Vietnam Journal of Science and Technology ***58*** *(3) (2020) 306-318*

doi:10.15625/2525-2518/58/3/14223

EVAPORATION MEASUREMENT FROM FREE WATER SURFACE

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Received: 16 August 2019; Accepted for publication: 21 April 2020

Abstract. This paper aims to quantify the amount of water surface evaporation with special regard to the EWM evaporation pan and to relate the direct measurements to the Penman and other empirical equations. Based on the available 10-minute interval data on the EWM pan evaporation and the data on precipitation for the same intervals, the net water surface evaporation was estimated for the period from July 2010 to October 2012 (excluding the time EWM pan did not function in winter). From the processing data, rain gauge appeared to underestimate the actual precipitation on average 5:3 times, and malfunction when heavy rains occurred. Thus, the net evaporation was estimated only from the fluctuation of water level in EWM pan. Other available weather data, including the dry/wet bulb temperature, water surface temperature, air humidity, wind speed and short-wave solar radiation were also summarized and corrected. These data were then used as input for the Penman equations to obtain semi-empirical daily values of evaporation from water surface. A comparison between the evaporation rates directly measured and those calculated by different methods shows that different values of albedo would improve the performance of the Penman equations. The result of this study contributed to optimization of the EWM data processing methods and to the analysis of variation of water surface evaporation within the diurnal cycle, as well as over longer periods.

Keywords: evaporation, empirical equations, precipitation, EWM pan.

Classification numbers: 3.7.1, 3.8.1.

1. INTRODUCTION

Evaporation is an important stage of the hydrological cycle. Its accurate estimation has been utilized quite frequently for irrigation and hydrological engineering. Since the first studies of evaporation in the 19^{th} century [1], many methods have been developed to achieve a better understanding and better estimation of evaporation. Most of them require one or more weather variables or other measurements as input.

One common group of methods requires computations, based on empirical or semi-empirical relations between the water evaporation or potential evapotranspiration rates and various weather elements. Within this group, the theory developed by Penman [2], which involved several meteorological factors, was the most widely recommended and used worldwide. However, difficulties occur at many sites owing to insufficient or complicated data. Consequently, depending on the available data acquired at particular sites, other empirical models are used as substitutes for the combination equation, or some of the inputs of the combination equation have to be derived indirectly. As there are intricate interactions among the variables and factors involved in evaporation process, most of the empirical and semi-empirical models, which unavoidably rely on explicit or implicit simplifying assumptions, are less accurate, especially when they are not locally calibrated and when they are used for short periods of time. The application of any empirical equation to a new location requires adjustments.

In this study, the net water surface evaporation was derived from automatic evaporimeter (refer to as EWM in Czech Republic) continuous measurement, the performance of the pan measurement was evaluated by comparing it with the Penman equation, simplified Penman equation and necessary adjustments to the latter were proposed. The EWM pan data was used to check the compatibility of one derived equation from Penman's theory in the study area.

2. MATERIAL AND METHODS

2.1. Study area

The study area is the experimental site of the Department of Water Resources, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences, Prague 6-Suchdol, north-west of Prague. The site lies at 14^{o}22'E and 50^{o}08'N and at 281 m above sea level.

Long-term weather data is taken from several weather stations in the surrounding areas, including Prague-Ruzyně and Prague-Karlov. Monthly weather data for these stations since 1961 are available from the Czech Hydrometeorological Institute. Long term averages are suitable to characterize the climate, because they smooth over short-term fluctuations. Over the period 1961-2000, the mean annual precipitation and temperature as observed in Prague-Karlov were 431 mm and 9.3^{o}C, respectively [3].

2.2. Methodology

In this study, water surface evaporation was estimated based principally on the processing of pan measurement data. In addition, the daily pan evaporation sums were compared to other empirical models, including the Penman equation and simplified Penman equation. The parameters of these equations were then optimized to fit the best with the measurement data and compared with their original values.

2.3. Physical principle of evaporation

Evaporation acts in accordance with several physical rules, namely the conservation of mass, momentum and energy, the gas state laws (applied to air and water vapor), the latent heat law of phase change and the transport laws (including the molecular and turbulent diffusion).

The movement of water vapor flow in the open air is almost always turbulent, which means that air eddies containing different amounts of water vapor and also having different temperature and momentum spontaneously create due to inertia and move in a random way. This process is similar to the movement of molecules during molecular diffusion. It is therefore called "turbulent diffusion" and it is acceptable to apply the equations similar to those for molecular diffusion to the transport of water vapor in the atmosphere [4].

In brief, the condition *sine qua non* for evaporation process are a supply of energy to provide the latent heat of vaporization, vapor pressure gradient and turbulent (or molecular) diffusion for removing the vapor once produced [4]. Dated back to 19^{th} century, the English scientist John Dalton formulated this statement in his equation which, in today's notation and using the basic SI units, is:

$$PE = f(u,z)(e_s(T_{ws}) - e_a) \tag{1}$$

where PE is the potential evaporation from free water surface (m s^{-1}), $e_s(T_{ws})$ is the saturated vapor pressure at the water surface temperature (Pa), e_a is the vapor pressure at a certain height above the water surface (Pa), f(u,z) is the turbulent exchange function that depends on the mixing characteristics of the air above the evaporating surface (m $s^{-1}Pa^{-1}$), and u is the wind speed (m s^{-1}) at the height z (m). Equation (1) above is visually represented in Figure 1.

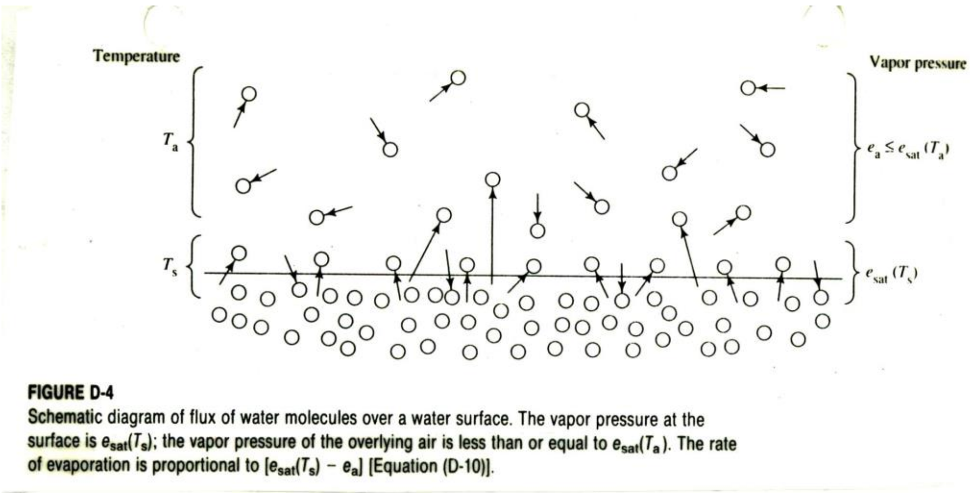

Figure 1. Movement of water molecules over a water surface [5].

Once the turbulent function is determined, it is not difficult to solve the Dalton equation. Dalton's theory can be applied to quantify the actual evaporation from bare soil or evapotranspiration from plant canopy based on exactly the same principle. Once the soil surface vapor pressure is known and the turbulent exchange function is assumed to be the same as that over water surface, we have [6]:

$$AE = f\left(u,z\right)(e^{'} - e_a) \tag{2}$$

with *AE* being the actual evaporation (m.s^{-1}), e' the actual vapor pressure at the soil surface (Pa) and e_a the vapor pressure in air. When the soil surface is smooth, the turbulent exchange function $f(u,z)$ can be considered to behave like in case of a water evaporation pan, while e' requires more effort to compute than $e_s(T_{ws})$ [7].

A special place within this group is occupied by the combination methods based on the Penman [2] approach, which in principle is exact rather than empirical and relies on a combination of the aerodynamic and the energy balance methods, made easier due to local linearization of the saturated vapor pressure curve.

Regarding the sensible heat flux H, Penman suggested to use the same turbulent exchange function:

$$H = \lambda\gamma f\left(u,z\right)(T_{ws} - T) \tag{3}$$

where γ is the psychrometric constant (kPa^{o}C^{-1}); λ is the latent heat of vaporization (MJ kg^{-1}), f(u,z) is the turbulent exchange function (mm d^{-1} kPa^{-1}).

Substituting (3) into the energy balance equation (4):

$$R_n = G + H + \lambda\rho E \tag{4}$$

where R_n is the net radiation, G is the soil (or water) heat flux, H is the sensible heat flux and λE is the latent heat flux with λ being the latent heat of evaporation (which approximately equals 2.45 MJ kg^{-1}when the temperature is not much different from 20 ^{o}C), ρ is the density of water (kg l^{-1}) and E is the evaporation rate (mm d^{-1}). The units of the other terms in (1) are MJ m^{-2} d^{-1}. Together with the Dalton equation (1) will form the well-known Penman equation for potential evaporation from water surface:

$$E = \frac{\dfrac{\Delta\left(T\right)\left(R_n - G\right)}{\lambda\rho} + \gamma f\left(u,z\right)(e_s\left(T\right) - e)}{\gamma + \Delta(T)} \tag{5}$$

where E is the potential evaporation (mm d^{-1}), Rn is the net radiation (MJ m^{-2} d^{-1}); G is the soil heat flux which is often neglected for daily interval; Δ is slope of the saturation vapor pressure curve (kPa ^{o}C^{-1}), γ is the psychrometric constant (kPa ^{o}C^{-1}); λ is the latent heat of vaporization (MJ kg^{-1}), ρ is the density of water (kg/L), D is water vapor pressure deficit (kPa), f(u,z) is the turbulent exchange function (mm d^{-1} kPa^{-1}), in this case the Penman's empirical wind function f(u,z) = a_u +b*u_2, with a_u and b_u are constant coefficient and u_2 the wind speed at 2 m. The units of u_2 determine the values of a_u and b_u.

The theory of Penman opened the possibility to modify the water evaporation equation so that it also describes the evapotranspiration from a vegetation canopy or evaporation from bare soil. Since 1948, several researchers have been successful in creating similar formula, some of which have been applied widely, especially in the field of irrigation management.

2.4. Potential evaporation measurement

Apart from eddy-correlation or aerodynamic methods [8], pan measurement has been considered as a reliable and commonly applicable method because the evaporation rate from a pan responds to climatic factors similar to those affecting the natural water bodies and can be obtained easily [9].

EWM pan has a sunken and cylindrical design, a cross-sectional area 3000 cm^2 and height of 60 cm (derived from the standard Russian evaporation pan GGI-3000) [10] was installed at the site to measure potential evaporation. The water level in the vessel is detected by a float and monitored by a digital optical position sensor with a resolution of 0.1 mm. Owing to evaporation or precipitation, the float falls or rises and the pan measurement is reset automatically at 7.30 CET everyday.

The EWM pan evaporation measurements processed in this study comprise two and a half growing seasons, namely, the following periods (with some gaps):Year 2010, From 7/30/2010 to 11/23/2010; Year 2011, From 4/23/2011 to 11/12/2011; Year 2012, From 4/25/2012 to 10/26/2012.

2.5. Precipitation measurement

An automatic tipping bucket rain gauge (MR3H from Meteoservis, v.o.s, Vodnany, Czech Republic, operated by the Institute of Atmospheric Physics, Czech Academy of Sciences) was placed at a distance of approximately10 m from the evaporation pan. It consists of two compartments balanced in unstable equilibrium; the accumulation of rain water in one compartment causes the bucket to tilt over after being filled with a certain amount of water. The tips produced in this manner are recorded. Each tip corresponds to 0.1 mm of precipitation. The precipitation sums over 10-minute intervals are then automatically calculated by interpolation.

Besides, to facilitate a comparison between the pan data and the theoretical models, other data measured on the site were used, including surface water temperature, solar radiation, air temperatures (dry and wet-bulb), wind speed, and relative humidity of air [11].

3. RESULTS AND DISCUSSIONS

3.1. Pan measurements

To calculate net evaporation from EWM pan, there are two factors that need to be considered: the evaporation itself and the precipitation. The amount of water evaporated from the pan is first obtained by calculating cumulative precipitation at 10-minute intervals and then subtracting it from the water level elevations in the pan, resulting in the net cumulative evaporation. It has a negative algebraic sign, because water level in the pan normally sinks down during rainless periods. The jumps in data produced by the restart of the EWM pan each morning at 7:30 CET mark natural starts and ends of both precipitation and net evaporation accumulation intervals. Subsequently, another procedure, which only uses data from EWM pan and eliminates the role of rain gauge, is employed [6]. This is because the pan is already capable of measuring the precipitation rate (if the evaporation is negligible during rain events), such that the effect of precipitation is already accounted for by the fluctuation of water level. Thus, only the non-positive changes (declines) in the pan water level are accounted for and added up for the cumulative net evaporation, while the positive changes (rises) are ignored.

Theoretically, the two methods above should provide the identical results if the independent precipitation measurements are accurate and exactly correspond to the precipitation that has fallen into the evaporation pan, and if the evaporation occurring during rain events can be neglected. However, these two methods provided incompatible results.

Examples of primary runs (in Microsoft Excel) of the former method (with precipitation) for a sample period (May 2011) are presented in Figure 2. In this, the net cumulative evaporation is plotted with a negative sign and the cumulative precipitation with a positive sign. It soon became evident that the cumulative precipitation values were underestimated. The net cumulative evaporation, which should be a non-increasing function of time except for the instants of restart, started to increase (i.e. to become less negative) during the rain events or even went positive when the rains were heavy, like if the water level in pan rose more during the rain than it would correspond to the amount of precipitation, which was impossible.

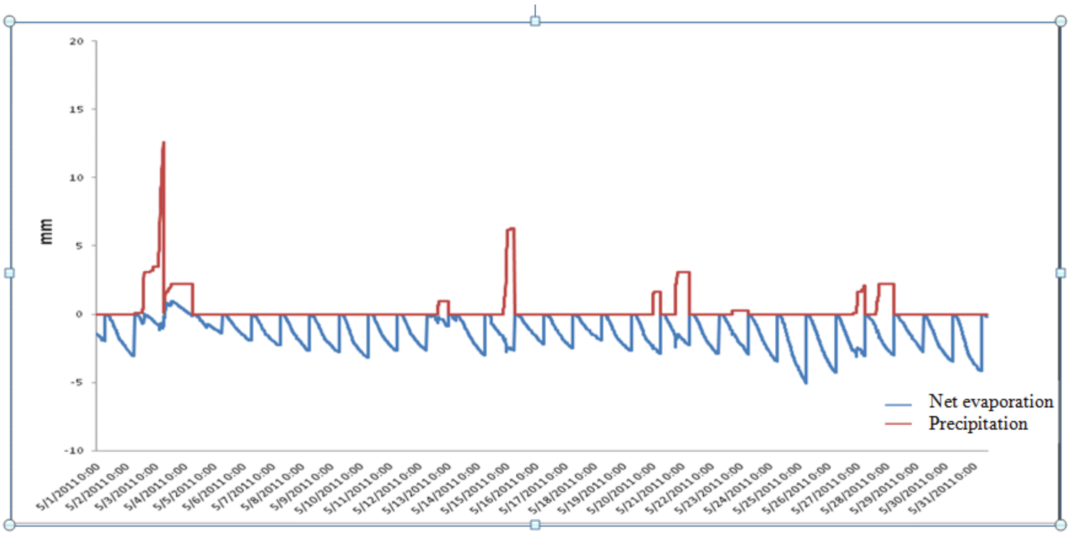

Figure 2. Graph on primary calculation Net evaporation = Water level in pan - Cumulative Precipitation.

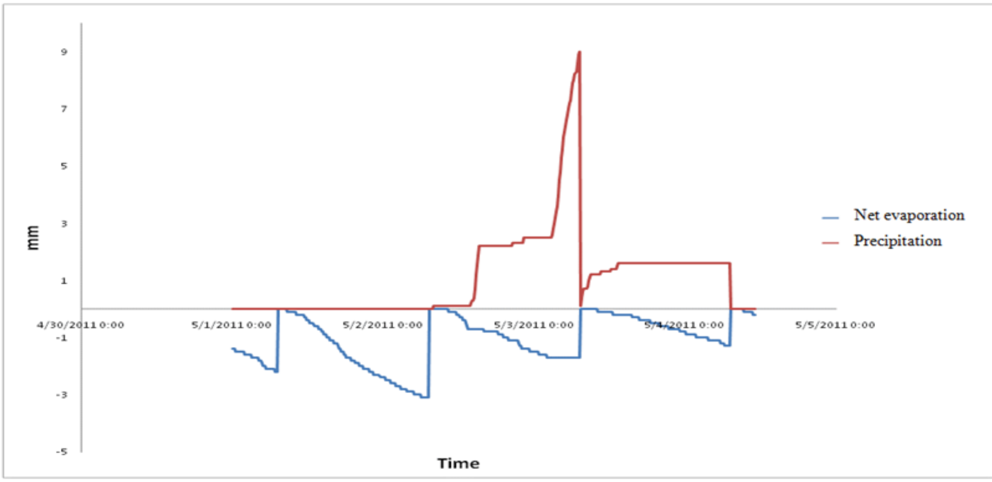

Figure 3. Net evaporation = Water level in pan - Cumulative precipitation from rain gauge data.

Figure 3 illustrates the method "without precipitation", depicting the first few days of May 2011. Compared to Figure 2, the results in Figure 3 is better looking, except for the fact that it perhaps slightly underestimate the evaporation rate during rain events. These problems were partially eliminated by multiplying the rain gauge precipitation with a coefficient larger than unity. The optimum value of the coefficient was sought, initially by trial and error. Figure 4 shows the result when this coefficient was taken as 1.4 (too small). By optimizing the coefficient further, it was proved that its value may have been simultaneously too large during some rain events and too small during others. It was then concluded that the method "with precipitation" is unsuitable for estimating evaporation rates in periods shorter than one day.

Another task was to estimate the instantaneous evaporation rate by differentiating the net cumulative evaporation. Although the water level elevation in reality is gradually increasing, the graph of the net cumulative evaporation derived from the primary records resembled a staircase-like broken line, because the recorded water level in the pan did not change after every 10 min. The sensitivity of the water level sensor (0.1 mm) was insufficient for this purpose. A numerical algorithm was developed in Microsoft Excel to identify the edges of individual stairs, i.e., the instants after which the net cumulative evaporation changed. The edges of consecutive stairs were connected with a broken straight line to present a continuous, albeit not smooth, approximation of the net cumulative evaporation. The continuously changing values of the net cumulative evaporation could then be calculated from this broken line at any instant of time, e.g. at hourly intervals. For each such interval, the average evaporation rate was calculated as the per-interval change in the net cumulative evaporation divided by the length of the interval.

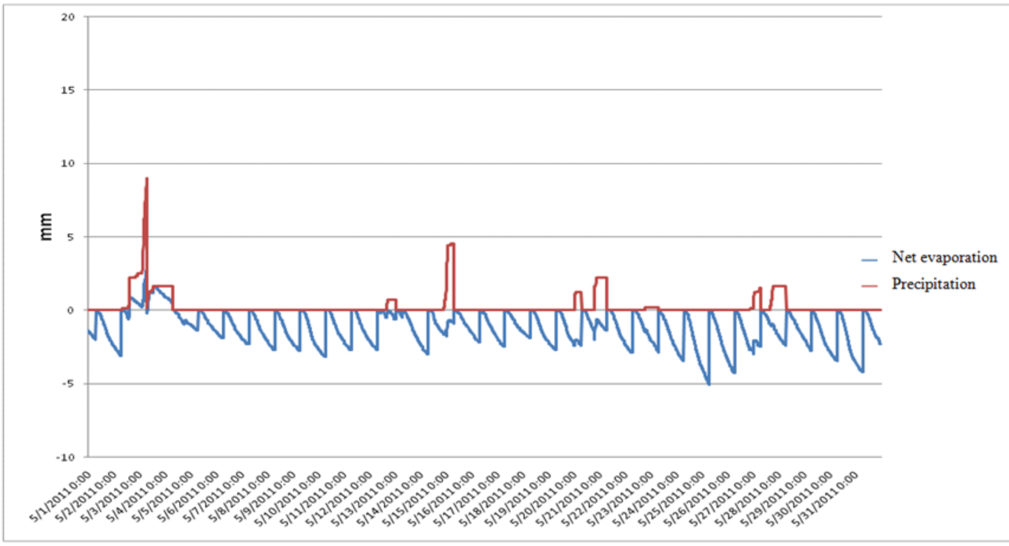

Figure 4. Net evaporation = Water level in pan - Cumulative precipitation * 1.4.

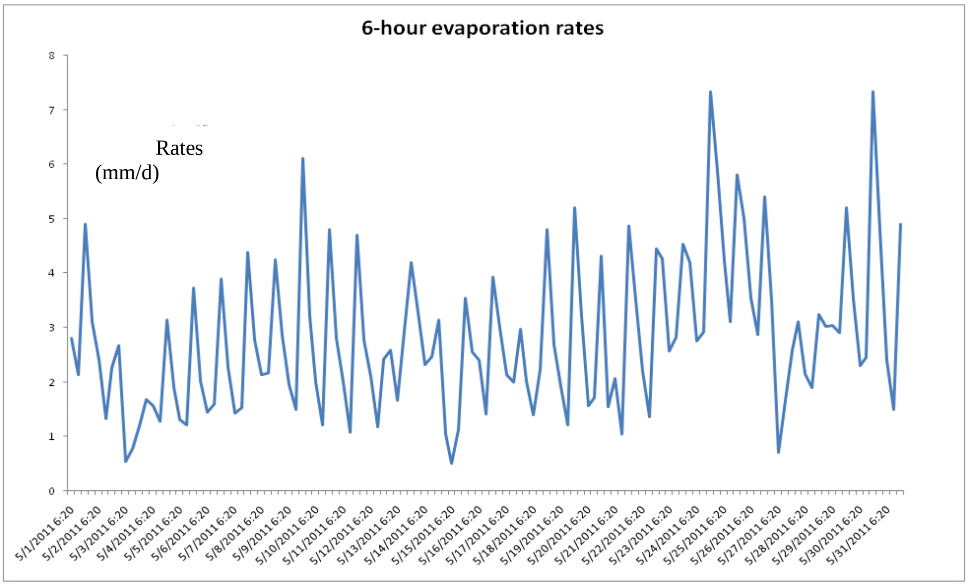

Figure 5. Six-hour evaporation rate.

One-hour, 3-hour, 6-hour, and daily intervals were calculated from that basis. After attempts with different calculations, 6-hour intervals were found to be the shortest intervals for which the resulting curve of evaporation rates is sufficiently smooth (Figure 5). In this manner, it was demonstrated that the net water surface evaporation rate can be solely determined from the EWM pan measurement. To verify the reliability of these results, we compared them with the results obtained by the method "with precipitation". The UFA precipitation data were compared with those of other weather stations in the vicinity, especially with the data of the Department of Agroecology and Biometeorology of the Faculty of Agrobiology, Food and Natural Resources in the other part of the CULS campus. It was concluded that the most appropriate coefficient to multiply the UFA precipitation is close the ratio 5:3. After this correction, the method "with precipitation" provided satisfactory results; however, it was only applied to daily intervals.

The results of the two methods agreed well on some days; however, the results were worse on other days. The values obtained using the method "with precipitation" showed larger variability. This can be explained by the large differences between the daily precipitation sums recorded by the UFA rain gauge and the EWM pan. The estimation of the EWM precipitation sum is explained below. On some days, the UFA rain gauge recorded high precipitation, while the pan did not show any or only a negligible water level rise during the same day. For days when the EWM pan resulted in higher values, the data were re-checked carefully, and the cause of the discrepancy was figured out; the situation on these days was opposite to the abovementioned cases. The UFA rain gauge did not record the precipitation when the water level in the pan increased.

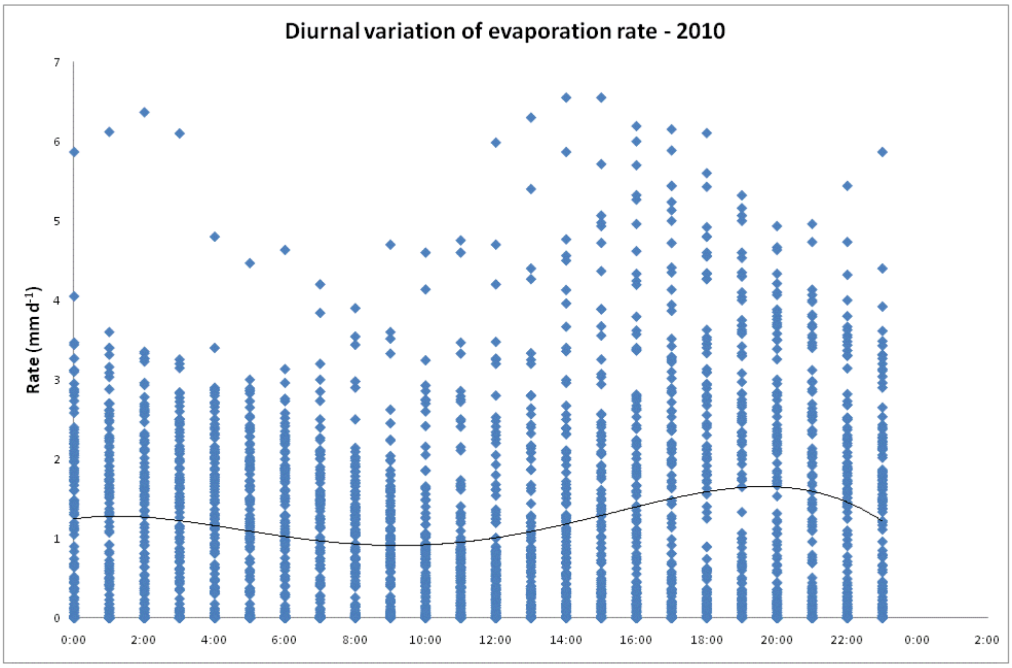

Figure 6. Diurnal variation of evaporation rate.

The evaporation rates were calculated four times a day (every six hours) as moving averages for each hour of the day (i.e., the middle of the 6-h interval) (Figure 6). Because the average 6-h evaporation rates exhibit a relative smooth curve, they can be used to clarify the typical diurnal fluctuation pattern of the evaporation rate. A polynomial function was employed to fit the data and to indicate the probable position of the maximum and minimum evaporation rates. A well-defined maximum occurs at about 19:00, while the lowest evaporation rate was observed at about 9:00. Each morning the evaporation rate gradually increases from 9:00 until about 19:00 and then decreases.

This diurnal pattern can be explained by the heating of the water in the pan during the day; the heat is stored till the evening, which prevents immediate decrease in the water temperature when atmospheric temperature decreases. The difference between the saturated vapor pressure at the water surface and the actual water vapor pressure in the air is the maximum in the evening, which results in the maximum evaporation rate, in accordance with Dalton’s law.

3.2. Semi-empirical equations for calculating potential evaporation

Following the procedures recommended in the FAO 56 documentation [12], several important solar radiation components were computed for the periods of investigation, while the downward short-wave solar radiation R_{sd}wasmeasured. The net radiation values for water $R_{n,w}$ and for soil covered with grass $R_{n,s}$were computed by applying different albedo.

The albedo value for water was taken as 0.08, while that for the grass was taken as 0.23. Adopting albedo 0.08 in the Penman equation (5) results in high potential evaporation values, exceeding the EWM panmeasurement, with larger different in summer months (from April to Mid of September), while in autumn months (September and October) the two data sets were to a greater extent similar. A reasonable explanation of the discrepancy might be the neglect of soil (water) heat flux term in the Penman equation. In summer time, the amount of heat transfer to the Earth subsurface would be greater than in other seasons. As a consequence, the radiation term in Penman equation in fact contains an overestimated energy supply rate, especially in summer months. Moreover, as pointed out by Mekonnen [7], the reflective characteristic of the metallic pan or unaccounted effect of water stratification due to mixing and conduction [7, 13] may act in the same direction.

Hence, the optimization of albedo was done for two different periods, corresponding to this argument. The pan measurement was taken as the potential evaporation in the Penman formula, then the corresponding net radiation was found out, because all other terms in Penman’s equation were fixed known either from measurements or from reliable empirical formula. An optimized value of albedo was estimated from the new value of net radiation, representingall the effect mentioned above, i.e. the seasonal fluctuation of soil and water heat flux and the actual reflectivity of the EWM water pan.

For summer time, an optimized value of albedo was 0.3486, while for autumn time it remained at 0.08.

The potential evaporation was also calculated according to the a simplified formula proposed by Valiantzas [14]:

$$E_{pen} \approx 0.051(1-\alpha)R_s\sqrt{T+9.5} - 0.188(T+13)(\frac{R_s}{R_a} - 0.194)$$
$$(1-0.00014\left(0.7T_{\max}+0.3T_{\min}+46\right)^2\sqrt{\frac{RH}{100}}) + 0.049\left(T_{\max}+16.3\right)\left(1-\frac{RH}{100}\right)(a_U+b_U u) \quad (6)$$

where E_{pen} is potential evaporation (mm d^{-1}), α is the albedo, which theoretically equals 0.08 for water surface and 0.23 for the reference grass, a_u and b_u are wind function coefficients, $R_s$is shortwave downward radiation (MJ m^{-2} d^{-1}), R_a is extraterrestrial radiation (MJ m^{-2} d^{-1}), T_{max}, T_{min} is maximum and minimum temperature, respectively (^oC), *RH* is relative humidity (%) and *u* is wind speed at 2 m height (m s^{-1}).

Values of albedo was set similar to the value applied above in Penman original formula. However, the turbulent exchange function was kept as Valiantzas suggested. It equaled $0.5 + 0.536*u_2$instead of the original Penman. Figure 7 offers a comparison of the EWM daily evaporation sums for 2011 with the values obtained by the Penman equation with the albedo optimized and by the Valiantzas (simplified Penman) equation.

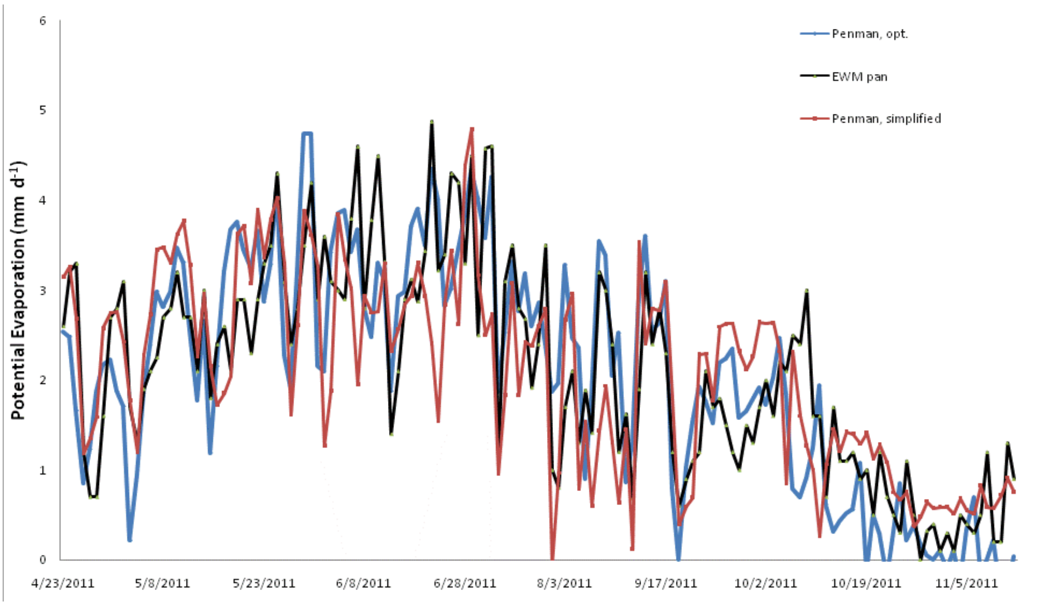

Figure 2. Comparison of different methods of estimating potential evaporation.

The Penman equation and the EWM pan measurements are in satisfactory agreement with each other. The Penman evaporation rates area slightly higher than the EWM pan rates, with some exceptions. On days with precipitation events, we expect the actual vapor pressure in the air to exceed the saturation vapor pressure at the water surface, which, along with small net radiation, leads to lower evaporation rates. However, the EWM pan maintains high evaporation rates on these days as well. This could be as attributed to the inaccuracy of the pan itself. The simplified Penman procedure usually underestimates the evaporation in the middle of the season and at the beginning and end of the season.

3.3. Discussion

As stated above, the two methods used to estimate the potential evaporation (with and without the precipitation data) did not provide the same results. Hence, it was necessary to check the compatibility of the two measurement equipments. By comparison with data from another CULS' weather station, it was found that the UFA rain gauge underestimated the precipitation events, as the ratio between the UFA data and other station's data was approximately 3:5. Hence, a coefficient of 5:3 was used multiplied with all original UFA precipitation data. Then, the net evaporation obtained with the UFA data better correlated with the net evaporation solely based on the EWM pan data. Nevertheless, some differences were observed, especially on days with heavy precipitation, recorded by a rain gauge. This might be a systematic error because of the incompatibility of the two measuring systems (the EWM pan and rain gauge) or spatial heterogeneity of intensive precipitation.

The EWM pan data made it possible to describe the fluctuation of the evaporation rate during the day and night. A polynomial curve, similar to a sine curve, approximates the average pattern diurnal variation over all days of a particular season to clarify this diurnal trend of evaporation with daily maxima and minima. Twenty-four series of average 6-h evaporation rates, each series shifted with respect to the previous by an hour, were calculated in this manner. These were plotted against the hour of the day in the middle of the 6-h interval. A clear trend was observed; on an average, the maximum evaporation was observed at about 19:00 every day. Then, it decreased gradually, and the minimum was observed at about 9:00 am. Then, the rate increased again.

Using the meteorological data from the field measurements, the Penman original equation and a simplified Penman equation proposed by Valiantzas were used to estimate the potential (water surface) evaporation. First, the recommended albedo value for water surface (0.08) was used; this led to the overestimation of the evaporation compared with the pan measurement. A larger difference was observed in summer, while in autumn and some days in winter (over which the EWM pan could operate) the difference was lower. Because of the larger values of the neglected soil heat flux in summer, compared with the other seasons. Hence, two different values of the albedo were applied. An optimized albedo, 0.3486, representing both higher reflectivity of the stainless steelpan and the neglected soil heat flux, was used in summer (from April to September), while the low value, 0.08 was used for the remaining days.

On some days, there were large differences between the values of the pan evaporation, original Penman equation and simplified Penman equation. An overall characterization of the correlations between these variables using the root mean squared error (RMSE) would not provide an accurate view of the correlation. Instead, the correlation was described in the form of linear regression, with acceptable values of the correlation coefficient.

Moreover, the accuracy of the UFA rain gauge should be revised because there was a large difference between the pan evaporation estimates “with precipitation” and “without precipitation” on rainy days.

The values obtained using the simplified Penman equation provided mostly accurate estimates of the potential evaporation, and they agreed with those of the Penman equation. However, the empirical parameters used must be changed to adapt well with the local conditions, which might require longer observation periods. Although there was limitation in the estimation methods (in empirical parameters) and in the data quality (such as difference in the EWM pan measurement), the Penman equation or the measurement from EWM pan can be used as alternatives for each other. Moreover, the combination of the empirical equation and pan observations after substantial calibration (which also require longer and more accurate observation) would help better understand the surface energy balance. This will further enable the study of surface hydrology balance and the effect of climate change on water evaporation.

4. CONCLUSIONS

The objectives of this study were to find out if and to what extent the EWM evaporation pan, the Penman and the Penman simplified equations give correct values of water surface evaporation, to elaborate an optimum method for correcting the gross evaporation data for the effect of precipitation and to explore the variation of water surface evaporation over the diurnal period and over longer time intervals. These objectives were fulfilled.

The report used data from the weather station belonging to the Department of Water Resources, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences for estimating potential evaporation from August 2010 to November 2012 (excluding winter months). Through the processing of pan and weather data, the accuracy of the equipment (EWM pan) was checked and ascertained incompatibility between the rain gauge and the EWM pan was discovered with a high probability of a malfunctioning of the instruments during heavy precipitation events. The net evaporation was from the EWM pan, its diurnal variation was estimated and also its seasonal variation (in a simplified manner). Two Penman-type equations based on the combination method were evaluated using weather data from the experimental site. The evaluation and comparison were done with both the original and the optimized albedo. In the case of using the recommended albedo of 0.08, the Penman equation and the simplified one both overestimated significantly the potential evaporation in summer time but not so much in other seasons in year. With a modified albedo, the results from the two Penman-type equations gave better estimation of net evaporation measured by EWM pan in the summer, because the modified albedo included the effect of larger soil heat flux in summer. Although better results were gained with the modified albedo, some differences still about its accurate value. Thus, it is better to conduct separate measurement of soil heat flux than to neglect it altogether and include its effect in an average albedo for the whole season.

Acknowledgments: We are very pleased to receive the support from Czech Hydrometeorological Institute - Czech Academy of Sciences in Prague for consultation, equipment's maintenance and providing necessary data. This work is partially supported by The Japan Society for the Promotion of Science, KAKENHI(B) (17H04484, 2017-2019), and KAKENHI(A) (17H01496, 2017-2020).

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