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# Estimating evapotranspiration using field measurements

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**Резюме**. Статията разглежда използването на полеви данни при моделиране на движението на водния поток с компютърния код HYDRUS-1D, като се отчита поглъщането на вода от кореновата система на растенията. Данните се отнасят за поле със соя в експерименталната ферма на Префектурният университет на гр. Мие (период от август до ноември 2014). Съдържанието на влага е измервано на три дълбочини (8, 18, 48 cm) посредством хоризонтално монтирани TDR датчици. Допълнително, средното съдържание на влага за интервала на дълбочина 0-30 cm е измервано с вертикално монтиран TDR датчик. Потенциалната евапотранспирация е изчислена въз основа на метеорологични данни по метода на Penman-Monteith. Действителната евапотранспирация е оценена с използване на метода на водният баланс, като се пренебрегва формирането на оттока поради значително по-ниска проницаемост на отложенията под коренообитаемия слой.

Както показа Šimůnek (2015), при моделиране с отчитане на поглъщането на вода от корените е важно да се раздели потенциалната евапотранспирация на транспирация и физическо изпарение. За да се предотврати изпарението от повърхността на почвата, бе използвано мулчиране на почвата с пластмасово покритие през периода от 11.09 – 16.10.2014 г. Затова през периода на мулчиране бе прието, че действителната евапотранспирация е равна на действителната транспирация.

Евапотранспирацията играе важна роля във водния и енергиен баланс на ненаситена зона. Поради факта, че този процес се осъществява през континуум/система включващ почва, растения и атмосфера, необходимо е да се изяснят процесите във всяка подсистема.

**Ключови думи**: поток в ненаситена среда, евапотранспирация, полеви експеримент, моделиране, HYDRUS-1D

**Abstract**. The paper demonstrates using of field measurements for water flow simulation with root water uptake by the numerical model HYDRUS-1D. A field monitoring experiment was conducted at a soybean field in the Mie University experimental farm since August to November 2014. Volumetric water content was measured at three depths (8, 18, 48 cm) by horizontally installed TDR probes, and the averaged water contents for 0 - 30 cm depth was measured with a vertically installed TDR probe. Potential evapotranspiration is calculated using meteorological dataset based on the Penman-Monteith approach. The actual evapotranspiration is assessed by the water balance

for the surface soil layer. The drainage below the soil zone was assumed as negligibly low since the hydraulic conductivity for the subsoil was significantly lower than that for the surface soil.

As Šimůnek (2015) showed, it is necessary to divide potential evapotranspiration into transpiration and evaporation from the soil surface to simulate unsaturated water flow in a soil with a plant water uptake model. To prevent evaporation, the soil surface was covered by plastic mulch in the period 11.09 – 16.10.2014. During the mulching period, the actual evapotranspiration was regarded as the actual transpiration rate, since the soil surface evaporation was assumed to be negligible.

Evapotranspiration plays an important role in the water and energy balance of the vadose zone. Since it is the process through the Soil-Plant-Atmosphere Continuum (SPAC), it is necessary to properly evaluate each subsystem (i.e., soil, plant, and climate) for the evaluation of evapotranspiration.

**Keywords**: unsaturated flow, evapotranspiration, field experiment, modeling, HYDRUS-1D

## Introduction

Evapotranspiration, *ET*, plays an important role in the water and energy balance of the vadose zone. On average, approximately 60 % of precipitation is assumed to evaporate from the soil surface, which may be higher and reach up to 90% of the annual rainfall in arid regions (Novak, 2012). Since *ET* is the process through the Soil-Plant-Atmosphere Continuum (SPAC), it is necessary to properly evaluate each subsystem (i.e., soil, plant, and climate) for the *ET* evaluation.

The potential evapotranspiration, $ET_p$, is the maximum evaporation rate atmosphere can extract from the field with given surface properties (Hillel, 1982), which consists of potential evaporation from the soil surface, $E_p$, and potential transpiration from plant leaves, $T_p$. $ET_p$ is generally evaluated with a model based on climate conditions such as the Penman-Monteith equation. The actual evapotranspiration, $ET_a$, becomes smaller than $ET_p$ when the *ET* rate is limited by the rate of water movement to the surface as the soil becomes dry. $ET_a$ is often measured using a weighing lysimeter based on the weight loss of the entire soil, or estimated from water balance of the root zone based on precipitation, irrigation, drainage, runoff, and water storage in the root zone. However, it is generally difficult to independently determine $T_p$ and/or $T_a$ since evaporation and transpiration take place at the same time.

As Šimůnek (2015) showed in this proceeding, it is necessary to divide $ET_p$ into $E_p$ and $T_p$ to simulate unsaturated water flow in a soil with a plant water uptake model. Although the fraction of the potential transpiration, $T_p$ / $ET_p$, is generally difficult to experimentally determine, it would be possible to estimate $T_a$ if we could prevent evaporation from the soil surface using a mulching cover. Furthermore, $T_a$ might be regarded as $T_p$ if the plant does not have water stress in the root zone.
The objective of this report is to demonstrate how we can evaluate $ET_p$ and $ET_a$ using meteorological and soil water content data observed in a soybean field with a mulching cover. Furthermore, we determined the ratio of $T_p$ to $ET_p$ assuming observed $ET_a$ could represent $T_p$ for a mulching field with relatively high water contents.

## Material and Methods

### *Field Measurements*

A field monitoring experiment was conducted at a soybean field in the Mie University experimental farm since August 2014. To monitor volumetric water content and soil water pressure head in a soil, TDR probes with two 30 cm long rods (CS650, Campbell sci.), and tensiometers with 4 cm diameter porous cup (mol INC.) were used (Fig. 1). After digging a 50 cm depth trench, five TDR probes were installed horizontally at 8, 18, 28, 38, and 48 cm depths, and four tensiometers were also horizontally installed at 18, 28, 38, and 48 cm depths. Additionally, another TDR probe was vertically installed from the soil surface to monitor average water content at 0 to 30 cm depth. Soybeans [*Fukuyutaka*] were transplanted with 70 and 20 cm spacing on Aug. 26,

2014. A plastic mulch was covered at the soil surface to prevent evaporation from the soil for Sep. 11 to Oct. 16, 2014.

*Fig. 1. TDR probes and tensiometers horizontally installed in a soil profile*
*Фиг. 1. TDR сензори и тензиометри инсталирани хоризонтално в почвения профил*

A weather station was built next to the soybean field (Fig. 2) with several sensors (Fig. 3) to collect meteorological data: CS215 for air temperature and relative humidity, Met one 034B windset for wind speed and direction, and CS300 pyranometer for solar radiation (Campbell Sci.). Two CS300 were installed in upward and downward directions to measure incoming radiation and upward shortwave radiation reflected from the ground. All sensors were mounted at 2 m height from the soil surface. TE525 tipping bucket rain gage (Campbell Sci.) was also set to measure precipitation rates. All data from subsurface and meteorological sensors were stored in a datalogger CR1000 (Campbell Sci.) at 15 minute intervals.

***Evaluation of actual evapotranspiration rate***
The water balance method is a traditional approach to calculate evapotranspiration in a field (Novak, 2012). The general equation describing the water balance in the surface soil layer can be expressed as (Jury, Horton, 2006);

*Fig. 2. A weather station for meteorological measurements in a soybean field*
*Фиг. 2. Метеорологична станция в опитното поле със соя*

$$P + I - R - ET_a = D + \Delta W \quad (1)$$

where $P$ is the precipitation, $I$ is the applied irrigation water, $R$ is the surface runoff, $ET_a$ is the actual evapotranspiration rate, $D$ is the drainage below the soil zone, and $\Delta W$ is the increase of water storage. The water balance equation can be simplified for a drying process after rainfall with no runoff condition as;

$$ET_a = -\Delta W - D \quad (2)$$

Although it is generally difficult to determine D at a certain depth, it is possible to further simplify Eq. (2) if D is negligible at the bottom of the soil layer (Novak, 2012). Hence ΔW can be simply determined from the difference in soil water content profiles in the soil zone between the time intervals.

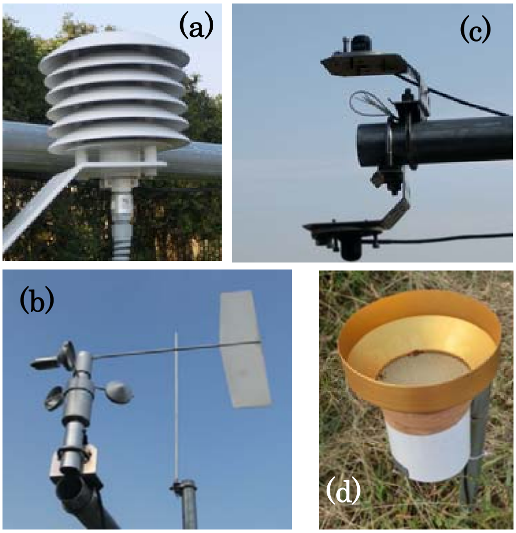


*Fig. 3. Meteorological measurements at the weather station: (a) air temperature and relative humidity sensors, (b) an anemometer for wind speed and direction, (c) pyranometers for incoming and reflected solar radiations and (d) a rain gage*
*Фиг. 3. Уреди на метеорологичната станция: (a) датчици за температурата на въздуха и относителната влажност, (b) анемометър за скоростта и посоката на вятъра, (c) пиранометри за сумарната и отразена слънчева радиация и (d) дъждомер*

***Estimation of Potential Evapotranspiration rate***

Potential evapotranspiration is generally calculated using meteorological dataset with a formula combining the aerodynamic and radiation terms based on the Penman-Monteith approach (Monteith, 1981; Monteith, Unsworth, 1990). FAO defined reference evapotranspiration, $ET_0$, as the evapotranspiration rate from a hypothetic crop with 12 cm crop height, 70 s m$^{-1}$ for the canopy resistance, and 0.23 for the albedo (FAO, 1990);

$$ET_0 = \frac{1}{\lambda}\left[\frac{\Delta(R_n - G)}{\Delta + \gamma(1 + r_c / r_a)} + \frac{\rho c_p (e_a - e_d) / r_a}{\Delta + \gamma(1 + r_c / r_a)}\right]$$

$$= \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T + 273} U_2 \left(e_a - e_d\right)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (3)$$

where $ET_0$ is the reference evapotranspiration rate [mm $d^{-1}$], $\lambda$ is the latent heat of vaporization [MJ $kg^{-1}$], $\Delta$ is the slope of the vapor pressure curve [kPa $^oC^{-1}$], $\gamma$ is the psychrometric constant, [kPa $^oC^{-1}$], $R_n$ is the net radiation at surface [MJ $m^{-2}$ $d^{-1}$], $G$ is the soil heat flux [= 0 MJ $m^{-2}$ $d^{-1}$], $\rho$ is the atmospheric density [kg $m^{-3}$], $c_p$ is the specific heat of moist air [kJ $kg^{-1}$ $^oC^{-1}$], $e_a$ is the saturation vapor pressure, $e_d$ is the actual vapor pressure [kPa], $r_c$ is the crop canopy resistance [$sm^{-1}$], $r_a$ is the aerodynamic resistance [$sm^{-1}$], $T$ is the air temperature [$^oC$], and $U_2$ is the wind speed measured at 2 m height [m $s^{-1}$].

In this study, $ET_0$ based on Eq. (3) with meteorological data was used as potential evapotranspiration rates, $ET_p$. HYDRUS-1D (Šimůnek et al., 2008) allows users to calculate the Penman-Monteith equation using several combinations of available meteorological dataset (Sakai et al., 2008). We used measured shortwave radiations, air temperature and humidity, and wind speed. $R_n$ was calculated using shortwave radiation and air temperature (Šimůnek, 2016), wind speed was used for $U_2$, and other parameters were determined by air temperature and relative humidity.

## Results

### *Meteorological data*

Figure 4 shows observed daily meteorological data. In rainy days, relative humidity increased close to 100% while shortwave radiation decreased. Air temperatures gradually decreased in autumn from September to November. Daily averaged wind speed greatly fluctuated between 50 to 250 km $d^{-1}$.

### *Soil water contents*

Figure 5 shows volumetric water content variations at three depths and averaged values for 30 cm from the surface at each depth obtained from the vertically installed TDR probe. Water contents at 8 cm quickly responded to precipitation and subsequent evapotranspiration, while water contents at other depths maintained at almost saturated condition (0.39 $cm^3$ $cm^{-3}$) for entire experimental period. Note that water contents at 8 cm increased even in the mulching period, implying rainwater infiltrated into soils from the joint part of the mulching sheets. After rainfall, water content decreased due to evapotranspiration and drainage. In this study field, since the saturated hydraulic conductivity of the subsoil below 20 cm depth was much smaller (0.04 cm $d^{-1}$) than for the surface soil, drainage was considered to be negligible.

Furthermore, soybean roots were found only within the surface 20 cm because the subsoil was hard for roots to penetrate. Hence the water content reduction rate within the surface layer could be regarded as the evapotranspiration rate.

### *Estimation of evapotranspiration*

Assuming the drainage from the soil zone, $D$, is negligibly small since the hydraulic conductivity for the subsoil was greatly smaller, the actual evapotranspiration rate, $ET_a$, was calculated according to Eq. (2) assuming $D = 0$:

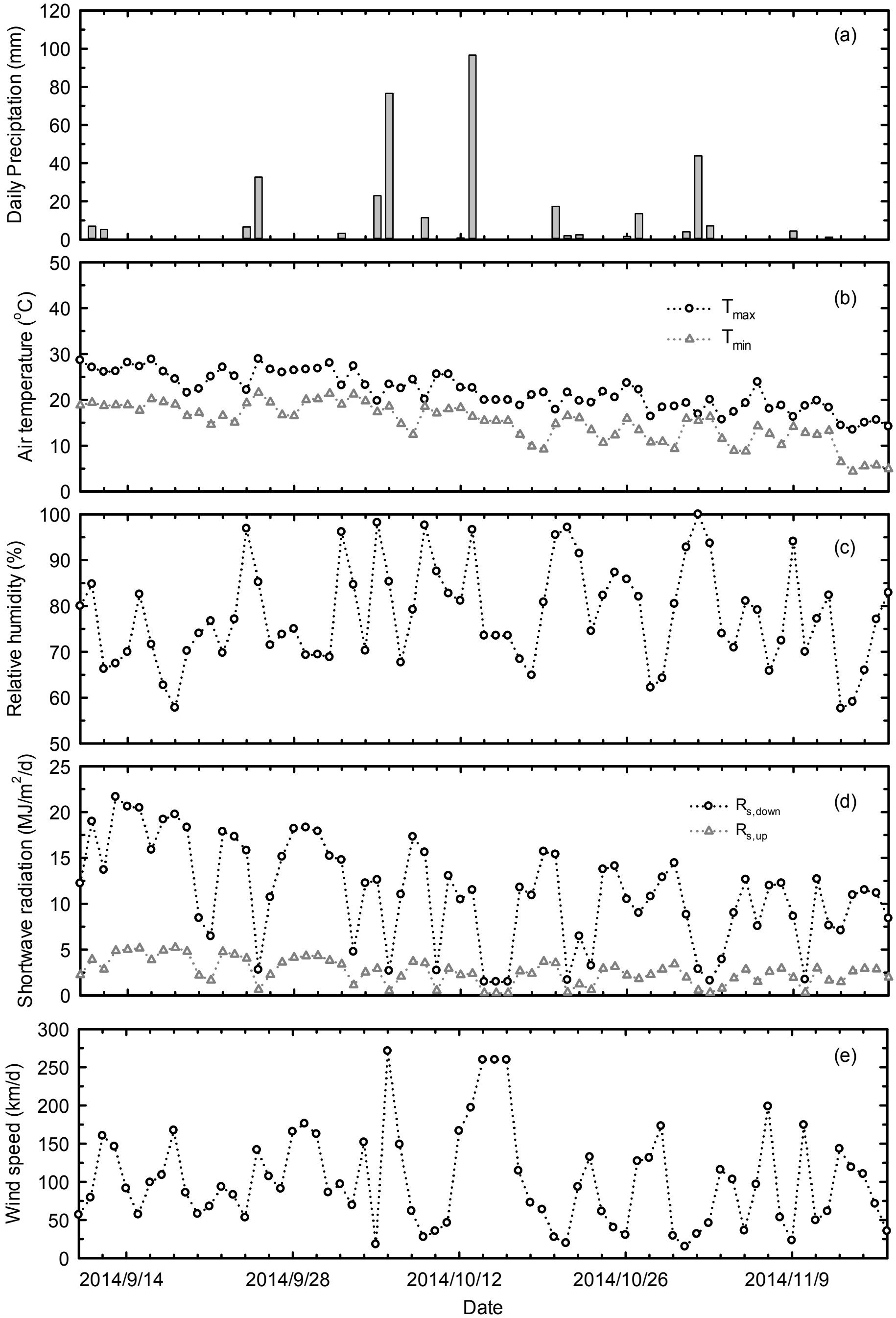


*Fig. 4. Meteorological and plant data observed in a soybean field: (a) daily precipitation, (b) daily maximum and minimum air temperatures, (c) relative humidity, (d) incoming and reflected solar radiations and (e) wind speed*

*Фиг. 4. Метеорологични данни в опитното поле със соя: (a) дневни валежи, (b) дневните максимална и минимална температури на въздуха, (c) относителна влажност, (d) сумарната и отразена слънчева радиация и (e) скорост на вятъра*

$$ET_a = -\Delta W = -\int_0^{30} \Delta\bar{\theta}\, dz \tag{4}$$

Since $\Delta W$ was evaluated using the average water contents, $\Delta\bar{\theta}$ by the vertically installed TDR measurements, the water balance was considered for the surface 30 cm in Eq. (4). Figure 6 shows actual evapotranspiration rates, $ET_a$, with the potential evapotranspiration rates, $ET_p$, according to Eq. (3) using the meteorological data (Fig. 4). During the mulching period from Sep. 11 to Oct. 16, $ET_a$ can be regarded as the actual transpiration rate, $T_a$, since the soil surface evaporation was assumed to be negligible.

It is possible to divide the $ET_a$ variation into two stages based on the soybean growth. In the first stage of the growing period until the beginning of October, $T_a$ was much smaller than $ET_p$ in a few day after the transplant on Sep. 11 and gradually increased. As the soybean grew, the leaf area also increased and eventually fully covered the surface. In the subsequent stage after soybeans had grown up, $T_a$ was almost close to $ET_p$. Notice that $T_a$ fluctuated and had a tendency to decrease as the water content in the root zone decreased (Fig. 5). In this period, the root water uptake was limited by water stress and $ET_a$ became smaller than the atmospheric evaporative demand, $ET_p$.

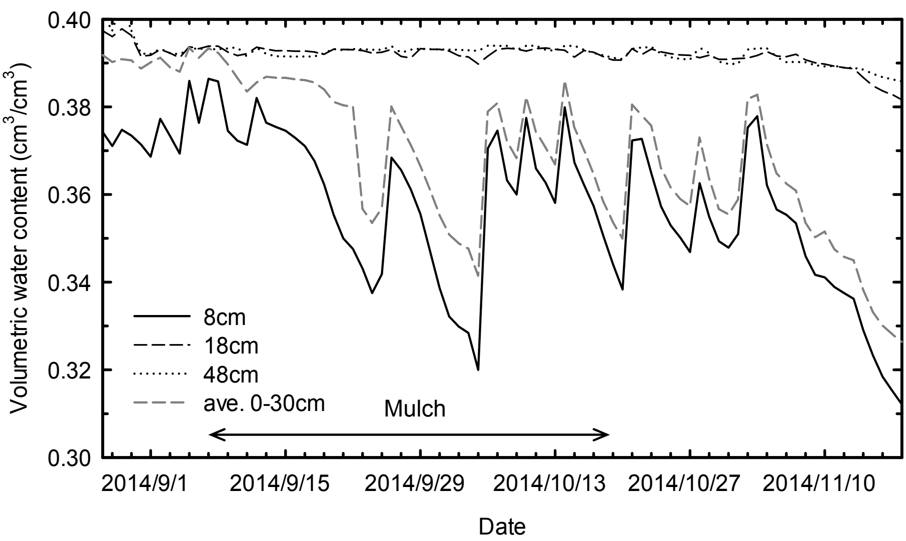


*Fig. 5. Volumetric water content variations at three depths measured with horizontally installed TDR probes, and averaged water contents for 0 - 30 cm depth measured with a vertically installed TDR probe*
*Фиг. 5. Изменение на обемната влажност на три дълбочини, измерени с хоризонтални TDR датчици, и осреднената обемна влажност за дълбочина 0 - 30 cm, измерена с вертикално монтиран TDR датчик*

Since the water content in the root zone was enough high for drought stress in the mulching period (Fig. 6), $T_a$ could be regarded as $T_p$. Since the $T_a$ data in Figure 6 were erratic, the $T_p/ET_p$ data were firstly fitted with the Verhulst-Pearl growth function and $ET_p$ was then partitioned into $T_p$ and $E_p$ using the fitted ratio as shown

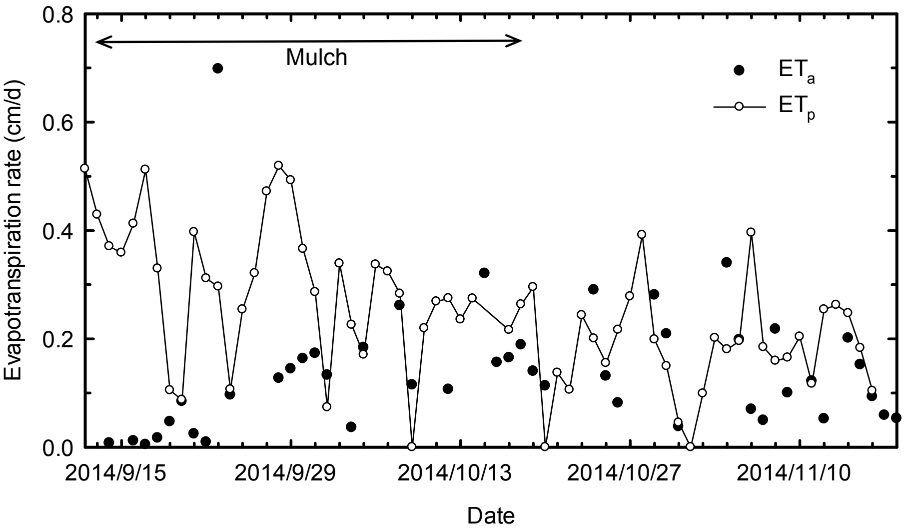


*Fig. 6. Potential evapotranspiration rate according to the Penman-Monteith combination equation ($ET_p$) and actual evapotranspiration rates based on the water mass balance ($ET_a$)*
*Фиг. 6. Потенциалната евапотранспирация по уравнение на Penman-Monteith ($ET_p$) и действителната евапотранспирация изчислена с използване на воден баланс ($ET_a$)*

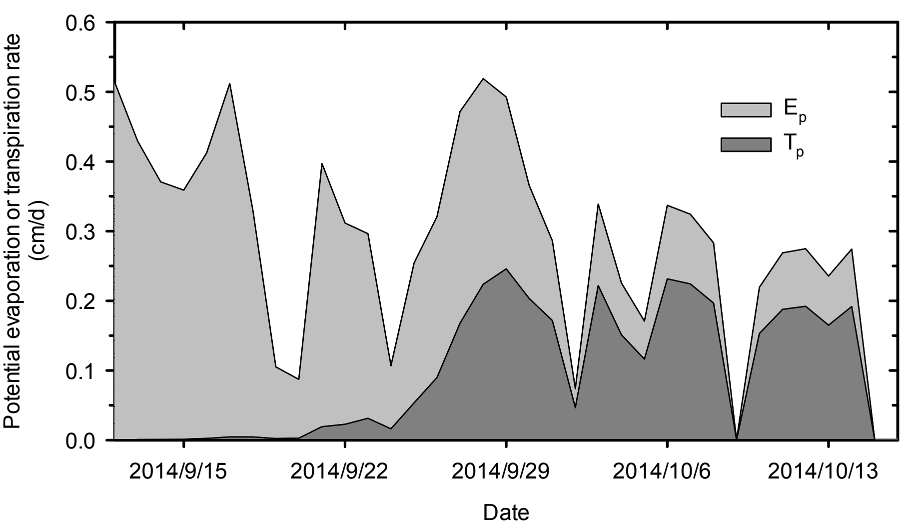


*Fig. 7. Potential evaporation ($E_p$) and potential transpiration rate ($T_p$) derived from partitioning of potential evapotranspiration ($ET_p$)*
*Фиг. 7. Потенциалното физическо изпарение ($E_p$) и потенциалната транспирацията ($T_p$), получени от разделянето на потенциалната евапотранспирация ($ET_p$)*

in Figure 7. $E_p$ was dominant in $ET_p$ and $T_p$ was very small when soybean was small in the middle of September. As the soybean grew, $T_p$ increased and reached 75% of $ET_p$ in the middle of October.


## Summary

In this report, we have demonstrated how we could utilize field measurements for water flow simulation with root water uptake using the numerical model such as HYDRUS-1D. The potential evapotranspiration in a soybean field, $ETp$, was evaluated using the meteorological data with the Penman-Monteith combination formula, and the actual evapotranspiration, $ETa$, was determined based on the water balance method assuming negligible drainage. In the mulching period, $ETa$, was regarded as $Ta$ due to negligible evaporation from the surface. Furthermore, $ETp$ was partitioned into $Tp$ and $Ep$ assuming $Ta$ was equal to $Tp$ due to no water stress in that period. It is necessary to further provide information for the root water uptake model as well as soil hydraulic properties to simulate soil water dynamics in a field as Šimůnek (2015) described in this proceeding.


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