Estimation of actual evapotranspiration by numerical modeling of water flow in the unsaturated zone: a case study in Buenos Aires, Argentina

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Abstract A method is presented to estimate actual evapotranspiration (ET_A) from potential evapotranspiration (ET_P) by numerical modeling of water flow in the unsaturated zone. Water flow is described by the Richards equation with a sink term representing the root water uptake. Evaporation is included in the model as a Neumann boundary condition at the soil surface. The Richards equation is solved in a one-dimensional domain using a mixed finite element method. The values of ET_A are obtained by applying a water stress factor to ET_P to account for soil moisture changes during the simulation period. The proposed numerical model is used to estimate ET_A in an experimental plot located in a flatland area in Buenos Aires (Argentina). Numerical results show that the proposed model is a useful tool for evaluating evapotranspiration under different scenarios.

Keywords Evapotranspiration · Unsaturated zone · Numerical modeling · Argentina

Introduction

Quantification of actual evapotranspiration (ET_A) is fundamental to obtaining reliable estimates of groundwater recharge and determining crop water requirements to maintain efficient irrigated agriculture (Zhang and Schilling 2006; Katerji and Rana 2006). Unfortunately, the estimation of ET_A is one of the most difficult tasks in hydrogeology and soil sciences due to complex interactions amongst the components of the land-plant-atmosphere system.

Direct measurements of ET_A can be obtained using the Bowen ratio-energy balance (Malek and Bingham 1993) and the eddy correlation method (Kosugi et al. 2007); however, these procedures are both time and labour consuming and applicable only when a number of requirements are fulfilled (Pauwels and Samson 2006; Gavilán et al. 2007). A useful alternative to direct measurements is the estimation of ET_A from climatic data using empirical and semi-empirical equations. The two most used equations to estimate ET_A are the Penman-Monteith (Monteith 1965) and the Priestley-Taylor (Priestley and Taylor 1972) equations. It is important to note that these equations provide values of potential evapotranspiration ET_P that are only equivalent to ET_A values when the soil moisture conditions are optimum, which is when water is abundantly available near soil surface. Then, to obtain ET_A under non-optimal moisture conditions, the estimated ET_P values have to be adjusted by a water stress coefficient. The objective of this work is to present a general procedure to estimate ET_A from ET_P by the numerical modeling of water flow in the unsaturated zone.

To facilitate the analysis of the evapotranspiration process, it is convenient to introduce the concept of reference evapotranspiration ET_0 (Allen et al. 1998). ET_0 is the evapotranspiration rate from a hypothetical reference surface under optimal soil water conditions. ET_0 is a climatic parameter that expresses the evaporation power of the atmosphere independently of vegetation characteristics and soil factors. To estimate ET_0, the Food and Agriculture Organization of the United Nations (FAO) has proposed the Penman-Monteith equation (Monteith 1965) adapted to a green grass of uniform height, actively growing and adequately watered (reference surface; Allen et al. 1998).

In this study, the potential evapotranspiration ET_P refers to the evapotranspiration of a specific crop from well-watered fields that achieve full production under the given climatic conditions. ET_P is determined by the following relationship:

$$ET_P = k_C ET_0 \tag{1}$$

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where k_C is the crop coefficient which is experimentally determined. It is important to note that the above definition of ET_P is equivalent to the definition of crop evapotranspiration under standard conditions, ET_C, given by Allen et al. (1998).

The actual evapotranspiration ET_A can be defined as the evapotranspiration from a crop grown under management and environmental conditions that differ from the standard conditions. ET_A can be expressed as follows:

$$ET_A = k_S ET_P \tag{2}$$

where k_S is a water stress coefficient which describes the effect of water stress on crop evapotranspiration and this coefficient ranges from 0 to 1.

In order to obtain a reliable estimate of k_S, it is necessary to model soil evaporation, root water uptake by plants and water flow in the unsaturated zone of the soil. During the last decade, several models based on numerical simulations of unsaturated flow using the Richards equation have been proposed to compute ET_A. Typically, the transpiration process is modelled by adding a sink term to the Richards equation that describes the root water uptake by plants (Varado et al. 2006a; Liu et al. 2005; Lai and Katul 2000; Droogers 2000). In most studies, the sink term is assumed to be a function of potential transpiration, root density and a water stress factor. On the other hand, the soil evaporation process is described using different models and boundary conditions in the Richards equation. Droogers (2000) simulated evaporation using the empirical formula proposed by Boesten and Stroosnijder (1986) that depends on an evaporation characteristic soil parameter and the time since the last significant rainfall. Liu et al. (2005) calculated evaporation as the upward flux driven by the pressure-potential gradient between the soil and the atmosphere (Lappala et al. 1987). More recently, Varado et al. (2006b) estimated soil evaporation from the maximum sustainable flow at the soil surface when the surface is assumed to be dry.

In the present work, a non-linear Neumann boundary condition is proposed to describe soil evaporation while transpiration is simulated by adding a sink term to the Richards equation. Both the top boundary condition and the sink term are assumed to be functions of ET_P and the leaf area index (LAI). The Richards equation is solved using a mixed finite element method in conjunction with a modified Picard iteration scheme to deal with non-linear terms. The soil hydraulic properties are described by the well-known van Genuchten constitutive model (van Genuchten 1980).

The performance of the proposed method is evaluated through the numerical estimate of ET_A in an experimental plot located in Buenos Aires (Argentina) for the period 2003–2004. The FAO Penman-Monteith equation with daily resolution is used to compute ET_0. The available meteorological data for estimating ET_0 include air temperature, wind speed, sunshine hours and relative humidity. LAI values and soil properties are obtained from the literature. The estimated values of ET_A are compared with estimated values provided by a water balance model (Carrica 1993), and a reasonably good agreement between the estimates of both methods is found. Numerical results show that the proposed numerical model is a useful tool for evaluating and predicting evapotranspiration under non-standard conditions.

Numerical modeling of water flow in the unsaturated zone

Water flow in the unsaturated zone is predominantly vertical and can be simulated as one-dimensional flow using the Richards equation. The simulation domain is assumed to extend from the soil surface (z_{top}) to an arbitrary point in the saturated zone (z_{bot}). In the mixed form, Richards equation reads (Richards 1931; Celia et al. 1990):

$$\frac{\partial\theta(h)}{\partial t} - \frac{\partial}{\partial z}\left[K(h)\frac{\partial}{\partial z}(h+z)\right] = S(h), \quad z \in (z_{bot}, z_{top}) \tag{3}$$

where θ is the water content, h is the pressure head, K is the hydraulic conductivity, S is a sink term representing the root water uptake by plants, z is the vertical coordinate (positive upward) and t is the time.

The proposed Neumann type boundary condition at the soil surface (z_{top}) is:

$$-K(h)\frac{\partial}{\partial z}(h+z) = \mathrm{P} - \mathrm{E}(h) \tag{4}$$

where P is the rainfall intensity and E is the soil evaporation intensity which depends on the soil water content near the surface. According to Eq. (4), the soil evaporation process is assumed to be limited to the soil surface and this boundary condition is valid only for non-flooded soils.

The following Dirichlet type boundary condition is prescribed at the bottom edge of the domain (z_{bot}):

$$h(t) = z_{wt}(t) - z_{bot} \tag{5}$$

where $z_{wt}(t)$ denotes the position of the water table as a function of time. The effect of water-table depth on ET_A estimations can be analyzed from the boundary condition expressed as Eq. (5) (Cesanelli and Guarracino 2007). Higher ET_A values occur in sites with shallow water tables and lower ET_A values in sites with deeper water tables. Water table depth is often cited as a principal factor controlling ET_A in phreatophyte communities (Cooper et al. 2006).

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Soil hydraulic functions $\theta(h)$ and $K(h)$ are described using the van Genuchten constitutive model (van Genuchten 1980). This model is widely used by the hydrological community and reads as:

$$\theta(h) = \begin{cases} (\theta_s - \theta_r)\left[1 + (\alpha|h|)^n\right]^{-1+1/n} + \theta_r & h < 0 \\ \theta_s & h \geq 0 \end{cases}$$
$$K(h) = \begin{cases} K_s \dfrac{\left[1-(\alpha|h|)^{n-1}\left(1+(\alpha|h|)^n\right)^{-1+1/n}\right]^2}{\left[1+(\alpha|h|)^n\right]^{1/2-1/2n}} & h < 0 \\ K_s & h \geq 0 \end{cases} \tag{6}$$

where θ_r and θ_s are the residual and saturated water contents, respectively; α and n are empirical fitting parameters and K_S is the saturated hydraulic conductivity.

The proposed mathematical models for soil evaporation $E(h)$ and root uptake sink term $S(h)$ depend on the potential soil evaporation E_P and the potential transpiration T_P, respectively. The partition between E_P and T_P is performed using a Beer-Lambert law based on the leaf area index LAI (Huygen et al. 1997):

$$\begin{aligned} E_P &= ET_P \exp(-\gamma \mathrm{LAI}) \\ T_P &= ET_P(1 - \exp(-\gamma \mathrm{LAI})) \end{aligned} \tag{7}$$

where γ accounts for the interception of the radiation by vegetation. A classical value for γ is 0.5 and this value will be used in the present analysis (Varado et al. 2006a). Equation (7) is assumed to be valid under non-ponded conditions.

The mathematical models for E and S are expressed as follows:

$$\begin{aligned} E(h) &= \beta_E(h) E_P \\ S(h) &= g(z)\beta_T(h) T_P \end{aligned} \tag{8}$$

where $\beta_E(h)$ and $\beta_T(h)$ are functions that describe respectively the effect of water stress on soil evaporation and crop transpiration, and $g(z)$ is the root density function. The water stress functions $\beta_E(h)$ and $\beta_T(h)$ range from 0 to 1 and in this study are assumed to have the following expressions:

$$\beta_E(h) = \begin{cases} 0 & h < h_{E1} \\ \frac{h-h_{E1}}{h_{E2}-h_{E1}} & h_{E1} \leq h \leq h_{E2} \\ 1 & h > h_{E2} \end{cases}$$
$$\beta_T(h) = \begin{cases} 0 & h < h_{T1} \\ \frac{h-h_{T1}}{h_{T2}-h_{T1}} & h_{T1} \leq h \leq h_{T2} \\ 1 & h > h_{T2} \end{cases} \tag{9}$$

where h_{E1} and h_{T1} are cut-off values for actual evaporation and transpiration, and h_{E2} and h_{T2} are cut-off values for evaporation and transpiration under standard conditions. Similar linear functions to describe water stress function have been used by Droogers (2000) and Varado et al. (2006a).

Commonly, the root density function $g(z)$ is described by exponential models (Varado et al. 2006a; Liu et al. 2005). For simplicity, in the present study a constant root density function is assumed (Droogers 2000):

$$g(z) = \frac{1}{z_{top} - z_{root}}, \quad z \in \left(z_{root}, z_{top}\right) \tag{10}$$

where z_{root} is the maximum root depth.

Richard's Eq. (3) and the boundary conditions expressed as Eqs. (4)–(5) are solved using a hybridized mixed finite element method for space discretization combined with a backward Euler scheme in time (Guarracino 2001). The non-linear terms of the Richards equation are linearized using the modified Picard iteration scheme proposed by Celia et al. (1990). The algorithm obtained with this approximation produces perfectly mass conservative numerical solutions and is computationally efficient (Cesanelli 2007).

Estimation of ET

The estimation of ET_P requires the computation of ET_0. In this study, ET_0 values are obtained with the FAO Penman-Monteith equation using the standard method presented in Allen et al. (1998). The selection of the time step with which ET_P is calculated depends on the purpose of the calculation, the accuracy required and the time step of the meteorological data available. For theoretical and practical reasons, a daily time step is adopted for ET_P calculation.

In order to derive an expression of the water stress coefficient k_S, the daily water balance in the domain simulation is analyzed. A water balance is obtained by integrating in time and space the Richards equation:

$$\int_{t_i}^{t_{i+1}} \int_{z_{bot}}^{z_{top}} \left[\frac{\partial \theta(h)}{\partial t} - \frac{\partial}{\partial z}\left(K(h)\frac{\partial}{\partial z}(h+z)\right) - S(h)\right] dz\, dt = 0 \tag{11}$$

where t_i and t_{i+1} are the beginning of day i and day i+1, respectively. Integrating Eq. (11) by parts and introducing the boundary conditions expressed as Eqs. (4) and (5) the following expression for the water balance is obtained (Cesanelli 2007):

$$\int_{z_{bot}}^{z_{top}} \theta(t_{i+1}) dz - \int_{z_{bot}}^{z_{top}} \theta(t_i) dz - \int_{t_i}^{t_{i+1}} \mathrm{P}\, dt + \int_{t_i}^{t_i+1} \mathrm{E}(h) \mathrm{d}t - \int_{t_i}^{t_{i+1}} K(h)\frac{\partial}{\partial z}(h+z)\Bigg|_{z_{bot}} dt - \int_{t_i}^{t_{i+1}} \int_{z_{root}}^{z_{top}} S(h) dz\, dt = 0 \tag{12}$$

The terms of the mass balance Eq. (12) represent, respectively, the water content in the soil profile at the beginning of the day i+1, the water content at the beginning of the day i, precipitation, soil evaporation,

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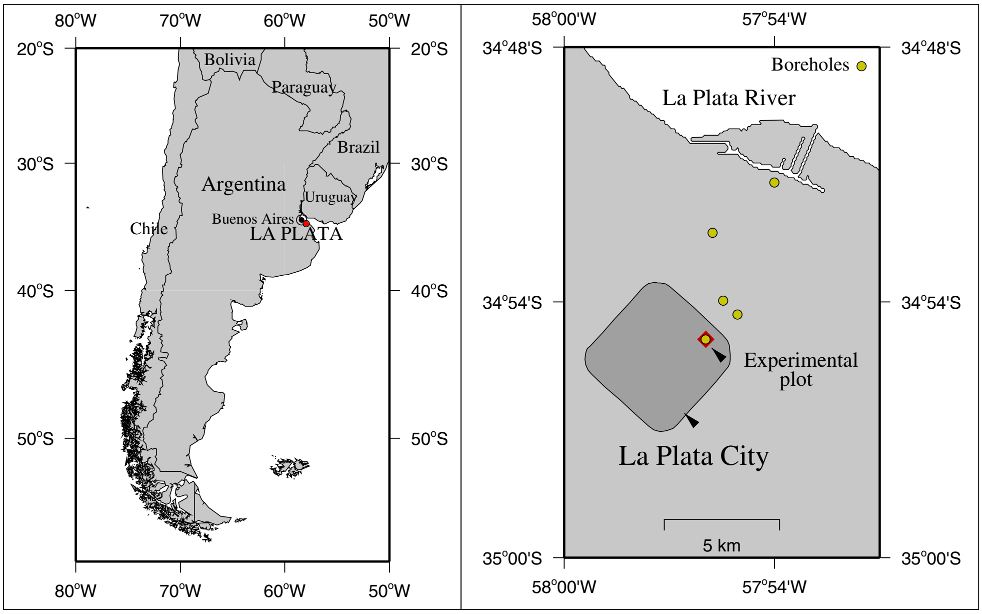

Fig. 1 Location map of the study site in La Plata, Argentina

deep percolation and root uptake on day i. Equation (12) was used to test the ability of the numerical algorithm to conserve mass. The integrals in Eq. (12) were computed using the numerical solutions of the Richards equation and the discrete form of the mass balance equation was exactly verified. Note that the time step for integrating the Richards equation has to be smaller than the time step for the mass water balance (1 day). In the present study, numerical solutions of the Richards equation were obtained using a 5-min time step.

Actual evaporation on day i, E_A^i, can be computed from the fourth term of Eq. (12) using the proposed model for E(*h*) Eq. (8):

$$E_A^i = \left[\frac{1}{(t_{i+1} - t_i)} \int_{t_i}^{t_{i+1}} \beta_E(h)dt\right] E_P^i \tag{13}$$

where E_P^i denotes potential evaporation on day i.

On the other hand, actual transpiration on day i, T_A^i, can be obtained from the sixth term of Eq. (12) using the proposed model for *S*(*h*) Eq. (8):

$$T_A^i = \left[\frac{1}{(t_{i+1} - t_i)} \int_{t_i}^{t_{i+1}} \int_{z_{root}}^{z_{top}} g(z)\beta_T(h)dz\,dt\right] T_P^i \tag{14}$$

where T_P^i denotes potential transpiration on day i.

Equations (13) and (14) provide a method to compute separately actual evaporation and transpiration. The water stress coefficient k_S^i on day i can be expressed as:

$$k_S^i = \frac{ET_A^i}{ET_P^i} = \frac{E_A^i + T_A^i}{ET_P^i} \tag{15}$$

where ET_P^i and ET_A^i denote potential and actual evapotranspiration on day i. Substitution of Eqs. (13), (14) and

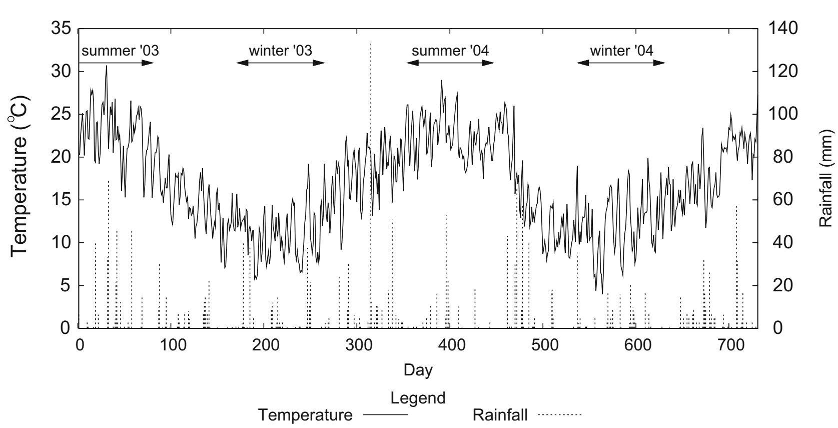

Fig. 2 Daily values of temperature and rainfall

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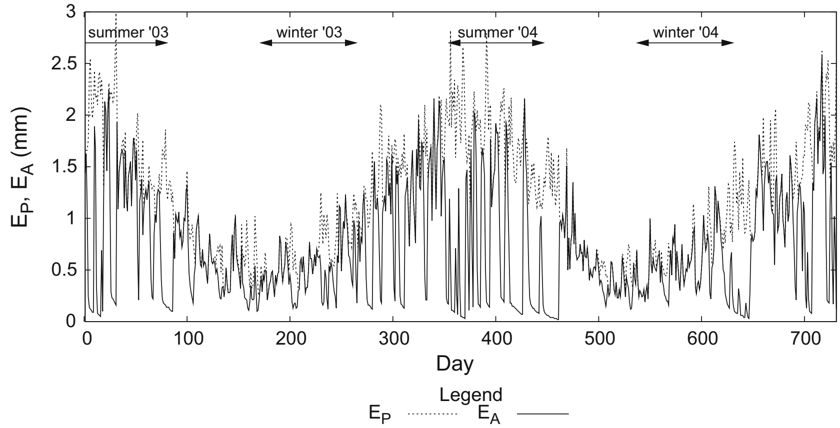

Fig. 3 Daily values of actual evaporation (E_A) and potential evaporation (E_P)

Eq. (7) in Eq. (15) yields the following expression for daily water stress coefficient:

$$k_S^i = \frac{\exp(-\gamma \mathrm{LAI})}{(t_{i+1} - t_i)} \int_{t_i}^{t_{i+1}} \beta_E(h)dt + \frac{1 - \exp(-\gamma \mathrm{LAI})}{(t_{i+1} - t_i)} \int_{t_i}^{t_{i+1}} \int_{z_{root}}^{z_{top}} g(z)\beta_T(h)dz\,dt. \tag{16}$$

The proposed method to estimate ET_A can be stated as follows:

1. Compute potential evapotranspiration ET_P using the FAO Penman-Monteith equation with daily resolution.
2. Solve the Richards equation using the proposed boundary conditions expressed as Eqs. (4)–(5) and soil evaporation and root uptake models expressed as Eq. (8).
3. Compute daily water stress coefficients k_S^i using Eq. (16).
4. Compute actual evapotranspiration ET_A^i values using Eq. (2).

Results

In this section, the proposed method is used to estimate ET_A on an experimental plot located in La Plata, Buenos Aires (Fig. 1). The climate of the area is warm and humid with a rainfall average of about 1,020 mm year^{-1}. The study site is characterized by a sandy loam soil, a shallow water table and low surface runoff. The land-surface vegetation is a green grass that completely covers the soil. The similarity between the site vegetation and the reference surface for which the FAO Penman-Monteith was derived allows consideration of a crop coefficient k_C=1. The LAI value is assumed to be 2, which corresponds to a natural pasture (Peter-Lidard et al. 2001).

The meteorological data measured at the Facultad de Ciencias Astronómicas y Geofísicas weather station include air temperature, wind speed, sunshine hours, relative humidity and precipitation. Figure 2 shows daily values of temperature and rainfall for the period 2003–2004, where day number 1 corresponds to 1 January 2003. The mean air temperature is about 17°C with monthly values ranging from 10 to 24°C. Daily values of ET_P were computed based on the available meteorological data and

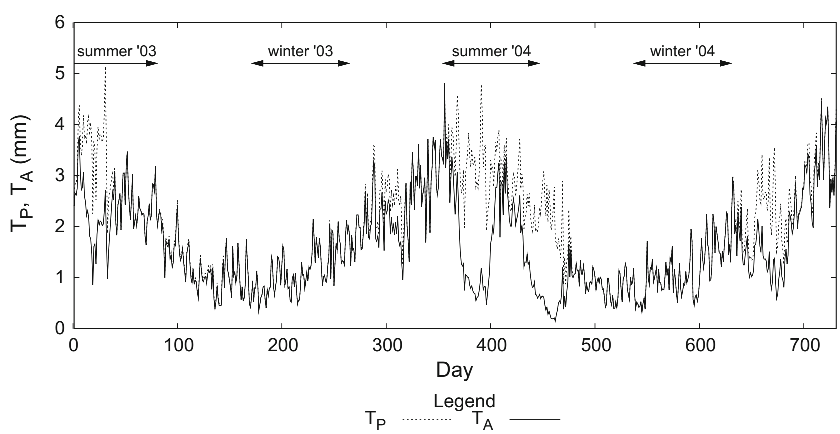

Fig. 4 Daily values of actual transpiration (T_A) and potential transpiration (T_P)

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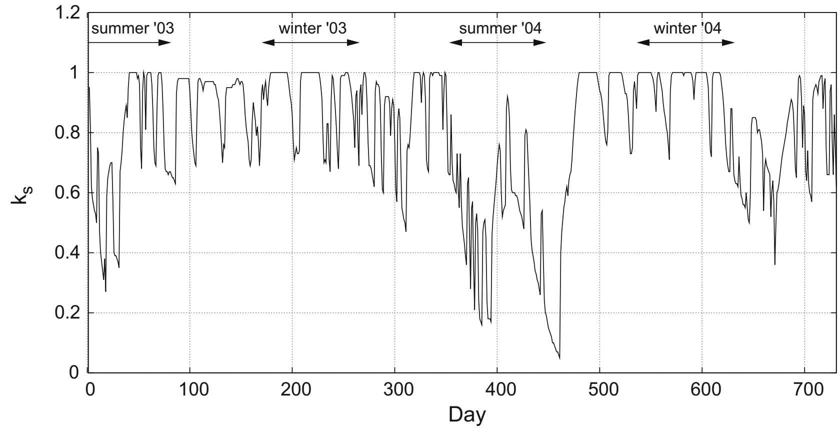

Fig. 5 Daily values of water stress coefficient (k_S)

the FAO Penman-Monteith equation. Finally, daily values of E_P and T_P were obtained using Eq. (7).

Based on available borehole data near the study site (Fig. 1), the water table was estimated to be 1.50 m below land surface for the period considered. The soil texture is characterized by the following van Genuchten parameters obtained by Carsel and Parrish (1988) for a sandy loam: θ_s= 0.410, θ_r=0.065, α=7.5 m^{-1}, n=1.89, K_s=1.061 mm day^{-1}. Cut-off values for water stress functions expressed as Eq. (9) are assumed to be $h_{E1}=h_{T1}=-4.0$ m and $h_{E2}=h_{T2}=-0.8$ m. The maximum root depth is 1.0 m and the soil profile considered for numerical simulation is 4.0 m wide.

Based on the parameter values presented above, the Richards equation with the proposed boundary conditions is solved. Using the approximate values of pressure head h, actual evaporation E_A and actual transpiration T_A are computed separately using Eqs. (13) and (14), respectively.

Figure 3 shows daily E_A and E_P values for the study period. Actual and potential values are similar during rainy days when the water content at the soil surface is at an optimum. E_A values decrease between two successive rain events in proportion to the amount of water available near the soil surface. Note that the differences between E_A and E_P show considerable variability.

Potential and actual transpiration values are shown in Fig. 4. Values of T_A and T_P are almost identical during the winter seasons indicating optimal soil-water conditions in the root zone. The main difference between T_A and T_P takes place during the summer when the root uptake is high and the water available in the root zone cannot respond to the transpiration demand.

The water stress coefficient k_S computed using Eq. (16) is shown in Fig. 5. k_S values are useful to identify periods where ET_A occurred under standard conditions (k_S=1) and under non-standard conditions (k_S<1). Figure 6 shows daily ET_P and ET_A obtained using Eq. (15). The largest differences between ET_A and ET_P take place during the summer in agreement with the largest differences between T_A and T_P. The analysis of Figs. 3, 4 and 6 suggests that ET_A in the study site is mainly determined by T_A.

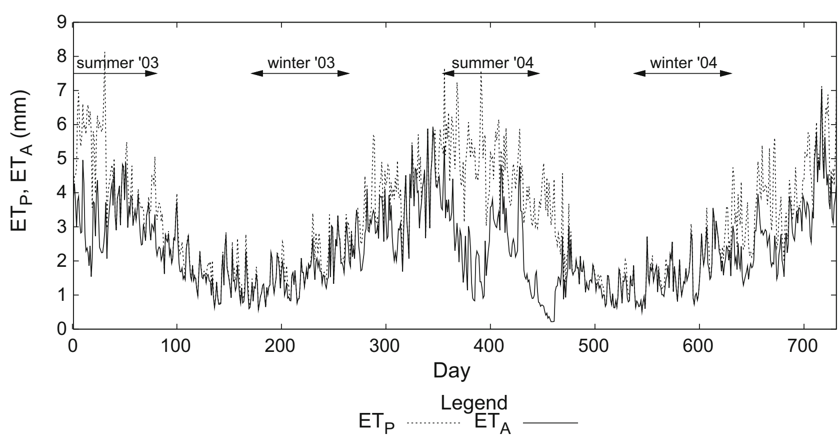

Fig. 6 Daily values of actual evapotranspiration (ET_A) and potential evapotranspiration (ET_P.)

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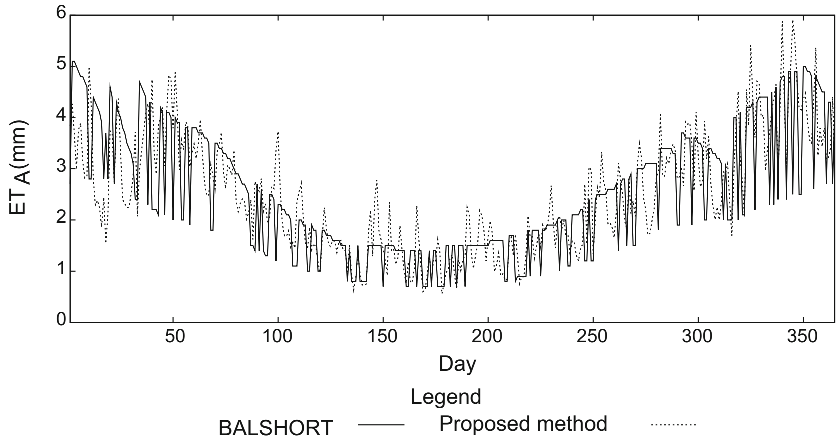

Fig. 7 Estimated values of actual evapotranspiration (ET_A) using the proposed method and BALSHORT for the year 2003

Estimated values of ET_A obtained with the proposed method were compared with estimated values provided by the BALSHORT water balance model (Carrica 1993). BALSHORT is a typical water balance model based on the Thornthwaite and Mather (1955) method calibrated for local soil textures. The input data to the model are values of ET_P, rainfall, water storage at field capacity and soil texture. The comparison of ET_A values for the year 2003 using both methods is shown in Fig. 7. Estimated values of ET_A provided by BALSHORT were obtained using a value of 200 mm for the water storage at field capacity (Auge 2001); although the proposed method is more sensitive to rain events and dry periods both methods yield similar results.

Finally, a linear regression analysis was performed to evaluate the agreement between estimated values of ET_A using both methods (Fig. 8). The slope of the linear regression is 0.9721 with a standard deviation of 0.83 mm day^{-1} and a coefficient of determination R^2 of 0.53. The wide scattering of the ET_A values around the regression line could be explained by the fact that the proposed method is more sensitive to moisture changes since it explicitly considers the root water uptake by plants and the soil-water distribution. Note that the deviations are smaller for low values of ET_A, which correspond to periods of low water uptake. However, the slope of the linear regression is close to 1, indicating a reasonably good agreement between estimated values using the proposed method and BALSHORT.

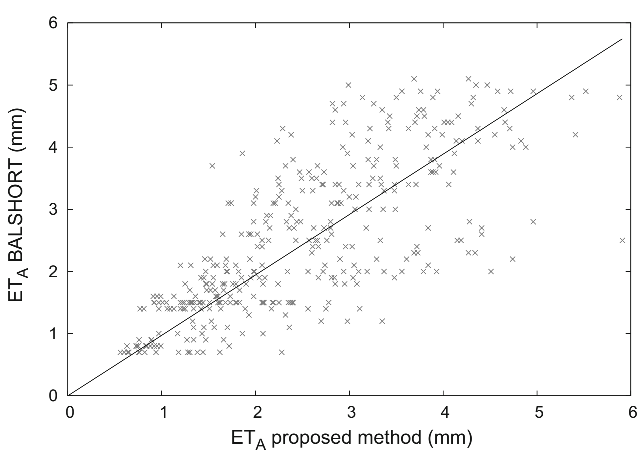

Fig. 8 Linear regression between estimated values of evapotranspiration (ET_A) using the proposed method and BALSHORT

Conclusions

A method to estimate actual evapotranspiration ET_A from potential evapotranspiration ET_P by numerical modeling of water flow in the unsaturated zone is presented. Soil evaporation and crop transpiration are separately modeled using a non-linear boundary condition and a sink term in the Richards equation. The proposed model includes the effect of water-table depth, soil texture, moisture and crop type on ET_A estimation. The derivation of the model is based on the assumption that the rainfall rate does not exceed the maximum infiltration rate. In case of flooded soils, the top boundary condition of the Richards equation and the Beer-Lambert law need to be modified or replaced.

The proposed method is an effort to understand and quantify evapotranspiration processes and it has been used to calculate ET_A on a daily scale for the period 2003–2004 in a flatland area in Buenos Aires (Argentina). Estimated ET_A values are in reasonably good agreement with values obtained using a classical water balance model. Numerical results show that the proposed model improves the understanding of the most important physical processes and becomes a useful tool for evaluating and predicting evapotranspiration under different scenarios and for studying problems like the influence of crop rotation on groundwater levels and aquifer recharge.

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