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Review

Diurnal fluctuations in shallow groundwater levels and streamflow rates and their interpretation – A review

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SUMMARY

Diurnal fluctuations of hydrological variables (e.g., shallow groundwater level or streamflow rate) are comparatively rarely investigated in the hydrologic literature although these short-term fluctuations may incorporate useful information for the characterization of hydro-ecological systems. The fluctuations can be induced by several factors like (a) alternating processes of freezing and thawing; (b) early afternoon rainfall events in the tropics; (c) changes in streambed hydraulic conductivity triggered by temperature variations, and; (d) diurnal cycle of water uptake by the vegetation. In temperate climates, one of the most important diurnal fluctuation-inducing factors is the water consumption of vegetation, therefore a detailed overview is provided on the history of such research. Beside a systematic categorization of the relevant historical studies, models that calculate groundwater evapotranspiration from diurnal fluctuations of groundwater level and/or streamflow rate have been reviewed. Compared to traditional evapotranspiration estimation methods these approaches may excel in that they generally employ a small number of parameters and/or variables to measure, are typically simple to use, and yet can yield results even on a short time-scale (i.e., hours). While, e.g., temperature-based methods of evapotranspiration are simple too, they cannot be applied or become inaccurate over shorter time periods. Similarly, traditional approaches (such as eddy-correlation or Bowen-ratio based) are accurate for shorter time steps but they require a number of measurable atmospheric input variables.

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Main characteristics of diurnal fluctuations

Short-term fluctuation of groundwater and streamflow during rainless periods is a phenomenon relatively rarely investigated throughout the world. Below we provide a concise overview of the relevant research literature. In the ensuing discussion special emphasis is put on the analysis of the diurnal cycle of the fluctuation.

Temporal variation of the groundwater levels and streamflow rates typically takes place at two distinct time-scales: long term (interannual and seasonal variability) and short term (e.g., daily or subdaily fluctuations). Seasonal variability is often discussed with regard to the seasonal rhythm of the ecosystems. While a large body of professional papers and textbooks deals with the characteristics of the seasonal change, the short-term fluctuations (e.g., daily) in groundwater levels and baseflow rates are rarely discussed in those same textbooks.

For example Baumgartner and Liebschner (1990) devote only a brief paragraph for short-term fluctuations explaining them by the diurnal change in air temperature. They base their conclusions on measurements from an experimental catchment in the Harz Mountains (Delfs et al., 1958). 'The Principles of Hydrology' textbook (Dyck and Peschke, 1995) [in German] in Pörtge (1996) mentions diurnal streamflow changes in the Werner Brook of Saxony. Hewlett (1984) in his textbook 'The Principles of Forest Hydrology' mentions similar diurnal fluctuations in streamflow that occur during the summer as a result of daily evapotranspiration (ET) along or near the stream channel. Lee (1980) in his book 'Forest Hydrology' discusses the diurnal signature in the groundwater briefly and demonstrates the original White-method White (1932) of estimating riparian ET, but does not analyse the problem in detail. Dingman (2002) examines the diurnal groundwater-level change and introduces the White-method as a simple approach for estimating ET in shallow groundwater areas. Pörtge (1996) explores the topic in several of his studies and investigates the diurnal streamflow change, among other short-term fluctuations, in great detail. In the Hungarian literature Juhász (2002) and Nagy (1965) mention the diurnal cycle of the groundwater. Both refer to the measurements of Ubell (1960) at the Kecskemét experimental station of the Center for Water Resources Research (VITUKI). In the above mentioned two textbooks the diurnal fluctuation of the shallow unconfined groundwater levels, observed during the growing season, is related to similar changes in the soil temperature causing humidity variations in the air of the pores which lead to within soil condensation and evaporation.

A review of recent papers, however, depicts a picture, different from that of the textbooks. Increasingly more articles appear with an aim to quantify certain water balance components by the observed diurnal cycle of groundwater and streamflow. A concise review of these studies is attempted here.

The diel signal, according to Pörtge (1996), can be detected only in small catchments (up to about 40 km^2 of drainage area) during drought/baseflow periods, and can be useful for further analysis if they are in the form of continuous hydrographs. He remarks that the phenomenon is rarely recognisable by a visual inspection of the stream. Lundquist and Cayan (2002) however claim that diurnal changes can be detected in large watersheds as well with a drainage area of several thousands of square-kilometers. Their claim is substantiated by the early works of Troxell (1936) and Meyboom (1965) who described diurnal changes on watersheds much larger than 40 km^2.

Probably the main reason that diurnal fluctuations of groundwater and streamflow drew only limited attention in the earlier scientific literature is that the associated change in the water balance components is insignificant in most cases, at least, from a water management point of view. Another compounding factor probably is that this phenomenon was generally unnoticed by the personnel performing the measurements since typically these diurnal stream-stage fluctuations are hard to recognise by visually inspecting the stream. On non-recording staff gages and on older recording ones with inadequate sensitivity the associated changes may not be perceivable.

With the recent development of high frequency digital data collection devices an increasing number of research opportunities arise because these instruments supply an abundance of detail as well as new information about the characteristics of the diel signal. The information content which can be deduced from the diurnal signal is useful not only for water resources management purposes in terms of quantifying available water resources but also the ensuing permissible rate of water use or for eco-hydrologic and hydrogeologic characterization of the given area or watershed. It may also serve a great supplement to the point-like temperature, precipitation and soil moisture measurements which are typically rarely available for low-order streams and frequently not fully representative of the catchment, especially when the vegetation cover and its biological feedback on mass and energy fluxes are considered.

In most cases solar radiation and air temperature are considered as the main inducing factors for the diel signal in shallow groundwater elevation and streamflow rate. They regulate the soil moisture content as well as the water uptake, transmission and release by the vegetation via the diurnal change in precipitation, potential evaporation, snowmelt, and/or freezing–thawing processes. Certain processes (like snow melting) are directly and quasi promptly detectable in the stream flow, while their significance may be smaller for groundwater and/or they appear with some delay.

Although some water management activities (such as the operation of hydropower stations and/or municipal well fields) may lead to a diurnal cycle in streamflow and/or groundwater elevation, the present paper focuses primarily on the natural causes of the diel signal.

Examining the diurnal cycles

The main categories of the diurnal cycle

Lundquist and Cayan (2002) categorize the types of the diel cycle and the diverse mechanisms which induce these periodicities in shallow groundwater levels and baseflow rates. Let us review the mechanisms in detail.

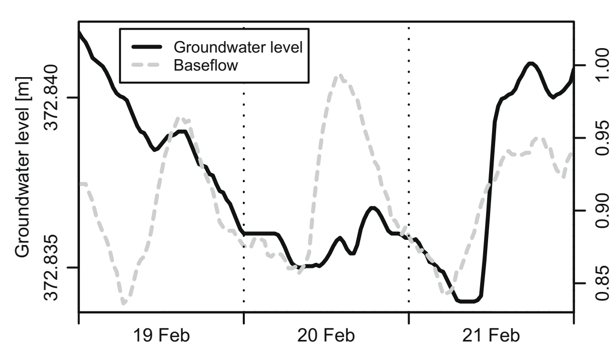

Fig. 1. Freezing–thawing type diel signal in the groundwater level and streamflow time series of the Hidegvíz Valley experimental catchment near Sopron, Hungary, 2007.

Water loss in losing streams

This phenomenon is detectable only in streamflow, and insignificant for groundwater. The viscosity of water and the hydraulic conductivity of the streambed are both temperature dependent thus the groundwater recharge from the losing stream or stream section will be influenced by the temperature change in the streamwater and in the hyporheic zone itself (Lundquist and Cayan, 2002). Typically the largest streamwater loss takes place when the water temperature is the highest. The amplitude of the diurnal change is the most pronounced when: (a) the stream discharge is low and/or the hydraulic radius is small and (b) the streamwater and also the streambed experience big temperature fluctuations (Lundquist and Cayan, 2002) especially in unshaded channels. The diel cycle of streamwater has a similar asymmetric hydrograph shape as that caused by evapotranspiration of the riparian vegetation: with sudden stage decrease in the morning and gradual rising at night.

In forested catchments, with ample shading for the stream, the diurnal fluctuation of the stream temperature is generally so small that earlier mentioned effect is practically undetectable. The temperature-induced density change is in the streamwater that leads also to a stage variation of about 4.8×10^{-4} (mm d^{-1} K^{-1}) during an average day in mid-latitudes (Czikowsky and Fitzjarrald, 2004).

Diurnal cycle caused by precipitation

Under tropical climates the early afternoon rain events can induce flood waves on the streams. These flood waves, influenced by watershed characteristics, will appear as diurnal fluctuation in the hydrograph (Wain, 1994). In temperate climate zones this type of the diurnal cycle in streamflow is largely absent.

Diurnal cycle caused by melting and freezing–thawing processes

Freezing–thawing processes induced diurnal cycle appears on frosty days when the temperature amplitude is around 10 °C and the maximum temperature is above the freezing-point. Groundwater-table elevation and the streamflow rate in this case strongly correlate with the air temperature, with a dawn/morning minimum and an early afternoon maximum. Such a signal (Fig. 1) can be detected normally at the end of winter or the beginning of spring in the Hidegvíz Valley experimental catchment in Hungary (Gribovszki et al., 2006).

Temperature-control is most typical in areas and periods where the melting of snow causes considerable changes in streamflow and shallow groundwater levels. The resulting diel signal is asymmetric with an abrupt increase and a gradual decrease (Lundquist and Cayan, 2002). The explanation of the asymmetry comes from the dynamics of snow melting and the ensuing vertical seepage within the snow layers. The seepage process can be described by Darcy's law since the snow is a porous medium. The seepage velocity of the melted snow water is proportional to the intensity of the melting process thus the more intense early afternoon melting produces a wave that overtakes the weaker, morning one. The resulting combined wave of water emerges as a shock-like sharp front in the snow-water hydrograph on the bottom of the snow layer and also in the hydrograph of the streamflow. Late afternoon melting fluxes and seepage velocities lag behind each other more and more, leading to ever decreasing fluxes detectable as a gradual slope in the falling limb of the hydrograph (Lundquist and Cayan, 2002). According to numerical modelling results the timing of maximum water flux is shifted ever earlier as the snow depth shrinks and snow density increases. The methods suggested by Caine (1992) and Jordan (1983a,b) give an estimate of snow depth and hydraulic conductivity of the snow cover from the shape of the meltwater diel wave and the timing of the peak discharge.

In snow-free areas or periods the alternating processes of freezing and thawing themselves may induce a diurnal rhythm similar to snow melting (Fig. 2). Bouyoucos (1915) has early recorded that the soil moisture in the pores moves from the warmer to the cooler places of the pores as water vapour. This is the well-known thermo-osmosis effect (Kézdy, 1977). In engineering practice it has long been known (Coduto, 1999) that such osmotic effect may become especially strong when the surface freezes, since over ice surfaces the partial pressure of the water vapour is smaller than over liquid ones, leading to a stronger gradient in vapour pressures within the soil pores which strengthens the capillary effect. As a result, water vapour freezes near the surface and enlarges the size of ice lentils there (Kézdy, 1977).

The diel fluctuation induced by freezing and thawing is generally more pronounced in the streamflow hydrograph than in the groundwater levels (Fig. 1). The explanation is that near the channel the groundwater level is close to the surface (across the stream bank) thus more vulnerable to suffer temperature changes (van Eimern, 1950). That is why this type of the diel signal is stronger in shallow groundwater systems (i.e., the water level is closer to the ground surface and thus more exposed to temperature variations). This process has first been described in detail by Pörtge (1979).

The maximum depth the soil may freeze is generally not more than 1–2 m. When the distance to the water table is greater than that the alternating processes of freezing and thawing cannot induce a diurnal rhythm, eventhough the thermo-osmotic effect is active leading to a faster drainage of the aquifer than under non-freezing conditions. As a consequence, such periods should not

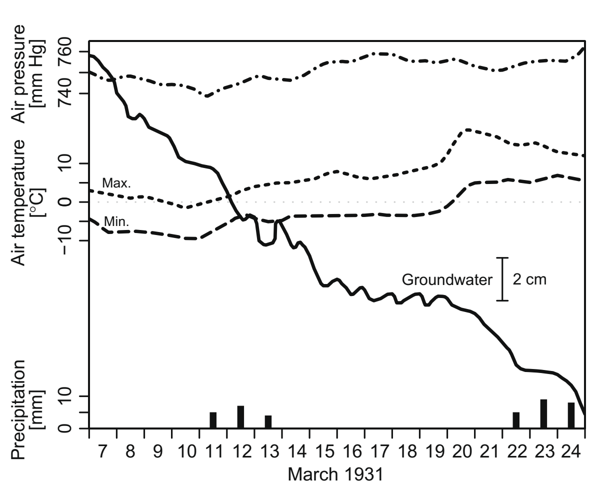

Fig. 2. Occurrence of the freezing–thawing diel signal in the groundwater level in comparison with the air pressure, precipitation and temperature signals for the March 7–24, 1931 period in the neighbourhood of Rheinkamp, Niederrhein (after van Eimern, 1950).

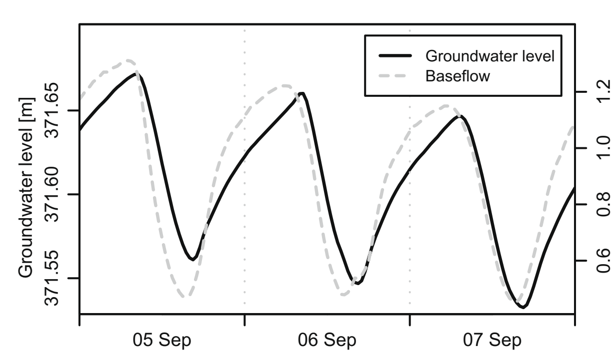

Fig. 3. ET-induced diel signal in groundwater level and streamflow rate, Hidegvíz Valley experimental catchment near Sopron, Hungary, 2005.

be used for classical drought-flow analysis (Brutsaert and Nieber, 1977; Brutsaert and Lopez, 1998; Parlange et al., 2001; Szilágyi et al., 1998) to estimate hydraulic properties (such as the specific yield or the saturated hydraulic conductivity) of the aquifer.

Diurnal cycle induced by evapotranspiration

The ET-induced diel signal is characterized by an early morning maximum and an afternoon minimum in the groundwater level and/or streamflow-rate values (Fig. 3). In this type of the diel signal, a clear relationship can be found 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 link however is not with radiation and relative humidity, but rather with evapotranspiration (in forested areas the latter dominated by transpiration) regulated by the former (and other) variables as the plants try to meet their water demands from the soil moisture or directly form the groundwater via their root systems.

Several authors have investigated the linkage between riparian transpiration and groundwater level and/or streamflow rates (Bond et al., 2002; Boronina et al., 2005; Butler et al., 2007; Croft, 1948; Gribovszki et al., 2006; Kalicz et al., 2005; Lautz, 2008; Loheide et al., 2005; Lundquist and Cayan, 2002; Meyboom, 1965; Pörtge, 1996; Shah et al., 2007; Troxell, 1936; Tschinkel, 1963) but only a few attempted to estimate the ET rate of the riparian zone with their own techniques (Engel et al., 2005; Bauer et al., 2004; Gribovszki et al., 2008; Loheide, 2008; Nachabe et al., 2005; Reigner, 1966; Schilling, 2007; White, 1932) using the observed streamflow, groundwater or soil moisture fluctuations or to provide an analytical description of these signals (Czikowsky, 2003; Czikowsky and Fitzjarrald, 2004).

In the Hidegvíz Valley experimental watershed in Hungary, Gribovszki et al. (2006) observed a fairly large-amplitude diel signal in riparian groundwater level and in streamflow induced by the ET of the riparian forest vegetation in the summer period (Fig. 3). Gribovszki et al. (2008) reported an interesting anomaly in the ET-induced diel signal such as, groundwater-level changes lag behind those of the streamflow rate by about 1–1.5 h (Fig. 3). The observed lag was reproduced by a numerical model (Szilágyi et al., 2008) and identified the cause as the time-varying relative importance of the local (induced by vegetational water uptake) and the regional hydraulic gradients.

Additional causes of diurnal periodicities

Anthropogenic activities can also cause diurnal fluctuations similar to those triggered by natural processes. Bousek (1933) observed a diel signal in groundwater levels in Hungary caused by time-varying rates of groundwater extractions to meet demand changing over the day. Nowadays this effect on groundwater levels and streamflow rates is widespread (e.g., Morgenschweis, 1995). In case of groundwater abstraction the ensuing fluctuation in groundwater level is generally much larger (the magnitude can be meters locally) than the one by natural causes (e.g., the ET of the riparian vegetation, yielding a maximum change of 20 cm in a hot summer day (Gribovszki et al., 2008)). Therefore in any given area natural effects can be masked by artifically-induced ones. In case of streamflow, for example, hydroelectric plants cause a diurnal change in the stage values of the Dráva River, shared by Croatia and Hungary, that may exceed a meter. In such larger river basins (where hydroelectric plants typically operate), however, the diurnal fluctuations of natural causes cannot typically be detected, therefore cannot be compared with man-made ones.

Often, periodicities having a repeat cycle shorter than a day (e.g., 12-h), are related to tidal effects (Senitz, 2001).

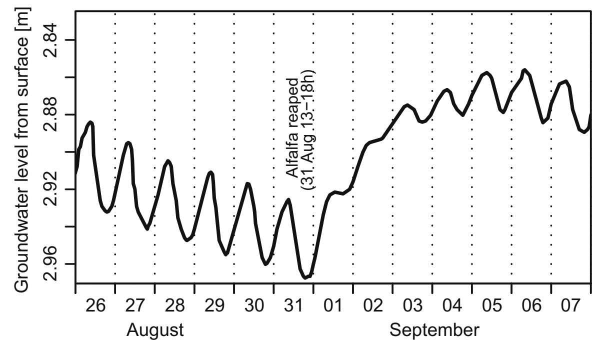

Fig. 4. The effect of vegetation removal on the groundwater level in Escalante Valley, Utah (after White, 1932).

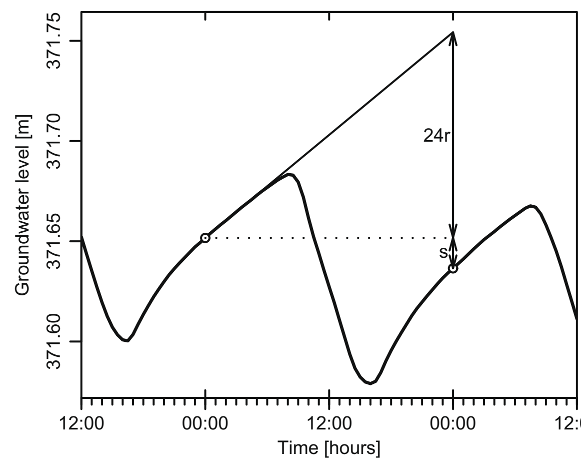

Fig. 5. The basic principle of ET estimation by the White-method.

ET-induced diel signal studies

The diurnal fluctuation of streamflow is generally attributable to similar changes of soil moisture and groundwater levels. Therefore, examinations of the latter (soil moisture, groundwater level, and also lake levels) should accompany the analysis of streamflow changes.

Historical overview

Blaney et al. (1930, 1933) detected an ET-induced diel signal in the stage values of the Santa Ana River in California and found a strong correlation with the diurnal cycle of air temperature and pan evaporation. They concluded that less than 6% of the total daily ET takes place between 8 p.m. and 8 a.m. and that between midnight and dawn the ET intensity is extremely low.

White (1932) observed a diurnal change of several centimeters (a drop during the day and a rebounce during nights) in the groundwater levels of Escalante Valley, Utah. He explained the observed change by evaporation, more specifically by the water uptake of vegetation and the accompanying transpiration. The diurnal signal was absent in areas without vegetation cover and where the depth to the groundwater table was significant. This periodic water table change disappeared with the start of the frost period and reappeared the following spring again. The connection between the diurnal change of the water table and transpiration is often clearly noticeable due to sudden anthropogenic impacts on the vegetation. As Fig. 4 demonstrates, removal of alfalfa resulted in elevated groundwater levels accompanied by a diminished diel signal amplitude.

White (1932) also published a method of estimating riparian ET rates based on fluctuations in the groundwater level. His approach provides the basis of all subsequent ET estimation algorithms that determine ET from the groundwater-level diel signal. The principle of the White-method is explained in Fig. 5.

White (1932) assumed that during the predawn/dawn hours when ET is negligible, the rate of the observed groundwater-level increase is directly proportional to the rate groundwater is supplied to the riparian zone from the neighbouring areas (Fig. 5). The slope, r (LT^{-1}), of the tangential line drawn to the groundwater level curve in these sections (from midnight to 4 a.m.), multiplied by the specific yield value, S_y (–), of the riparian zone, therefore, represents the rate of water supply to a unit area. By extending the tangential line over a 24-h period and taking the so-obtained difference in groundwater levels, one would obtain an estimate of the total water supply to the unit area over a day. The resulting daily rate of water supply must typically be modified by s (L), the difference in the observed groundwater levels over the 24-h period. The daily ET rate this way is obtained as

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

where S_y is the specific yield of the soil/aquifer system.

Troxell (1936) continued the experiments started by Blaney et al. (1930, 1933) along the Santa Ana River. He examined the diel signal of the groundwater levels and streamflow rates together and suggested a modification of the White-method because he realised that the rate of groundwater replenishment due to head differences in space along the day is not a constant, however he could not formulate an exact solution of the problem. His proposed corrections yielded a common starting point for subsequent methods (Gribovszki et al., 2008; Loheide, 2008) explained in more detail later in this study.

Bousek (1933) detected a diurnal rise and fall of the groundwater levels near Fischa-Dagnitz in Austria. The amplitude of the groundwater diel signal was about 5–7 cm, the minimum values in water levels occurring around 10 p.m. Kozeny (1933) quoting several authors, also discusses the diurnal signal in groundwater levels. By his explanation the phenomenon is driven by the diurnal rhythm in air temperature causing an increase in the vapour pressure gradients between the land surface and air.

In the Netherlands, near Wageningen, Thal-Larsen (1934) examined the diurnal change in groundwater levels at two adjacent plots. From the two plots separated only by 60 m, the wooded site expressed a diurnal fluctuation of about 5–11 cm while the neighbouring agricultural site had practically none (Fig. 6).

Wicht (1941, 1942) observed the diel signals of streamflow and groundwater level in the Jonkershoeck catchment in South-Africa. In the same watershed, Rycroft (1955) with his field experiments demonstrated the effect of riparian shrub removal on streamflow gains. Burger (1945) described a streamflow diel signal in Valle de Melera during the dry period of September, 1936.

In the Appalachian Mountains in North Carolina, Dunford and Fletcher (1947) reported diel signal in stream baseflow. They found that a damped diel signal persisted in streamflow even after the total removal of riparian vegetation. Croft (1948) demonstrated the effect of vegetation on the streamflow of Farmington Brook in northern Utah. He estimated riparian ET with the help of the streamflow hydrograph and established a strong correlation between riparian ET and pan evaporation rates along the brook. He found that frost and defoliation have an effect on the streamflow diel signal.

Haise and Kelley (1950) observed a diel signal of the soil moisture in their tensiometer experiments. The amplitude of the diurnal change in soil moisture decreased by depth (Fig. 7).

van Eimern (1950) distinguished a winter- and a summer-type diel signal in groundwater levels based on his measurements in Reinkamp, Niederrhein. He specified the cause of the observed periodicities as changes in evaporation and air pressure as well as the alternating processes of freezing and thawing. Kausch (1957) through his experiments in the botanical garden of Darmstadt College of Technology demonstrated that the inducing factor of the diurnal change in summer groundwater levels was the transpiration of the vegetation and not the air pressure change (Fig. 8).

Delfs et al. (1958) in the early 1950s observed a diurnal rhythm of streamflow in the Harz Mountains. They associated the phenomenon with evaporation from areas having a constantly high soil moisture content. They found the signal stronger in forested catchments thus concluded that transpiration must play a distinguished role. They mentioned no such diurnal signal in spring hydrographs of the catchments. Meyer (1960) detected a diurnal change of groundwater levels in Minnesota and Nebraska. He considered temperature as the main cause, but added that in the summer transpiration was an additive factor. The amplitude of the diel signal, according to his measurements, was larger in summer time than in autumn. In winter the diurnal rhythm was observable with a contrasting daily course.

As we mentioned earlier, Ubell (1960, 1961) observed a diurnal periodicity of the groundwater level in an experimental catchment of VITUKI near Kecskemét, Hungary, and explained it by the changing soil temperature leading to thermo-osmosis. In the Vesser and

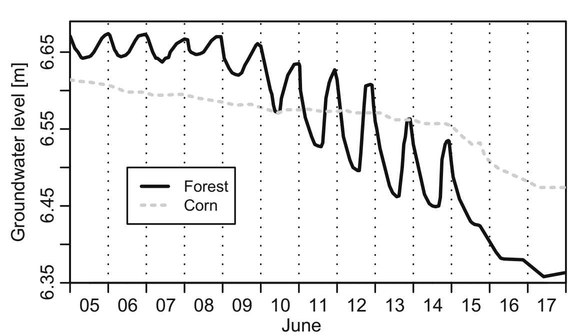

Fig. 6. Different diel signals in two adjacent sites (a forested and an agricultural field) near Wageningen (after Thal-Larsen, 1934).

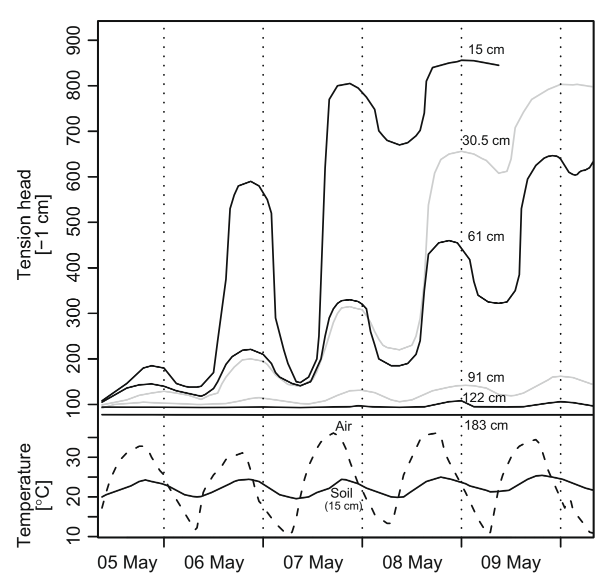

Fig. 7. The diurnal signal in soil moisture by depth, plotted with soil and air temperature near Yuma, Arizona (after Haise and Kelley, 1950).

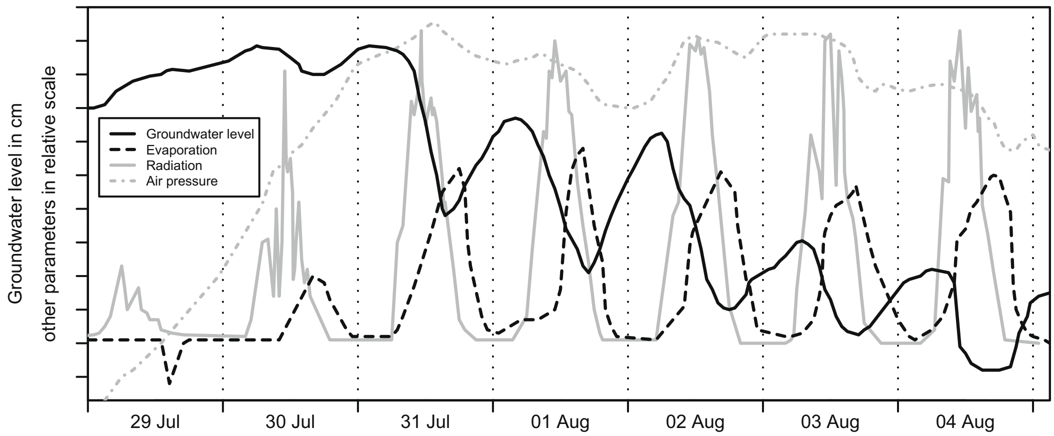

Fig. 8. The diel signal of the groundwater level compared to that of evaporation, radiation and air pressure. Darmstadt botanical garden (after Kausch, 1957).

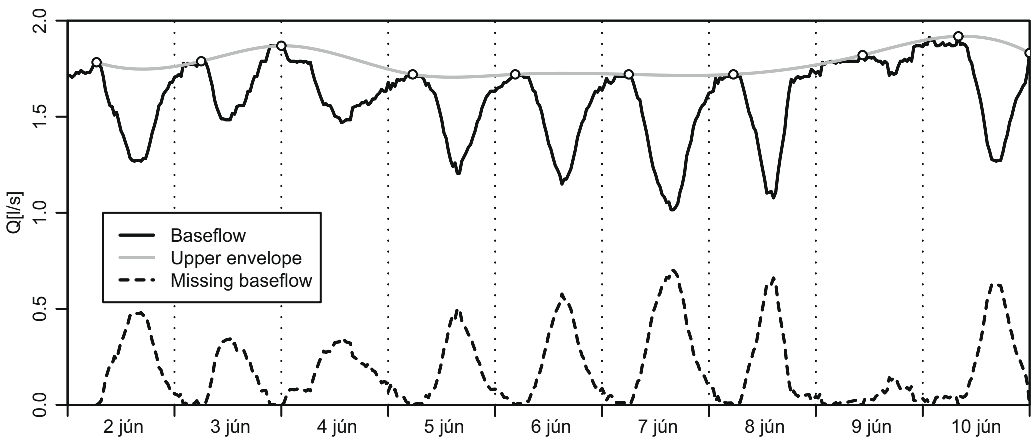

Fig. 9. Riparian ET rate estimation from measured streamflow rates by considering the difference between the maximum possible streamflow, represented by a spline curve (grey), and the actual diurnal hydrograph (after Kalicz et al., 2005).

Zahmer Gera catchments, Heikel (1963) detected a diel signal of the groundwater levels not connected to precipitation events and he explained it by thermo-osmosis. In his subsequent papers Heikel (1964) also detected diurnal periodicities in streamflow and recognized its connection with the transpiration of vegetation.

Tschinkel (1963) in the San Gabriel Mountains in Southern California examined the seasonal and diurnal change of streamflow which he explained by the evaporational and transpirational processes of the watersheds. Through multiple regression between the daily average streamflow rate and daily pan evaporation as explanatory variables, he obtained an explained variance of 0.853 for the observed diurnal fluctuation in streamflow. Based on his analyses, the vapour pressure deficit of the five previous days influence the actual evapotranspiration rate of a given day the most significantly. He formulated an ingenious method for the calculation of riparian evapotranspiration based on the water balances of the saturated zone and the streambed, and also considering the deviation of the actual streamflow recession curve from the potential, so-called master recession curve. He pointed out that the extent of the riparian saturated zone generally shrinks during the course of the growing season, so the calculated water use by vegetation comes from an increasingly smaller area. A decade later Federer (1973) also demonstrated the effect of evapotranspiration on the streamflow recession curves of forested watersheds in the White Mountains of New England.

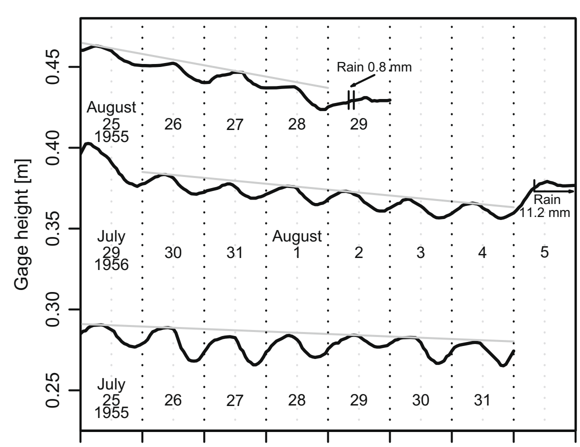

Fig. 10. Streamflow records expressing diurnal fluctuations and the estimated master recession curves. The vertical lines with dates on them designate midday (after Reigner, 1966).

Klinker and Hansen (1964) measured a simultaneous diurnal change in the groundwater levels and streamflow in Elbeniederung near Wittenberg, Germany.

Meyboom (1965), working in Saskatchewan, Canada, formulated a relationship between the diurnal streamflow change and the transpiration rate of the riparian zone, the latter he estimated by the White-method. As a correction to the White-method, he recommended that only 50% of the specific yield (S_y) value is to be applied in Eq. (1) to avoid an overestimation of the actual evapotranspiration rate. He recommends specific yield values of 7.5–11.25 % for silty-clay and sandy-clay soil textures.

Meyboom (1965) calculates the water volume of streamflow used by ET as a difference between the curve connecting the maximum streamflow rates and the actual diurnal hydrograph. Fig. 9 demonstrates the principle of the method. He describes a drastic decrease of river discharge in the summer dry periods when the water uptake of the riparian vegetation exceeds groundwater-flow rates to the riparian zone, causing the originally gaining stream reach to become a losing one.

Reigner (1966) performed his diurnal change investigations in the Dilldown Creek watershed in Pennsylvania. In his construction of a master streamflow recession curve he chose only those local maxima of the streamflow values for which it was true that the relative humidity of the air remained above 95% for a minimum time period of 8 h (Fig. 10). According to him, such periods followed each other with an average frequency of 5 days, in the most ideal case. The water loss of the riparian zone, taken as mainly transpiration of the riparian vegetation, was calculated as the difference between the obtained master recession curve and the actual diurnal hydrograph (Fig. 9). He presented a multivariate nonlinear regression between the water loss (as dependent variable) and the daily mean discharge as well as actual and previous-day weighted vapour pressure deficit (as explanatory variables) values. The obtained relationship explained 76% of the variance. Reigner (1966) also noted that riparian groundwater levels close to the stream (up to 2 m from the streambank) expressed a diurnal rhythm similar to streamflow, while further away (in excess of 10 m) from the streambank such periodical fluctuation in the groundwater levels could not be detected. He found an almost magnitude difference between the evapotranspiration rates estimated from the streamflow hydrograph and the potential evapotranspiration rates calculated from other (using mainly meteorological variables) methods, the latter yielding the larger values. He inferred the reason of the difference being in the improper determination of the lateral extent of the riparian zone. He proposed that this zone may shrink and expand dynamically in extent with changes in the groundwater levels.

Rönsch (1967) examined the meteorological variables (vapour pressure deficit, global radiation) in connection with the diurnal streamflow change in the Selke watershed of the Harz Mountains.

Hylckama (1968), through his measurements in Arizona, established a strong relationship between the diurnal change in groundwater levels and air pressure. Despite of the obtained strong relationship he considered evaporation as the main cause of the diurnal signal in groundwater.

Hegemann (1969) described different types of the change in streamflow over a watershed of the Ruhr region. As two extremes, he found a smooth streamflow recession, while in prolonged rainless periods, an undulating recession with a diurnal period.

Roche (1970) observed a diurnal change in water levels at lake Chad in Africa.

In the Schiefer Mountains, Rhineland, Germany, in precipitation-free periods Weyer (1972) detected streamflow changes simultaneous with that of evaporation.

In the Bonneville region, Utah, Turk (1975) measured the diurnal change in groundwater levels. In the summer, the amplitude of the signal was in the range of 1.5–6 cm, while in winter it remained between 0.5 and 1 cm. According to Turk, the most likely cause of the change is air pressure fluctuations.

Feddes et al. (1976) in Wageningen, the Netherlands, described a diurnal change in the soil moisture content close to the surface.

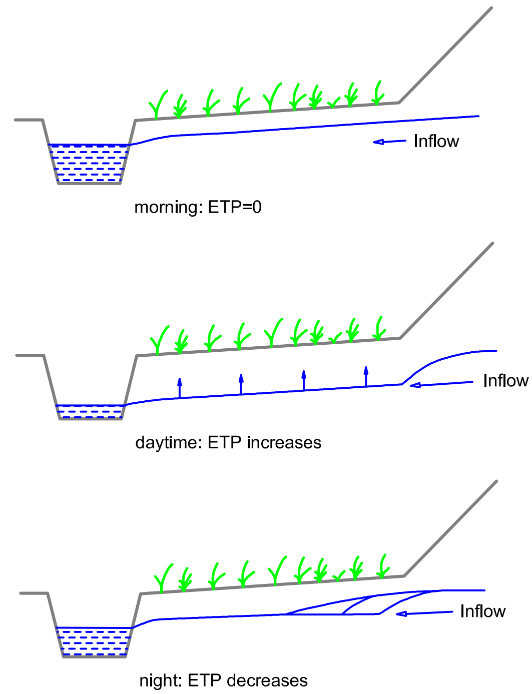

Fig. 11. Response in stream stage under different scenarios of riparian zone evapotranspiration (after Olivry, 1976). ETP: evapotranspiration.

Olivry (1976) detected diurnally changing streamflow rates in the Bamiéké watershed, Cameroon. He suspected the inducing factor to be the subdaily change in evapotranspiration rates (Fig. 11).

Also in the Bamiéké watershed, Callède (1977) researched the diurnal fluctuations of streamflow. He performed a detailed analysis of the vegetation-water-uptake induced diurnal hydraulic-head changes within the unsaturated zone and their impact on the saturated zone. He further provided a good review of the different types of diurnal fluctuations and their causes, and treated the role of dew as well as other climatic and geomorphologic factors that may influence the evaporation-induced diurnal streamflow fluctuations. Callède (1977) noted that the diurnal fluctuations in streamflow can lead to errors in daily mean discharge calculations if the latter are based on only one stage measurement per day.

Luft (1980) observed diurnal changes in streamflow rate and groundwater level in the area near Kaiserstuhl, Germany.

Gerla (1992), in the wetlands of north-east Dakota, determined evapotranspiration rates from the groundwater signal by the White-method. He proposed a novel way of determining the value of the specific yield (S_y), the only parameter in the White-approach. The procedure seeks a relationship between recharge and the subsequent groundwater rise. The relationship may prove useful in shallow groundwater areas for the determination of the S_y value.

Pörtge (1996) measured the diurnal signal of streamflow in the Gross Lengden and Wöllmarshausen experimental catchments in Germany.

Rosenberry and Winter (1997) as well as Lott and Hunt (2001) applied the White-method (similar to Gerla (1992)) in estimating evapotranspiration rates from continental wetlands.

By measuring the water transport in tree trunks using an Electrical Potential Difference (EPD) technique, near Sopron, Hungary, Koppán et al. (2000) found a diurnal fluctuation in xylem-sapflow intensity. The resulting EPD time series parallel the streamflow diel signal (Gribovszki, 2004).

Mentes (2000) reported a diurnal signal of groundwater levels using geophysical measurement techniques in Germany and

Hungary. Major (2002) reported a diurnal periodicity of 4–5 cm in amplitude in the groundwater level (obtained in the 1970s) around an individual mature pine tree at the VITUKI experimatal site near Komlósitelep, Hungary.

Gribovszki (2000) reported diurnal streamflow, water temperature, pH and specific conductivity fluctuations along a low-order stream in the experimental watershed of Hidegvíz Valley (in the Sopron Hills of Hungary) as a result of an expeditionary measurement campaign in the summer of 1999. The streamflow fluctuation was parallelled by fluctuations in specific conductivity and pH (with certain delay in the latter), but the streamflow hydrograph and the temperature had opposing phases. The dominant causes of the observed periodicities in this area were temperature-change induced fluctuations in biological activities such as the indirect effect of photosynthesis of riparian vegetation and the direct effect of decomposition of organic materials in the streambed, mainly in a clear-felled section of the stream. In the same watershed, starting in 2000, automatic data loggers are gathering information of diurnal streamflow changes for subsequent future analysis (Gribovszki and Kalicz, 2001; Gribovszki et al., 2002, 2006).

Goodrich et al. (2000) examined riparian ET along the San Pedro River and described a diurnal cycle in streamflow and riparian zone groundwater levels induced by evapotranspiration of the riparian vegetation. They regarded the simultaneous occurrence of these periodicities in the groundwater table and streamflow as an indirect verification of the existence of a tight connection between the vegetation and the streamflow regime, getting an even stronger evidence that with the appearance of frost (signaling the end of the growing season) the observed periodic behavior disappears from one day to the next.

Hughes et al. (2001) examined evapotranspiration of a temperate salt marsh and mentioned the diurnal fluctuation of the marsh water stage. The observed fluctuations however are strongly influenced by tidal effects, therefore the shape of the signal is not appropriate for the estimation of evapotranspiration rates. Hughes et al. (2001) found the Penman–Monteith approach to be the most reliable method for estimating evapotranspiration from densely vegetated wetlands.

Bond et al. (2002) estimated riparian forest evapotranspiration and the areal extent of the riparian zone from the diurnal change of the streamflow rates. The principle of the calculation was the determination of the missing (due to ET) volume of water from the streamflow. They supposed (similarly to Meyboom (1965) that the morning maximum streamflow rate is only minimally influenced by ET. On the basis of sap flow measurements the actual ET rate of a unit area of the riparian zone could be estimated. The subsequent estimation of the areal extent of the active riparian zone took place as the ratio of the missing streamflow volume (over a given time period, e.g., hour) and the actual ET rate of the riparian zone. They also determined the characteristic phase-shift between the diurnal streamflow signal and the estimated transpiration rates.

Bauer et al. (2004) outlined an ET-estimation method based on the diurnal fluctuation of the groundwater-table elevation. The method was tested with data from the delta region of the Okavango River in Botswana. First a simple conceptual model of the sandy aquifer was constructed with constant boundary conditions (BC) and an impervious bottom. A time-varying step function simulated the impact of the diurnally changing ET rates (i.e., the ET is constant during the day and drops to zero during the night). The resulting equations of the conceptual model are solved analytically. They found that the fixed hydraulic heads as BCs on the edges of the model domain influence the resulting groundwater levels over only about 1% of the total model domain. The unsaturated zone was modeled by a 1D version of the Richards equation. With the help of HYSTFLOW (Stauffer and Kinzelbach, 2001), the problem of soil moisture dynamics was solved numerically using the measured groundwater fluctuations (using pressure transducers in the field) as a lower boundary for the unsaturated zone, and the ET rates were estimated from the calculated storage capacity change in the unsaturated zone.

Boronina et al. (2005) for the Kouris watershed in Cyprus worked out a simplified version of the Meyboom (1965) approach, where the riparian zone ET is estimated from the difference of the master/potential hydrograph and the actual diurnal hydrograph as

$$\mathrm{ET}_{\mathrm{alluv}}^{\mathrm{daily}} = \sum_{i=1}^{24} (Q_{max} - Q_i)\Delta t \tag{2}$$

where $\mathrm{ET}_{\mathrm{alluv}}^{\mathrm{daily}}$ represents the daily amount of water lost from the river due to evapotranspiration, Q_{max} is the daily maximum flow rate in the river (observed between noon and 3 p.m.), Q_i is the averaged flow rate for every hour of the day, Δt is 1 h.

Czikowsky and Fitzjarrald (2004) studied the diel signal in the streamflow hydrographs of small watersheds (drainage area less than 200 km^2) in the eastern USA. The diurnal behavior of the streamflow signal due to ET variations is obtained by an analytical solution of the coupled water balance equations for the aquifer of the riparian zone and the streambed.

Via numerical modeling experiments (using the VS2D software (Lappala et al., 1987)) Loheide et al. (2005) demonstrated that the ET rate given by the White-method is not influenced perceptably by the geometry of the vadose zone. They realized that S_y in the White method is not only a soil-texture specific constant value.

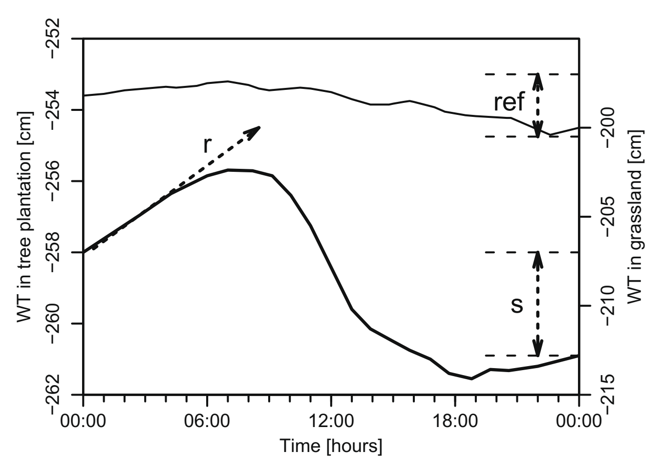

Fig. 12. Graphical representation of the components of diurnal water table (WT) fluctuations in a tree plantation and surrounding grassland over a 24-h period. These terms are combined in Eq. (3) to estimate direct groundwater withdrawals by the tree plantation (after Engel et al., 2005).

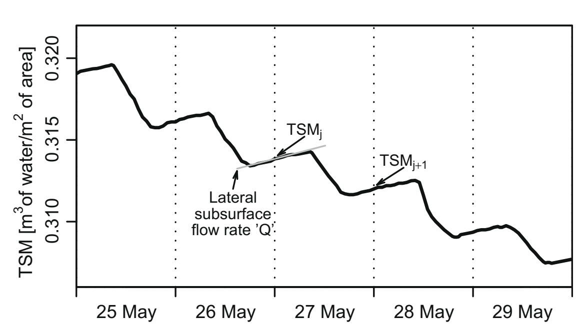

Fig. 13. Total soil moisture (*TSM*) versus time in the groundwater discharge area. The subsurface flux is the positive slope of the line between midnight and 4 a.m. (after Nachabe et al., 2005).

Based on the study of Nachabe (2002), Loheide et al. (2005) suggested certain guidelines and an equation to obtain estimates of the S_y value as a function of sediment texture, depth to the groundwater table and elapsed time of the drainage.

Engel et al. (2005) modified the White-method by introducing an additive constant (*ref*) into Eq. (3). This additive constant represents the regional groundwater-level change not associated with local (e.g., increased water uptake of vegetation) influences (Fig. 12)

$$\mathrm{ET} = S_y(24r \pm s \pm ref) \tag{3}$$

where S_y is the specific yield of the aquifer, r is the rate of increase in groundwater levels (mm/h) from midnight to 4 a.m., s is the net change of groundwater level (mm/day) over a 24 h period and *ref* is in mm/day.

Nosetto et al. (2007) determined the *ref* parameter experimentally as they estimated oak forest ET from diurnal groundwater readings in the Hungarian Great Plains. *ref* was equal to the groundwater elevation change in a neighbouring groundwater well in an area with natural grass cover so that the root system could not significantly tap the groundwater or the capillary fringe.

Nachabe et al. (2005) researched the diurnal rhythm of the soil moisture change in western Florida (Fig. 13). The two sites they examined were a pasture as groundwater recharge and a forest as groundwater discharge area, close to each other. Nachabe et al. (2005) determined the evapotranspiration rates from high-frequency soil moisture profile data employing an adaptation of the White-method for soil moisture measurements as

$$\mathrm{ET} = TSM_j^{0h} - TSM_{j+1}^{0h} + \left(24 \cdot \frac{TSM_j^{4h} - TSM_j^{0h}}{4}\right) \tag{4}$$

where TSM_j^{0h} is the total soil moisture at midnight on day j, TSM_{j+1}^{0h} is the total soil moisture 24 h later (at midnight the following day), and TSM_j^{4h} is the total soil moisture measured at 4 a.m., respectively.

Nachabe et al. (2005) state that the dynamics of the soil moisture and the groundwater are strongly connected in shallow groundwater areas and the diel signal of the soil moisture lags behind that of the groundwater-table elevation by about 2 h.

Shah et al. (2007) examined numerically (with the Hydrus software (Simunek et al., 1998)) the coupled dynamics of the soil moisture and the groundwater in three kinds of surface cover (bare soil, grass, forest) in shallow groundwater environments. They assessed that for a water table within half a meter of the land surface, nearly all ET comes from groundwater due to the close hydraulic connection between the unsaturated and the saturated zones. For deep-rooted vegetation, the decoupling of groundwater and vadose-zone dynamics was found to begin at a water table depths between 30 and 100 cm, depending on the soil texture. The decline of ET with increasing depth to the water table is better simulated by an exponential decay function than the commonly used linear one.

Butler et al. (2007) examined riparian ET and the diel signal in groundwater-table elevations at four different sites in the United States. The signal characteristics were analysed in detail under different soil conditions, vegetation cover and meteorological parameters. They estimated ET with different methods, e.g., application of traditional micrometeorological variables, sap flow measurements and the White-approach with S_y obtained after Loheide et al. (2005). They concluded that the diel signal is appropriate for the calculation of groundwater ET, but not at the individual plant scale, but rather at the scale of the plant community. It was established that the depth to the groundwater and the vertical extent of the root zone jointly influence the shape of the signal. They emphasized that riparian plant water uptake originates only partly from the groundwater. For the identification of the ET source (groundwater or soil moisture) they suggest a combined use of isotopic tracers and the White-method.

Chen (2007) analysed the interconnectedness of streamflow and the riparian zone taking into account the role of riparian vegetation using a finite element modelling environment along the Platte River in Nebraska, USA. He found a strong correlation between the diel signal of the riparian groundwater-table level, induced by vegetation-water-uptake, and streamflow signifying a hydraulic connection between them. He demonstrated that the groundwater streamlines, which would be terminating at the river without the water consumption of riparian vegetation, become attracted to the riparian zone by the hydraulic lift (Caldwell et al., 1998) of the root-system suction and therefore contribute less to the stream.

In their investigations in Iowa, Schilling (2007) and Schilling and Kiniry (2007) found that the diel signal of the groundwater elevation displays a step-like pattern in time. This step-like pattern of groundwater elevations is usually made up of alternating daytime (8 a.m.–8 p.m.) continuous declines followed by nighttime (9 p.m.–7 a.m.) constant or gently sloping segments (Fig. 14). Such a step-like pattern can be detected in groundwater recharge areas generally in the upper part of the watersheds. This kind of pattern is somewhat different from the previously reported signals (daytime decline, nighttime incline) in shallow groundwater environments (Fig. 14). The nighttime incline pattern is induced by groundwater supply to the observed area, therefore can be detected at groundwater discharge areas generally close to the bottom of the valleys. Nighttime recharge by the groundwater is typically weak in areas expressing the continuously declining (although with different slopes) step-like pattern. In such cases the following formula may be well suited for estimating groundwater (gw) evapotranspiration, ET_{gw}, as:

$$\mathrm{ET}_{gw} = \sum (d_i - d_{i-1}) S_y \tag{5}$$

where ET_{gw} (mm/day) is the average daily ET rate for the monitoring period; d_i and d_{i-1} are the observed depths to the groundwater table in hours $i-1$ and i, respectively; and S_y is the specific yield of the soil.

Lautz (2008) analysed vegetation-water-uptake and the diurnal fluctuations in groundwater-table elevations in the riparian zone of Red-Canyon Creek, Wyoming. She mentions air pressure and temperature changes as possible causes of the diurnal rhythm beside water consumption of the vegetation. Subsequently, however, she demonstrates that the former effects are insufficient to induce the observed diurnal magnitude. She corroborated earlier findings

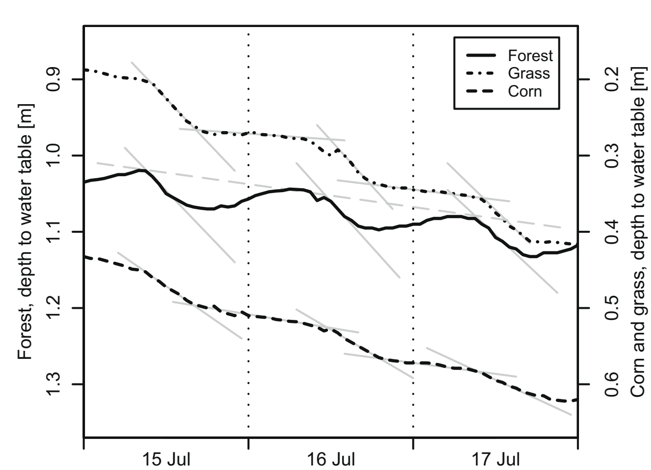

Fig. 14. Depth to the water table in the riparian zone of Walnut Creek (Iowa), July, 2004 (after Schilling, 2007).

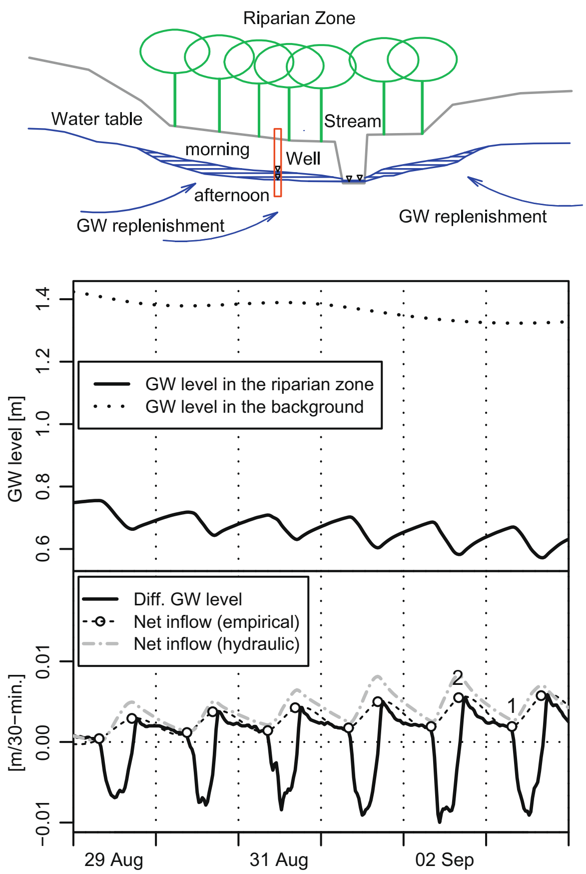

Fig. 15. Demonstration of the upgraded White-method (lower) and a schematic representation of the riparian zone (upper) (after Gribovszki et al., 2008).

that the date of the daily minimum temperature rising above the freezing-point and also falling bellow as the chief influencing factor for the start and end of vegetation activity, is also identifiable in the occurrence and disappearance of the diurnal rhythm of groundwater-table elevations.

Groundwater consumption by the vegetation was estimated by the White-method and compared with potential ET rates calculated by the Priestley–Taylor equation. By comparing data from two neighbouring groundwater wells she found that the White-method is very sensitive for the accurate determination of S_y. She noted however that the specific yield value could be estimated with appropriate accuracy from knowledge of the sediment distribution of the aquifer. She calls the attention to her observation that in semi-arid environments in periods following intensive rainfall events groundwater ET may comprise a growing part of potential ET rates. Her explanation is that the vegetation relies more and more on water from the groundwater instead of on the declining soil moisture with the progress of the dry period.

Gribovszki et al. (2008) upgraded the White-method based on the fundamental assumption of Troxell (1936) that groundwater supply per unit area, Q_{net}, to the riparian zone changes over the day. In the late night/dawn period of the day ET is negligible and the storage change ($\mathrm{d}S/\mathrm{d}t$) per unit area of the riparian zone is equal the net groundwater supply, Q_{net}

$$\frac{\mathrm{d}S}{\mathrm{d}t} = S_y^* \frac{\mathrm{d}h}{\mathrm{d}t} = Q_{\text{net}} \tag{6}$$

where h is the groundwater level in the riparian zone, S_y^* is the readily available specific yield, associated with short time-scales of aquifer drawdown and a shallow water table (Nachabe, 2002).

An empirical and a hydraulic version of the upgraded White-method were developed. In the empirical approach the maximum of Q_{net} for each day was calculated by selecting control points (red circles in Fig. 15) as the largest positive time rate of change values in the groundwater level (h) readings such as $Q_{\text{net}} \approx S_y \mathrm{d}h/\mathrm{d}t$, while the minimum was obtained by calculating the mean of the smallest time rate of change taken in the predawn/dawn hours. The resulting values of the Q_{net} extrema in Fig. 15 then were assigned to those temporal locations where the groundwater level extrema took place. It was followed by a spline interpolation of the Q_{net} values to derive intermediate values between the specified extrema.

The hydraulic version calculates the background (i.e., outside the riparian zone) hydraulic head, H, a distance, l, from the riparian zone by the late night Q_{net} value using Darcy's law and the above simplified water balance equation as

$$H = \frac{S_y^*}{k} \frac{\mathrm{d}h}{\mathrm{d}t} l + h \tag{7}$$

where k is the saturated hydraulic conductivity. To obtain intermediate H values, again a spline interpolation is employed. The subsequent Q_{net} values over the day are then obtained from Darcy's equation ($Q_{\text{net}} = k(H - h)/l$) making use of the interpolated H values.

Finally, for both versions the ET rates, characteristic of the riparian zone, can be obtained as

$$\mathrm{ET}_G = Q_{\text{net}} - S_y^* \frac{\mathrm{d}h}{\mathrm{d}t} \tag{8}$$

The method was tested with hydrometeorological data from growing season of 2005 at the Hidegvíz Valley experimental catchment, located in the Sopron Hills region near the western border of Hungary (Gribovszki et al., 2008). ET estimates by this method are compared with the Penman–Monteith estimates on a half hourly basis and with the White estimates on a daily time-scale. At the start and end of the growing season the ET rates of the proposed method lag behind those of the Penman–Monteith method (Allen et al., 1998) but otherwise the two estimates compare favourably for the day. On a daily basis the newly-derived ET rates are typically 50% higher than the ones obtainable with the original White-method. The empirical version of the method was also tested successfully with groundwater well data in the Nyírség sand area of the Hungarian Great Plains. At that place the ET estimates on the dry summer days of the 2007 growing season compared again favourably with the Penman–Monteith estimates. This result has not yet been published.

Loheide (2008), similar to Gribovszki et al. (2008), modified the original White-method and estimated subdaily evapotranspiration values of the riparian zone. He supposed a linear relationship (valid only for short time periods) between groundwater levels in the riparian zone and those in the background. As a first step, he removed the trend (assuming it linear with a slope m_T and intercept b_T from the groundwater-level time series, $h(t)$, for the chosen day to obtain detrended values, $h_{DT}(t)$,

$$h_{DT}(t) = h(t) - m_T t - b_T \tag{9}$$

With this the detrended hydraulic head, H_{DT}, in the background becomes a constant.

Application of this detrending procedure yields a relationship to predict $\mathrm{d}H_{DT}/\mathrm{d}t$ as a sole function, Γ, of the detrended water table depth, h_{DT}, for the periods between midnight and 6 a.m. when ET_G is close to zero. By this function the net inflow, Q_{net}, rate can be estimated as

$$Q_{\text{net}} = S_y^* [\Gamma(h_{DT}) + m_T] \tag{10}$$

The $\Gamma(h_{DT})$ function is obtained from the detrended late night observations of the actual and of the previous day. It is further surmised that the Γ function is approximately linear and stable over

Table 1
The chronological list of the most important developments in ET-induced diel signal studies.

Author(s) (year of publ.)	Basic information about the development
White (1932)	ET estimation based on groundwater-level diel signal
Troxell (1936)	Suggestions for upgrading the White-method since the rate of groundwater (gw) supply over the day is not a constant
Meyboom (1965)	Riparian ET was calculated as a difference between the maximum baseflow rates curve and the actual diurnal hydrograph. Realized that only about 50% of the specific yield value has to be applied in the White-method
Reigner (1966)	Development of diurnal streamflow-signal-based riparian ET-estimation method
Bauer et al. (2004)	New ET-estimation method based on numerical solution of the soil moisture dynamics using measured gw level fluctuations
Engel et al. (2005)	Upgrading the White-method by introducing an additive constant (represents regional gw level change)
Nachabe et al. (2005)	Adaptation of the White-method for high-frequency soil moisture measurements
Schilling (2007)	ET-estimation method based on an assumed step-like pattern of the gw diurnal signal
Gribovszki et al. (2008)	Subdaily ET estimation by an upgrade of the White method taking into account a diurnally changing gw supply
Loheide (2008)	Regression-based subdaily ET estimation by an upgrade of the White-method

the small range of diurnal water table fluctuations along the day. When Q_{net} is estimated this way, ET_G can be calculated directly from Eq. (8).

The method was validated with synthetic data of a numerical model and with field measurements as well. In the latter case a reference ET by the Penman–Monteith equation (Allen et al., 1998) was employed for the validation.

Summary of the evapotranspiration-induced diel signal research

The characteristic evaporation-induced diel signal in groundwater levels and streamflow rates occur in areas where: (a) the typically shallow groundwater becomes influenced by evapotranspiration and (b) replenishment of the depleted groundwater storage during low ET periods is possible through a local hydraulic gradient in the saturated zone. The latter is typical in groundwater discharge zones and in areas where a considerable upward hydraulic gradient exists. In groundwater recharge areas, with no sufficient replenishment mechanisms, the ET-induced signal may take up a step-like pattern and noticeable mostly in the soil moisture values, and only rarely in the groundwater levels of the shallow groundwater system.

A chronological list of the most important developments in ET-induced diel signal studies, where a new method was developed or an earlier method was significantly modified, is constructed in Table 1. The White-method (White, 1932) provides a common approach of evapotranspiration estimation when relying on the diurnal fluctuations of groundwater levels and, less frequently, of soil moisture values. The White-method, however modified many times, especially in the last decade (Table 1), can be readily employed in preliminary riparian zone studies due to its simplicity. With streamflow data, the differences between the curves that connect the daily maxima and the actual streamflow rates serve as the basis for riparian ET estimation. Between these two basic ET-estimation methods, as mentioned by several authors, a magnitude difference may exist. Presumably the White-method, relying on the groundwater signal, is more accurate because the so-derived ET rates compare favourably with traditional ET-estimation (Penman–Monteith or Bowen-ratio based) methods. It is felt that the information content residing in the diurnal cycle of the hydrological variables is still not explored to its full potential, therefore further research is highly recommended.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration – Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage, vol. 56. FAO, Rome. <http://www.fao.org/docrep/X0490E/x0490e06.htm>.

Bauer, P., Thabeng, G., Stauffer, F., Kinzelbach, W., 2004. Estimation of the evapotranspiration rate from diurnal groundwater level fluctuations in the Okavango Delta, Botswana. Journal of Hydrology 288 (3–4), 344–355.

Baumgartner, A., Liebschner, H.-J., 1990. Allgemeine Hydrologie Quantitative Hydrologie. Gebrüder Borntraeger.

Blaney, H.F., Taylor, C.A., Young, A.A., 1930. Rainfall penetration and consumptive use of water in the Santa Ana River Valley and Coastal Plain. California Department of Public Works, Division of Water Resorces, Bulletin 33, 162pp.

Blaney, H.F., Taylor, C.A., Young, A.A., Nickle, H.G., 1933. Water losses under natural conditions from wet areas in southern Cailfornia. California Department of Public Works, Division of Water Resorces, Bulletin 44 (1), 139pp.

Bond, B.J., Jones, J.A., Moore, G., Phillips, N., Post, D., McDonnell, J.J., 2002. The zone of vegetation influence on baseflow revealed by diel patterns of streamflow and vegetation water use in a headwater basin. Hydrological Processes 16, 1671–1677.

Boronina, A., Golubev, S., Balderer, W.S., 2005. Estimation of actual evapotranspiration from an alluvial aquifer of the Kouris catchment (Cyprus) using continuous streamflow records. Hydrological Processes 19, 4055–4068.

Bousek, R., 1933. Das tägliche periodische Steigen und Fallen des Grundwasserspiegels. Die Wasserwirtschaft 31, 427–429.

Bouyoucos, G.J., 1915. Effect of temperature on movement of water vapor and capillary moisture in soils. Journal of Agricultural Research 5, 141–172.

Brutsaert, W., Lopez, J.P., 1998. Basin-scale geohydrologic drought flow features of riparian aquifers in the southern Great Plains. Water Resources Research 34 (2), 233–240.

Brutsaert, W., Nieber, J.L., 1977. Regionalized drought flow hydrographs from a mature glaciated plateau. Water Resources Research 13 (3), 637–643.

Burger, H., 1945. Einfluss des Waldes auf den Stand der Sewasser. Tech. rep., IV. Mittlg. Der Wasserhaushalt im Valle di Melera von 1934/35 bis 1943/44 – Mitt. d. Schweiz. Anstalt f. forstl. Versuchsw., 25 Bd. 1.

Butler Jr., J.J., Kluitenberg, G.J., Whittemore, D.O., Loheide II., S.P., Jin, W., Billinger, M.A., Zhan, X., 2007. A field investigation of preatophyte-induced fluctuations in the water table. Water Resources Research 43. doi:10.1029/2005WR004627.

Caine, N., 1992. Modulation of the diurnal streamflow response by the seasonal snowcover of an alpine basin. Journal of Hydrology 137 (1–4), 245–260.

Caldwell, M., Dawson, T., Richards, J., 1998. Hydraulic lift consequenses of water efflux from the roots of plants. Oecologica 113, 151–161.

Callède, J., 1977. Oscillations journalières du débit des rivières en l'absence de précipitations. Cahiers de l'OSTROM, Série Hydrologie 14 (3), 219–283.

Chen, X., 2007. Hydrologic connections of a stream-aquifer-vegetation zone in south-central Platte River valley, Nebraska. Journal of Hydrology 333 (2–4), 554–568.

Coduto, D.P., 1999. Geotechnical Engineering: Principles and Practices. Prentice Hall.

Croft, A.R., 1948. Water loss by stream surface evaporation and transpiration by riparian vegetation. Transactions, American Geophysical Union 29 (2), 235–239.

Czikowsky, J.M., 2003. Seasonal and Successional Effects on Evapotranspiration and Streamflow. Master's Thesis, Department of Earth and Atmospheric Sciences, The University at Albany, State University of New York.

Czikowsky, J.M., Fitzjarrald, D.R., 2004. Evidence of seasonal changes in evapotranspiration in Eastern U.S. hydrological records. Journal of Hydrometeorology 5, 974–988.

Delfs, J., Friedrich, W., Kiesekamp, H., Wagenhoff, A., 1958. Der Einfluß des Waldes und des kahlschlages auf den Abflußvorgang, den Wasserhaushalt und den Bodenabtrag. Mitt. A. d. Nieders. Landes-forstverwaltung, Aus dem Walde 3, 223.

Dingman, S.L., 2002. Physical Hydrology. Prentice Hall.

Dunford, A.R., Fletcher, P.W., 1947. Effect of removal of streambank vegetation upon water yield. Transactions, American Geophysical Union 28, 105–110.

Dyck, S., Peschke, G., 1995. Grundlagen der Hydrologie, third ed. Verlag für Bauwesen.

Engel, V., Jobbágy, E.G., Stieglitz, M., Williams, M., Jackson, R.B., 2005. The hydrological consequences of Eucalyptus afforestation in the Argentine Pampas. Water Resources Research 41. W10409. <http://dx.doi.org/10.1029/2004WR003761>.

Feddes, R.A., Kowalik, P., Kolinska-Malinka, K., Zaradny, H., 1976. Simulation of field water uptake by plants using soil water dependent root extraction function. Journal of Hydrology 31 (1–2), 13–26.

Federer, C.A., 1973. Forest transpiration greatly speeds streamflow recession. Water Resources Research 9 (6), 1599–1604.

Gerla, P.J., 1992. The relationship of water table changes to the capillary fringe, evapotranspiration and precipitation in intermittent wetlands. Wetlands 12 (2), 91–98.

Goodrich, D.C., Scott, R., Qi, J., Goff, B., Unkrich, C.L., Moran, M.S., Williams, D., Schaeffer, S., Snyder, K., MacNish, R., Maddock, T., Poole, D., Chehbounif, A., Cooperg, D.I., Eichingerh, W.E., Shuttleworth, W.J., Kerri, Y., Marsetta, R., Ni, W., 2000. Seasonal estimates of riparian evapotranspiration using remote and in situ measurements. Agricultural and Forest Meteorology 105 (1–3), 281–309.

Gribovszki, Z., 2000. Erdei patakok vízminőségi jellemzőinek napi ritmusa nyári időszakban (Diurnal summer cycle of stream water quality parameters in forested catchments). In: Az Erdőmérnöki Kar Tudományos Konferenciájának előadásai. NYME Erdőmérnöki Kar, Sopron, pp. 59–66 (in Hungarian).

Gribovszki, Z., 2004. Evapotranszspiráció hatása a lefolyás napi ritmusára erdészeti kisvízgyjtőkön (Evapotranspiration impact on the streamflow diurnal fluctuation in a forested catchment). In: Mátyás, C., Vig, P. (Eds.), Erdő és Klíma, vol. 4. NYME, Sopron, pp. 171–183 (in Hungarian).

Gribovszki, Z., Kalicz, P., 2001. Erdei patakok alapvízhozamának elemzése idősor analízissel (a Soproni-hegységben eredő farkas-ároki patak példáján) (Time series analysis of stream baseflow in forested land). Alkalmazott matematika és mechanika tudományos konferencia kiadványa, Sopron, 2001, November 23, pp. 30–32 (in Hungarian).

Gribovszki, Z., Kalicz, P., Kucsara, M., 2002. Erdősült felső vízgyjtők vízhozamának napi változása (Diurnal change of stream discharge in forested upper watershed). In: GEO 2002 – Magyar Földtudományi Szakemberek VI Világtalálkozója kiadványa (in Hungarian).

Gribovszki, Z., Kalicz, P., Kucsara, M., 2006. Streamflow characteristics of two forested catchments in Sopron Hills. Acta Silvatica et Lignaria Hungarica 2, 81–92. <http://aslh.nyme.hu/>.

Gribovszki, Z., Kalicz, P., Szilágyi, J., Kucsara, M., 2008. Riparian zone evapotranspiration estimation from diurnal groundwater level fluctuations. Journal of Hydrology 349 (1–2), 6–17.

Haise, H.R., Kelley, O.J., 1950. Causes of diurnal fluctuations of tensiometers. Soil Science 70, 301–313.

Hegemann, H., 1969. Tagesabfluschwankungen in niederschlagsfreien Perioden. In: Kirkwald, E. (Ed.), Wasserhaushalt und Einzugsgebiet – Gewässerkundliche Untersuchungen im Einzugsgebiet der Ruhr in den Jahren 1951–1965, vol. 1. Vulkan, Essen, pp. 338–344.

Heikel, W., 1963. Grundwasservorkommen in der talböden kristalliner mittelgebirge, dargestellt am beispiel der Vesser und Zahmen Gera im mittleren Thüringer Wald. Wissenschaftliche Z. der Friedrich-Schiller-Universitat Jena 12, 341–353.

Heikel, W., 1964. Zur charakteristik des aflussverhaltens in der thüringer waldflussgebieten des vesser und zahmen gera. Archiv für Naturschutz 4, 51–82.

Hewlett, J.D., 1984. Principles of Forest Hydrology. University of Georgia Press.

Hughes, C.E., Kalma, J.D., Binning, P., Willgoose, G.R., Vertzonis, M., 2001. Estimating evapotranspiration for a temperate salt marsh, Newcastle, Australia. Hydrological Processes 15, 957–975. doi:10.1002/hyp.189.

Hylckama, T.E.A.V., 1968. Water level fluctuations in evapotranspirometers. Water Resources Research 4, 761–768.

Jordan, P., 1983a. Meltwater movement in a deep snowpack 1. Field observations. Water Resources Research 19 (4), 971–978. <http://dx.doi.org/10.1029/WR019i004p00971>.

Jordan, P., 1983b. Meltwater movement in a deep snowpack 2. Simulation model. Water Resources Research 19 (4), 979–985. <http://dx.doi.org/10.1029/WR019i004p00979>.

Juhász, J., 2002. Hidrogeológia (Hydrogeology). Akadémiai kiadó (in Hungarian).

Kalicz, P., Gribovszki, Z., Kucsara, M., Vig, P., 2005. A vegetáció hatása egy kisvízgyjtő patakjának alapvízhozam mintázatára (Vegetation influence on base flow characteristics of upper watersheds' streams). Hidrológiai Közlöny 85 (6), 50–52 (in Hungarian).

Kausch, W., 1957. Die transpiration als ursache für tägliche grundwasserschwankungen. Berichte der Deutschen Botanischen Gesellschaft 70, 436–444.

Kézdy, Á., 1977. Talajmechanika (Soil Mechanics). Tankönyvkiadó.

Klinker, L., Hansen, H., 1964. Bemerkungen zur tagesperiodischen variationen des grundwasserhorizontes und des wasserstandes in kleinen wasserlaufen. Zeitschrift für Meteorologie 17, 240–245.

Koppán, A., Wesztergom, V., Szarka, L., 2000. Annual fluctuation in amplitudes of daily variations of electrical signals measured in the trunk of a standing tree. Life Sciences 323, 559–563.

Kozeny, J., 1933. Das tägliche periodische steigen und fallen des grundwasserspiegels. Die Wasserwirtschaft 31, 424–427.

Lappala, E.G., Healy, R., Weeks, E.P., 1987. Documentation of Computer Program VS2D to Solve the Equations of Fluid Flow in Variably Saturated Porous Media. Water-Resources Investigations Report 83-4099, US Geological Survey, Denver, Colorado.

Lautz, L.K., 2008. Estimating groundwater evapotranspiration rates using diurnal water-table fluctuations in semi-arid riparian zone. Hydrogeology Journal 16, 483–497.

Lee, R., 1980. Forest Hydrology. Columbia University Press.

Loheide II., S.P., 2008. A method for estimating subdaily evapotranspiration of shallow groundwater using diurnal water table fluctuations. Ecohydrology 1, 59–66. doi:10.1002/eco.7.

Loheide II., S.P., Butler Jr., J.J., Gorelick, S.M., 2005. Use of diurnal water table fluctuations to estimate groundwater consumption by phreatophytes: a saturated-unsaturated flow assessment. Water Resources Research 41. doi:10.1029/2005WR003942.

Lott, R.B., Hunt, R.J., 2001. Estimating evapotranspiration in natural and constructed wetlands. Wetlands 21 (4), 614–628.

Luft, G., 1980. Abfluß und retention im löß, dargestellt am beispiel des hydrologischen versuchsgebietes Ripach, Ostkaiserstuhl, beiträge zur Hydrologie, Sonderherft 1.

Lundquist, J.D., Cayan, D.R., 2002. Seasonal and spatial patterns in diurnal cycles in streamflow in the western United States. Journal of Hydrometeorology 3 (October), 591–1603.

Major, P., 2002. Síkvidéki erdők hatása a vízháztartásra (Impact of lowland forests on the land water budget). Az erdőgazdálkodás és a vízgazdálkodás kapcsolatáról c. szakmai konferencia, Budapest 2002. május 23 (in Hungarian).

Mentes, Gy., 2000. Sekély mélységfúrólyuk-dőlésmérők alkalmazási lehetőségei lokális geodinamikai jelenségek monitorozására. Geomatikai közlemények 3, 139–147 (in Hungarian).

Meyboom, P., 1965. Three observations on streamflow depletion by phreatophytes. Journal of Hydrology 2 (3), 248–261.

Meyer, A.F., 1960. Effect of temperature on ground-water levels. Journal of Geophysical Research 65, 1747–1752.

Morgenschweis, G., 1995. Kurzzeitige vorhersage der wasserentnahme aus einem flussgebiet. Vortragsmanusskript zur 8. Wiss. Tagung Hydrologie und wasserwirtschaft zum Thema Verfügbarkeit von Wasser vom 22./23. Marz 1995 in Bochum, 16 Seite.

Nachabe, M., Shah, N., Ross, M., Womacka, J., 2005. Evapotranspiration of two vegetation covers in a shallow water table environment. Soil Science Society of America Journal 69, 492–499.

Nachabe, M.H., 2002. Analytical expressions for transient specific yield and shallow water table drainage. Water Resources Research 38 (10), 1193.

Nagy, V.I., 1965. Hidrológia (Hydrology). Tankönyvkiadó.

Nosetto, M.D., Jobbágy, E.G., Toth, T., Bella, C.M.D., 2007. The effects of tree establishment on water and salt dynamics in naturally salt-affected grasslands. Oecologia 152, 695–705. doi:10.1007/s00442-007-0694-2.

Olivry, J.C., 1976. Régimes hydrologiques en pays Bamiléké. Cahiers de l'OSTROM, Série Hydrologie 13 (1), 37–71.

Parlange, J.-Y., Stagnitti, F., Heilig, A., Szilágyi, J., Parlange, M.B., Steenhuis, T.S., Hogarth, W.L., Barry, D.A., Li, L., 2001. Sudden drawdown and drainage of a horizontal aquifer. Water Resources Research 37 (8), 2097–2101. <http://dx.doi.org/10.1029/2000WR000189>.

Pörtge, K.-H., 1979. Oberflächenabfluss und aquatischer materialtransport in zwei kleinen eizzugsgebietenstlich Göttingen (Sdniedersachsen). Dissertation zur erlangung des doktorgrades, Georg-August-Universität zu Göttingen, Göttingen.

Pörtge, K.-H., 1996. Tagesperiodische Schwankungen des Abflusses in kleinen Einzugsgebieten als Ausdruck komplexer Wasser- und Stoffflüsse. Verlag Erich Goltze GmbH KG.

Reigner, I.C., 1966. A method for estimating streamflow loss by evapotranspiration from the riparian zone. Forest Science 12 (2), 130–139.

Roche, M.A., 1970. Hydrogéologie des côtes du la Tchàd a No, Tchingam et Soro (Kanem). Cahiers de l'OSTROM, Série Hydrologie 7 (3), 89–111.

Rönsch, H., 1967. Tagesgänge in abfluss und deren metorologische ursachen. Zeitschrift für Meteorologie 20, 364–371.

Rosenberry, D.O., Winter, T.C., 1997. Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlands in North Dakota. Journal of Hydrology 191 (1–4), 226–289.

Rycroft, H.B., 1955. The effect of riparian vegetation on water-loss from an irrigation furrow at Jonkershoek. Journal of the South African Forestry Association 26, 2–9.

Schilling, K.E., 2007. Water table fluctuations under three riparian land covers, Iowa (USA). Hydrological Processes 21, 2415–2424. doi:10.1002/hyp6393.

Schilling, K.E., Kiniry, J.R., 2007. Estimation of evapotranspiration by reed canarygrass using field observations and model simulations. Journal of Hydrology 337 (3–4), 356–363.

Senitz, S., 2001. Untersuchung und Anwendung kurzperiodischer Schwankungen des Grundwasserspiegels in Thüringen. Grundwasser 4, 163–173.

Shah, N., Nachabe, M., Ross, M., 2007. Extinction depth and evapotranspiration from ground water under selected land covers. Ground Water 45 (3), 329–338.

Simunek, J., Sejna, M., van Genuchten, M.T., 1998. The HYDRUS 1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and Multiple Solutes in Variably-Saturated Media. US Salinity Laboratory, ARS/USDA, Riverside, California, Version 2.0. Edition.

Stauffer, F., Kinzelbach, W., 2001. Cyclic hysteretic flow in porous medium column: model, experiment, and simulations. Journal of Hydrology 240 (3–4), 264–275.

Szilágyi, J., Gribovszki, Z., Kalicz, P., Kucsara, M., 2008. On diurnal riparian zone groundwater-level and streamflow fluctuations. Journal of Hydrology 349 (1–2), 1–5.

Szilágyi, J., Parlange, M.B., Albertson, J.D., 1998. Recession flow analysis for aquifer parameter determination. Water Resources Research 34 (7), 1851–1857. <http://dx.doi.org/10.1029/98WR01009>.

Thal-Larsen, J.H., 1934. Fluctuations in the level of the phreatic surface with an atmospheric deposit in the form of dew. Bodenkundliche Forschung 4, 223–233.

Troxell, H.C., 1936. The diurnal fluctuation in the ground-water and flow of the Santa Anna River and its meaning. Transactions, American Geophysical Union 17 (4), 496–504.

Tschinkel, H.M., 1963. Short-term fluctuation in streamflow as related to evaporation and transpiration. Journal of Geophysical Research 68 (24), 6459–6469.

Turk, L.J., 1975. Diurnal fluctuation of water tables induced by atmospheric pressure changes. Journal of Hydrology 26 (1–2), 1–16.

Ubell, K., 1960. A talajvízállás előrejelzése. Technical Report, VITUKI (in Hungarian).

Ubell, K., 1961. Über die gesetzmassigkeiten des grundwassergangs and des grundwasserhaushalts in flachlandgebieten. Wasserwirtschaft und Wassertechnik 11, 366–372.

van Eimern, J., 1950. Beobachtungen und Bemerkungen zur Wasserbewegung im Boden und zur Frosthebung des Bodens. Zeitschrift für Acker- und Pflanzenbau 108, 375–383.

Wain, A.S., 1994. Diurnal river flow variations and development planning in the tropics. The Geographical Journal 160 (3), 295–306.

Weyer, K. U., 1972. Ermittlung der Grundwassermengen in den Festgesteinen der Mittelgebirge aus Messungen des Trockenwetterabflusses. Dissertation, Rheinischen-Friedrich-Wilhelms Universität, Bonn.

White, W.N., 1932. Method of Estimating Groundwater Supplies Based on Discharge by Plants and Evaporation from Soil – Results of Investigation in Escalante Valley. Tech. Rep., Utah – US Geological Survey. Water Supply Paper 659-A.

Wicht, C.L., 1941. Diurnal fluctuation in Jonkershoeckstreams due to evaporation and transpiration. Journal of the South African Forestry Association 7, 34–49.

Wicht, C.L., 1942. Depletion of ground water flow in Jonkershoeck streams. J.S. African For. Ass. 8, 50–63.