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Evapotranspiration Calculation on the Basis of the Riparian Zone Water Balance

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Abstract – Riparian forests have a strong influence on groundwater levels and groundwater sustained stream baseflow. An empirical and a hydraulic version of a new method were developed to calculate evapotranspiration values from riparian zone groundwater levels. The new technique was tested on the hydrometeorological data set of the Hidegvíz Valley (located in Sopron Hills at the eastern foothills of the Alps) experimental catchment. Evapotranspiration values of this new method were compared to the Penman-Monteith evapotranspiration values on a half hourly scale and to the White method evapotranspiration values on a daily scale. Sensitivity analysis showed that the more reliable hydraulic version of our ET estimation technique is most sensitive (i.e., linearly) to the values of the saturated hydraulic conductivity and specific yield taken from the riparian zone.

evapotranspiration / riparian zone / water resources / alder forest

Kivonat – Evapotranszspiráció számítása a vízfolyásmenti zóna talajvízmérlegéből. A ligeterdő társulások hatása jelentős a vízfolyásmenti zóna talajvízmérlegére és így a vízfolyások talajvízutánpótlásból származó alapvízhozamára is. A vízfolyás menti zóna talajvízszint változásának vizsgálata alapján egy hidraulikus és egy empirikus almódszerekből álló új eljárást fejlesztettünk ki az ottani vegetáció csapadékmentes időszakokban jellemző, elsősorban a talajvízből táplálkozó evapotranszspirációjának számítására. Az új módszert a Sopron melletti Hidegvíz-völgy kísérleti vízgyűjtőjének adatain teszteltük. A módszer által szolgáltatott evapotranszspirációs értékeket összehasonlítottuk a Penman-Monteith-féle egyenlettel számolt adatokkal félórás időfelbontásban, és a White módszer által szolgáltatott adatokkal napi időfelbontásban. A módszerre készített érzékenységvizsgálat szerint a talaj telített hidraulikus vezetőképességnek és fajlagos hozamának a pontos ismerete nagyon fontos a modell megfelelő működéséhez.

evapotranszspiráció / vízfolyásmenti zóna / vízkészletek / égerliget

1 INTRODUCTION

Riparian vegetation (especially riparian forest ecosystems) typically has a great influence on groundwater levels and groundwater-sustained stream baseflow, therefore calculation of

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correct evapotranspiration values is very important from the point of view of nature protection and utilization of water resources. Numerical hydrodynamic models demand exact groundwater evapotranspiration data also to calculate regional or local water balances. Therefore vegetation influence on the riparian groundwater resources and on the baseflow regime has been intensively investigated in almost all parts of the world in the last decades (e.g. Federer 1973, Goodrich et al. 2000 etc.). In Hungary at the Komlósi telep experimental station of VITUKI, the evapotranspiration impact onto the groundwater investigated, and a method developed to estimate groundwater evapotranspiration based on the daily groundwater level readings of piesometer nests (Major 1974).

In the summer season, there is a strong diurnal fluctuation of groundwater levels (*Figure 1 upper*) and stream base flow (*Figure 1 lower*) exists. As a rule, in the case of base flow, the maximum discharge occurs around seven o'clock in the morning and the minimum about in the middle of the afternoon. A detailed description of this characteristic signal and vegetation impact on riparian groundwater balance in case of our experimental catchment (Hidegvíz Valley) can be found in Gribovszki et al. (2006) and Kalicz et al. (2005).

In early investigations the main driving force of the diurnal signal was thought to be the diurnal temperature change-induced succession of evaporation and condensation processes in a shallow groundwater environment (Ubell 1961). Later it was confirmed that this fluctuation is mainly caused by the evapotranspiration of riparian zone vegetation (Pörtge 1996).

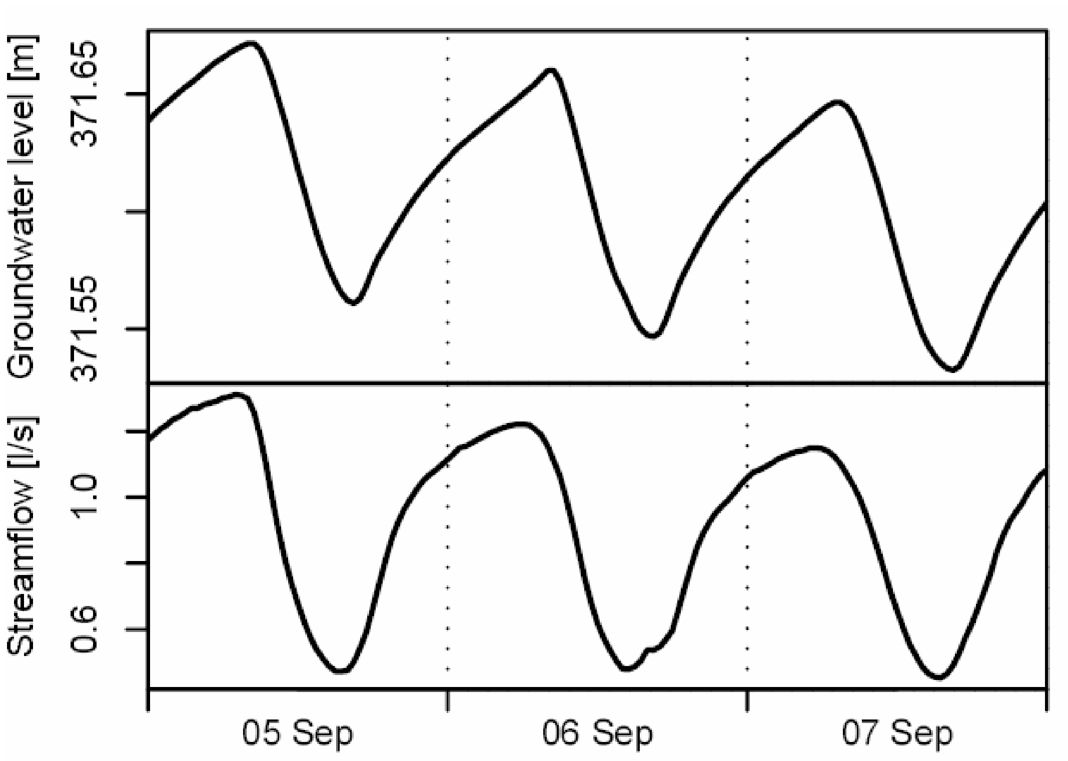

Figure 1. Diurnal fluctuation of riparian groundwater levels and stream base flow in 2005 in the Hidegvíz Valley

Several authors have investigated the linkage between riparian transpiration and streamflow rates (Troxell 1936, Croft 1948, Tschinkel 1963, Reigner 1966, Pörtge 1996, Lundquist and Cayan 2002) but only a few attempted to estimate the evapotranspiration (ET) rate of the riparian zone (White 1932, Bond et al. 2002) by using the observed streamflow and groundwater fluctuations, or to provide an analytical description of these signals (Czikowsky 2003, Czikowsky - Fitzjarrald 2004).

It can readily be established that the diurnal fluctuation of the riparian zone groundwater table and stream base flow (*Figure 1 and Figure 2*) are due to the transpiration needs of the plant life (because evaporation is negligible in the riparian forest in dry periods). The water to supply these needs can be drawn from the inflow to the area or from groundwater storage, or from both. For example, during highest groundwater levels, the water table remains constant for a short period. This means that during this period the inflow to the groundwater table is sufficient to supply all the transpiration demands. At sinking part of the groundwater levels transpiration not only uses all the inflow but also heavily utilizes the groundwater supply. At the minimum point the transpiration losses have decreased to a level where the inflow is again sufficient to supply these needs. At the rising part of the curve the transpiration needs are much less than the inflow, and surplus water is stored, causing a rise in the groundwater table. It is thus apparent that the groundwater record is merely an accumulative curve of the rates of inflow and the transpiration-use (Troxell 1936).

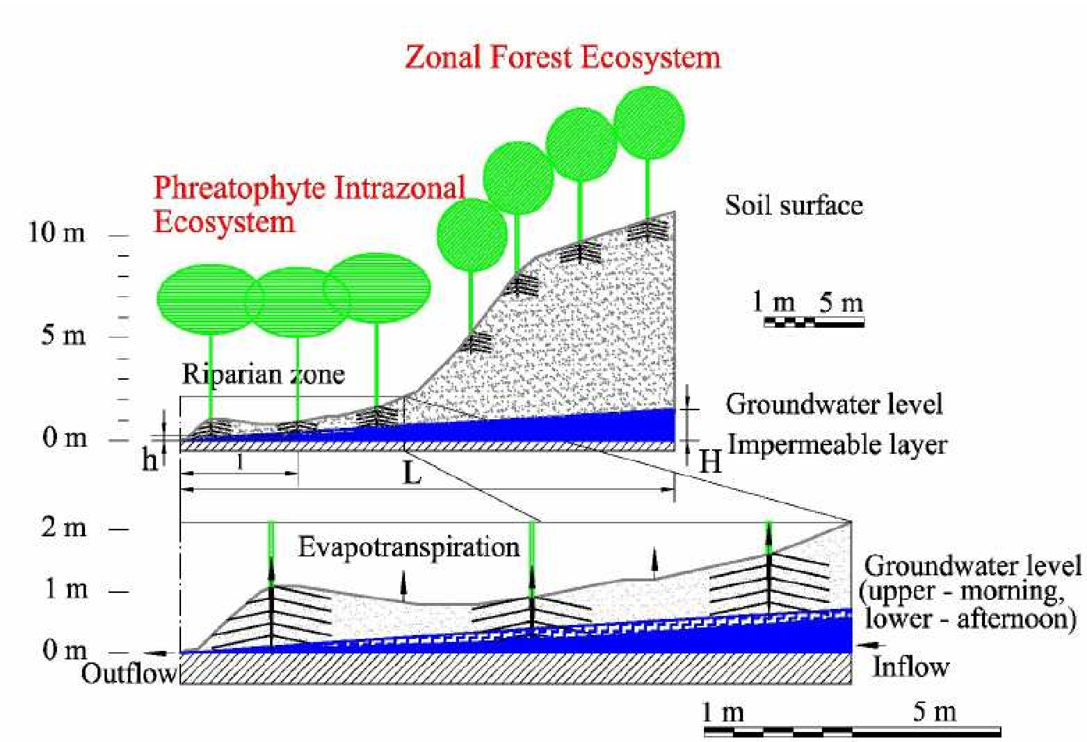

Figure 2. Schematic model of riparian zone

The maximum transpiration will occur at the point showing the maximum rate of decrease in the groundwater table. This point of maximum use occurs at or near the time of maximum temperature. Likewise the period of minimum transpiration begins when there is the point showing the maximum rate of rise in the groundwater table. This point agrees fairly well with the beginning of the night, and therefore lower temperature period, without significant net radiation (*Figure 1*).

Walter N. White (1932) suggested that it was possible to determine the daily transpiration by means of groundwater records diurnal fluctuation (*Figure 3*). If the transpiration is assumed to be practically zero during the early hours of the morning, about 2:00 to 4:00 a.m., then the rate of rise in the groundwater table during that period would be the rate of recharge. A tangent was then drawn to the curve at this point marked *r* [L]. This represents the rate of recharge of the groundwater table. If this rate was to continue throughout the 24 hours and there were no transpiration or other losses, the water table would rise an amount equivalent to the distance marked *24r*. Transpiration occurred, of course, and instead of rising, the groundwater table dropped the distance *s* [L] during the day. Consequently, the transpiration-loss would be the following equation (1).

$$ET = S_y(24r \pm s) \tag{1}$$

Where S_y is the readily available specific yield of a soil in which the fluctuation takes place. The readily available specific yield is taken as 50% of its specific yield (Meyboom 1964). A reduction is certainly justified since it takes some time for the drainage to adjust to any new conditions introduced.

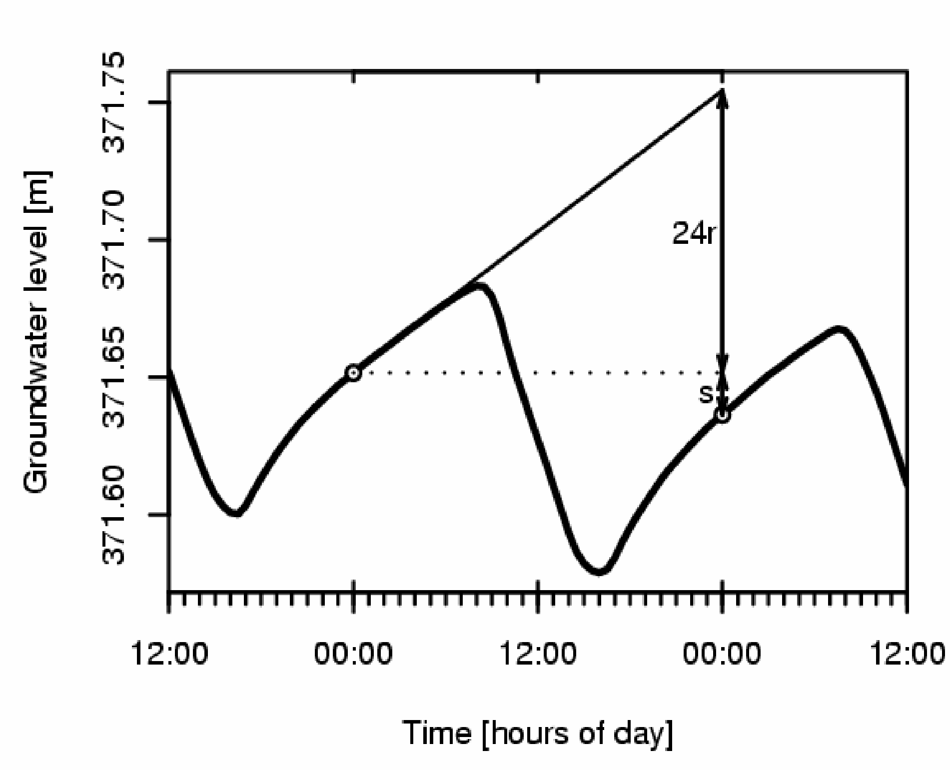

Figure 3. Basic principle of White method

2 MATERIAL AND METHODS

Although White method might provide a fairly good estimate, they are subject to a certain error. This error is based on the assumption that the rate of recharge continues as a straight line throughout the 24 hours (Troxell 1936). *Figure 4* shows a typical daily fluctuation of the riparian zone groundwater table. Late at night or early in the morning, when transpiration is practically nothing, the height of the groundwater table and the static head are nearly the same and the processes are similar to those in the dormant season. In early morning, when the groundwater table in the riparian zone is the highest, the difference between the static head and the ground water level the smallest, so the rate of recharge will be the minimum at this time. The increase of the transpiration drain on the groundwater supply causes a depression in the riparian zone. As the water table drops, the distance between the static head and the ground water increases. This increase in difference of height causes an increase in the rate of recharge *r*, so that in the afternoon the rate of recharge will be the maximum.

Thus it is evident that the rate of recharge *r* is not a straight line but a curve which ranges from zero at the height of the static head to a maximum some distance below that point. In view of *Figure 4.* it is not unreasonable to expect that at the point of maximum groundwater levels, the rate of recharge will be a minimum and at the point of minimum groundwater levels, the rate will be a maximum.

Evapotranspiration rates were calculated from the diurnal cycle of groundwater levels. A simplified water balance equation (2) and Dupuit's theory equation (3) (Kovács 1972) were used for the evapotranspiration calculation.

$$\mathrm{d}S/dt = Q_{net} - ET \tag{2}$$

$$Q_{net} = Q_{inflow} - Q_{outflow} = \frac{k}{2(L-l)}\left(H^2 - h^2\right) - \frac{k}{2l}\left(h^2 - h_0^2\right) \tag{3}$$

Where S [L^3] is the stored volume of a unit area of the riparian zone, ET [L^3T^{-1}] is the evapotranspiration rate and Q_{net} [L^3T^{-1}] is the net inflow rate (which represents the recharge rate and is defined as the difference between in- (Q_{inflow}) and outflows (Q_{out}) to the unit area of the riparian zone), k [LT^{-1}] is the average saturated hydraulic conductivity of the riparian zone aquifer, H [L] is the groundwater levels far enough (L [L]) from the riparian zone where diurnal fluctuation or its impact is close to zero, l [L] is the position (distance from the stream) and h [L] is the water levels of the riparian zone groundwater well, h_0 [L] is the water levels in a stream (*Figure 2*). dS/dt calculated from $dh\ Sy\ /dt$. H, h and h_0 are taken relative to an assumed horizontal impervious layer (*Figure 2*), not necessarily at the stream-bed elevation. The method is moderately sensitive to the elevation of this impervious layer as datum. With every 0.1 m lowering of the datum (within the 0–0.5 m interval, which seems realistic in our geomorphological situation), the daily *ET* estimates increased by only 3–5%.

We assumed that in a small scale catchment the drought streamwater levels (only a few cm) compared to riparian zone groundwater levels is negligible ($h_0 \approx 0$). Therefore equation (3) can be simplified to equation (3a).

$$Q_{netinflow} = k\left(\frac{(H^2 - h^2)}{2(L-l)} - \frac{h^2}{2l}\right) \tag{3a}$$

The method of *ET* calculation has the following steps (*Figure 4*):

First derivatives of groundwater levels were made (half hourly interval). This curve represents the rate of change in the riparian groundwater table, or the rate of Q_{net} minus the rate of *ET* are divided by S_y.

Q_{net} values were calculated with two different methods (empirical and hydraulic).

In the empirical method the maximum of Q_{net} for each day was calculated by selecting the largest positive time rate of change value in the groundwater level readings such as $Q_{net} \approx S_y\ dh\ /\ dt$, while the minimum was obtained by calculating the mean of the smallest time rate of change in h taken in the predawn hours. The resulting values of the Q_{net} maximum and minimum in *Figure 4* then were assigned to those temporal locations where the groundwater level minimum and maximum took place. It was followed by a spline interpolation of the Q_{net} values to derive intermediate values between the specified extrema. Most probably the resulting empirical maxima are somewhat smaller than the corresponding actual maximum supply rates by virtue of the *ET* term being unaccounted for in Eq. 6 in this empirical method. At the same time, the estimated minima are somewhat larger than the actual minimum supply rates, due to the necessary averaging and due to observational evidence that groundwater levels reach their maxima somewhat later, i.e., between 6 and 8 a.m. in the summer. However, the dh / dt values of this period (i.e., between 6 and 8 a.m.) should not be used because by that time ET may have already become significant, thus leading to increased dh / dt rates.

In the *hydraulic method* we use Dupuit's assumption (3) to calculate Q_{net} (*Figure 4*). The values of k, h, l, H, and L are required for calculating of $Q_{net.}$ The values of k, h and l are known from local measurements, but H and L must be estimated. H values can be determined from the assumption, that in the late night hours when ET is around zero, $dS/dt = Q_{net}$ (4).

$$H = \sqrt{\left(\frac{dS}{dt}\frac{1}{k} + \frac{h^2}{2l}\right)2(L-l) + h^2} \qquad (4)$$

Only one H value (between 2 and 4 am) can be calculated for each day. We must interpolate between these H values so as to get as much H data as we need. (Spline interpolation was used.)

If we have information about the exact direction of the groundwater flow in the riparian zone at the baseflow period, we can better describe the real situation if we lay down the cross section in the main direction of the groundwater flow. This is important when the groundwater streamlines become parallel to stream near the steam channel.

Half hourly ET values were computed from the difference between Q_{net} values and the stored volume change (dS) of the riparian zone (*Figure 4*) as rearranging Eq. 2. $ET = Q_{net} - dS / dt$.

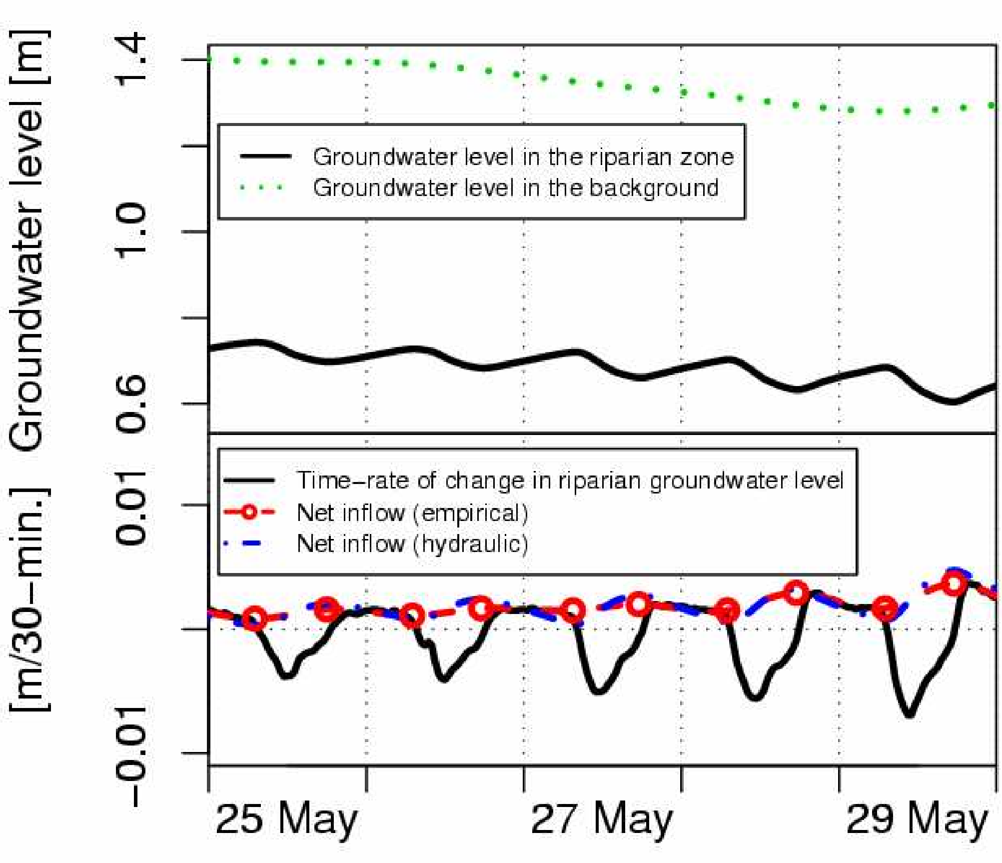

Figure 4. Groundwater levels, their derivative and the transformed Q_{net} (recharge)

Before the application of the hydraulic theory, one has to decide about the location at which the groundwater levels must be observed, and its temporal derivatives must be computed. As Bauer et al. (2004) and Loheide et al. (2005) demonstrated, the middle part of the riparian zone expresses the least spatial variations and represents average conditions as long as the riparian-zone vegetation is fairly homogeneous. They also note that boundary condition effects (such as a heavily damped signal of diurnal groundwater level fluctuations near the channel) typically die out within a few meters from the stream.

It is important to note, that the exactness and undisturbed state of the basic groundwater level data set is very important, because differentiation of the groundwater level record may invoke large errors in the resulting ET estimation whenever the original groundwater level measurements are inaccurate. Therefore in most cases it is necessary to smooth data with a low pass filter. But you must care about the width of the filter window and the type of the filter, so not to loose too much information. One of the solutions to get a better data set is to collect as frequent data as possible, and afterward a stronger filter can be used (e.g. if you need hourly *ET* data, you must sample groundwater data at least every ten minutes).

3 RESULTS

We compared diurnal patterns of vegetation transpiration with riparian groundwater levels in our study site (6 km^2 the Hidegvíz Valley watershed in Sopron Hills) in Western Hungary (*Figure 5*). A detailed description of the study catchment characteristics can be found in Gribovszki et al. (2006).

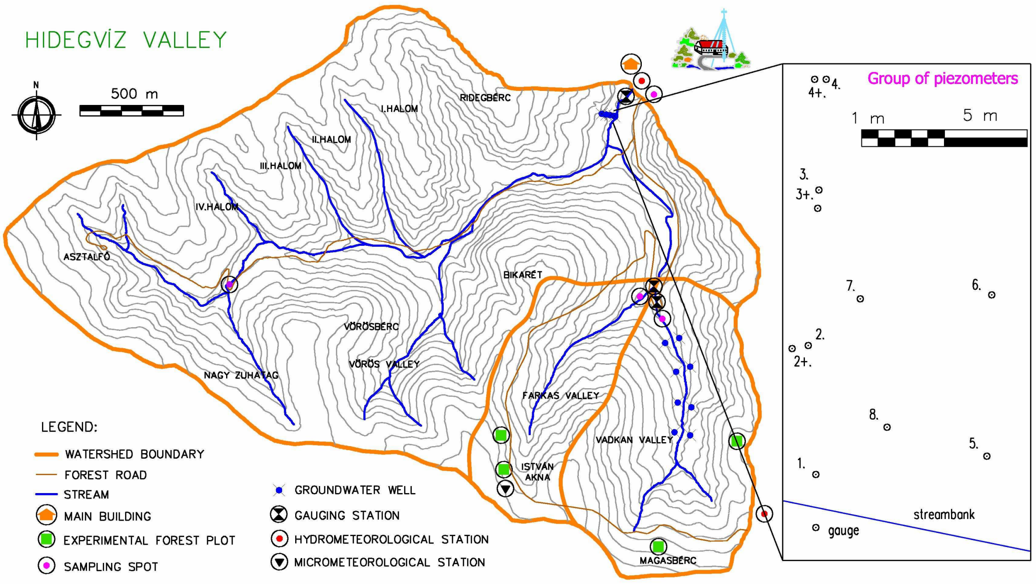

Figure 5. The study catchment and the location of the group of groundwater wells

The geology of the catchment is crystalline bedrock deposited in the tertiary (Miocene) period, and fluvial sediment, which is strongly unclassified. The fluvial sediment was deposited in five layers.

Only the two upper layers appear on the surface. On the hilltop and hill slope a Felstödl Gravel Formation is found. It is 10 – 50 meters thick. This contains coarser gravels and finest loam, and is therefore strongly unclassified. On the valley bottom, the finer material of the Magasbérc Sand Formation appears everywhere. These layers are a good aquifer, so the valleys have a perennial streamflow (Kisházi-Ivancsics 1981-85).

The riparian zone vegetation is an alder [Alnus glutinosa (L.) Gaertn.] dominated forest ecosystem. The mean height of the young to middle aged riparian forest stand is 15 m and the mean diameter of the trees is 13 cm.

The groundwater levels distance form the soil surface changes between 0.6-0.9 m in the riparian zone in dry periods. Therefore the root zone of the trees can reach groundwater levels (or at least the zone of capillarity) every day of the year.

Groundwater levels were measured close to the outlet point of the main study catchment (where a group of wells were bored some years ago) by sensors functioning on the principle of water pressure (*Figure 5*). We used the data of one groundwater well (denoted by 2+ in *Figure 5*), which is situated in the middle of an approximately 20-m wide riparian zone of the west bank of the stream.

The above mentioned parameters of our site, which are necessary for the *ET* calculation can be found in *Table 1*. *H* values come from the computation. The *h* values were measured in the groundwater well of the riparian zone.

Table 1. Parameters for ET calculation

	k (m/s)	S_y	l (m)	L (m)
Used values	$1.8\ 10^{-5}$	0.05	9.4	30
Range	$1.1\ 10^{-6}$ - $2.9\ 10^{-4}$	0.01 - 0.1	-	20 - 110

k saturated hydraulic conductivity, determined from several (16) slug tests (Thyll et al. 1983, Schwartz-Zhang 2003).
S_y, readily available specific yield, computed from $n_0/2$, where n_0 is the drainable porosity (we assumed that in case of shallow groundwater table the drainable porosity and specific yield is nearly the same).
l, the position (distance from the stream) of the riparian zone groundwater well
L, the distance from the stream, where diurnal fluctuation probably has no impact on the water table

Representative rainless periods in the year 2005 have been chosen from hydro-meteorological data sets for analysis. Some micro-meteorological models (Monin-Obukhov, Svedrup, Thornthwaite-Holzmann, Penman-Monteith) were used to calculate the riparian evapotranspiration and results were compared with each other. The Penman-Monteith model (Allen et al., 1998) was the best correlation with evapotranspiration values which were determined from groundwater levels. Therefore it was used in the further analyses. Parameters (which were used for the Penman-Montieth method) were measured some hundred meters from the group of groundwater wells.

Firstly three dry periods (a spring, a summer and an autumn) was chosen for the analysis of the new method. Half hourly *ET* values were computed and these values were compared with the Penman-Monteith *ET* values (*Figure 6*). This comparison showed that the Penman-Monteith *ET* values are similar in daytime but lower at night than empirical and hydraulic diurnal method *ET* values.

A problem can be seen around the time of the maximal change of groundwater levels. *ET* values of the new method go to zero or below zero at this time. This mistake was caused because the calculated Q_{net} rate is not able to follow the strong change of the real recharge rate. The problem is most obvious on hot days and almost negligible in the first part of the recession periods.

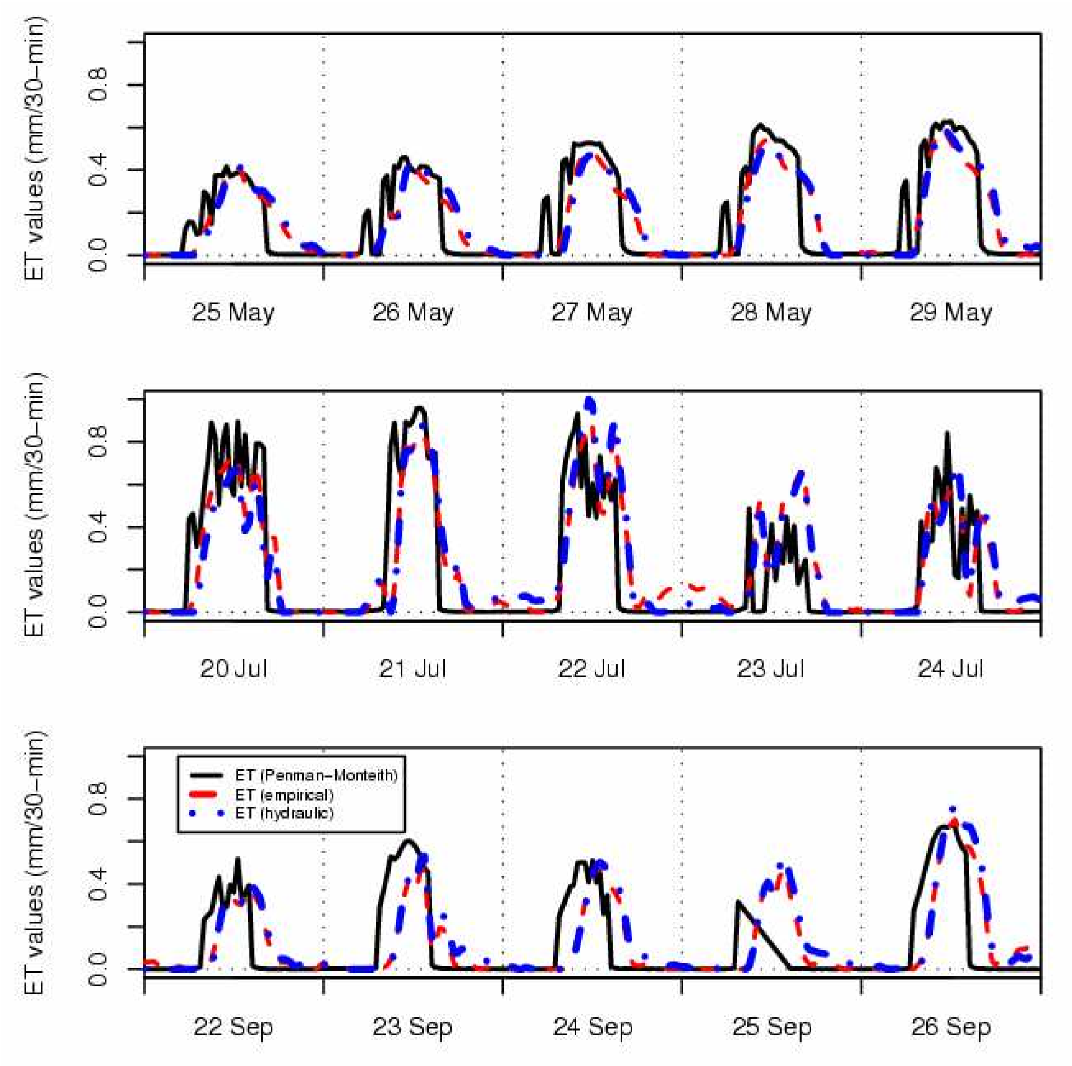

Figure 6. Half hourly ET values for three characteristic periods

The White method was used for calculation of comparable daily *ET* values (Eq. 4). Daily *ET* values of new methods were computed from summing up half hourly *ET* data and compared with the White *ET* values (*Figure 7*). Both empirical and hydraulic diurnal methods give higher daily *ET* values than the White method. These differences come from the basis of the methods. The White method takes a constant recharge rate into consideration for the whole day, and this recharge rate comes from the minimum recharge period (in the late night), when groundwater level differences between the riparian zone and the background is minimal. Empirical and hydraulic methods calculate a periodical changing recharge rate, which is maximal in the afternoon and minimal in the late night or early morning. Therefore they give higher daily *ET* rates (*Figure 6*). Making a comparison between the hydraulic and empirical methods, we found that different methods give different values in different seasons. Generally we can say that mistakes in water table records influence empirical method values more. Therefore the hydraulic method values are more reliable.

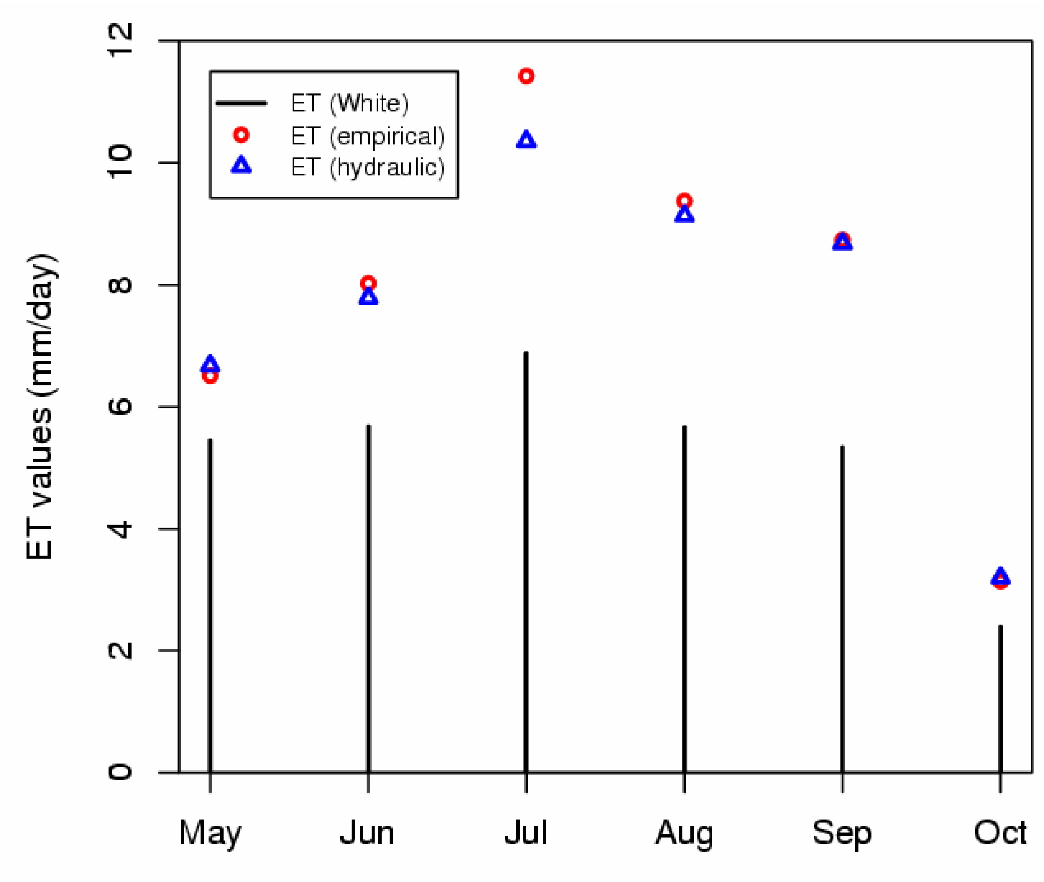

Figure 7. Daily ET values of White, empirical and hydraulic method

Sensitivity analysis (*Table2*) of the above mentioned hydraulic method showed that changing of the hydraulic conductivity (*k*) values has a strong influence on *ET* values. Changing of *L* cause only a slight modification of *ET* values.

Table 2. Sensitivity analysis of the method for k and L (test period 29.08 to 09.09)

	k (m/s)	S_y	*ET* value (mm/day)
k minimum	1.1×10^{-6}	0.01	1.32
k median	1.8×10^{-5}	0.05	8.51
k maximum	2.9×10^{-4}	0.1	55.10
	L (m)		*ET* value (mm/day)
L (side of the riparian zone)	20		9.43
L (proper distance)	40		8.51
L (a magnitude further)	110		7.93

Sy is also changed, because it is strongly related to k.

L (side of the riparian zone) means that distance of *H* from the stream is exactly the same as the width of the riparian zone.

L (proper distance) means the distance, where the riparian diurnal fluctuation has no significant impact on groundwater levels any more.

L (a magnitude further) means that *L* - *l* distance is one magnitude longer than *L* (side of the riparian zone)

4 CONCLUSIONS

The new *ET* estimation method is a modified version of the original White method (1932). This new method is based on the diurnal fluctuation of groundwater and can give daily or more frequent *ET* values. These *ET* values can be estimated from the record (in a rainless period) of one correctly situated groundwater well. Two sub methods were developed (called an empirical and a hydraulic method). For *ET* determination using the hydraulic method we need only high frequent groundwater levels data and a reasonable value of riparian zone saturated hydraulic conductivity. If you had no reasonable value of hydraulic conductivity, you should use the empirical method for *ET* calculation.

The new hydraulic method is sensitive to the exact determination of k (hydraulic conductivity) and S_y (specific yield) values. If we want to use this method for hourly or more frequent *ET* determination, we must note that the method (which comes from the main principle of the assumption) always gives *ET* values around zero at late night.

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