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Diurnal Method for Evapotranspiration Estimation from Soil Moisture Profile

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Abstract – Water use of plants is manifested in diurnal signal of soil moisture changes, and also in water table fluctuations in shallow water table environments. The signal can be especially strong in case of groundwater dependent forest vegetation with high water demand, where the water uptake is partly happening across the capillary zone. A new technique for water uptake estimation was elaborated on the basis of high frequency soil moisture profile data taking into account diurnally changing replenishment rates. The method is of great benefit to provide sufficient accuracy without soil specific calibration. The method was tested on the soil moisture dataset of a riparian alder forest in Hidegvíz Valley experimental catchment. Using this new method significantly higher and more realistic water uptake can be calculated compared to the traditional soil moisture method. The method is taking into account soil moisture replenishment from groundwater, which can provide a high portion (up to 90%) of evapotranspiration in dry periods. For the above mentioned reason the new technique is recommended to be used for evapotranspiration estimation in groundwater discharge areas, where the traditional methods and simple one-dimensional hydrological models are generally inaccurate.

diurnal signal / water uptake / replenishment rate / discharge areas

Kivonat – A talajnedvesség profil napi ingadozásán alapuló párolgásbecslő módszer. A növényi vízfelvétel hatása sekély talajvízű területeken megjelenhet a talajnedvesség és a talajvízszint napi ciklusú ingadozásában is. Ez az ingadozás különösen erős lehet a nagy vízigénnyel jellemezhető, talajvízfüggő erdőtársulások esetében, ahol a vízfelvétel részben a kapilláris zónán keresztül történik. A talajnedvesség nagy frekvenciás mérésén alapuló új vízfelvétel becslésére alkalmas technika került kifejlesztésére, amely napon belül változó talajvízutánpótlás figyelembevételével dolgozik. A módszer nagy előnye, hogy talajspecifikus kalibrálás nélkül is megfelelő pontosságot szolgáltat. Az új eljárás az Alpok keleti lábainál fekvő Hidegvíz-völgy kísérleti vízgyűjtőjében található vízfolyásmenti égeres talajnedvesség profil adatain került tesztelésre. Az új módszerrel lényegen nagyobb és az adott körülményeknek pontosabban megfelelő vízfelvétel számítható, mint a tradicionális talajnedvesség mérésen alapuló módszerekkel. Az új eljárás a talajvízből táplálkozó talajvízutánpótlódással számol, ami igen jelentős részét (akár 90%) is képezheti a száraz periódusokban az evapotranszspirációnak. Az előbbi okból kifejezetten javasolt az eljárás a párolgás becslésére, a sekély talajvíztükörrel rendelkező talajvíz feláramlási zónákban, ahol a szokványos módszerek és az egyszerű egy-dimenziós hidrológiai modellek általában pontatlanul működnek.

napi ingadozás / vízfelvétel / utánpótlódás / feláramlási területek

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1 INTRODUCTION

In Hungary the evapotranspiration (*ET*) is about 90% of the precipitation therefore it is a very important part of the water balance (it must be noted that globally "only" 62% of the rainfall is evapotranspired from the continents (Dingman 2002)). In spite of its significance, ET is treated generally as a lumped residual flux from a water budget of a watershed, or estimated from an energy budget using dataset of a local meteorological station. Nowadays researchers start to use remotely sensed data and hydrologic models to determine evapotranspiration in spatially distributed manner. Despite the developments in above mentioned methods, their application in shallow water table environments with mosaic land cover characteristic remains very limited (Nachabe et al. 2005).

In shallow water table environments transpiration of plant communities induce diurnal signal of soil moisture and water table (Gribovszki et al. 2010). These fluctuations are especially strong in arid and semi arid climate and can be detected mainly in groundwater discharge areas. Some researchers attempted to estimate *ET* rate of shallow groundwater areas with their own developed techniques (Bauer et al. 2004, Engel et al. 2005, Gribovszki et al. 2008, Loheide 2008, Nachabe et al. 2005, Schilling 2007, White 1932) using the observed groundwater or soil moisture fluctuations.

ET-induced diurnal signal is characterized by an early morning maximum and an afternoon minimum in the soil moisture (*Figure 1*) and also in groundwater level. In case of ET induced diurnal signal, a relationship can be detected between the daily courses of these values and that of the relative humidity, the latter mainly a function of surface irradiation at a diurnal time-scale. The direct driving force however is not radiation and relative humidity, but rather evapotranspiration (in forested areas the latter dominated by transpiration) regulated by the former variables as the plants use soil moisture or directly groundwater via their root systems.

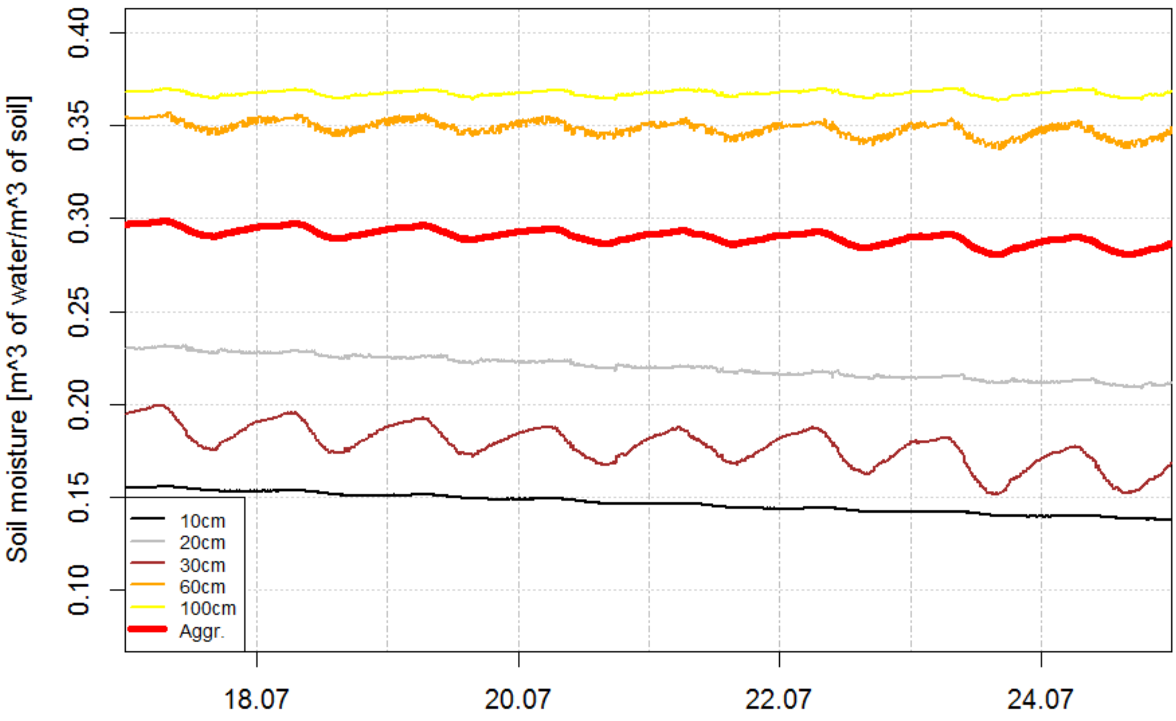

Figure 1. Diurnal signal in soil moisture profile (Aggr. means total soil moisture for profile)

As first attempt White (1932) proposed a method that uses observations of shallow water table diurnal signal to calculate the groundwater uptake by plants. This method was widely used later for estimation of ET. The limitation of the former and of all groundwater signal based methods lies in the difficulty of specific yield estimation. Nachabe et al. (2005) adapted White's (1932) original method for high frequent soil moisture profile data to eliminate the application of the specific yield. With that method a grassland and a neighbouring forest evapotranspiration were successfully estimated. Nachabe's (2005) constant upwelling recharge rate of soil moisture profile was used throughout the day for his calculation. In this paper a new technique is demonstrated by which evapotranspiration values can be calculated from aggregated soil moisture taking into account diurnally changing replenishment rate.

2 MATERIAL AND METHODS

The dataset used for testing the new method originated from a valley position (*Figure 2*) of the Hidegvíz Valley experimental catchment in Hungary, located at the eastern foothills of the Alps close to Austro-Hungarian border in the neighbourhood of city Sopron.

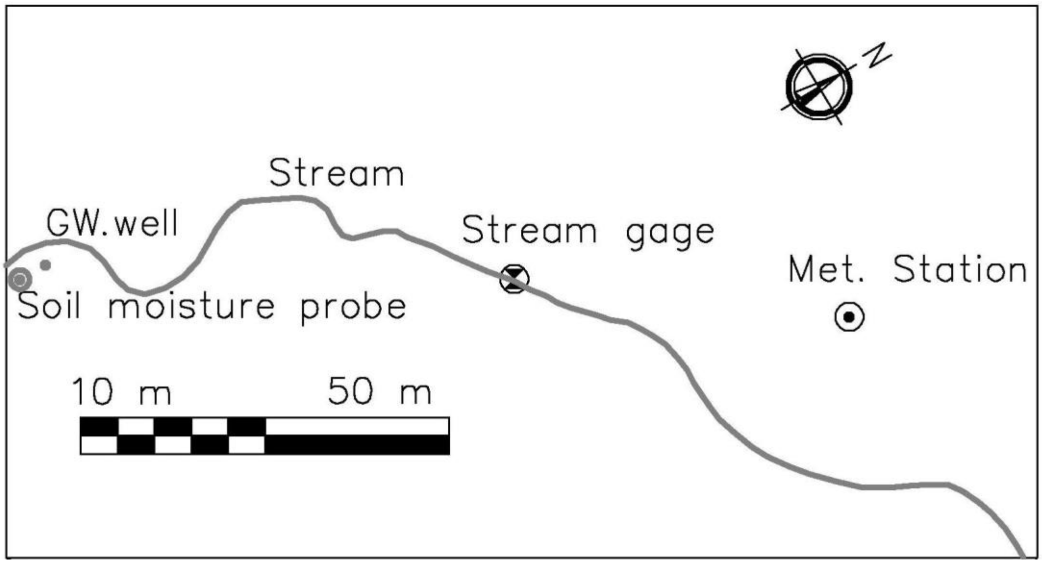

Figure 2. Location of the study site close to the outlet point of the experimental catchment at the eastern foothills of the Alps

The geological basis of the catchment is fluvial sediments deposited in five distinct layers (hundreds of meters thick) in the tertiary (Miocene) period on crystalline bedrock. On the surface only the two upper layers of the latter appear. Over the slopes and hilltops the strongly unclassified (coarse gravel and fine loam as well) formation is found in a 10–50 m-thick layer. In the valley bottoms, a finer-grained layer appears, which is a good aquifer, giving rise to perennial streams (Kisházi–Ivancsics 1985).

The soil type of the sampling point is loamy sand determined by grading test of the sampled soil profile.

The vegetation in the valleys is a typical phreatophyte intrazonal ecosystem dominated by alder (Alnus glutinosa (L.) Gaertn.). The mean height of the middle-aged riparian forest stand (where the sensors are located close to the outlet point of the experimental catchment) is about 15 m with a mean trunk diameter (at a height of 1.3 m) of 13 cm. Leaf area index (*LAI*) of this forest stand was approximately 7.

The area has a sub-alpine climate, with daily mean temperatures of 17 °C in the summer, 0 °C in the winter, and with an annual precipitation of 750 mm. In that region late spring and early summer are the wettest and fall is the driest seasons (Danszky 1963; Marosi–Somogyi 1990). Detailed characterisation of the research area can be found in Gribovszki et al. 2006.

2.1 Soil moisture data collection

A profile probe carrying six soil moisture sensor was installed in a riparian alder forest for soil moisture monitoring (*Figure 2*). Access tube was installed for probe and soil moisture sensors were distributed at 10, 20, 30, 40, 60 and 100 cm bellow the ground surface. Sensors work on capacitance principle and provide volumetric water content ranging from oven dryness to saturation with accuracy: ± 0.06 m^3/m^3. The default calibration equation provided by DeltaT company for profile probes were used in this study (http://www.delta-t.co.uk/). Soil moisture data were collected at each depth every 10 minutes.

The dataset of soil moisture sensors were used for estimation of total soil moisture of the soil column (1m soil profile) using the following equation:

$$\theta_T = \int_0^{1.0} \theta \cdot dz \tag{1}$$

where θ_T is total soil moisture (m), z is depth (m) below the ground surface, and θ is the water content (m^3 water in m^3 soil). Because there is no water content measurement at the ground surface (z = 0 depth), a uniform water content is assumed in the top 15 cm. Numerically the total soil moisture was calculated using the former approximation (1):

$$\theta_T = \sum_{i=2}^{6} \left(\frac{z_{i+1} + z_i}{2} - \frac{z_i + z_{i-1}}{2} \right) \cdot \theta_i + \left(\frac{z_2 + z_1}{2} - 0 \right) \cdot \theta_1 \tag{2}$$

where z_i is depth (m) of the *i*-th sensor from the ground surface, and θ_i is the water content at the *i*-th sensor (m^3 water in m^3 soil). The total soil moisture data for a selected period can be seen on *Figure 1.* with red thick line (*Aggr.*).

A screened (screened to the bottom (1.6 m), starting 25 cm below the surface) groundwater well was also installed close to the profile probe. Water table (*h*) in the well was recorded by a pressure transducer at a 10-min sampling interval and with an accuracy of 1 mm (www.dataqua.hu). The well was dug with a 70-mm drill. The PVC well casing has a diameter of 50 mm.

Using groundwater well dataset it can be stated that depth to the groundwater in the riparian zone varied between 0.8 to 1.1 m during typical drought periods. Consequently, the root system of the trees is in direct contact with the saturated zone, or at least the capillary fringe throughout the year. Following Shah et al. (2007), the decoupling of the groundwater dynamics from the vadose zone in the soil of our experimental site was found to start at a depth of 0.8–0.9 m, therefore almost all year long the total *ET* is very close to groundwater *ET*.

2.2 Theoretical basis of the new method

The diurnal method for ET_{gw} (evapotranspiration from groundwater) estimation using groundwater level data developed by Gribovszki et al. (2008) can be applied also for soil moisture data after some modifications.

The basic expression is the water balance equation for soil moisture profile (3):

$$\frac{dS}{dt} = \frac{d\theta_T}{dt} = Q_i - Q_o - ET = Q_{net} - ET \tag{3}$$

where S is stored volume of water in the soil moisture profile in a unit area (m^3/m^2), which is the same as θ_T (total soil moisture) in this case (m), Q_i is the incoming and Q_o the outgoing water flux ($m^3/s/m^2$) to and from the soil column, $Q_{net} = Q_i - Q_o$ is the net flux/supply ($m^3/s/m^2$) or replenishment rate and ET is evapotranspiration ($m^3/s/m^2$).

The transpirational need of the vegetation is generally met by the soil moisture. In drought periods the soil moisture profile of the shallow water table areas used by evapotranspiration is typically replenished via groundwater flow or by so-called induced recharge. Around the timing of the soil moisture extrema, supply and demand are in an equilibrium, while along the rising limb of the soil moisture signal the ET rate exceeds the rate of replenishment (Q_{net}), and vice versa on the falling limb (Gribovszki et al. 2008, Troxell, 1936)

For estimation of Q_{net} water balance equation (3) for late night hours when ET is almost zero was used:

$$\frac{dS}{dt} = \frac{d\theta_T}{dt} = Q_{net} \tag{4}$$

In order to obtain the net supply rate (Q_{net}) a so called empirical submethod (after Gribovszki et al. 2008) is employed.

The maximum of Q_{net} for each day was calculated by selecting the largest positive time rate of change value in the total soil moisture ($Q_{net\_max} = max(d\theta_T/dt)$), while the minimum was obtained by calculating the mean of the smallest time-rate of change in θ_T taken in the predawn/dawn hours ($Q_{net\_min} = mean(d\theta_{Tpredawn}/dt)$). The averaging is necessary in order to minimize the relatively large role of measurement error when the changes are small. The resulting values of the Q_{net} extrema ("Characteristic points" in *Figure 3*) then were assigned to those temporal locations where the soil moisture extrema took place. It was followed by a spline (or when the data are very noisy a linear) interpolation of the Q_{net} values to derive intermediate values between the specified extrema (after Gribovszki et al. (2008), *Figure 3.*). For calculation of time-rate of change in soil moisture (soil moisture difference) 30 minutes time step was used.

Finally, when Q_{net} values have been obtained the ET rates of new method (ET_{new}) can be obtained by rearranging the former water balance equation as

$$ET_{new} = Q_{net} - \frac{d\theta_T}{dt} \tag{5}$$

30-min water uptake data were aggregated along the day to get daily ET_{new}.

Traditional ET calculation (ET_{trad}) from soil moisture data without replenishment is the following:

$$ET_{trad} = \theta_{Tj} - \theta_{Tj-1} \tag{6}$$

where: θ_{Tj} is a total soil moisture of an j-th day, θ_{Tj-1} is a total soil moisture of an (j–1)-th day. This method is used for comparison with ET_{new}. It has to be noted that soil moisture difference in equation (6) is calculated for daily and not for 30 minutes time step compared to equations (3), (4) and (5).

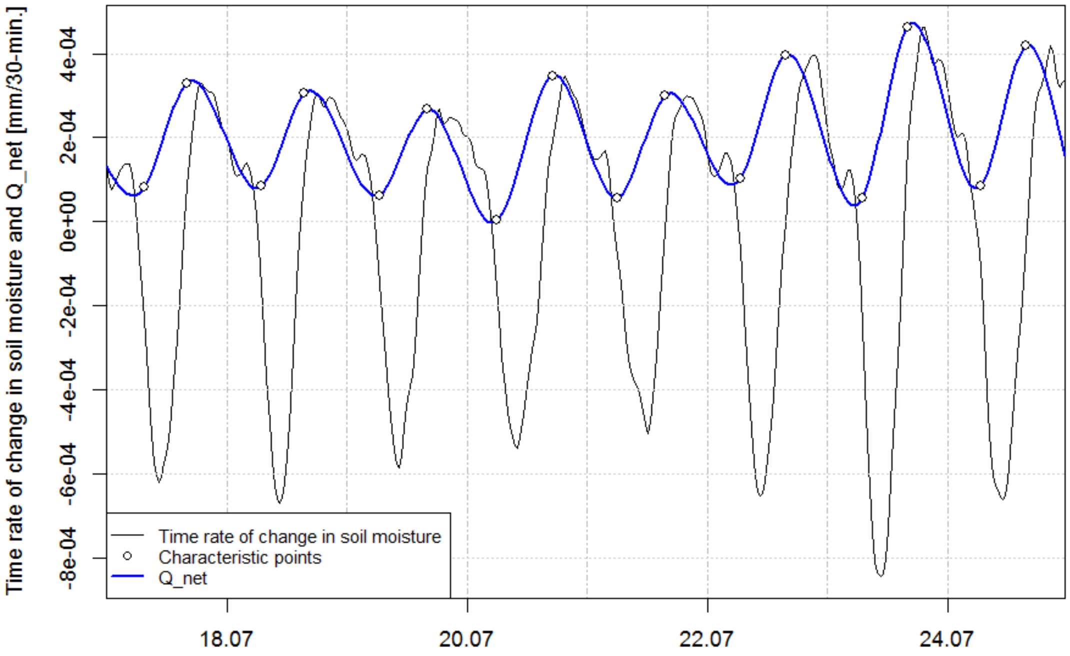

Figure 3. Graphical representation of the estimation method. See details in text.

3 RESULTS AND DISCUSSION

Figure 4 shows us daily ET_{new} values from June to September of 2013 for only dry days (daily rainfall is less than 5 mm). Mean average values for dry days of 2013 summer is 8.8 mm, a little lower in June and a bigger in July and August *(Table 1)*. Daily water uptake seems to be great amount, but taking account that this is a groundwater discharge area in a valley bottom location (where positive groundwater flux toward to the unsaturated soil profile acts to support the high *ET*) and all around dry and warm environment can be found (therefore oasis effect can enhance *ET*) the data is acceptable.

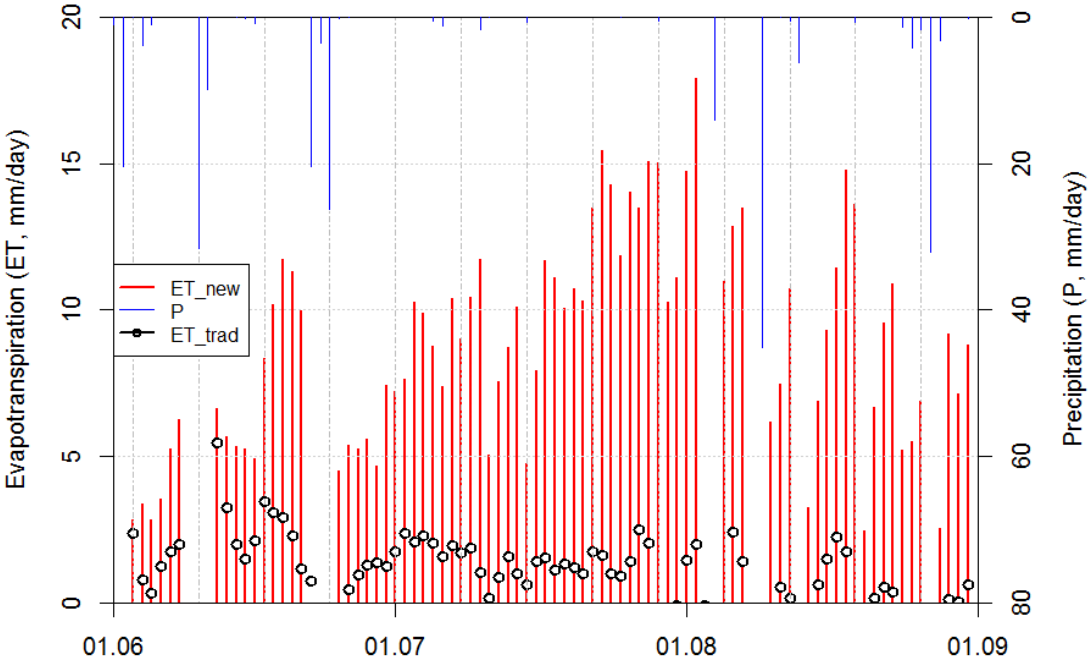

Figure 4. Daily ET values calculated by new (ET_{new}) and traditional (ET_{trad}) methods for dry days from June to August in 2013

If we compare *ET* values determined by traditional method (ET_{trad}) with estimates obtained by the new technique (*Figure 4*) a significant difference can be found. Mean average values of ET_{trad} for dry days of 2013 summer is only 1.50 mm, and a decreasing trend can be seen from data along summer (*Figure 4* and *Table 1*). The diminishing of ET_{trad} values are caused by the almost continuous drying out processes of the soil profile parallel with the increasing importance of replenishment rate in real *ET*. The ratio of ET_{trad} and ET_{new} is about 20% and also generally decreased from June to August. This significant deviation between two methods is probably caused by the continuous water uptake from groundwater across the capillary zone which is not considered in traditional method.

Soil moisture replenishment from groundwater provided nearly 80% of the total *ET* represented by ET_{new} (*Figure 5* and *Table 1*). For the visualization of seasonal trend of ET_{new} and replenishment rate (Q_{net}) a scatter-plot smoother (loess, Cleveland et al. 1992) was also applied on *Figure 5*. The data and the trends show us the importance of the net inflow rate, which was tendentiously increased along the summer (from 60% of June to 88% of August, *Figure 5*). The values of the replenishment ratio can explain the difference between the traditional and new method (roughly 4/5 of *ET* is not detected when calculating *ET* by traditional method).

The higher positive correlation coefficient between ET_{new}–Q_{net} (0.92) compared to ET_{new}–ET_{trad} (0.12) also confirmed the significance of the replenishment rates in *ET* of the groundwater discharge areas and the inaccurate values of the traditional calculation.

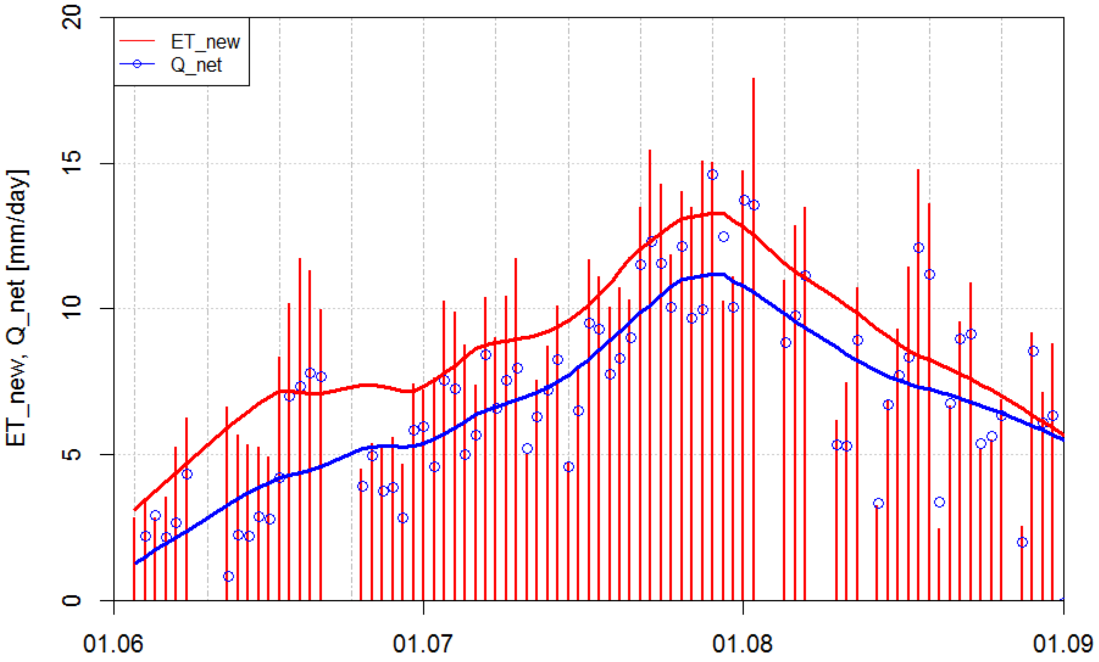

Figure 5. Daily ET_{new} values and replenishment rates (Q_{net}) for dry days with loess (local regression) smoothers for trend visualization from June to September

The magnitude of the soil moisture replenishment rate from below clearly illustrates the dependence of hygrophyte forests on groundwater. These groundwater discharge areas in Hungary can be found not only on the narrow bands of the valley locations in the mountainous and hilly regions (as our test area) but also on the broad lowland areas in Hungarian plains. Therefore for exact water uptake determination of high water demand forests located in groundwater discharge areas these kinds of methods are indispensable.

It can be also stated that hydrological models and methods, which ignore this above mentioned replenishment rate will estimate *ET* with big bias in groundwater discharge areas, and the magnitude of the bias can be 5–10 fold.

Table 1. Calculated monthly mean ET values and Replenishment rates (Q_{net}) for dry days of summer 2013

	June	July	August	June to August
ET_{new} (mm/day)	6.19 (2.61)	10.48 (2.78)	9.14 (4.04)	8.84 (3.61)
ET_{trad} (mm/day)	1.89 (1.19)	1.48 (0.56)	0.99 (0.82)	1.50 (0.93)
ET_{trad} / ET_{new}	0.33 (0.20)	0.15 (0.06)	0.08 (0.06)	0.19 (0.16)
Q_{net} (mm/day)	3.80 (2.22)	8.48 (2.56)	7.78 (3.07)	6.94 (3.28)
Q_{net} / ET_{new}	0.60 (0.27)	0.81 (0.12)	0.88 (0.14)	0.78 (0.21)

Standard deviations in brackets after each mean values

4 CONCLUSIONS

A new technique was elaborated using the diurnal signal of an aggregated soil moisture dataset. This method was successfully tested on the riparian soil moisture profile dataset in the summer of 2013. The water uptake values seem to be acceptable if oasis effect (Morton 1983) is taken into account in a well watered valley situation in a period when hot and dry environment can add significant amount of heat enhancing ET. Compared to traditional ET determination from soil moisture data, this new method gives much higher water uptake taking into account continuous soil moisture replenishment from shallow groundwater. The advantage of the new technique over the traditionally used method is that only a soil moisture profile dataset (down to the groundwater) is needed for calculation of both ET and replenishment rate and there is no need for specific soil calibration. However, future users of the new technique are cautioned, that the absolute value of ET is not available for the analysed period, thus nothing can be said about the real accuracy of the method. On the other hand the results obtained are promising and have potential benefits. As the climate changes, warmer and drier summer is forecasted. This hot and dry environment will significantly enhance the ET of the well watered areas, therefore this method can be a very useful technique for the more precise detection of impact of climate change on groundwater discharge areas.

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