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Comparison of actual evaporation from water surface measured by GGI-3000 evaporimeter with values calculated by the Penman equation

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Abstract: Information about water evaporation is essential for the calculation of water balance. Evaporation, however, is a very complex physical process and it is therefore difficult to quantify. Evaporation measurements from the weather station network of the Czech Hydrometeorological Institute between 1968 and 2011 were performed using the evaporimeter GGI-3000. Evaporation was calculated using modified standard method based on FAO. The aim of the article was to compare the measured values and calculations. It has been found that the evaporation values from water surface calculated using the empirical equation are usually higher than the measured values by on average 0.8 mm, in extreme cases even 6.9 mm. The measured data shows higher variability than the calculated values, which means that correlations between series are not strong, the correlation coefficient being 0.7. Nevertheless the findings can be used for homogenization of series measured by the GGI-3000 evaporimeter.

Key words: evaporation, GGI-3000 evaporimeter, evaporation calculation using the FAO method, statistical analysis

1. Introduction

One of the main components of the natural water cycle is evaporation, alternatively evapotranspiration (*Novák, 1995*). Together with atmospheric precipitation and runoff it is involved in maintaining hydrological balance in landscape. It is in fact a very complicated physical process that occurs at all humid surfaces depending on the amount of energy available for evaporation. The extent of evaporation is determined by physical properties of

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the surface, solar radiation balance given by its transformation on this surface, air humidity and flow, plant cover, etc. Given this complexity it is not surprising that, unlike many other meteorological parameters, measuring evaporation is very difficult (*Brutsaert, 1982; Burman and Pochop, 1994*).

From physical point of view, evaporation from water surface is relatively the simplest case of evaporation. Unlike evaporation from other surfaces (bare soil, grass cover, plant cover, agricultural crops), its intensity is not limited by the amount of water available. Evaporation from water surface can therefore be considered as the potential evaporation, i.e. the maximum possible evaporation, with its intensity dependent only on atmospheric conditions. In other words, the potential evaporation depends on the basic meteorological parameters including air temperature and humidity, global radiation, wind speed, etc.

Measurements of evaporation from water surface were performed at stations of the Czech Hydrometeorological Institute (hereinafter CHMI) network using several devices (*Kříž, 1966*). Some imperfections were sooner or later discovered in all of them and this could more or less affect the measured values of evaporation. The standard device used to measure evaporation from water surface in daily intervals during the second half of the last century was the manual evaporimeter GGI-3000 (*Slabá, 1972; Lapin, 1977; Fišák, 1994*).

Due to complexity and difficulty of these measurements, nowadays, in order to determine evaporation from water surface (unlike water level of evaporimeter we consider free water level) in daily intervals, simple and more complex equations or algorithms are used, simpler ones having only regional significance.

From the computational methods and procedures, which are currently available for the quantification of the balance parameter in the Czech Republic and abroad, in practice the most important is the original Penman equation (*Penman, 1948*). Its modified version formed the basis for the standard internationally recognized FAO method.

2. Materials and methods

Regular measurements of evaporation from water surface (hereinafter V_VH) using the GGI-3000 evaporimeter at stations of the CHMI network began in 1968 and ended in 2011.

GGI-3000 evaporimeter measures V_VH and consists of several parts including:

– collector,
– rain gauge,
– burette,
– index tube,
– thermometer (standard station thermometer).

Detailed description of GGI-3000 is given in the "Manual for observers at the meteorological stations CHMI" (*Žídek and Lipina, 2003*). The evaporimeter is a cylindrical pan made of steel (or plastic) with a cone-shaped bottom. In the center of the tank, there is an index tube upon which a volumetric burette is set. The burette has a valve that allows maintaining equal water level in the pan. The area of the pan collector is 3000 cm^2.

The rain gauge is also a cylindrical container made of steel (or plastic) with a cone-shaped bottom. A funnel with an area of 3000 cm^2 is placed on top of this container. The collected water is emptied into the cylinder placed in the bottom part of the rain gauge. Part of the rain gauge is also a calibrated graduated cylinder which allows measuring the amount of collected rainfall.

At the measuring location, the pan is placed so that it is not shaded by other devices or surrounding obstacles. Both the pan and the rain gauge are set in the soil so that their rim is 75 mm above the ground and at a horizontal distance of 1 m from one another.

Measurements of V_VH using GGI-3000 are performed during nonfreezing part of the year at 7 am after all other meteorological observations are finished, but no later than 7.30 am CET (8.30 CEST), always at the same time. If at the time of V_VH measurement there is a heavy rain at the station, the V_VH and the amount of water in the rain gauge of the evaporation measuring set is measured after the rain ends, but at the time of the next climatological measurement at the latest. Measurement of the amount of rainfall using a standard rain gauge is always performed at 7 am.

Water temperature at the water surface is measured three times a day at 7 am, 2 pm and 9 pm using the station thermometer, which is carefully submerged into the water inside the pan.

Average values of the initial and the final water level heights are calculated from the three measured values of the initial (H1) and the final (H2) water level height in the pan. The V_VH is calculated as follows:

$$V = H1 + S - H2\,,$$

where $H1$ – the initial water level height,
$H2$ – the final water level height,
S – the amount of collected rainfall,
V – the evaporation from water surface.

In order to ensure uniform and homogeneous evaluation of V_VH measured using GGI-3000 in the area of the Czech Republic, it was necessary to choose a reference period for the daily precipitation analysis. The chosen reference period was from 1st May to 30th September, i.e. during the vegetation season. As it was already mentioned, the GGI-3000 was operating at various stations during various periods and so it was not possible to analyze and evaluate all the V_VH-measuring locations. Detailed analysis was performed for a basic set of 10 selected climatological stations using data of the period from 1971 to 2000 and for 4 stations from the Moravian region using data of the period from 1981 to 2010. The measured data series were not always complete, missing values were completed using methods of basic linear regression.

2.1. Calculation of evaporation from water surface

One of the main problems with practical use of measured data in climatological and bioclimatological applications is their incompleteness. Selecting the appropriate method to add the missing values is therefore highly important. Many simple and complex procedures and algorithms are specified in scientific literature, some of which can only be applied regionally (*Walkusz and Jańczak, 2007*).

Penman equation modified based on the FAO method (*Bos et al., 1996*) is:

$$E_0 = \frac{\Delta}{\Delta + \gamma} \cdot \frac{R_n - G}{\lambda} + \frac{\gamma}{\Delta\gamma} \cdot E_a\,,$$

where E_0 – open water evaporation rate [kg.m^{-2}.s^{-1}],
Δ – slope of saturation water pressure depending on air temperature [kPa. °C^{-1}],
γ – psychrometric constant [kPa. °C^{-1}],
R_n – net radiation [W.m^{-2}],
G – heat flux density into water environment [W.m^{-2}],
E_a – isothermal evaporation [kg.m^{-2}.s^{-1}].

Second equation is the Penman equation in a modified form (M is an auxiliary variable):

$$E_0 = \frac{\frac{p_0\Delta}{p\gamma}\Big[\,M\,\Big] + 0.26\,(e_s - e_d)\,(0.5 + 0.54\,u)}{1 + \frac{p_0\Delta}{p\gamma}}$$

$$M = 0.95\,R_A\left(0.18 + 0.55\frac{n}{N}\right) - \sigma T^4\left(0.56 - 0.079\,e_d^{\frac{1}{2}}\right)\cdot\left(0.1 + 0.9\frac{n}{N}\right)$$

where E_0 – open water evaporation rate [mm],
p_o, p – atmospheric pressure at sea level at the given location [mb],
Δ – slope of saturation water pressure depending on air temperature [mb. °C^{-1}],
γ – psychrometric constant [kPa. °C^{-1}],
R_A – daily total of the global radiation at clear sky conditions [cal.cm^{-2}.day^{-1}],
n – actual duration of sunshine [h],
N – maximum possible duration of sunshine (daylight hours) [h],
σ – Stefan-Boltzmann constant [W.m^{-2}.K^{-4}],
T – air temperature [°C],
e_d, e_s – actual water vapor pressure and saturated water vapor pressure [hPa],
u – wind speed [m.s^{-1}].

Both of the above stated relationships were used for the calculation of V_VH (calculated V_VH, labeled as V_VVH) in daily intervals. This procedure was applied for the reconstruction of missing or dubious evaporation data of the periods 1971 – 2000 and 1981 – 2010.

3. Results and discussion

As part of a detailed analysis of the calculated V_VVH and measured V_VH, the differences between the corresponding data for each day of the analyzed period were evaluated. It turns out that the both series correlate quite well, but there are cases where the measured and calculated values differ, which could be due to inaccuracy of the measuring device or poor quality of measurement. In order to eliminate dubious data in the measured data series, the method of quantile error estimation was used. This method is commonly applied in statistical analyses of experimental data (*Meloun and Militký, 2004*). Outlying data were determined in the differences of daily V_VVH and V_VH. These outliers were defined based on 1.5 of large multiple of interquartile range from upper or lower quartile, determined separately for each station (*Štěpánek, 2004*). Figure 1 shows an example of the frequency of differences between V_VVH and V_VH at the station in Kroměříž of the period from 1971 to 2000. Suspected dubious days are highlighted in the figure by circles, in which the difference between the calculated and measured values is outside of the interval between −2.6 mm and +2.5 mm. Subse-

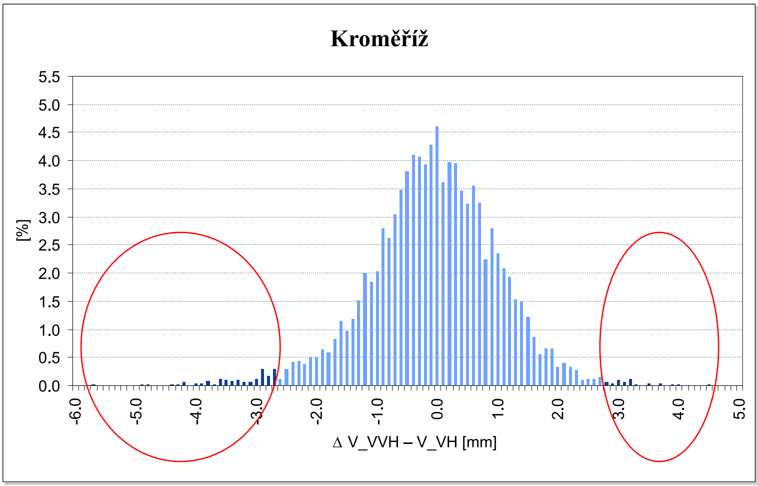

Fig. 1. Kroměříž, histogram of frequency of differences in daily evaporation between calculated data and data measured by GGI-300 during the vegetation period from May to September (1971–2000). The x-axis label symbol Δ denotes the difference between V_VVH and V_VH in mm.

quently, the suspicious data were verified by comparing them with values from other stations. If the difference between the calculated and measured value on a particular day was not rare and large differences between V_VVH and V_VH were observed at three or more stations, the measured value was considered as correct, because they were considered as effects of weather variability. In the opposite case, outliers were deleted and replaced with a different value determined by the same procedure as used for completing missing data. The proportion of corrected values from all data at particular stations fluctuates around 2%.

After completing data series from V_VH measurements, differences between V_VVH and V_VH were recalculated and again analyzed. The results show that the calculated V_VVH values are usually larger than the measured V_VH. During the period from 1971 to 2000 (analysis of data from 10 stations), daily evaporation ranged on average from 0.0 mm (Kroměříž station) to 1.2 mm (Svratouch station), see Table 1. The maximum differences, however, remain large. Positive values mean that the calculated V_VVH on a particular day exceeds the measured value, while negative values show the opposite. Most significant extremes were observed at the station in Kuchaoovice (−4.3 to +4.8 mm) and Prague-Libuš (−6.3 mm to +4.8 mm). It must be noted, however, that the frequency of these extreme

Table 1. Differences and correlations between measured and calculated data of evaporation from water surface during the vegetation period (1971 – 2000)

Climatological station	**Average difference**	**Maximum difference**		**Correlation meas./calc.**
		negative	**positive**	
Doksany	–0.17	–5.30	2.90	0.7490
Holovousy*	–0.14	–4.30	3.90	0.6638
Cheb	0.48	–3.00	4.60	0.7796
Kostelní Myslová	0.30	–3.60	4.00	0.7571
Kroměříž	–0.02	–4.20	3.00	0.7547
Kuchařovice	0.50	–4.30	4.80	0.7205
Ostrava-Poruba	0.12	–4.10	3.60	0.6935
Prague-Libuš	–0.11	–6.30	4.80	0.7351
Svratouch	1.19	–2.30	5.60	0.7802
Ústí nad Orlicí	0.19	–4.00	4.70	0.7814

deviations was not very high. Correlation coefficients calculated from the pairs of daily evaporation values (i.e. V_VH and V_VVH) were in general around 0.70, strongest correlation was observed at stations in Cheb, Svratouch and Ústí nad Orlicí.

In the period from 1981 to 2010 (analysis of data from 4 stations) daily evaporation on average differed least at stations in Bzenec and Brod nad Dyjí (−0.1 mm and +0.1 mm), while the highest average difference was observed at station in Kroměříž (−0.3 mm). The highest maximum differences were observed in Brod nad Dyjí (−5.3 mm and +4.5 mm). Correlation coefficients for all stations are above 0.70, see Table 2.

Table 2. Statistical data showing differences and correlations in daily evaporation measured by GGI-3000 and values calculated (V–IX, 1981 – 2010)

Climatological station	Average difference	Maximum difference		Correlation meas./calc.
		negative	positive	
Brod nad Dyjí	0.09	–5.30	4.50	0.723
Bzenec*	–0.07	–5.00	3.70	0.725
Dyjákovice	0.31	–4.00	4.40	0.746
Kroměříž	–0.28	–3.50	2.30	0.768

4. Conclusion

Water evaporation is an essential component of the water cycle in landscape and significantly affects the water balance. Information about evaporation is, therefore, highly important for the balance of water bodies. It is a complex physical process and it is this complexity that makes it, unlike many other meteorological parameters, quite difficult to measure. Several devices were used to measure evaporation from water surface at stations from the Czech Hydrometeorological Institute (CHMI) weather station network. Some imperfections were sooner or later discovered in all of them and this could more or less affect the measured values of evaporation. The standard device used to measure evaporation from water surface in daily intervals from 1968 to 2011 used to be the manual evaporimeter GGI-3000. Since the beginning of measurements until today, there has been a total of 50 evaporation measuring stations in the region of the Czech Republic. However, not all of them measured throughout the entire period simultaneously. The highest number of stations measured in the period between 1970 and 1972, when 30 GGI-3000 evaporimeters were in operation. When comparing the measured data from the individual stations, variable length of the observation period is a serious problem. Longest series of daily evaporation from water surface, exceeding 30 years, can be seen at 13 climatological stations. Nevertheless, even in these series there are missing data. In addition, with regards to the fact that using the GGI-3000 device is relatively difficult, errors in measuring process are not uncommon. Substantial part of this work therefore consisted of data quality verification and completion of missing data.

We have decided to use the worldwide recognized standard FAO method, based on the original Penman equation. The time of the year to be analyzed was chosen from 1st May to 30th September. Statistical analysis was performed for two periods, the first one from 1971 to 2000 (analysis of data from 10 stations) and the second one from 1981 to 2010 (data from 4 stations analyzed). The results show that only very rarely there are differences of more than 1 mm in the monthly averages. In the daily values there are occasionally larger differences, usually around 4 mm, the extreme difference is 5.3 mm. Correlation coefficients calculated from the pairs of daily evaporations (i.e. V_VH and V_VVH) were in general positive around 0.70. Strongest relationship was found for the station in Ústí nad Orlicí (r = 0.7814), weakest in case of the station in Holovousy (r = 0.6638). Taking into account the technical capabilities of the GGI-3000 evaporimeter, we consider the results as a proof that the calculated evaporation data using the FAO equation can be used to complete data series of evaporation from water surface.

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