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Assessment of potential evapotranspiration at Chisinau station

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Abstract

A comparison between two empirical methods for calculating potential evapotranspiration (PET), namely Hargreaves and Penman-Monteith is presented using the downscaled time series from CRU TS3.21 observation dataset at the closest grid point to Chisinau station coordinates, and observation series at Chisinau climatological station in the Republic of Moldova for the period 1951-2012. The Hargreaves PET model is based on minimum and maximum air temperature and extra-terrestrial radiation, while the Penman-Monteith method is based on minimum, maximum and mean air temperature, vapour pressure and cloud cover. The following diagnostic statistical quantities are analysed: (1) correlation coefficient (r) and (2) coefficient of determination (R in %).

Key words: potential evapotranspiration**,** Hargreaves method, Penman-Monteith metod

Introduction

Potential evapotranspiration (PET) is an important variable in drought identification to determine evaporative demand of the atmosphere. The PET concept was first introduced in the late 1940s and beginning of 1950s by Penman. It is defined as “the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile”. Recent drought studies (e.g. Dai, 2011; Begueria et al., 2013) have enhanced the debate on the effect of actual evapotranspiration (ETa), reference evapotranspiration (ETo) and/or potential evapotranspiration (PET) on drought quantification. ETa is the water lost under real conditions. The ETo is defined as "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, bulk surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, and no moisture stress " (Allen et al., 1994). Estimates of ETo are largely applied in irrigation schemes to define crop water requirements.

Since the 1940s a number of methods have been developed for calculating evapotranspiration. Based on the principal climatic element or physical process involved in the formula of its calculation these methods can be grouped into five categories: (1) water budget (Guitjens, 1982), (2) mass-transfer (Harbeck, 1962), (3) combination (Penman, 1948), (4) radiation (Priestley and Taylor, 1972), and (5) temperature-based (Thornthwaite, 1948). The Food and Agriculture Organization of the United Nations (FAO) and American Society of Civil Engineers (ASCE) have adopted the Penman-Monteith (PM) method as the standard for computing the PET from climate data (Allen et al., 1998; Penman, 1948). The PM equation requires extensive meteorological data and long-term records of these variables which are not always available. Hargreaves and Allen (2003) have demonstrated that the Hargreaves (Hg) method is the best alternative for quantifying evapotranspiration when accurate meteorological data are missing. The Hargreaves formula to calculate PET is a function of maximum and minimum temperature, and extraterrestrial radiation calculated as a function of latitude and the day of the year. Studies have demonstrated that PET estimates from the Hg and PM equations are very similar, with differences less than 2 mm per day (Droogers and Allen, 2002). Hargreaves and Allen (2003) showed that the monthly PET calculated with the Hg equation was within 97–101% of PET measured by a lysimeter for semi-arid and sub-humid regions of the United States.

The main objectives of this study are: 1) to compare the PET series calculated with Hargreaves method using CRU TS3.21 data downscaled at the closest grid point to Chisinau station coordinates and, using observation at station, and 2) to compare the CRU PET series calculate with a variant of Penman Monteith method with the PET calculated with Hargreaves method in the closest grid point to Chisinau station coordinates.

Materials and methods

This study was carried based on observational data recorded at a secular climatological station Chisinau available from Moldova's State Hydrometeorological Service for the period 1951-2012. The geographical coordinates of the station are 46°58'03''N; 28°51'23''E, and the altitude is 173 m above sea level. Due to the availability of quality controlled long and continuous series, we chose the Chisinau station as representative for Moldova domain to compare the time series of monthly averages of daily minimum (Tmin), daily maximum (Tmax) and daily mean (Tmean) of CRU TS3.21 at the closest grid point to the station coordinates, and station observations. These data were further used to calculate PET with Hargreaves method (Hargreaves and Allen, 2003) and to compare it with the PET CRU TS3.21 time series calculated with a variant of Penman Monteith method (Ekstrom at al. 2007). The Hargreaves method used in this study to calculate PET (Hargreaves and Samni, 1985) is:

$$PET = 0.0023 \cdot Ra \cdot TD^{0.5} \cdot (Tm + 17.8) \quad (1)$$

where

Ra - extraterrestrial radiation (MJ $m^{-2}day^{-1}$)

TD - the difference between the maximum and minimum temperatures in °C

Tm - the average monthly temperature (t_{max}+ t_{min}/2).

The variant of Penman Monteith method used by CRU to calculate PET in TS3.21 is based on minimum, maximum and mean air temperature, vapour pressure and cloud cover (Harris et al., 2014).

The following statistical quantities were analysed: (1) correlation coefficient (r) and (2) coefficient of determination (R^2). The R^2 of the best-fit regression line, which is the ratio of the explained variance to total variance, is used to determine the quality of the fit between the Hg and PM estimates for PET.

Results

At the first stage, the CRU TS3.2 time series of monthly averages of daily minimum, maximum and mean air temperature at the closest grid point to Chisinau station coordinates have been compared with the corresponding series of observations. The left panels of Figure 1 present the comparison between the multiannual means of Tmean, Tmax and Tmin calculated for the closest grid point to station coordinates from CRU TS3.21 and the corresponding series of observations. The results show that the CRU data does quite well in representing the multiannual means of daily extremes (t_{max} and t_{min}) and mean air temperature (t_{mean}). Slightly differences are observed in the right-hand panels of Figure 1 where the frequency distribution of temperature CRU TS3.21 series and station series are represented on a single graph axially-symmetric.

The values of CRU series t_{mean} range between -11.5 and 24.9 °C while at station the t_{mean} values range between -11.9 and 26.0 °C, respectively. The t_{max} (t_{min}) values of CRU series range between 7.9 and 31.4 °C (-15.2 to 19.1 °C) while at station the values range between -8.7 and 32.6 °C (-15.4 and 20.2 °C), respectively

The differences in the frequency distribution of CRU TS3.21 series and observation series at station can be explained by the CRU metadata corresponding to the cell centred at 47.25ºN; 28.75ºE. The values in that grid point depend on the number of stations that could have influenced the data value for that cell for each time step. The sphere of influence is the correlation decay distance, which is 750 km for diurnal temperature range, and 1200 km for mean temperature (New et al,2000). The averaged number of stations that have influenced the values in the closest CRU TS3.21 grid point to station coordinates is 92.

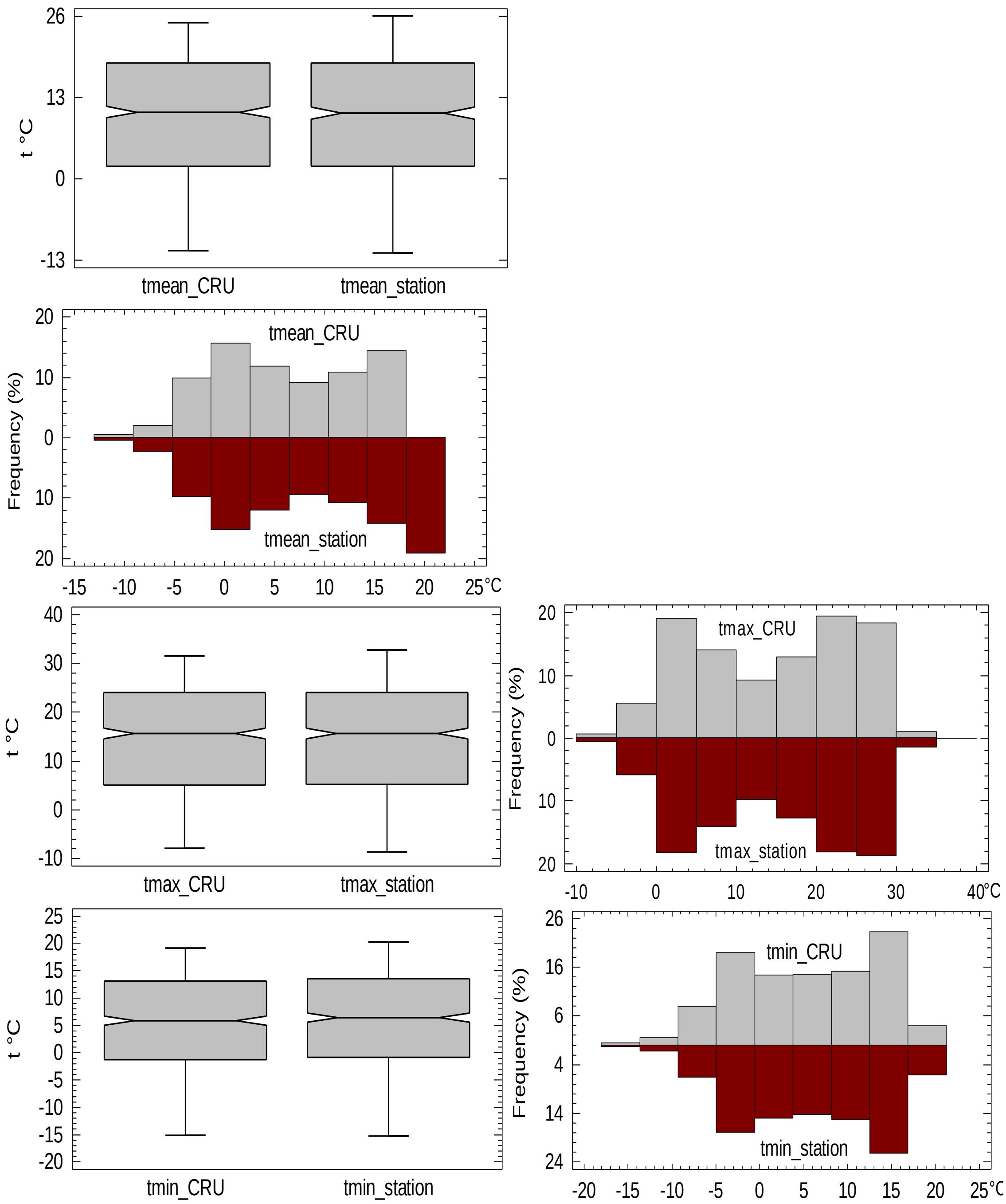

Fig. 1 Comparison between the multiannual means of monthly averages of daily means, daily maximum and daily minimum of CRU TS3.21 series at the closest grid point to Chisinau station coordinates and the corresponding series of station observations (1951-2012). The height of the box portion shows the interquartile range of the dataset, and range between the 25th and the 75th percentiles. The horizontal bar within the box represents the median value. The margins of the whiskers indicate the 10th and 90th percentile values, respectively

At the second stage of the study, we calculated PET with Hargreaves method using as input data the series of Tmax and Tmin both for CRU TS3.21 series downloaded at the closest grid point to Chisinau station coordinates, and for series of observations at station. The estimates of PET with Hg method using CRU data is almost similar to PET with Hg method using observations at Chisinau station (Fig. 2a). This result is supported by the CRU TS3.21 metadata which shows that the actual number of all station observations in the cell centred at 47.20ºN; 28.75ºE is 1 which actually is the Chisinau station.

Next, the differences between estimates of PET with two empirical methods - Penman-Monteith and Hargreaves – based on CRU data at the closest grid point to Chisinau station and based of observations at station were analysed. Fig. 2a shows the comparison between the multiannual mean of monthly PET of CRU_PM series at the closest grid point to station coordinate, and PET_Hg series calculated with CRU and station data for the period 1951-2012. The estimates of PET_Hg range between 0.0 and 5.9 mm/day, while the estimates of PET_PM range between 0.0 and 6.6 mm/day. The scatter plot of the differences between the time series PET_Hg and PET_PM based on CRU data at the closest grid point to station coordinates is shown in Fig. 2b. The correlation coefficient between these time series of PET is very high (r = 0.99) while the coefficient of determination indicates that the regression line perfectly fits the PET series (97.38%). These results show that PET_Hg is a reliable method to estimate PET_PM at Chisinau station with limited input meteorological data.

(a) (b)

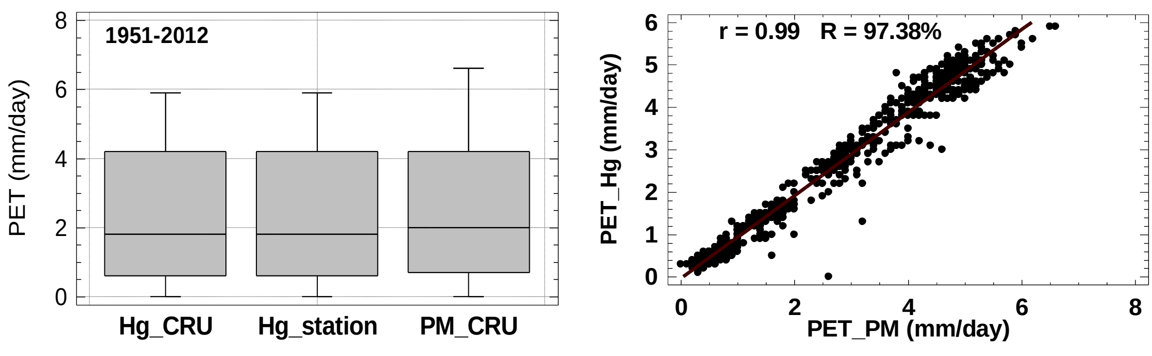

Fig. 2 (a) Box plot of multiannual mean of monthly potential evapotranspiration (PET, mm/day) estimates with Hargreaves method based on CRU TS3.21 data at the closest grid point to Chisinau station coordinates (Hg_CRU), and based on station observations (Hg_station) and, CRU TS3.21 series of PET estimates with Penman-Monteith (PM_CRU) for the period 1951-2012 ; (b) Scater plots of monthly PET series calculated with Hg and PM methods based on CRU TS3.21 data, and the correlation coefficient between these two series of PET

Detailed results on the correlation and various statistics of monthly PET_Hg and PET_PM based on CRU TS3.21 series at the closest grid point to Chisinau station coordinates for the period 1951-2012 are summarized in Table 1.

Table 1 Statistics of monthly potential evapotranspiration (mm/day) estimates with Hargreaves (Hg) and Penman-Monteith (PM) methods using CRU TS3.21 dataset

	mean		STDev		Min		Max		r	R^2	MAE
	Hg	PM	Hg	PM	Hg	PM	Hg	PM		(%)	
Jan	0.4	0.4	0.1	0.2	0.2	0.0	0.6	1.0	0.65	41.9	0.1
Feb	0.6	0.7	0.2	0.3	0.3	0.4	1.0	1.6	0.74	54.1	0.1
Mar	1.4	1.4	0.3	0.4	0.9	0.7	2.0	2.6	0.94	88.7	0.1
Apr	2.7	2.8	0.3	0.4	2.0	1.8	3.5	3.9	0.88	77.4	0.1
May	4.1	4.1	0.3	0.5	3.3	3.0	4.9	5.5	0.92	84.3	0.1
Jun	4.9	4.7	0.4	0.5	4.2	3.7	5.6	6.2	0.89	79.8	0.1
July	5.0	5.1	0.3	0.5	4.3	4.1	5.8	6.6	0.92	85.1	0.1
Aug	4.3	4.6	0.3	0.4	3.6	3.5	5.0	5.6	0.90	81.6	0.1
Sep	2.9	3.0	0.3	0.2	2.1	2.0	3.3	4.0	0.86	74.0	0.1
Oct	1.5	1.6	0.2	0.3	1.2	1.0	1.9	2.0	0.73	53.4	0.1
Nov	0.6	0.7	0.1	0.2	0.5	0.3	1.0	1.6	0.79	62.1	0.1
Dec	0.4	0.4	0.1	0.1	0.3	0.1	0.5	0.8	0.45	20.6	0.1

The Table 1 presents the monthly means (mean) and the standard deviations (STDev) of PET_Hg and PET_PM series, the lowest (Min) and the highest (Max) values of these series, the correlation coefficient (r), the coefficient of determination (R^2) which indicates how well the regression line approximates the distribution of real data and, the mean absolute error (MAE) which is the average value of the residuals.

According to the correlation coefficients and the coefficient of determination for each month, it is obvious that the lowest likelihood between Hg and PM was found in January ($r = 0.65$; $R^2 = 41.9\%$) and December ($r = 0.45$; $R^2 = 20.6\%$). On the other hand, the highest likelihood between the monthly series of PET_Hg and PET_PM was identify in the following months: March ($r = 0.94$; R^2

= 88.7%), May (r = 0.92; R^2 = 84.3%), July (r = 0.92; R^2 = 85.1%) and August (r = 0.90; R^2 = 81.6%).

The next step of the comparison between monthly estimates of PET_PM and PET_Hg using the CRU data refers to the differences between the monthly multiannual means of these two series of PET estimates. The results are shown in Figure 3a. Relative high difference between the PET estimates with PM and Hg is shown in May (PET_Hg are slightly lower than PET_PM) and in June (PET_Hg are slightly higher than PET_PM). The lowest difference between the two estimates was found during winter and autumn months. The annual cycle of monthly PET calculated with PM and Hg methods is presented in Figure 3b. The picture shows that July is the month with the highest water surface evapotranspiration in the Republic of Moldova, with a multiannual average of PET_Hg equal to 151.7 mm and of PET_PM equal to 157.1 mm, respectively. During the month of July the highest PET_Hg was 183.1 mm while PET_PM was 205.0 mm, and the lowest PET_Hg was 99.4 mm while PET_PM was 127 mm. The multiannual means of PET_Hg and PET_PM during summer were 428.9 mm and 441.0 mm, respectively for the period 1951-2012. The multiannual means of the annual PET_Hg and PET_PM range between 607.0 mm and 800.0 mm, and 748.0 mm and 1073.0 mm, respectively.

(a) (b)

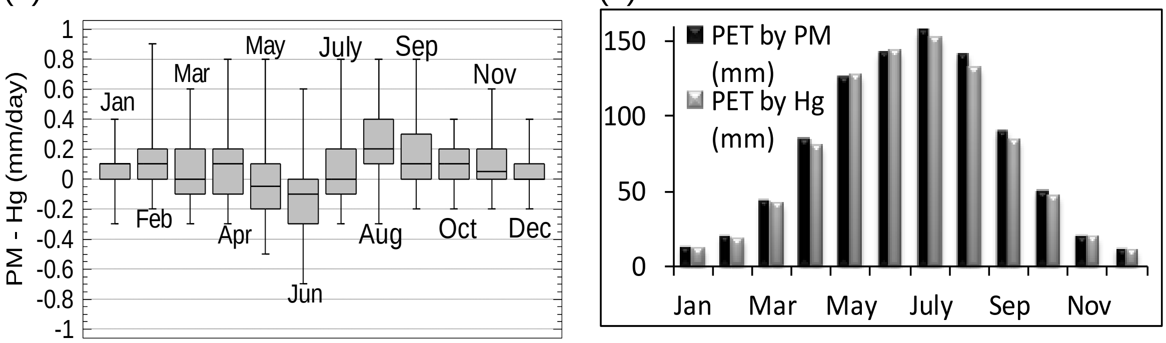

Fig. 3 (a) Box-and-whisker plot of the differences (mm/day) between PET estimates using PM and Hg methods. (b) Annual cycle of monthly PET calculated with PM and Hg methods

Discussion

In the recent decades many authors have adopted the Penman-Monteith method as the standard way to estimate PET. The main drawback associated with this method is the relatively high data demand. An alternative approach where only mean maximum and mean minimum air temperature and extraterrestrial radiation are required is the Hargreaves method (Hargreaves and Allen, 2003). The Hg method has been intensively used because it produces very acceptable results under various climates. Though the most accurate method is the one that is physically based on the PM equation (Popova et al., 2006, Vicente-Serrano et al., 2007, Shahidian et at., 2013), the large number of parameters required for its calculation made it difficult to obtain due spatial coverage of data for PET calculations needed to assess the drought conditions at country level. A number of studies have demonstrated that PET estimates with Hargreaves for periods longer than 1 week (Hargreaves and Allen, 2003) provide similar results to those obtained using the Penman-Monteith equation. In the present study, we have also obtained similar results with both methods. In addition, previous studies (Potop, 2011) confirm that the role of temperature is evident in summer drought episodes, which depend on temperature anomalies that contribute to the increasing of PET. The extremely dry summer of 2007 in the Republic of Moldova is illustrative in regard of temperature roll for PET estimates As the results of the present study show, PET estimates with Hargreaves method can be considered as reasonable quantities to detect drought, under Moldova's currently warming climate.

Jensen et al. (1997) compared the PET_Hg estimates with PET calculated with other empirical methods and concluded that the differences in PET values computed with other methods were not larger than those introduced by measuring. Lopez-Urrea et al. (2006) compared seven PET equations in semiarid area in the southern Spain with lysimeter data and concluded that the Hargreaves method was the second best after the PM method. The use of Hargreaves method to calculate PET in various climates has helped researchers to search ways to improve precision of PET estimates at local scale where no previous data exist (Shahidian et at., 2013).

Conclusion

The CRU TS3.21 series of PET calculated with the Penman-Monteith method downscaled at the closest grid point to Chisinau station coordinates has been compared with the PET series calculated with Hargreaves method using CRU data and observation data at Chisinau station. The range of correlation coefficient between the PET series calculated with Hargreaves and Penman-Monteith methods range between 0.45 and 0.94 for all months. The results confirm, that Hargreaves method can be used as an acceptable alternative to Penman-Monteith method to estimate PET in the Republic of Moldova.

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Summary

Tato práce se zabývá srovnáním dvou empirických metod pro stanovení potenciální evapotranspirace (PET), a to Hargreaves a Penman-Monteith na

sekulární klimatologické stanici Kišiněv. Vzhledem k dostupnosti kvalitní, dlouhé a nepřetržité řady meteorologických měření, byl zvolen Kišiněv jako reprezentativní stanice pro porovnávání vstupních datových souborů CRU a naměřených staničních dat, které byly dále využity k výpočtu PET v Moldavské republice. Pro analýzu využitelnosti zkoumaných metod byla použita za období 1951-2012 klimatologická databáze sítě s vysokým rozlišením CRU verze TS3.2 a datový soubor z klimatologické stanice Kišiněv. Výpočet PET Hargreaves modelem (Hg) je založen na minimální a maximální teplotě vzduchu a na úhrnu globální radiace vztažné k zeměpisné šířce klimatologické stanice, zatímco metoda Penman-Monteith (PM) je založena na minimální, maximální a průměrné teplotě vzduchu, tlaku vodní páry a oblačnosti. Ke statistickému vyhodnocení vztahu mezi PET vypočtenou těmito metodami byly použity korelační koeficient (r), koeficient determinace (R^2) a ukazatel průměrné systematické chyby (MBE).

Podle koeficientů korelace byla zjištěna nízká korelace mezi PM a Hg v lednu (r = 0,65; R^2 = 41,9 %) a v prosinci (r = 0,45; R^2 = 20,6 %), naopak nejvyšší v měsících březnu (r = 0,94; R^2 = 88,7 %), květnu (r = 0,92; R^2 = 84,3 %), červenci (r = 0,92; R^2 = 85,1 %) a srpnu (r = 0,90; R^2 = 81,6 %). Řada studií ukázala, že PET vypočtená Hargreaves modelem na dobu delší než 1 týden, poskytuje podobné výsledky jako při použití Penman-Monteith rovnice. V této studii byly získány podobné výsledky.

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