e.g. 75-75-65% of field capacity, were also recorded and accounted for. The volumes of water seeping beneath the root zone were determined from the level rise of groundwater table after irrigation.

Knowing the values of E_w and G, the coefficients of groundwater use (K_r) were determined for different phases of the cotton growing season according as the ratio:

$$K_g = \frac{G}{E_w} \tag{24}$$

Vice versa, the amount of groundwater use by the cotton crop is obtained as:

$$G = E_w K_g \tag{25}$$

Substituting (25) into the equation of water balance (23) enables us to estimate the required irrigation depth *M*:

$$M = E_w(1-K_r) - P - (W_1 - W_2) + F \tag{26}$$

Denoting W_1-W_2 = δ (where δ is the soil water depletion), we get

$$M = E_w(1-K_r) - (P+\delta) + F \tag{27}$$

Considering that the optimal water supply should minimize the deep percolation *F*, that is, $F \approx 0$, we get:

$$M = E_w(1-K_r) - (P+\delta) \tag{28}$$

The last equation (28) is the calculation formula for determining the optimal water supply and the conditions of closely adjacent fresh groundwater. This formula was used in the development of cotton irrigation regimes for the zone under consideration.

Experimental data on the total water consumption (evapotranspiration) in particular phases of development of cotton crop achieved at various groundwater depths between 0.7 and 2.0 m without surface irrigation (series 2 described above) are given in Table 3. With shallow groundwater the total water consumption is larger than necessary for obtaining reasonably high yields of cotton.

*Table 3.*The main results of experiments for determining the total evapotranspiration from groundwater.

Indicator	Depth of groundwater, m					
	0,7	1,0	1,2	1,5	1,7	2,0
Total evapotranspiration (m3/ha) 25th May — 14th August	10860	9920	8200	6900	4888	2443
Evapotranspiration (m3/ha) before flowering 25th May — 25th June	2895	2763	2339	1867	1316	598
Evapotranspiration (m3/ha) from flowering to fruit formation 26th June - 25th July	5981	5335	4441	3828	2726	1435
Evapotranspiration (m3/ha) during maturation 26th July – 14th August	1984	1822	1420	1213	846	410
Cotton yield (tons/ha)	2.25	1.8	1.41	1.06	0.56	0.23
Excessive evaporation m^3/ha	3172	2232	512	-	-	-
Soil water content in the layer 0-0.3 m, %	14.6-20.2	14.1-18.0	13.5-16.7	13.8-15.2	13.8-15.3	13.8-15.3

The same in % of field capacity (mean)	0.67	0.62	0.58	0.56	0.56	0.56
The depth at which field capacity is reached (m)	0.5	0.7	0.9	1.2	1.3	1.6
Crop water productivity (m^3/ton)	483	551	582	651	873	1062

CHAPTER 3

MATERIALS AND METHODS

3.1 Site description

The field research was conducted in Prague – Suchdol (50°8'N, 14°23'E, 286 m a.s.l.) under moderately warm and moderately dry climate. Average annual temperature and precipitation are 9.1 °C and 495 mm, respectively (Černý et al., 2012). According to Němeček (2009, personal communication), the soil is Udic Haplustoll (Soil Survey Staff, 1999) or haplic Chernozem (IUSS Working Group WRB, 2006) of loamy texture on an aeolic loessial substrate. The fine earth contains 22–32.5 % sand (0.05 to 2 mm), 39.5–54 % silt (0.002 to 0.05 mm) and 22–28 % clay (below 0.002 mm) (Krkavcová, 2010, unpublished). The topsoil contains about 2.5 % (dry matter basis) of total organic carbon (Nedvěd et al., 2008) and 7.8 % of calcium carbonate (Brodský et al., 2011). There is virtually no textural difference between topsoil and subsoil. The boundary between the A and the C horizons lies at about 35 cm. The transitional A/C horizon is only about 10 cm thick. The layer between about 15 to 25 cm of depth is perceptibly more compacted than the rest of the profile. No permanent saturated zone exists either in the soil profile or in the underlying loess down to at least few meters. The soil has some capacity to swell and shrink. During dry spells, cracks about 1 to 3 mm wide appear at the surface 15 to 20 cm apart. The structure is granular in the A horizon and subpolyhedric in the loessial C horizon. At the higher level of organization, the structure is prismatic. Biopores are frequent. The saturated hydraulic conductivity (100 cm^3 cores) varies roughly between 6×10^{-4} and 4×10^{-1} cm min^{-1}. The total porosity varies between 40% vol. (plough sole) and 54% vol. (topsoil). Its mean value is 45.7% vol. (0–100 cm). The field capacity varies between 30 and 35% vol. (Doležal et al., 2015a). The average water retention curve obtained from 100 cm^3 cores (Kozáková, 1994, unpublished) can be approximated e.g. by the van Genuchten (1980) equation with the saturated water content θ_s = 47.5% vol., the residual water content θ_r = 0.1% vol., the capillary rise parameter α = 0.06548cm^{-1} and the shape factor n = 1.11534. The terrain is flat. No overland flow or accumulation of water at the surface were observed, except in some furrows compacted by machinery. The soil had been ploughed for several centuries, but grass (commercial park lawn mixture) was sown in spring 2009 and is maintained there since then as a short lawn. The site is neither irrigated nor tile-drained. No fertilizers have been added since the grass has been sown. The lawn often suffers from water stress and has already slightly degraded because of drought and nitrogen deficiency, as witnessed by local appearance of legumes and mosses. The lawn is cut about 4 times a year. The average height of the canopy in the lysimeter and around it is about 6 cm. The size of the grass field around the lysimeter is about 20 x 20 m. It is surrounded by a mosaic of agricultural research parcels and facilities, containing croplands, orchards, trees, hedges, roads and occasional buildings. Only a small part of the surrounded area is irrigated.

3.2 Field measurements

The Smart Field Lysimeter SFL-300, manufactured by UMS GmbH (now METER Group AG), München, (http://www.ums-muc.de/en/lysimeter/smart-field-lysimeter/, accessed 28 January 2017) was installed on 25 April 2013. The core part of the lysimeter is a stainless steel cylinder 30 cm high with internal diameter 30 cm. A soil monolith of the same size was cut with this cylinder from the soil on the same site. The cylinder with the soil is placed in a sunken barrel on an electronic balance. The suction at the bottom of the monolith is automatically maintained corresponding to the suction of water in the native soil nearby (at about 1 meter distance) at the same depth (30 cm), measured by a tensiometer T8 (UMS). This provision makes the regime of soil water in the lysimeter approximately the same as that in the native soil. Any water that percolates through the bottom of the monolith is automatically pumped into a storage vessel, which is placed in another underground container on another electronic balance. If the soil in the lysimeter becomes drier than the native soil around, it may suck some water back from the space beneath the porous bottom of the lysimeter and from the tube which connects the lysimeter with the vacuum pump. The primary data of the two electronic balances are recorded at 1 minute intervals. The soil monolith in the lysimeter is equipped with three soil water content, temperature and electrical conductivity sensors 5TE (Decagon) at 5, 15 and 25 cm below the soil surface and with three MPS2 matric potential sensors at the same depths. These sensors were not individually calibrated. Of them, only the sensors placed at 5 cm are used in this thesis. The sensor readings are recorded at 10-min intervals. Mild winters allowed conduct the measurements all the year round after laying thermal insulation matrasses onto the water collection box. The shallow underground collar of the lysimeter made it difficult for grass to grow within an annular strip about 15 cm wide around the lysimeter. The strip was mostly bare and probably contributed a little to the increase of evapotranspiration from the lysimeter. This effect has not yet been quantitatively studied, as far as we know. The facility for taking proportional samples for water analysis, which is also a part of the smart field lysimeter, was not used in this thesis.

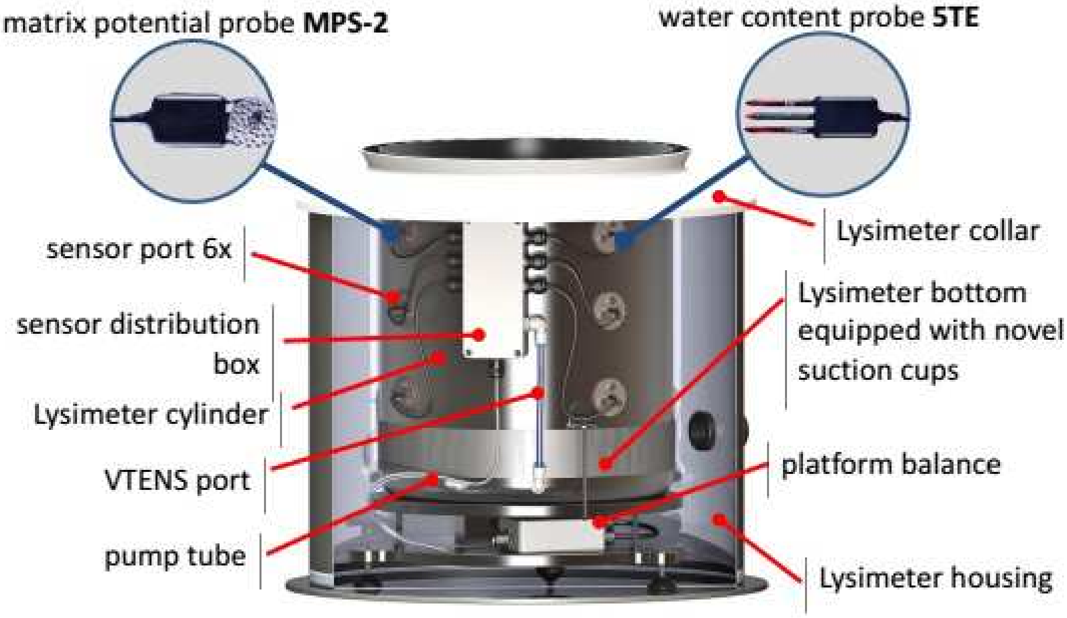


Figure 5. Schematic illustration of the small smart lysimeter SFL300 (UMS, 2013)

Weather data were measured on the same site at 2 m height above the soil surface and a horizontal distance of several meters from the lysimeter and were recorded at 10-min intervals. Precipitation was recorded using a 0.1 mm heated tipping-bucket rain gauge MR3H (Meteoservis, v.o.s, Vodňany). The air temperature and humidity were measured by a combined probe HMP 45A/D (Vaisala), the solar radiation by the pyranometer LP02 (Hukseflux), the wind speed by an ultrasonic sensor Windsonic (Gill Instruments Ltd.).

3.3 Lysimeter data selection

The starting data were the instantaneous values of the lysimeter mass (*LYW*) and its storage vessel mass (*SWW*). They were available at 1-min intervals. For this thesis, the daily evapotranspiration (minus precipitation) sum for each day was estimated from the difference between the (*LYW*+*SWW*) value at midnight in the end of the day and that at the beginning of the day without any smoothing. Evapotranspiration came out as positive, precipitation or condensation as negative. Only the regularly-looking data collected over rainless periods were used. The error due to not smoothing the curves of *LYW* and *SWW* is estimated to be smaller than 1 to 2 %. Out of the total of 1286 days from 25 April 2013 to 31 October 2016, five categories of days were excluded:

- first, the days (referred to briefly as “visually irregular”) for which the graph of 1-minute (*LYW*+*SWW*) values vs. time was not smooth and/or contained irregularities, either explainable (e.g. as effects of precipitation or instrumental errors or maintenance) or unexplainable (altogether 637 days, of which 169 were rainless),

- second, the days (referred to briefly as “non-rainless”) on which non-zero precipitation was measured with the heated rain gauge, be it rain or snow or any other form (502 days, of which 34 were visually regular),
- third, the days for which the daily reference crop evapotranspiration ET_0, estimated by the standard FAO 56 procedure (see below), came out negative or zero (8 days, of which 3 were both visually regular and rainless),
- fourth, as soon as the actual daily evapotranspiration sums ET_a had been derived from these data, the days on which the ratio ET_a/ET_0 appeared to be anomalous, either too high or too low; this ratio was tentatively taken for too low if it was lower than 0.1 and too high if it was higher than X, X being 1.4 in summer (April to September) and 2.0 in winter (October to March) (26 days with positive ET_0 that were at the same time visually regular and rainless),
- fifth, the first five days of the period were excluded, so that the 5-day antecedent precipitation sums (not shown in this thesis) could be calculated for all days (5 days, of which only one was found regular according to the previous four criteria).

The remaining daily ($LYW+SWW$) data, altogether 1286 – 637 - 34 – 3 – 26 – 1 = 585 days, were regarded as regular and were used for further processing. Of these days, the following shares (numbers of days) fall on particular months of year: January=17, February=38, March=47, April=56, May=52, June=39, July=63, August=67, September 63, October=67, November=41, December=35. The regular data were divided into two groups, relating respectively to the growing season (April to September, 340 days) and the dormant season (October to March, 245 days), briefly referred to as “summer” and “winter”, respectively.

3.4 Evapotranspiration calculations

The actual evapotranspiration E_a (mm) was estimated as:

$$ET_{a,i} = \frac{(LYW_i + SWW_i) - (LYW_{i+1} + SWW_{i+1})}{\frac{\pi}{4} 0.3^2} \qquad (29)$$

where

$ET_{a,i}$ = actual evapotranspiration over the *i*-th day,

LYW_i, SWW_i = respectively, the lysimeter mass and the percolate storage vessel mass (both in kg) at the beginning midnight of the *i*-th day,

LYW_{i+1}, SWW_{i+1} = the same items at the ending midnight of the *i*-th day.

The equation (29) assumes the density of water to be 1000 kg m^{-3} and the inner horizontal diameter of the lysimeter 0.3 m.

The reference low crop evapotranspiration was estimated according to the standard FAO 56 Penman-Monteith procedure defined by Allen et al. (1998) and put in an easy form e.g. by Zotarelli et al. (2015). The basic equation used was (3).

The directly measured solar radiation was used. The net radition R_n was then calculated from it and from other data as detailed below. The soil heat flux was neglected. The air temperature, humidity and wind speed were directly measured at 2 m above the ground and averaged. The mean daily temperature was taken as the average of the daily maximum and daily minimum according to (4). The slope Δ was calculated from this mean daily temperature according to (5). The mean daily wind speed was obtained by arithmetic averaging of all 10-min values. The psychrometric constant was calculated from the elevation above the sea level (286 m). The mean daily saturated (e_s) and actual (e_a) vapor pressures were calculated according (7) to (10) The standard shortwave albedo (0.23) was taken. The net outgoing longwave radiation R_{nl} (MJ m^{-2} d^{-1}) was calculated according to the standard FAO 56 procedure, i.e. equation (17). The clear-sky solar radiation (MJ m^{-2} d^{-1}) was calculated for a particular day of year from known astronomic formulae (11) to (16). It is known (e.g. Yin et al., 2008) that the FAO 56 formula (17) underestimates the net outgoing longwave radiation for the sites that are drier than the ideal reference crop, which is our case also. This formula, however, can be understood as a tool for approximate prediction of the radiation condition that would occur on the same site if it were adequately watered. It may therefore suit well the purpose of estimating the reference crop evapotranspiration, even for the non-reference sites. The daily sum of net radiation R_n (MJ m^{-2} d^{-1}) was then calculated from (18).

In order to check whether or not the FAO 56 Penman-Monteith procedure gives an at least approximately unbiased estimate of the reference crop evapotranspiration, two other equations were employed relying solely on the radiation and temperature data and regarded sometimes as suitable for this purpose (e.g. de Bruin and Stricker, 2000; de Bruin et al., 2016). The first of the two is the Makkink (1957b, 1959) equation:

$$ET_0 = \frac{1}{\lambda}\left(c_1 \frac{\Delta}{\Delta + \gamma} R_s + c_2 \right) \tag{30}$$

where:

λ = the latent heat of vaporization (MJ kg^{-1}),

c_1, c_2 = empirical coefficients,

R_s = solar radiation (MJ m^{-2} d^{-1}),

Δ = slope of the saturated vapor pressure curve [$\partial e_s/\partial T$, where e_s = saturated vapor pressure (kPa) and T = daily mean temperature (°C)],

γ = psychrometric constant (kPa °C^{-1})

In this thesis, λ was taken in accordance with FAO 56 procedure as 2.45 MJ kg^{-1} and the empirical coefficients were taken $c_1 = 0.65$, $c_2 = 0$ according to de Bruin et al. (2016). It is worth mentioning that the paper by Makkink (1957a), frequently cited in this context, does not contain the Makkink equation.

The second equation is by Priestley and Taylor (1972):

$$ET_0 = \frac{1}{\lambda}\left[\alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \right] \tag{31}$$

where:

α = an empirical coefficient,

R_n = net radiation (MJ m^{-2} d^{-1}),

G = sensible heat flux into the soil (MJ m^{-2}d^{-1}),

and the other symbols are the same as above. In this thesis, the original Priestley and Taylor's coefficient $\alpha = 1.26$ was used and, as in the FAO 56 equation (29), the soil heat flux G was neglected.

3.5 The ET_a/ET_0 ratio (crop coefficient)

The crop coefficient is a ratio of the actual crop evapotranspiration to the reference crop evapotranspiration (Allen et al., 1998). The single-coefficient approach is used in this thesis, that is, no distinction is made between transpiration and soil evaporation. However, a distinction is made between the potential crop evapotranspiration, non-restricted by water stress, and the actual one, water-stress restricted. In the first step, the ratio ET_a/ET_0 was calculated for each regular day. Its relations to the soil water content and matric potential were explored, using the summer data only, which show a better trend than the winter data. Attempt was made to fit the data with broken straight lines:

$$\frac{ET_a}{ET_0} = A_\theta \quad for \quad \theta > \theta_t \quad or \quad \frac{ET_a}{ET_0} = A_s \quad for \quad s < s_t$$
$$\frac{ET_a}{ET_0} = A_\theta + B_\theta(\theta - \theta_t) \quad for \quad \theta \le \theta_t \quad or \quad \frac{ETa}{ET0} = A_s + B_s(s - s_t) \quad for \quad s \ge s_t \tag{32}$$

where:

A_θ, A_s = mean ratios ET_a/ET_0 for the unstressed parts of data,

θ = volumetric soil water content (% vol.), measured by a 5TE sensor at 5 cm depth,

s (kPa) = soil water suction (the matric potential without the negative sign), measured by the MPS2 sensor at the same depth,

θ_t , s_t = threshold values of θ and s, respectively,

B_θ (fraction of unity per 1% vol.), B_s (kPa^{-1}) = the corresponding regression slopes, obtained by a least-squares optimization. The suctions (positive values) were used instead of the matric potentials (negative values) in order to facilitate the plotting on a logarithmic scale.

In the second step, all regular data points (both summer and winter) were sorted with respect to the soil water content at 5 cm. The ratio ET_a/ET_0 was plotted with respect to the day of year for the regular days when $\theta > \theta_s$. The lower envelope of these points, except for outliers, was approximated by a sine curve:

$$K_c = \left(\frac{ETa}{ET0}\right)_{\min} = P\sin\left(\frac{2\pi}{365}DOY + C\right) + D \tag{33}$$

where:

K_c = the standard (unstressed) crop coefficient,

DOY = the day of year (starting from 1 January),

P, C and D = the coefficients to be optimised.

Formula (33) represents a first estimate of the standard crop coefficient curve for the grass canopy investigated. Using the lower envelope intends to leave aside (i.e. above the sine curve) the points affected by evaporation from the wet soil surface, from the water intercepted on grass, from snow, dew, rime and similar phenomena.

3.6 Surface resistance

The low reference crop (grass) of the FAO 56 and ASCE concept (Allen et al., 1998; Jensen and Allen, 2016) is defined as being 0.12 m high and having surface resistance 70 s m^{-1}. The non-irrigated and non-fertilized grass investigated in this thesis is expected to have a higher surface resistance even when it was sufficiently supplied with soil water. The surface resistance is supposed to have become even higher on the days when water stress occurred. These concepts were semi-quantified in this thesis, using the daily ET_a/ET_0 values for the summer period only and expressing both the numerator and the denominator of this ratio in terms of the Penman-Monteith equation. The formula (29) was used for ET_0. A modified version of (29), into which an unknown surface resistance r_s was substituted, was employed to approximate ET_a. To keep the analysis simple, only the surface resistance was varied and not the height of the canopy, the net radiation or any other parameter. This simplification may of course have added some error to the analysis, which is to be quantified at a later stage. However, it made it possible to carry out the analysis by modifying a single constant in (29), namely, by replacing the factor 0.34 in the denominator of (29) by the ratio $r_s/208$, where r_s (s m^{-1}) is the unknown surface resistance and $208/u_2$ is the aerodynamic resistance for a crop 0.12 m high. Then:

$$\frac{ET_a}{ET_0} = \frac{\mathit{\Delta} + \gamma(1 + \frac{r_s}{208} u_2)}{\mathit{\Delta} + \gamma(1 + 0.34 u_2)} \tag{34}$$

from which:

$$r_s = \frac{208}{u2} \left\{ \frac{1}{\gamma} \left[\frac{ET_0}{ET_a} [(\Delta + \gamma(1 + 0.34 u_2)] - \Delta \right] - 1 \right\} \tag{35}$$

The surface resistance was calculated according to (35) for each regular point of the summer period. The values were then plotted with respect to the soil water content θ (% vol.) and the suction s (kPa), as measured by the sensors at 5 cm depth. The data were approximated by broken straight lines in the same way as the ET_a/ET_0 ratios above in (32). A difference lies in the fact that the resistance r_s increases when the soil is drying out, while the ratio ET_a/ET_0 decreases:

$$\begin{aligned} &r_s = r_{0\theta} \quad for \quad \theta > \theta_t \quad or \quad r_s = r_{0s} \quad for \quad s < s_t \\ &r_s = r_{0\theta} + B_{r\theta}(\theta - \theta_t) \quad for \quad \theta \le \theta_t \quad or \quad r_s = r_{0s} + B_{rs}(s - s_t) \quad for \quad s \ge s_t \end{aligned} \qquad (36)$$

where:

$r_{0\theta}$, r_{0s} = mean surface resistances for the unstressed parts of data,

Br_θ (s m^{-1} per 1% vol.), B_s (s m^{-1} kPa^{-1}) = the corresponding regression slopes, obtained by least-squares optimization,

and all other symbols are the same as above.

3.7 Advection

In this context, the term advection means horizontal inflow or outflow of heat and vapor to or from the site when the vertical sensible and latent heat flux is being discussed, measured or calculated. The field site described above is not homogeneous enough to make the advection impacts effectively unimportant. Moreover, large scale advection may have occurred in winter time, when the solar radiation was low, while warm or cold wind may have produced a substantial inflow or outflow of energy from or to distant places. A simple test indicating a strong advection capable of inverting the direction of the vertical sensible heat flux, was proposed by Priestley ad Taylor (1972, their formula (7b)). It consists in comparing the magnitude of the net radiation R_n and that of the latent heat flux λET_a.. If the latter is larger, it means that a part of the energy required for evapotranspiration must have been obtained by advection. The two quantities were therefore plotted onto two scatter graphs (separately for the summer and the winter periods) and interpreted them in qualitative terms.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Evapotranspiration

Fig. 6 shows the daily sums of actual evapotranspiration ET_a and the reference crop evapotranspiration ET_0 over the entire period of investigation. Only the regular data are plotted. The gaps between them are, in the case of ET_0, bridged with straight lines. The two series vary over time in a qualitative similar manner, being high in the growing season and low (with few exceptions) in the season regarded as dormant, October to March). It is easy to notice that the summer 2015 was the driest. No negative daily sums occurred among the regular data. Within individual diurnal cycles, there were sometimes shorter periods of soil water condensation or dewfall (the details are not shown). ET_a is smaller than ET_0 on most days, which is illustrated by Fig. 7, where these two series are plotted against each other and compared with a one-to-one line. The cases when $ET_a > ET_0$ are more frequent in winter (70 days) than in summer (30 days). This is due to more frequent dew or rime on grass or wet soil surfaces in winter. The effect of snow is difficult to analyse with the data available (neither the days with snowpack nor the thickness and continuity of the snowpack were systematically recorded). One may conclude that the FAO 56 procedure of computing ET_0 (equations (29) to (33) is adequate for the site studied and does not leading to a large bias. It seems to be a reasonable estimator of the non-stressed evapotranspiration from the weather data measured in a moderately stressed environment like ours.

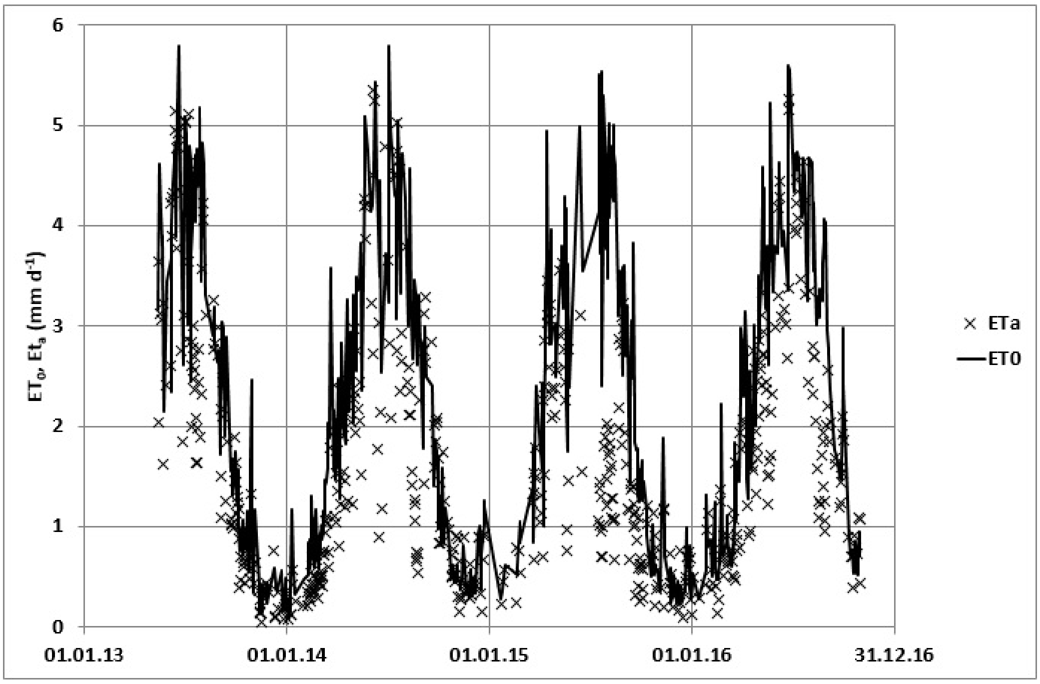


Figure 6 Daily sums of actual evapotranspiration ET_a and the reference crop evapotranspiration ET_0 for 585 regular days of the total of 1286 days from 25 April 2013 to 31 October 2016. The gaps between regular data are, in the case of ET_0, bridged with straight lines.

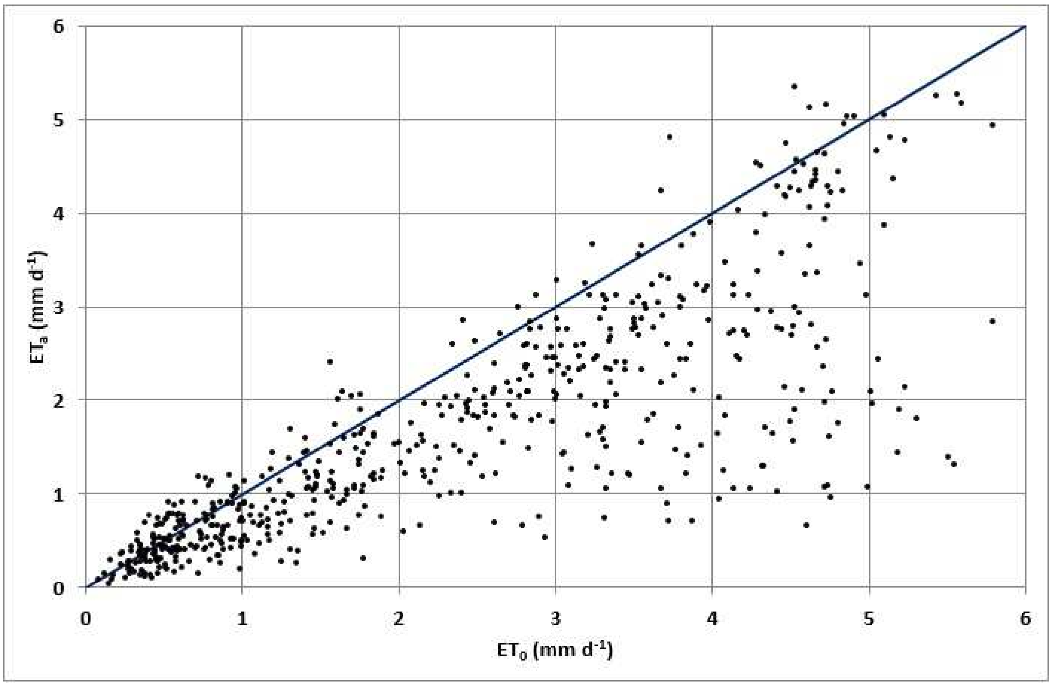


Figure 7. Daily sums of actual evapotranspiration ET_a and the reference crop evapotranspiration ET_0 for all regular days plotted against each other and compared with a one-to-one line.

This conclusion is confirmed by the values of ET_0 obtained with the Makkink equation (30) and the Priestley-Taylor equation (31) for the growing seasons, which are in good correlation with the FAO 56 ET_0 values, even though differences on particular days are perceivable. The linear regressions are ET_0 (Makkink) = 1.015 * ET_0 (FAO 56) – 0.027 ($R^2 = 0.8675$) and ET_0 (Priestley-Taylor) = 1.141 * ET_0 (FAO 56) – 0.288 ($R^2 = 0.9095$). Analogous correlations for the winter periods are, however, poor. Both (30) and especially (31) underestimate the dormant season evapotranspiration, compared to (29). The details are not shown. The performance of both the Makkink and the Priestley and Taylor equations obviously depends on the values of the coefficients chosen.

4.2 The ET_a/ET_0 ratio and the crop coefficient curve

The values of ET_a/ET_0 were regressed to the soil water content θ (% vol.) and the soil water suction s (kPa), both measured by sensors in the lysimeter monolith at the depth 5 cm. The sensors used were not individually calibrated and so the measurements may have been biased. This is especially the case of the water content sensor, as it becomes clear when the soil field capacity measured in the past independently on undisturbed soil samples (30 to 35 % vol.) is compared with the data plotted in Fig. 8. These data are the average daily suctions s and the corresponding average daily soil water contents θ for all regular days. Assuming that the field capacity corresponds to suctions between 10 and 33 kPa (Vanderlinden and Giráldez, 2011), we can derive its value from Fig. 8 as 22 to 23 % vol., i.e. by about 8 to 12 % vol. smaller than it was previously found in the undisturbed samples. The following discussion refers to the sensor-measured values only, to avoid ambiguity.

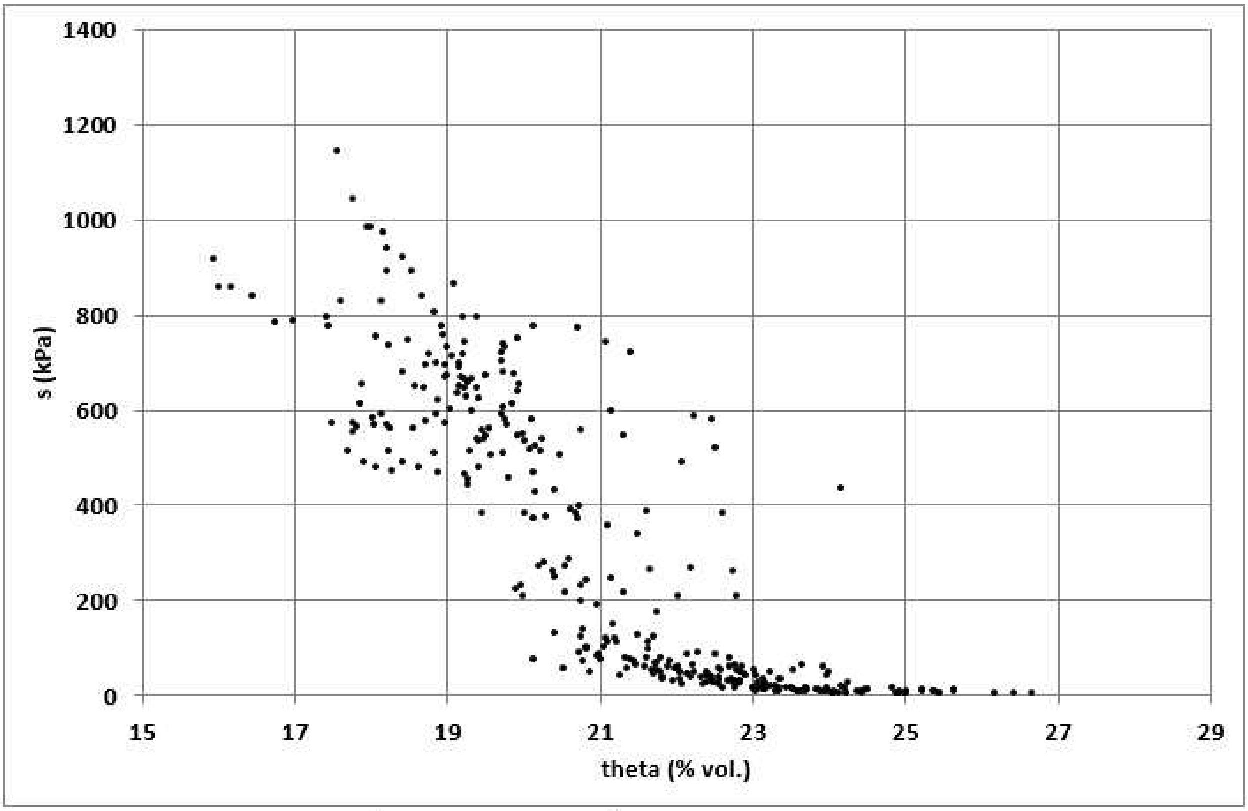


Figure 8. Average daily suctions s vs. average daily soil water contents θ for all regular days.

Figs. 9 and 10 demonstrate how the ET_a/ET_0 ratio depends on the soil water content and suction, respectively, for the summer periods. The graphs distinctly break down into two parts, one non-stressed, where ET_a/ET_0 is virtually independent of the control variable, and the other one water-stressed, where the ET_a/ET_0 declines, very loosely depending on the control variable, tending (albeit not very strongly) to decrease when the soil becomes drier. The positions of the thresholds in terms of the soil water content or suction were estimated a priori by visual inspection of the graphs (with regard also to Fig. 8), trying to make the non-stressed means A_θ and A_s in (32) close to each other. The positions of the approximative horizontal lines in the non-stressed portions of the graphs are arithmetic averages of the non-stresses ET_a/ET_0 values. Given these estimates, the slopes of the inclined portions of the graphs were estimated by the least squares optimization.

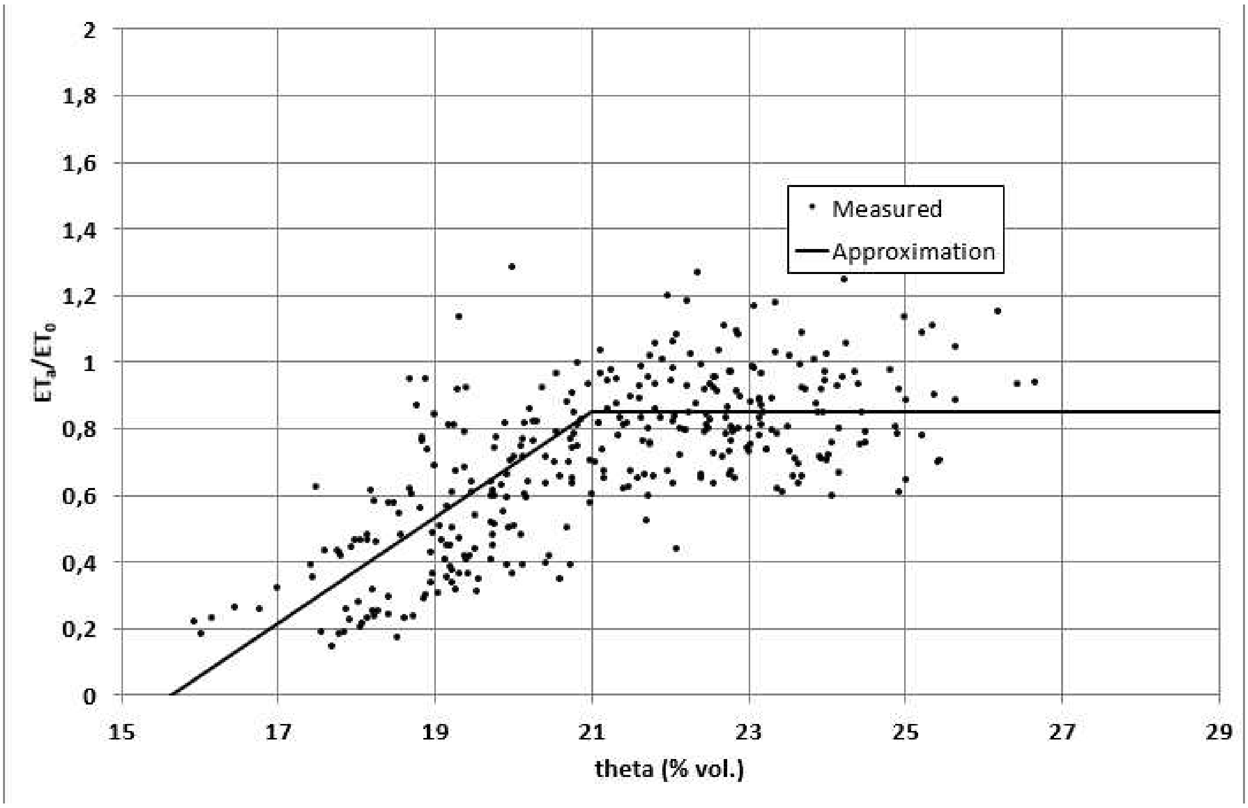


Figure 9. ET$_a$/ET$_0$ ratio dependence on soil water content θ for summer periods.

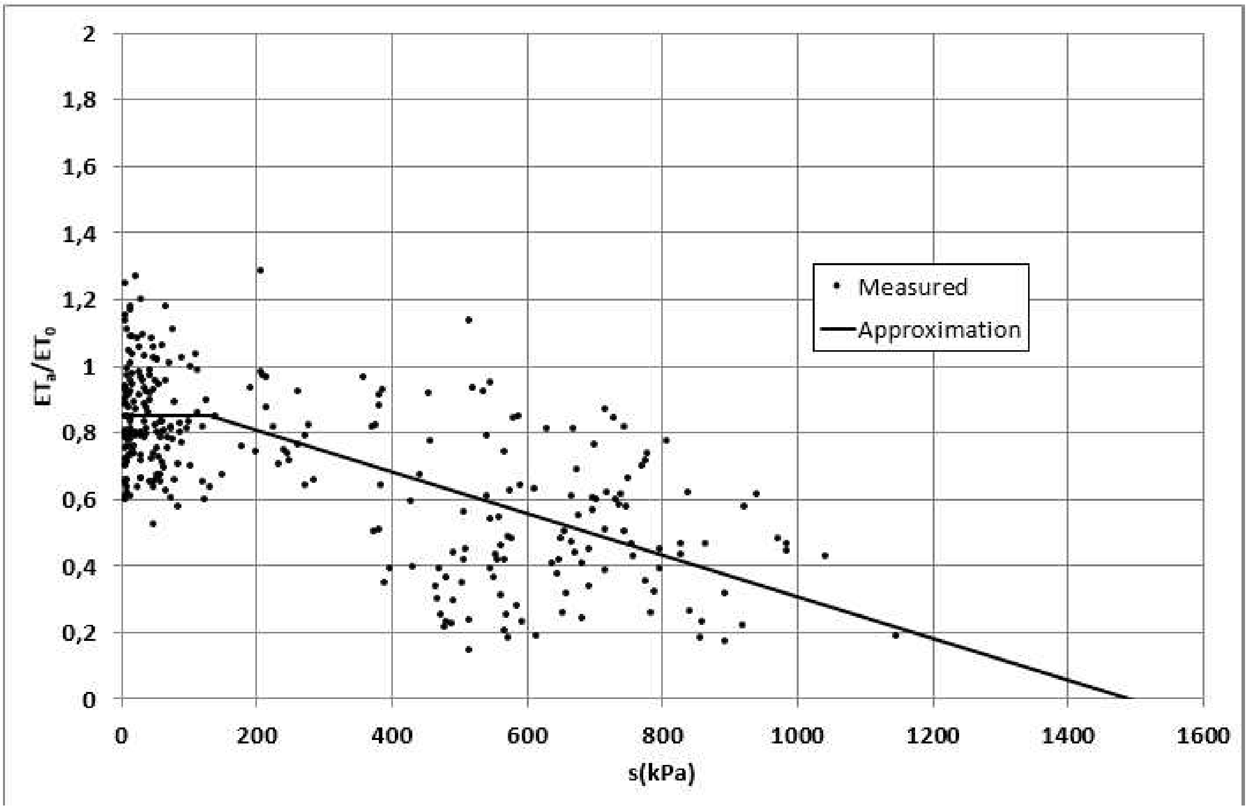


Figure 10. ET$_a$/ET$_0$ ratio dependence on soil water suction s for summer periods.

The parameters so obtained are summarized in Table 4. It follows from them that that a typical weather-station grass canopy, when it is not under water stress, will have evapotranspiration at the level of about 85 % of the reference crop.

Table 4 Parameters of the relations between ET_a/ET_0 ratio and either the soil water content or the soil water suction according to (32).

ET_a/ET_0 vs. θ (Fig. 9)			ET_a/ET_0 vs. s (Fig. 10)		
θ_t =	21	% vol.	s_t =	130	kPa
A_θ =	0.8497		A_s =	0.8504	
B_θ =	0.1588	$(\% \text{ vol.})^{-1}$	B_s =	-0.0006233	kPa^{-1}

Fig. 11 depicts the ET_a/ET_0 ratios in relation to the day of year for all regular data fulfilling the condition $\theta > \theta_t$. The sine curve according to (33) was drawn, based on visual judgement, so that it approximates the lower envelope of the points plotted, except for few outlying points. Its parameters, estimated by trial and error, are $P = -0.27$, $C = 1.38$ and $D = 0.58$. This curve can be regarded as a first estimate of the standard (unstressed) crop coefficient for the low, non-irrigated and non-fertilized grass, which is probably a common canopy on many standard weather stations. Fig. 11 demonstrates frequent high ET_a/ET_0 ratios in winter, when the wet surfaces (wet soil, dew or raindrops or soft rime on plant surfaces) are much more common and persistent than in summer. The peak of the sine curve occurs on 13 July and the parameters above were chosen so that the peak height (0.85) approximately corresponds to the mean unstressed ET_a/ET_0 values A_θ and A_s in Table 4.The minimum of the sine curves occurs on 11 January and is 0.31, which roughly corresponds to the initial-season single crop coefficients for many crops (Allen et al., 1998).

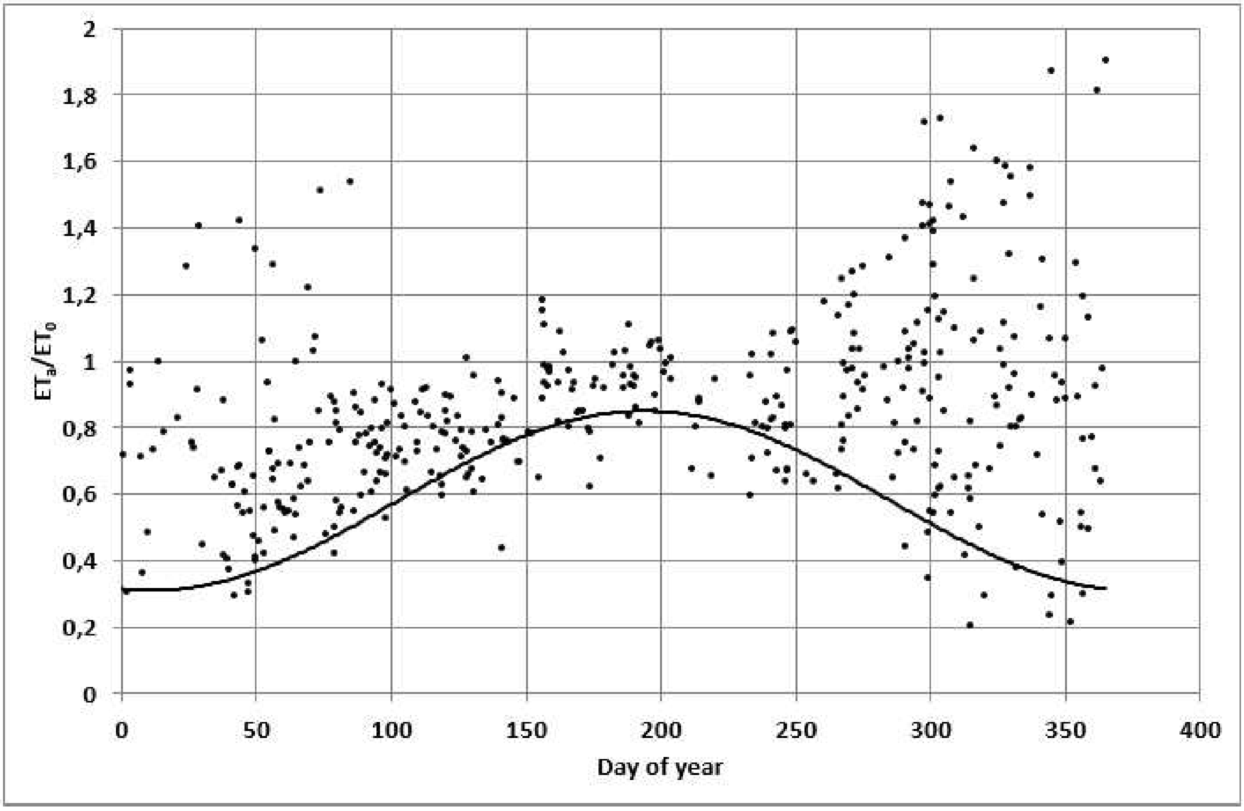


Figure 11. ET_a/ET_0 ratio in relation to the day of year for all regular data fulfilling the condition $\theta > \theta_t$. The sine curve according to (33) approximates the lower envelope of the points plotted, except for few outliers.

4.3 Surface resistance

Figs. 12 and 13 show the approximate dependence of the surface resistance, calculated for every regular summer day according to (35), on the soil water content θ and the soil water suction s, respectively. As in Figs. 9 and 10, the graphs break down into two parts, one non-stressed and the other one water-stressed. The cluster of non-stressed points is more compact than in the case of ET_a/ET_0, but the stressed part of the graph does not seem to resemble a sloping line. Nevertheless, the broken-line approximation was calculated in the same way as in the case of of ET_a/ET_0.

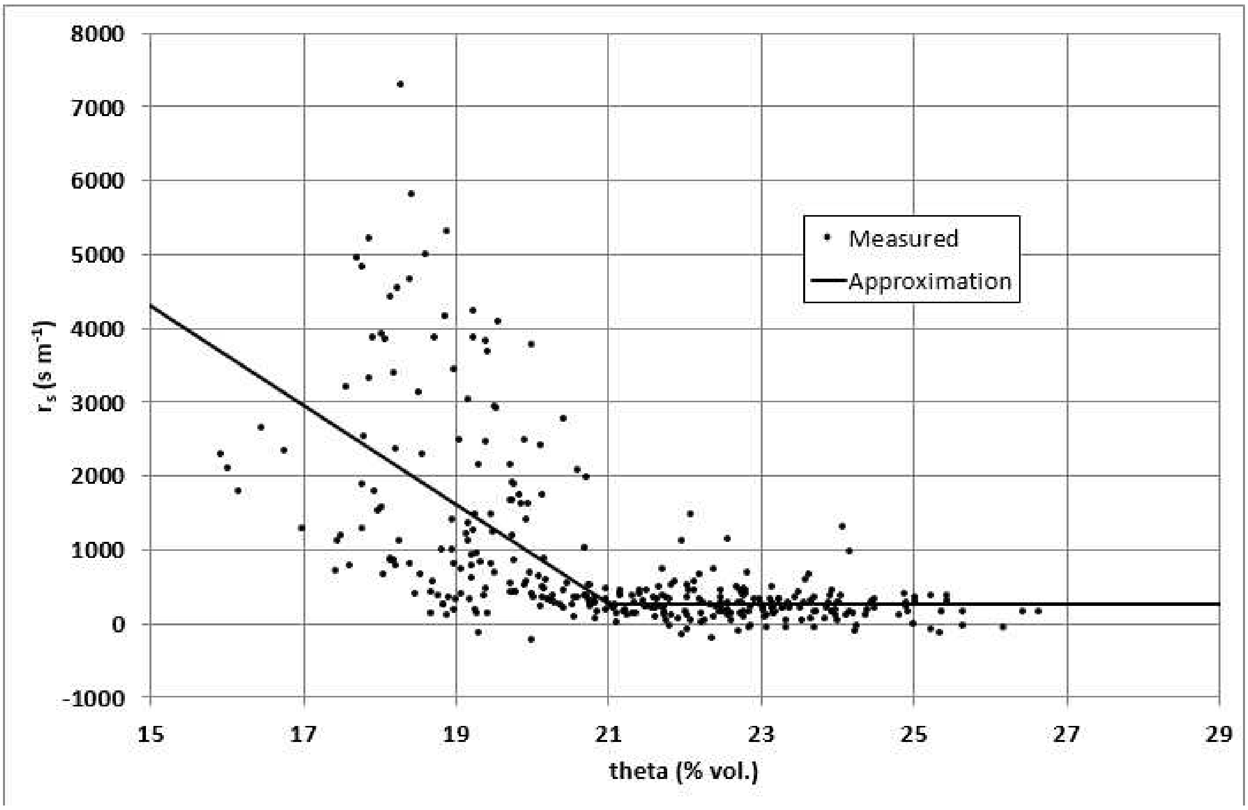


Figure 12. Surface resistance r_s dependence on soil water content θ for summer periods.

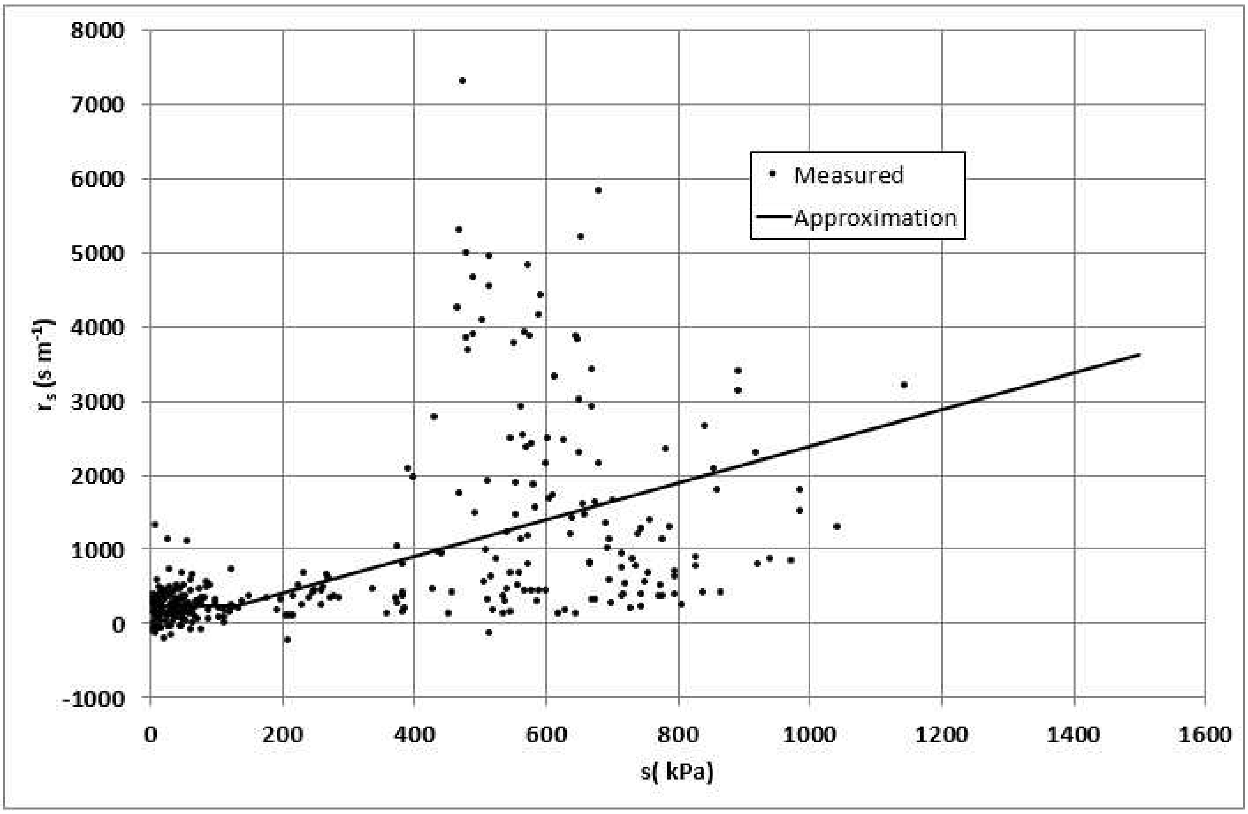


Figure 13. Surface resistance r_s dependence on soil water suction s for summer periods.

The parameters so obtained are summarized in Table 5.

Table 5 Parameters of the relations between the surface resistance r_s and either the soil water content or the soil water suction according to (36).

rs vs. θ (Fig. 12)			*rs* vs. *s* (Fig. 13)		
θ_t =	21	% vol.	s_t =	130	kPa
$r_{0\theta}$ =	256.4	s m^{-1}	r_{0s} =	239.4	s m^{-1}
$B_{r\theta}$ =	-672.2	s m^{-1} (% vol.)$^{-1}$	B_{rs} =	2.463	s m-1 kPa^{-1}

It follows from these calculations that the surface resistance of a typical weather-station grass canopy is higher than 70 s m^{-1} defining the low reference crop. Rather, its surface resistance in the unstressed state is about 250 s m^{-1}.

4.4 Advection criterion

Figs. 14 and 15 compare the latent heat flux λET_a with the net radiation, according to a criterion by Priestley and Taylor (1972, their equation (7b)). When a point lies above the one-to-one line, it is probable that there was a significant horizontal advection of heat on that day, which caused the average daily sensible heat flux to change its direction from upward to downward and raised the latent heat flux above the level of the energy supplied by radiation. Only four such days occurred during the summer periods, while many more can be observed in winter. This finding is encouraging, because it suggests that the effect of advection during the growing season is not so significant. The winter advection effect was expectable.

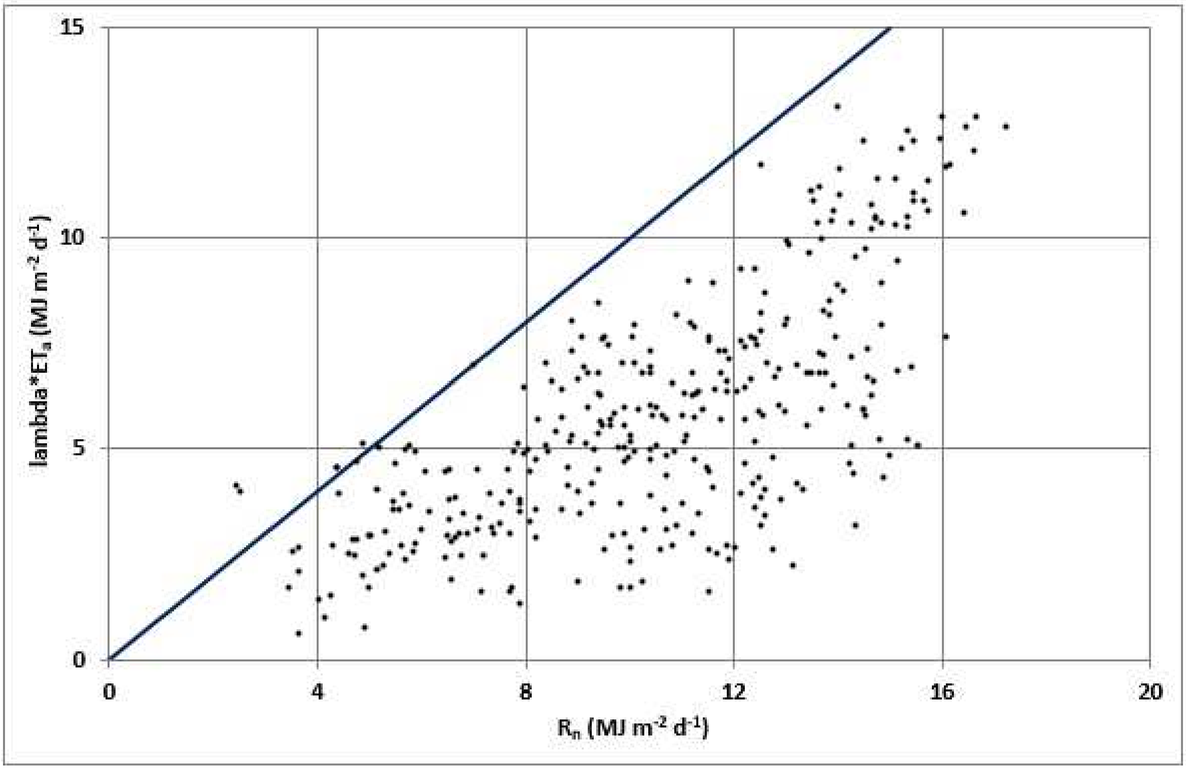


Figure 14. Comparison of the latent heat flux λET_a with the net radiation R_n and the one-to-one line; an advection test by Priestley and Taylor (1972) for summer periods.

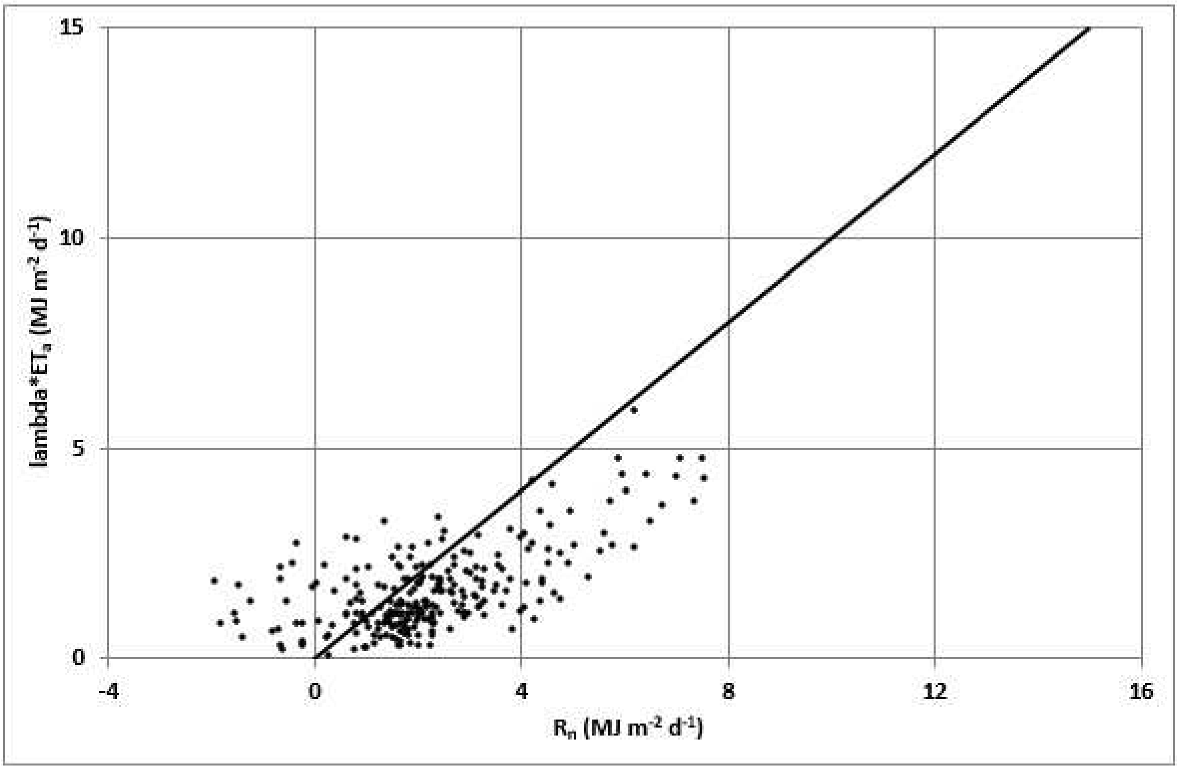


Figure 15. Comparison of the latent heat flux λET_a with the net radiation R_n and the one-to-one line; an advection test by Priestley and Taylor (1972) for winter periods.

CHAPTER 5

COMPARISON WITH ANOTHER LYSIMETER

The assignment for this thesis assumed that another, older lysimeter, installed in the same experimental area, would be used for comparison. This was only partly possible, because the data of the older lysimeter have not yet been processed enough and will hardly be so in future, as is demonstrated below. The old lysimeter is of the same size as the new one (described in the Materials and Methods section), that is, 30 cm diameter and 30 cm depth, and the suction at the bottom of the old lysimeter is also maintained at the level of the suction in the native soil nearby, measured at the same depth (30 cm) by a reference tensiometer T4 (UMS), in a similar way as in the new lysimeter. The old lysimeter, however, differs from the new one by absence of the automatic percolate collection and registration. In the old lysimeters, the percolate has to be collected manually from time to time (typically twice a week, if there is any percolate). Another difference lies in the construction of the lysimeter bottom, which in the old lysimeter is made of a porous ceramics, of which the air entry value is only about 0.5 bar. Yet another difference consists in different electronics, less sophisticated in the old lysimeter, where all data are recorder at 1-hour intervals only.

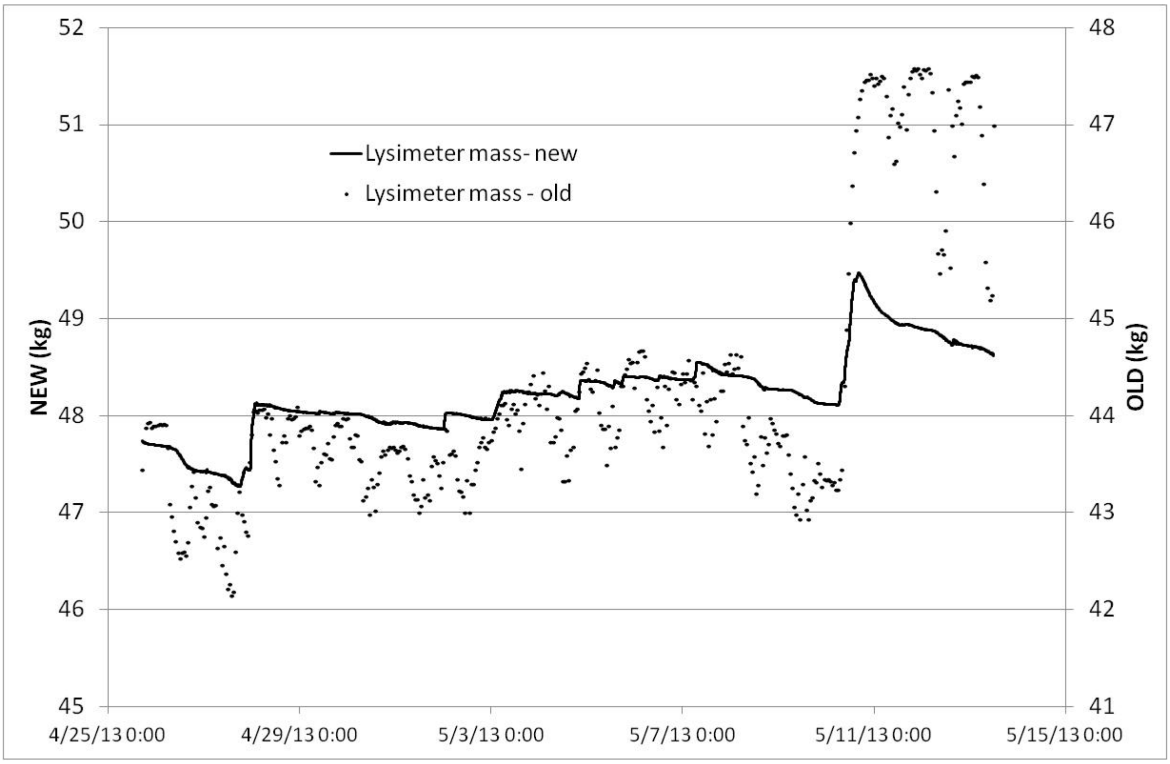


Figure 16 Comparison of the old lysimeter with the new one in terms of their mass dynamics (affected by precipitation and evapotranspiration).

The older lysimeter data suffer from several defects, among them the most serious one is the low accuracy and high variability of the lysimeter balance readings. It is for this reason that UMS GmbH replaced the old lysimeter with a new one. The old lysimeter was afterwards left in place and can be used for at least a qualitative comparison with the new lysimeter. Example comparison of the data of the two lysimeters is provided below for a short period between 25th April 2013 17:00 and 13th May 2013 12:00. Fig. 16 compares the lysimeter masses, Fig. 17 compares the reference tensiometer readings. The site experienced two more significant rain events during the example period, one (7.8 mm) on 27th April and the other one (15.4 mm) on 10th May. Minor showers occurred on most other days of this period.

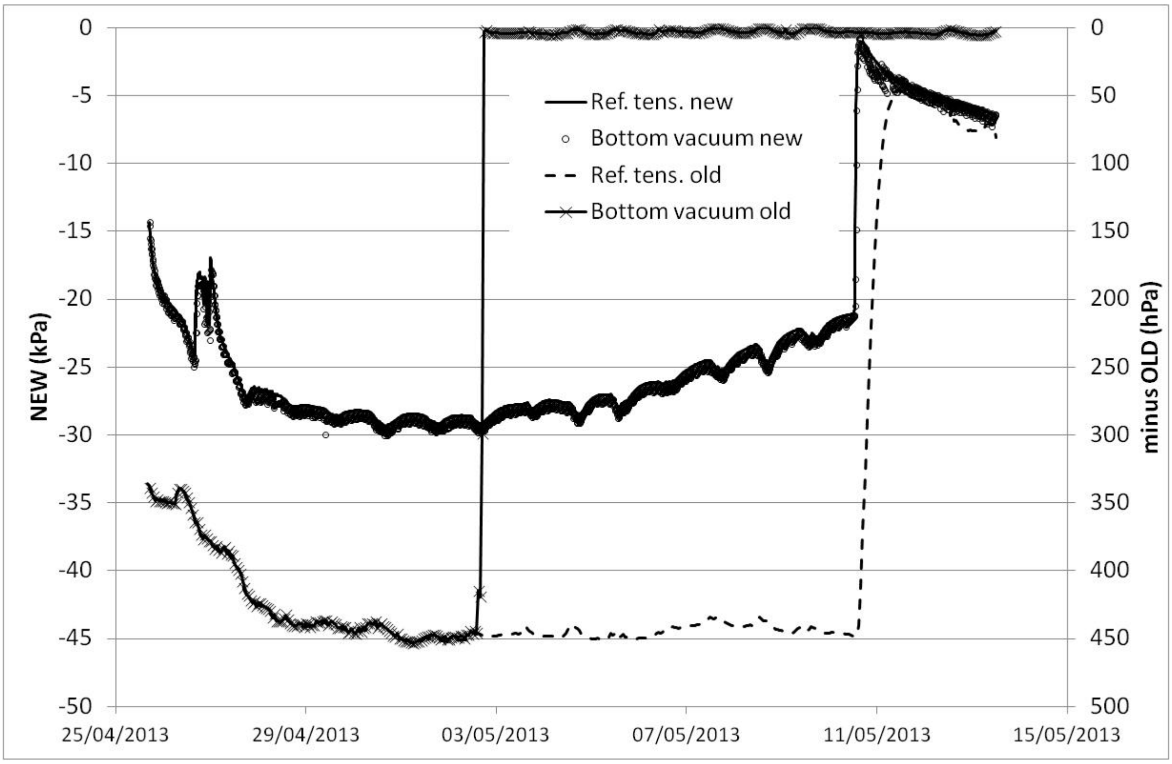


Figure 17 Comparison of the old lysimeter with the new one in terms of the reference tensiometer readings (in the native soil outside the lysimeters at 30 cm depth) and the vacuum applied at the lysimeter bottom. Note different units and algebraic sign conventions.

The comment on the data demonstrated in Figs. 16 and 17 can be as follows: The two lysimeters behave similarly in the qualitiative sense. The mass of both lysimeters has on average a decreasing trend in the periods without rain and increases if rain occurs. However, the old lysimeter mass varies over day and night in a quasi-periodic way, with maxima occurring typically early in the morning and minima on afternoons, but this is not an unconditional rule. The amplitude of this variation is of the order of one kilogram. Any calculation of evapotranspiration would only be possible from average daily lysimeter masses, not from the instantaneous (hourly) masses. The second difference lies in the reaction of the lysimeter mass on a substantial rain event. The increase of mass due to rain on 10th May is much larger in the case of the old lysimeter, which can be explained by efficient drainage through the new lysimeter bottom, while the old lysimeter vacuum pump had been deliberately (manually) switched off on 2th May, when the suction in the soil around the old lysimeter was approaching the air entry value and the ceramics at the old lysimeter bottom started to leak (see Fig. 17). The reference tensiometers of both lysimeters were working reasonably well. Their reading in Fig. 17 illustrate the inherent heterogeneity of the soil (the site around the old lysimeter is drier.

CHAPTER 6

CONCLUSIONS

The research of evapotranspiration of low, dense and shallow-rooting crops is well possible even with a small lysimeter 30 cm in diameter and 30 cm deep. Saying this does not does not belittle the importance of such lysimeters for the investigation of soil water fluxes (e.g. percolation). Virtually all results discussed in this thesis were obtained with the newer and more perfect lysimeter, while the older lysimeter and its problems were discussed only shortly. The older lysimeter can be operated in parallel with the new one, but its main use is to serve as a check for soil water suction and percolation measurements, rather than evapotranspiration measurements.

A brief overview of some lysimeter research results obtained in Uzbekistan is also provided. It is mainly based on older results from 1980's. The main topic of this research is the effect of shallow groundwater on total water consumption of irrigated and non-irrigated cotton crop. It is found that this effect is very important. The very shallow fresh groundwater may replace surface irrigation, but there is always a risk of soil salinization and oxygen stress. The small lysimeter used in this thesis project is not large enough for a sufficient exploration of this problem. It would have to be much deeper (more than 2 m) and its diameter would have to be larger, of the order of 1 m or more, to adequately represent the cotton canopy. Such lysimeters, equipped in the same sophisticated way as our small smart field lysimeter, are available, but they are costly and would require substantial funding.

Important qualitative differences were found between the processes observed in the growing seasons (April to September) and the dormant seasons (October to March). During the growing seasons, the FA0 56 equation (29) gives reasonably good estimations of the reference crop evapotranspiration, i.e. the evapotranspiration of a standard well-watered grass canopy subject to the same solar radiation, temperature, wind and humidity as the actual site. The Makkink equation (30) in de Bruin's modification, as well as the Priestley-Taylor equation (31) with the original coefficient 1.26, give almost the same average results, but non-negligible difference between the three equations can be observed on particular days. The actual evapotranspiration of low, non-irrigated and non-fertilized grass on our site was, in the growing season, almost always smaller than that of the FAO 56 low reference crop. The grass on our site, when it does not suffer from water stress, produces about 85 % of the FAO 56 reference grass evapotranspiration and its surface resistance is on average about 250 s m^{-1}, rather that the reference value 70 s m^{-1}. A first estimate of the annual crop coefficient curve for this grass was made in the form of a sine curve, peaking in July at about 0.85 and acquiring its minimum in January at about 0.31. This estimate may of course be improved in future. It nevertheless provides us with a basic idea about the evapotranspiration behavior of a canopy that can be found on many standard weather stations.

Much less successful are all three equations evapotranspiration in the dormant season, when the soil surface is frequently wet and the grass is frequently covered with dew, raindrops, soft rime or snow. It is important to stress that the site studied belong to the warmest and driest places in Bohemia, so that the probability of occurrence and persistence of snowpack is rather low, on average about one quarter of the dormant season duration. The evaporation from snow was however not studied as such. The advection test by Priestley and Taylor (1972, their equation (7b) showed that the advection disturbance of the near-surface vertical transport of heat and vapor can be quite frequent. Nevertheless, the results show that it is worth trying to analyze the growth and evapotranspiration of grass stands in the dormant season, at least at the temperatures typical for the warmer part of this season in the temperate climatic zone (between 5 and 15 ^{o}C).

Bibliography

Aboukhaled, A., Alfaro, J. F., Smith, M. 1982. Lysimeters. Irrigation and Drainage Paper 39. Food and Agriculture Organization of the United Nations. Rome. p. 73. ISBN: 92-5-101186-9.

Akhmedjanov, G., Akhmedjonov, D. G. 2013. Vodny rezhim pochvy, vodosberegayushchie technologii poliva khlopchatnika. Tashkent, TIIM, p. 167.

Alkaeed, O., Flores, C., Jinno, K., Tsutsumi, A. 2006. Comparison of several reference evapotranspiration methods for Itoshima Peninsula area, Fukuoka, Japan. Memoirs of the Faculty of Engineering, Kyushu University. 66 (1). p. 14. Available from: < http://kenkyo.eng.kyushu-u.ac.jp/memoirs-eng/bulletin/66/1/paper1.pdf>.

Alimov, P., Rysbekov Y. 1985. Vliyanie gruntovykh vod na vodopotreblenie khlopchatnika. Khlopkovodstvo. (7). 31-32.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. Irrigation and Drainage Paper 56. Food and Agriculture Organization of the United Nations. Rome. p. 174.

Alpatyev, A. M. 1954. Vlagooboroty v prirode i ikh preobrazovaniya. Leningrad. Gidrometeoizdat. p.322.

Attarod, P., Komori, D., Hayashi, K., Aoki, M., Ishida, T., Fukumura, K., Boonyawat, S., Polsan, P., Tongdeenok, P., Somboon, P., Punkngum, S. 2005. Comparison of the evapotranspiration among a paddy field, cassava plantation and teak plantation in Thailand. Journal of Agricultural Meteorology. 60. 789–792.

Aver'yanov S. F. 1966. Vliyaniye orositel'nykh sistem na rezhim gruntovykh vod. Moscow. Izdatel’stvo AN SSSR. p. 59-73.

Brodský, L., Klement, A., Penížek, V., Kodešová, R., Borůvka, L. 2011. Building soil spectral library of the Czech soils for quantitative digital soil mapping. Soil & Water Research. 6.165–172.

Černý, J., Balík, J., Kulhánek, M., Vašák, F., Peklová, L., Sedlář, O. 2012. The effect of mineral N fertiliser and sewage sludge on yield and nitrogen efficiency of silage maize. Plant, Soil and Environment. 58.76–83.

Chapovskaya, E. V. 1971. Solevoy rezhim pochvogruntov pri raznom urovne gruntovykh vod v lizimetrakh. TrudyTadzhikskogo Nauchno-Issledovatel'kogo Instituta Pochvovedeniya. Dushanbe. 14. p.133-145.

de Bruin, H. A. R., Stricker, J. N. M. 2000. Evaporation of grass under non-restricted soil moisture conditions. Hydrological Sciences Journal. 45.391-406.

de Bruin, H. A. R., Trigo, I. F., Bosveld, F. C., Meirink, J. F. 2016. A thermodynamically based model for actual evapotranspiration of extensive grass field close to FAO reference, suitable for remote sensing applications. Journal of Hydrometeorology. 17.1373-1382.

Doležal F., Matula, S., Moreira Barradas, J. M. 2015a. Rapid percolation of water through soil macropores affects reading and calibration of large encapsulated TDR sensors. Soil & Water Research. 10.155-163.

Hernández Gomis, R. 2016. Short grass actual evapotranspiration and its dependence on soil water status. M.Sc. thesis. Czech University of Life Sciences in Prague. Faculty of Agrobiology, Food and Natural Resources. Department of Water Resources.

Howell, T. A., Evett, S. R. 2006. The Penman-Monteith Method. Available from: http://www.cprl.ars.usda.gov/wmru/pdfs/PM%20COLO%20Bar%202004%20corrected%209apr04.pdf

Howell, T. A., Schneider, A. D., Jensen, M. E. 1991. History of lysimeter design and use for evapotranspiration measurements. In: Lysimeters for Evapotranspiration and Environmental Measurements. IR Div/ASCE/Honolulu, HI/July 23-25, 1991. Available from < https://www.researchgate.net/publication/279560720_History_of_Lysimeter_Design_and_Use_for_Evapotranspiration_Measurements>.

Irmak, S., Haman, D. Z. 2003. Evapotranspiration: Potential or Reference? Publication #ABE 343. Gainesville. University of Florida Institute of Food and Agricultural Sciences (IFAS) Extension. Available from < http://edis.ifas.ufl.edu/ae256>.

IUSS Working Group WRB. 2006. World reference base for soil resources 2006. World Soil Resources Reports No. 103. FAO. Rome.

Ivanov, N. N. 1970. Raschotnye znacheniya orositel'nych norm sel'skochozyaistvennych kul'tur v bassejnakh reki Syrdarya i Amudarya. Tashkent. Sredazgiprovodkhlopok. p. 111-118.

Jensen, M. E., Allen, R. G. (ed.). 2016. Evaporation, evapotranspiration and irrigation water requirements. Second Edition. ASCE Manuals and Reports on Engineering Practice No. 70. American Society of Civil Engineers, Reston, VA.

Johnson, T., Odin, O. 1978. Measurements of evapotranspiration using a dynamic lysimeter. Studia Forestalia Suecica. 146. p. 29. Available from < http://epsilon.slu.se/studia/SFS146.pdf>.

Kohnke, H., Dreirelbis, F. R., Davidson, J.M. 1940. A survey and discussion of lysimeters and a bibliography on their construction and performance. Washington, D. C. United States Department of Agriculture Miscellaneous Publication No. 372. p. 68. Available from < http://agrienvarchive.ca/download/lysimeter_rev_usda_1940.pdf>.

Kovda, V. A. 1972. Nauchnye osnovy melioratsii pochv (sbornik). Moscow. Nauka, p.32-35.

Lanthaler, C. 2004. Lysimeter stations and soil hydrology measuring sites in Europe -Purpose, Equipment, Research Results, Future Developments. Lanthaler, C. 2004. Lysimeter stations and soil hydrology measuring sites in Europe -Purpose, Equipment, Research Results, Future Developments. Diploma thesis. Graz. School of Natural Sciences. Karl-Franzens University. Available from http://www.lysimeter.at/documents/sites/projects/THESIS_LYSIMETERS.pdf.

Makkink, G. F. 1957a. Testing the Penman formula by means of lysimeters. Journal of the Institution of Water Engineers. 11. 277-288.

Makkink, G. F. 1957b. Ekzameno de la formulo de Penman. Netherlands Journal of Agricultural Science. 5. 290-305.

Makkink, G. F. 1959. De verdamping uit vegetaties in verband met de formule van Penman. Chapter VII in Evaporation Symposium and Report on the Lysimeters in the Netherlands (II). Proceedings and Informations no. 4, Committee for Hydrological Research T.N.O., The Hague, pp. 90-115. Available from <http://library.wur.nl/WebQuery/clc?reeks-ppn=%3D831496401&wq_ofs=20&wq_max=20&wq_inf_title=>.

Matin, M.A., Bourque, C. P.-A. 2013.Influence of vegetation cover on regional evapotranspiration in semi-arid watersheds in Northwest China. Chapter 6 in: Alexandris, S. G. (ed.) Evapotranspiration – An Overview. InTech. DOI: 10.5772/3383. Available from < https://www.intechopen.com/books/evapotranspiration-an-overview>.

Monteith, J. L. 1965. Evaporation and environment. In: Proceedings of the 19th Symposium of the Society for Environmental Biology. New York. Cambridge University Press. p. 205-233.

Nedvěd, V., Balík, J., Černý, J., Kulhánek, M., Balíková, M. 2008. The changes of soil nitrogen and carbon contents in a long-term field experiment under different systems of nitrogen fertilization. Plant, Soil and Environment. 54. 463–470.

Nolz, R., Kammerer, G., Cepuder, P. 2013. Improving interpretation of lysimeter weighing data. Die Bodenkultur. 64 (1–2). 27-35. Available from <https://diebodenkultur.boku.ac.at/volltexte/band-64/heft-1-2/nolz.pdf>.

Penman, H. L. 1948. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences. 193 (1032). 120-145.

Penman, H. L. 1956. Evaporation: An introductory survey, Netherlands Journal of Agricultural Science. 4. 9–29.

Pidwirny, M. 2006. Evaporation and Transpiration. In: Fundamentals of Physical Geography. 2nd Edition. Available from <http://www.physicalgeography.net/fundamentals/8i.html>.

Pisarenko, V. A., Meshchukova, L. S. 1983. Rezhim vodopotrebleniya i orosheniya raznykh po geneticheskim kharakteristikam sortov zemlevodstva. Kiyev. (28). 6-9.

Priestley, C. H. B., Taylor, R. J. 1972. On the assessment of surface heat flux and evaporation using large scale parameters. Monthly Weather Review. 100. 81-92.

Rakhimbayev F. M., Ibragimov G. A. 1978. Ispol'zovaniye drenazhnykh i gruntovykh vod dlya orosheniya. Moscow. Kolos. p. 86-91.

Rachinsky A. A. 1965. Vozmozhnost' ispol'zovaniya gruntovykh vod dlya promyvok I vegetatsionnykh polivov. Voprosy gidrotekhniki. Tashkent. Fan. p. 71-86.

Rana, G., Katerji, N. 2000. Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. European Journal of Agronomy. 13. 125-153.

Salisbury, F. B., Ross, C.W. 1969. Plant Physiology. Belmont, CA. Wadsworth Pub. Co. p. 747.

Soil Survey Staff. 1999. Soil taxonomy. A basic system of soil classification for making and interpreting soil surveys. Second edition. Agriculture Handbook No. 436. United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC.

Soyfer A. M., Soyfer S. Y., 1971. Rayonirovanie oroshaemykh zemel' po tipovym fil'tratsionnym skhemam. Trudy Sredazgiprovodkhlopok. Tashkent. p. 196-200.

Thornthwaite, C. W., 1948. An approach toward a rational classification of climate, Geographical Review. 38. 55–94.

Truong, N. 2012. Quantifying evapotranspiration through a sensitive study of climate factors and water table interactions for a constructed wetland mesocosm. M.Sc.thesis. Villanova University. The Graduate School. Department of Civil and Environmental Engineering. Available from: < http://www.emba.villanova.edu/content/dam/villanova/engineering/vcase/vusp/Nha%20Troung.pdf>.

UMS. 2013. SmartField Lysimeter. User Manual. Munich. UMS GmbH. p. 65.

van Genuchten, M. T. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal. 44. 892-898.

Vanderlinden, K., Giráldez, J. V. 2011. Field capacity. In: Encyclopedia of Agrophysics.

Verstraeten, W. W. Veroustraete. F., Feyen, J. 2008. Assessment of evapotranspiration and soil moisture content across different scales of observation. Sensors. 8. 70-117.

WMO. 1992. International Meteorological Vocabulary. Second edition. WMO No. 182. Geneva. World Meteorological Organization.

WMO. 2008. Guide to Hydrological Practices. Volume I. Hydrology – From Measurement to Hydrological Information, Sixth edition. WMO-No. 168. Geneva. World Meteorological Organization.

Yin, Y. H., Wu, S. H., Zheng, D., Yang, Q. Y. 2008. Radiation calibration of FAO56 Penman–Monteith model to estimate reference crop evapotranspiration in China. Agricultural Water Management. 95.77-84.

Ziemer, R. R. 1979. Evaporation and transpiration. Reviews of Geophysics and Space Physics. 17 (6). 1175-1186. Available from < https://www.fs.fed.us/psw/publications/ziemer/Ziemer79.pdf >.

Zotarelli, L., Dukes, M. D., Romero, C. C. Migliaccio, K. W., Morgan, K. T. 2010. Step by step calculation of the Penman-Monteith evapotranspiration (FAO-56 method). Publication AE459. Gainesville. University of Florida Institute of Food and Agricultural Sciences (IFAS) Extension. Available from < http://edis.ifas.ufl.edu/pdffiles/ae/ae45900.pdf>.