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RIPARIAN EVAPOTRANSPIRATION MODELLING: MODEL DESCRIPTION AND IMPLEMENTATION FOR PREDICTING VEGETATION SPATIAL DISTRIBUTION IN SEMI-ARID ENVIRONMENTS

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ABSTRACT

Biotic and abiotic interactions between the riparian zone and the river determine relevant hydrological processes and exert control over riparian and bordering upland vegetation types. Vegetation growth and development are mainly controlled by water availability on semi-arid regions so the closeness to the river yields a moisture gradient which clearly determines the boundaries between exuberant riparian zone and semi-arid upland. A mathematical model named *RibAV* is presented. Its conceptualization is based on the main worldwide ecosystem modelling approaches and field expertise. The implementation of *RibAV* that is proposed in this paper allows the simulation of the vegetation functional types distribution in riparian zones. An evapotranspiration index (E_{idx}) obtained through *RibAV* is used as criterion for long-term plant absence/presence prediction. Two permanent river reaches of semi-arid Mediterranean basins, the Terde reach (Mijares River, Spain) and the Lorcha reach (Serpis River, Spain), have been selected as case studies for the evaluation of the model performance. Several criteria based on the confusion matrix were used to analyze the efficiency of RibAV on the prediction of plant distribution. The model outstanding performance to establish riparian vegetation types distribution and the limit between this zone and the bordering upland is demonstrated in this paper; the strength of the E_{idx} to classify plant functional types in riparian semi-arid environments is additionally proved.

KEY WORDS Soil moisture; evapotranspiration modelling; riparian vegetation; spatial distribution; functional types

INTRODUCTION

Of particular interest are the riparian ecosystems from an ecohydrological point of view. The importance of these ecosystems lies in their continuous interaction with the river. Riparian ecosystems have important regulation capabilities on the hydrological processes, including different degrees of water balance control, retention of sediments and regulation of nutrients, etc. In this context, the riparian vegetation exerts a main role in the hydrological feedback mechanisms between the river-soil-atmosphere systems (Lowrance *et al.,* 1998; Scott *et al.,* 2000; Tabacchi, 2000; Rodriguez-Iturbe *et al*., 2001). On the other hand, the hydrological regime of the river is responsible for the riparian ecosystem maintenance (Malanson, 1993; Lambers *et al*., 1998; Richards *et al*., 2002; Vidon and Hill, 2004; Naiman, 2005; Merrit *et al*., 2010). Due to this connection, a better knowledge of the interactions between the river and the riparian forest is essential to manage properly the conservation and restoration initiatives (Stromberg, 2001; Glenz, 2005). For management purposes, mathematical models are important tools that allow systematic analyses of river ecosystems. The European Water Framework Directive (WFD 2000/60/EC) pointed out the importance that have the development of new advanced tools for helping to achieve the good ecological status of river related ecosystems by predicting the effects caused by changes of the ecosystem driving forces (Perona *et al*., 2009).

Floods have been traditionally considered as an essential driving force of disturbance for the riparian ecosystems, as they force the vegetation succession cycle and the biotic factors resettlement (e.g., Azami *et al.,* 2004; Choi *et al.,* 2005; Glenz*,* 2005; Tabacchi, 2005; Ocampo *et al.,* 2006; Wen *et al.,* 2010, Benjankar *et al*., 2011, García-Arias *et al*., submitted for publication). Nevertheless, in semi-arid riparian zones where the annual flood period is short, the droughts can be harder than the flood itself and the occurrence of scarce water availability become a limiting factor that is responsible for the vegetation hydrological stress (Porporato *et al*., 2001; Rodríguez-Iturbe and Porporato, 2004). The riparian vegetation distribution is, in consequence, mainly driven by the soil moisture and the water table elevation, which are determined by the hydrological regime of the river (Richards *et al.,* 1996; Hughes *et al.,* 2003).

Under these conditions, the water balance is conditioned by the riparian forest and, in consequence, there has been a growing interest in the riparian vegetation evapotranspiration modelling (e.g. Altier *et al*., 2002; Baird and Maddock III, 2005; Mac Nish *et al*., 2000; Serrat-Capdevila *et al*., 2011). However, to our knowledge, the previous models have overlooked that the evapotranspiration of the riparian plants occurs from the two possible sources of water availability, the static storage and the saturated zone, being used often simultaneously.

The primary objective in this paper is to provide the conceptualization of a new model called *RibAV*. This mathematical model has been performed from an ecohydrological point of view to predict the riparian vegetation evapotranspiration in semi-arid environments, considering both sources of water availability. The model, taking as reference previous studies (Scott *et al.*, 2000; Porporato *et al.*, 2001; Altier *et al.*, 2002; Baird and Maddock III, 2005), considers the water availability as the main driving force that determines the vegetation comfort. For different plant functional types (PFTs), and considering their distinct adaptation and response mechanisms to collect the available water from the saturated and the unsaturated zones, *RibAV* calculates rates of actual evapotranspiration. The definition of the parameters in *RibAV* is based in the architecture of several biotic and abiotic models developed for the riparian zone all over the world (Welsch, 1991; Stromberg *et al.,* 1993, 1996; Bendix, 1994; Lowrance *et al.*, 1998; Brinson and Verhoeven, 1999; Brooks *et al.*, 2000; Snyder and Williams, 2000; Horton *et al.*, 2001; Altier *et al.*, 2002; Sparovek *et al.*, 2002; Maddock III and Baird, 2003; Baird and Maddock III, 2005; Lamontagne *et al.*, 2005; Lite *et al.*, 2005; Stave *et al.*, 2005; Webb and Leake, 2006; Merrit *et al.*, 2010).

Aditionally, the present paper extends the use of the *RibAV* model by proposing an index called E_{idx} that relates the actual evapotranspiration to the potential evapotranspiration of the PFTs. The maximum evapotranspiration rates are frequently used as a measure of plant growth and productivity (Quevedo and Francés 2008), and as an indicator of the optimum environmental conditions for different vegetation types in semi-arid zones (Porporato *et al.*, 2001). Indirectly, the temporal series of evapotranspiration rates can be considered as both, a measure of water use (Laio *et al.*, 2001; Lautz, 2008), and plant resistance to saturation in the root zone (Baird and Maddock III, 2005). Given this, in order to predict the spatial distribution of different PFTs in the riparian zone, and the limit between the riparian zone and the neighbouring upland zone through the *RibAV* model, the E_{idx} is used. For the distribution modelling, it has been established that the PFT with a higher value of E_{idx}, is the one which has a better response/adaptation to the variable environmental conditions of each unit area, compared to the other PFTs analyzed under the same conditions and during the same period. The proposed hypothesis considers the static comparison and hierarchical organization of the PFTs respective E_{idx} values as a good criterion for long-term zonation prediction. The second part of the paper includes the *RibAV* model implementation, through the E_{idx} as criterion for vegetation zonation prediction, in two semi-arid Mediterranean rivers reaches in order to validate this last hypothesis.

THE *RIBAV* MODEL

General description

The *RibAV* model has been designed to simulate water availability and evapotranspiration near the river, especially in the riparian zone. This water availability from the saturated and unsaturated zones of the soil depends on the local climate and it is strongly controlled by the river flow regime and the vegetation adaptation mechanisms. *RibAV* has based its approach on the concept of soil-plant-atmosphere continuum and consequently it requires the inclusion of vegetation and soil parameters to allow the representation of its conceptual framework. In *RibAV*, vegetation is considered fixed in time but variable in space. The theory of PFTs is applied, considering the taxonomical vegetation characteristics, in order to parameterize the vegetation from the model point of view.

The *RibAV* model is distributed in space, using a regular division in cells. Due to the strong sensitivity to vertical distances and lengths, altitude differences must be limited. Consequently, cell sizes used in *RibAV* are recommended to be lower than 10 m. To capture properly the evapotranspiration dynamics, the model uses daily temporal discretization.

The general conceptualization of *RibAV* is shown in Figure 1. Its conceptualization is oriented to a proper, but simple as possible, modelling of the evapotranspiration. For each cell, the actual evapotranspiration (*E*) is computed as the sum of the evapotranspiration from the unsaturated zone, represented by the static storage (Figure 1), and the direct transpiration from the saturated zone. The static storage represents the capillary water availability for evapotranspiration in the upper part of the soil. Therefore, it is limited by the soil surface elevation (Z_s), the effective root depth (D_e) and the moistures corresponding to wilting point (θ_{wp}) and field capacity (θ_{fc}). The saturated zone is defined by the water table elevation (Z_{wt}), which is variable in time and which is only controlled by the river water level in *RibAV*. Considering this hypothesis, it is not needed to establish the water balance in the saturated zone.

As shown in Figure 1, the possible flows between the static storage and the saturated zone are the unsaturated vertical flow and the hydraulic lift by roots (*U*). The first one can be a downward percolation (*Pe*) or an upward capillary water flow (*Cwf). Pe* is not simulated explicitly in *RibAV*, because is included in the excess water (*X*) of the static storage and there is no need of water balance in the saturated zone. *X* also includes the surface runoff (*Sr*).

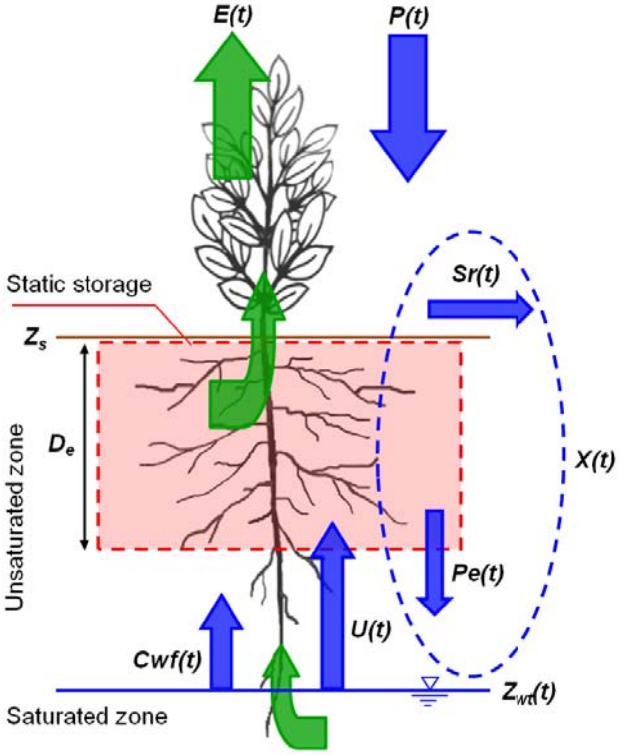

Figure 1. General conceptualization for one cell in the RibAV model. Arrows represent water fluxes in and out of the system; the actual evapotranspiration is represented with green arrows, considering as sources the saturated and unsaturated zones of the soil profile.

Soil parameters

Soil parameters are used in *RibAV* for the definition of the static water storage. These parameters, described below, are specific for each type of soil present in the study site.

The moisture content at field capacity (θ_{fc}) can be measured in the laboratory or calculated from the soil-water retention curve for any of the different pressures cited by various authors as reference for field capacity (Ψ_{fc}): 33 kPa (Wild, 1992; Kramer and Boyer, 1995; Dingman, 2002), 15 kPa (Larcher, 2003) or in the range between 202.65 and 303.98 kPa (Guymon, 1994). The latter methodology is also applicable to obtain the bubbling pressure (Ψ_b), considering the soil textural class and its physical properties (Rawls *et al.,* 1993).

The hydraulic conductivity of the saturated soil (K_s) can be measured in laboratory or can be obtained from the soil textural class using pedotransfer functions (Saxton *et al.,* 1986).

In this work, we have used the Campbell's soil-water retention curve (Campbell, 1974), and the corresponding equation for the hydraulic conductivity of the unsaturated soil (K_u), given by:

$$\psi(\mathrm{t}) = \frac{\psi_b}{\left(\dfrac{H(t)}{D_e \cdot \phi}\right)^{1/\lambda}} \tag{1}$$

$$\mathrm{K_u(t)} = \mathrm{K_s} \cdot \left(\frac{\psi_b}{\psi(t)}\right)^{3\lambda+2} \tag{2}$$

where Ψ is the capillary pressure of the soil, Ψ_b is the bubbling pressure, λ is the pore size distribution index, H is the water content in the static storage, Φ is the soil porosity, and D_e is the effective root depth, a vegetation parameter.

The pore size distribution index (λ) is defined by physical properties related to the soil textural class (Rawls *et al.,* 1993), while the soil porosity (Φ) can be derived by this methodology or can be measured in the laboratory.

The maximum depth to consider upward capillary flow from the water table to the static storage (D_c) can be established through reference values that can be found in Brouwer *et al.* (1985). It has to be noticed that the upward capillary flow is considered cancelled when the water table is below this parameter. D_c has to be referred to the soil surface elevation (Z_s) in order to obtain the minimum elevation to consider capillary rise from the water table (Z_c).

Vegetation parameters

The plant coverage fraction (Cv) is related to the ratio between the soil covered by the perpendicular projection of the vegetation canopy and the total area of soil occupied by each functional type. It is defined as a fixed value between 1 and 0.25, and its establishment can be done through field observation, geographic information systems, aerial photography or literature reported values (Causton, 1988; Bonham, 1989; Maddock III and Baird, 2003; Scott *et al*., 2003).

Some plant specific pressure points are included as vegetation parameters. The optimum plant transpiration pressure (Ψ^*) is defined as the pressure in the precise moment when the plant still has no water availability limitations. According to Eagleson (2002), this pressure corresponds to a value of 500 kPa. In the Ecohydrological vision of Porporato *et al*. (2001), this parameter is defined as the 'point of incipient stomata closure', and can correspond to pressures up to 3000 kPa (Laio *et al*., 2001), but it depends on each plant adaptation to water scarcity. The wilting point pressure (Ψ_{wp}) is considered as the pressure in the precise moment when the plant halts its transpiration. The value can be defined considering theoretical values reported by other authors in the range between 506.63 and 1519.90 kPa (Guymon, 1994). Although many authors have agreed to consider a typical value of 1500 kPa (e.g., Kramer and Boyer, 1995; Terradas, 2001), higher values as 3000 kPa or 5.000 kPa have been suggested for plants adapted to arid environments (Laio *et al*., 2001).

The model includes, in addition, three important parameters related to root depths. The maximum root depth (D_r) defines the soil depth considered for presence of roots, while the effective root depth (D_e) defines the soil depth considered for static storage. These parameters are based on field measurement or criteria according to expert databases or references (Canadell *et al*., 1996; Kellman and Roulet, 1990; Schulze *et al.*, 1996; Schenk and Jackson 2002, 2005; Baird and Maddock III, 2005). The asphyxia root depth (D_a) sets the maximum water table elevation tolerated by roots. It can be negative for submersion resistant plants, which are tolerant to water table elevations over the soil surface. The value can be established based on field observations, expert rules or background references (Snyder and Williams, 2000; Maddock III and Baird, 2003; Baird and Maddock III, 2005; Webb and Leake, 2006). Since *RibAV* defines the interaction of biotic and abiotic factors in a spatial context, it is necessary to refer the root depth parameters to the Z_s. In this sense, the following derived parameters are defined: the maximum root depth elevation (Z_r), the effective root depth elevation (Z_e), and finally the asphyxia by saturation root depth elevation (Z_a).

Finally, two transpiration factors related to the water source are included. These parameters establish the capability and preference of the considered PFTs to transpire water from the static storage and/or the saturated zone. The first one is the transpiration factor from the unsaturated zone (r_u) which take into consideration the root system located over D_e. The second is the transpiration factor from the saturated zone (r_s) due to the part of the root system located under Z_{wt}. These parameters must assume values between 0 and 1, being the higher values those which represent a higher use of specific water source for transpiration, and being able to add more than one (Cooper *et al*., 2006; Butler Jr. *et al*., 2007). Both parameters can be established by expert rules, taking as reference the relative density of roots in both zones of the soil, unsaturated and saturated, field observation or literature reported values (e.g., Sparks, 1995; Schaeffer and Williams, 1998; Mac Nish *et al*., 2000; Snyder and Williams, 2000; Horton *et al*., 2001; Hughes *et al*., 2003; Lambs, 2004; Lamontagne *et al*., 2005; Lite and Stromberg, 2005; Scott *et al*., 2006; David *et al*., 2007; Wen *et al*., 2010).

Relations between capillary pressures and water content in the static storage

The state variable in the *RibAV* model that represents the moisture in the upper part of the soil is the water content in the static storage. Therefore, it will be needed to convert capillary pressures into water contents. Thus, other derived parameters of the model are established by using the Campbell´s equation (1), as the wilting point moisture (θ_{wp}), the optimum plant transpiration point moisture (θ^*), and the moisture content at field capacity (θ_{fc}).

The parameter D_e allows relating these pressures to water contents. This is the case of the water content equivalent to the wilting point (H_{wp}), the water content equivalent to the optimum plant transpiration point (H^*), and the water content equivalent to field capacity (H_{fc}), given by the multiplication of each specific moisture and D_e.

Hydraulic and hydrometeorological inputs

For computing the soil moisture in the unsaturated zone and the actual evapotranspiration, the *RibAV* model requires as input the daily meteorological series: precipitation (P) and potential evapotranspiration (E_0).

On the other hand, in this riparian model the hydrological regime determines the water-table fluctuations on the riparian zone. Instead of having a time series of Z_{wt} maps, it is required as input the daily series of river flows (Q) and a set of water table elevation maps ($Z_{wt,\, j}$) associated to reference flows (Q_j). Thereby, the Z_{wt} for each cell is estimated by interpolation of the reference $Z_{wt,\, j}$ maps:

$$\mathrm{Z_{wt}}(t) = \mathrm{Z_{wt,\, j\text{-}1}} + \left(\frac{Q(t) - Q_{j-1}}{Q_j - Q_{j-1}} \right) \cdot \left(Z_{wt,j} - Z_{wt,j-1} \right) \tag{3}$$

where Q is interpolated with the immediately higher and lower reference values, Q_j and Q_{j-1}, and their corresponding reference water table elevations, $Z_{wt,\, j}$ and $Z_{wt,\, j-1}$.

Water balance in the static storage

The static storage represents the upper part of the soil that is unsaturated. Since the water content in this soil layer (H) ranges between H_{fc} and H_{wp}, water can be extracted from the static storage only by evapotranspiration. As it is represented in Figure 2, the water content at the end of day t is given by the next balance equation:

$$H(t) = Max \left| \begin{array}{l} I(t) + H(t-1) - Eu(t) \\ H_{wp} \end{array} \right. \tag{4}$$

where I represents the water inputs to the static storage, and E_u is the actual evapotranspiration from the unsaturated zone.

By adding the local precipitation, the contributions from the saturated zone and the excess water, I can be calculated:

$$I(t) = P(t) + U(t) + Cwf(t) - X(t) \tag{5}$$

$$X(t) = Max \begin{vmatrix} 0 \\ P(t) + U(t) + Cwf(t) - H_{fc} + H(t-1) \end{vmatrix} \tag{6}$$

where *U* is the hydraulic lift or root water uptake, *Cwf* is the upward capillary water flow, *X* is the excess or gravitational water, *P* is the precipitation and H_{fc} is the upper limit of *H.*

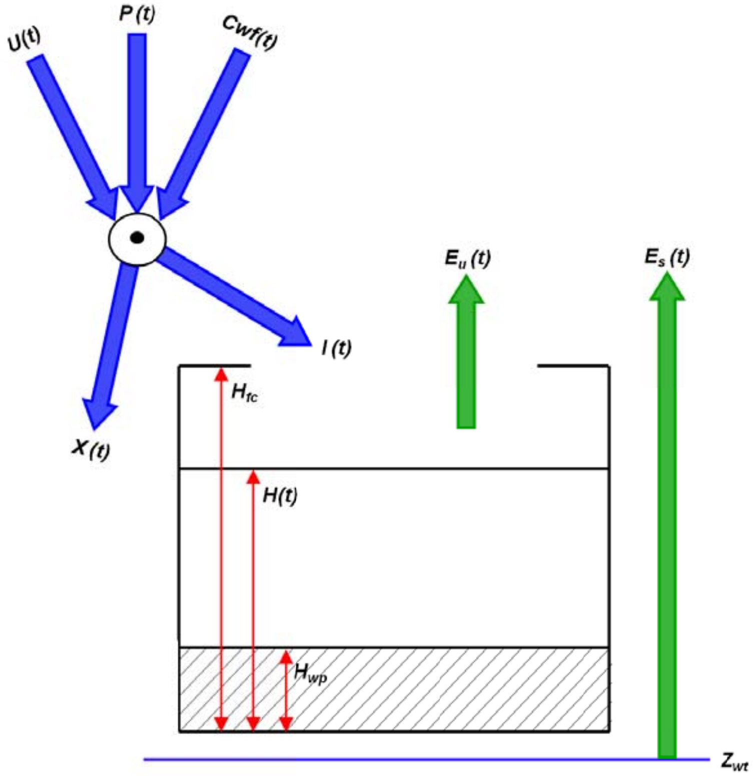

Figure 2. Tank conceptualization schema of the static storage (unsaturated upper soil) in RibAV. The input and output water fluxes are represented by blue and green thick arrows. Water contents are represented by red thin arrows. The specific meaning of the symbol representing each parameter can be found in the Appendix section.

Water fluxes from the saturated zone

The water fluxes from the saturated zone are basically two: the hydraulic lift (*U*) and the upward capillary water flow (*Cwf*).

The modelling of the *U*, root water uptake from the saturated zone, is a remarkable novelty developed in *RibAV*. This approach is based in the research of Ryel *et al.* (2002) and takes into account some considerations proposed by Lee *et al*. (2005) and Zheng and Wang (2007). Following the approach proposed by Ryel *et al.* (2002), the hourly hydraulic lift between two layers of the soil *'i,j'* ($q_{hr(i,j)}$) can be defined as function of the maximum water conductivity in root-soil interface (*Cr*), the difference between the capillary pressure of both layers of the soil ($\Delta\Psi$), the relative water conductivity in root-soil interface (C_j), the efficiency of the root conductivity expressed in terms of roots distribution in the soil (F_{root}), and a factor of occurrence (S_t):

$$q_{hr(i,j)} = -Cr \cdot \Delta \psi \cdot C_j \cdot \left(\frac{F_{root_i} \cdot F_{root_j}}{1 - F_{root_j}} \right) \cdot S_t \qquad (7)$$

S_t was considered to adopt the value 1 during the nighttime, since the hydraulic lift usually occurs during the night (e.g. Amenu and Kumar, 2008). Whereas *RibAV* has been designed for the daily scale, a corrector factor that corresponds to the number of night hours (h_n) has been included. This nighttime can be approximated to 10 hours as reported by Ryel *et al*. (2002).
The parameter F_{root} adopts values between 0 and 1 (Ryel *et al*., 2002). *RibAV* models the hydraulic lift from the water table to a unique layer, the static storage. In consequence, simplifying is possible by considering the relative density of roots in the saturated zone of the soil, which can be assumed as the vegetation parameter r_s, the transpiration factor from the saturated zone.
C_j ranges between 0 and 1, and follows an empirical relation with Ψ (Ryel *et al*., 2002; Zheng and Wang, 2007):

$$C_j = \frac{1}{1 + \left(\psi(t) / \psi_{50} \right)^{3.22}} \qquad (8)$$

where Ψ_{50} is the midpoint saturation pressure that corresponds to a relative soil moisture of 50%, and Ψ is the capillary pressure of the soil.
Moreover, Ryel *et al*. (2002) estimated the value of *Cr* as 0.97 mm MPa^{-1} h^{-1}, and this value has been consolidated in other studies (i.e. Zheng and Wang, 2007).
Taking these considerations into account, the calculation of *U* in *RibAV* is proposed as follows when the water table elevation is connected to the root system during the night:

$$U(t) = Max \left| \begin{matrix} 0 \\ -Cr \cdot h_n \cdot (\psi_{fc} - \psi(t)) \cdot \left[\frac{1}{1 + \left(\frac{\psi(t)}{\psi_{50}} \right)^{3.22}} \right] \cdot r_s \end{matrix} \right. \qquad (9)$$

where, for each unit area, *Cr* corresponds to 0.97 mm MPa^{-1} h^{-1}, h_n corresponds to 10 hours of nighttime, Ψ_{fc} is the field capacity point pressure, and r_s corresponds to the value of the transpiration factor from the saturated zone.
On the other hand, in order to describe the *Cwf* in riparian zones, the Darcy's equation (Skaggs, 1978) is used, considering K_u (the hydraulic conductivity of the unsaturated soil), which is calculated through the equation 2. There are two possible cases. Firstly, if $Z_e > Z_{wt}$, the upward capillary water flow from the saturated zone is given by:

$$Cwf(t) = Max\left|\begin{array}{l} 0 \\ Min\left|\begin{array}{l} H_{fc} - H(t-1) - U(t) \\ \left[\left(\dfrac{-0.102\cdot\psi(t)}{Z_{wt}(t) - Z_e}\right) - 1\right]\cdot 24K_u(t) \end{array}\right. \end{array}\right. \tag{10}$$

In this case, two values are required to be included as dimensional corrections, *[0.102 m water column kPa^{-1}]* and *[24 h d^{-1}]*. In a second case when $Z_{wt} \geq Z_e$, it is assumed the hypothesis in which the upward capillary water flow is enough to fill the static storage tank up to field capacity. Then, *Cwf* is calculated with the following equation:

$$Cwf(t) = H_{fc} - H(t-1) - U(t) \tag{11}$$

Finally, since the Z_c threshold corresponds to the minimum elevation needed to be exceeded by the Z_{wt} to allow capillary water rise, if $Z_c \geq Z_{wt}$ the *Cwf* is 0.

Actual evapotranspiration in the riparian zone

In *RibAV*, the actual evapotranspiration (E) is determined by the soil saturation, the roots connectivity with the water table (Maddock III and Baird, 2003; Baird and Maddock III, 2005), and the soil moisture content (Inamdar *et al.,* 1999; Altier *et al.,* 2002; Dahm *et al.,* 2002). This is the reason why the actual evapotranspiration estimation in the *RibAV* model includes the evapotranspiration from the unsaturated upper part of the soil (E_u) represented by the static storage, and the evapotranspiration from the saturated zone of the soil (E_s):

$$E(t) = E_u(t) + E_s(t) \tag{12}$$

In order to estimate E, *RibAV* starts from the potential evapotranspiration (E_0), as the simplest and most traditional way to represent the energy availability and the atmospheric conditions in the process (Allen *et al.*, 1998; Butler Jr. *et al.,* 2007). As it has been explained before, the water source for the transpiration is defined by the vegetation factors that control the capacity and/or preference of water collecting from the static storage and/or the groundwater, r_u and r_s.

The process extinction, evapotranspiration equal to cero, is simulated both when the water table and the root system are disconnected and when the upper part of the soil is saturated in an unbearable level for the plants. The first case is specific for the evapotranspiration from the saturated zone and is defined by the maximum root depth elevation. When the root system and the water table are not connected ($Z_{wt} < Z_r$), E_s is 0. The second case of evapotranspiration extinction considers flood duration, frequency, depth, and seasonality as critical factors for the riparian species composition and distribution (Brinson and Verhoeven, 1999; Tabacchi *et al.,* 2005), since the soil saturation generates anaerobic conditions that affect the plant physiology. In order to include this effect in the model, the vegetation parameter asphyxia by saturation root depth elevation represents the maximum water table elevation from which the roots are not able to collect more water due to soil saturation. Thus, E is 0 when the water table exceeds this critical elevation ($Z_{wt} \geq Z_a$).

There are two more possible cases considering the effective root depth elevation (Z_e) threshold. The first case considers the water table between Z_a and Z_e. In this case ($Z_a > Z_{wt} \geq Z_e$) the evapotranspiration can be at potential rate, being the unsaturated evapotranspiration proportional to the relative water availability between Z_{wt} and Z_a:

$$E_u(t) = r_u \cdot Cv \cdot E_0(t) \cdot \left(1 - \frac{Z_{wt} - Z_e}{Z_a - Z_e}\right) \tag{13}$$

and being given the evapotranspiration from the saturated soil by:

$$E_s(t) = Min \left| \begin{array}{l} Cv \cdot E_0(t) - E_u(t) \\ r_s \cdot Cv \cdot E_0(t) \cdot \left(1 - \dfrac{Z_{wt} - Z_e}{Z_a - Z_e}\right) \end{array} \right. \tag{14}$$

The second case occurs if the water table is located below the effective root depth but connected with the root system ($Z_e > Z_{wt} \geq Z_r$). In this case the E_u is determined by the static storage of water in the soil, by the plant coverage and by the efficiency of water transpiration defined by the extraction curve. In *RibAV*, it is assumed that plants transpirate with no restrictions when there are optimum moisture content conditions in the soil (θ^*). It is considered also that the evapotranspiration is reduced linearly as the moisture is lower (e.g. Laio *et al.*, 2001), until it remains null at the wilting point moisture (θ_{wp}). Thereby, if the water content before the evapotranspiration from the unsaturated zone starts is under the wilting point water content ($H(t-1) \leq H_{wp}$), E_u is null. On the contrary, if $H(t-1) > H_{wp}$, the relative water content (H_{rel}) is calculated by the following expression (15) and takes part in the E_u equation (16):

$$H_{rel}(t) = Min \left| \begin{array}{l} 1 \\ \dfrac{H(t-1) - H_{wp}}{H^* - H_{wp}} \end{array} \right. \tag{15}$$

$$E_u(t) = Min \left| \begin{array}{l} H(t-1) - H_{wp} \\ r_u \cdot Cv \cdot E_0(t) \cdot H_{rel}(t) \end{array} \right. \tag{16}$$

Finally, in this case the E_s calculation considers a linear increasing evapotranspiration curve (Maddock III and Baird, 2003), the coverage vegetation factor, and the efficiency in water collecting, with a limitation of the available energy after the E_u:

$$E_s(t) = Min \left| \begin{array}{l} Cv \cdot E_0(t) - E_u(t) \\ r_s \cdot Cv \cdot E_0(t) \cdot \left(\dfrac{Z_{wt}(t) - Z_r}{Z_e - Z_r}\right) \end{array} \right. \tag{17}$$

The evapotranspiration index, E_{idx}

In the present paper, the E_{idx} is proposed for the modelling of the spatial distribution of different PFTs. The E_{idx} is a dimensionless measure of the interaction between abiotic and biotic factors in the riparian zone. It is defined as a relation between the actual evapotranspiration rate calculated by *RibAV* and the potential evapotranspiration corrected by the coverage of the analyzed PFT, for the simulation period between day *t=1* and day *n*:

$$E_{idx}(t) = \frac{1}{n}\sum_{t=1}^{n}\frac{E(t)}{Cv \cdot E_0(t)} \tag{18}$$

where E is the actual evapotranspiration rate, E_0 is the potential evapotranspiration, and Cv is the coverage.

The E_{idx} assumes values between 0 and 1. An E_{idx} value equal to 1 represents a maximum evapotranspiration rate, equivalent to the potential evapotranspiration of the analyzed PFT. On the contrary, a value equal to 0 represents a persistent extinction of the evapotranspiration.

The followed methodology considers as predicted PFT for a specific unit area, the one with a higher value of E_{idx}, compared to the other PFTs analyzed under the same conditions and during the same time-period.

Study sites description

Two study sites have been selected to implement the *RibAV* model: the Terde reach in the Mijares River and the Lorcha reach in the Serpis River (Figure 3). Both reaches are located in the Jucar River Basin district, under semi-arid environmental conditions.

The Terde reach (Mijares River). The Terde reach is located in the Mijares River, upstream the village of Sarrión in the province of Teruel (UTM coordinates: 689350, 4448916). It is located at 850 m.a.s.l. and it has 539 m length. Terde is a typical Mediterranean reach that shows an important seasonality and considerably variability in the discharge between humid and dry years. The average annual values of temperature and precipitation are 11 ºC and 500 mm respectively, being most of the rainfall concentrated in the autumn and spring seasons. The accumulated basin area is 665 km^2 and the average daily discharge is 0.855 $m^3 s^{-1}$ for available data between 1948 and 2009. Terde can be considered near to natural conditions because there is not important flow regulation upstream and the riparian area is continuous and connected with the terrestrial vegetation areas. Willows and poplars are dominant within the riparian main vegetation. The substrate is varied being predominant gravels or blocks in different areas of the reach.

The Lorcha reach (Serpis River). The Lorcha reach, with 239 m long, is located in the Serpis River at 229 m.a.s.l. below the Beniarrés dam, near the village of Lorcha in the province of Alicante (UTM coordinates: 733362, 4304165). The average annual values of temperature and precipitation are 18 ºC and 820 mm

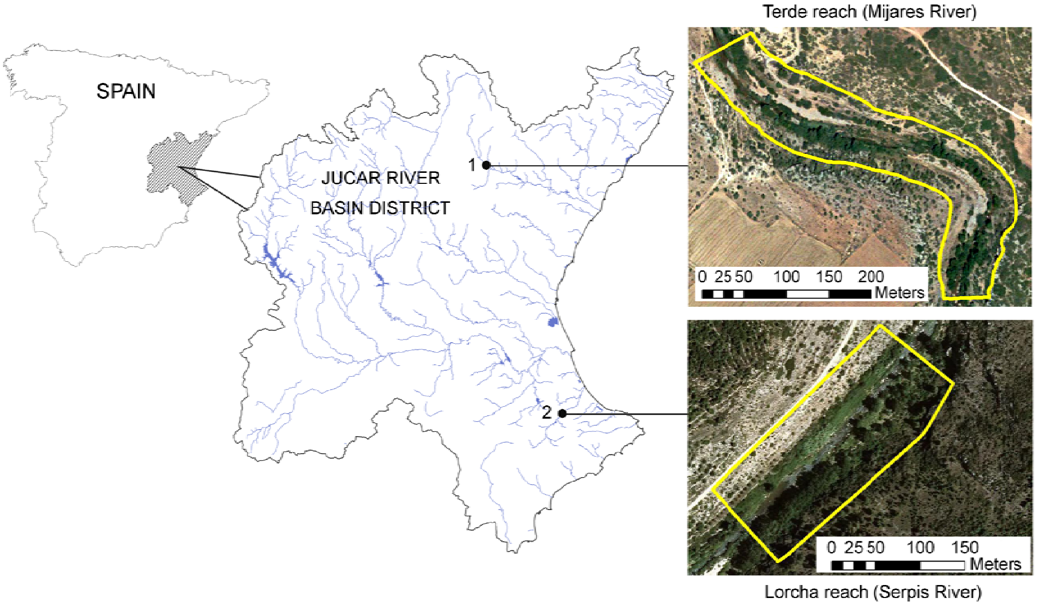

Figure 3. Location of the study sites in the Júcar River Basin District, East Spain. (1) Terde reach in the Mijares River (Teruel, Spain); (2) Lorcha reach in the Serpis River (Alicante, Spain).

respectively, with a summer season especially dry that is characterized by scarcity of rainfall and high temperatures. The accumulated basin area is 753 km^2 and the average daily discharge is 1.27 m^3 s^{-1} for available data between 1998 and 2009. The bed is fairly stable and large blocks are occasionally present. The differences between the both margins are important in terms of substrate and insolation. In the left margin the gravel dominates while in the right margin the substrate is mainly composed by sand. The riparian main vegetation consists of willows, being oleanders and brambles also abundant. The reach has flow regulation upstream. However, the environmental conditions in the riparian zone are considered good in terms of structure, connectivity and diversity.

Plant functional types definition

Three PFTs were considered for the *RibAV* model implementation: herbaceous riparian vegetation (HRV), woody riparian vegetation (WRV), and terrestrial vegetation (TV).

The HRV functional type included the non-woody plants that require frequent saturated soil conditions to have a good development. These species have shallow root systems and can be found usually in areas adjacent to the stream, where the water table elevation is also shallow. Different plants, from small herbaceous stands to well-developed reed beds, were included in this PFT. The WRV functional type included riparian woody trees and shrubs, most of them poplars, willows and oleanders. The plants considered in this PFT have long roots with a high efficiency extracting water from the saturated zone. Although they have also a certain tolerance to root asphyxia, it is lower than those included in HRV. Finally, TV grouped all the terrestrial vegetation, meaning all the herbs, shrubs and trees that are not part of the riparian ecosystem itself. In fact, the species included in this PFT represent the zonal vegetation of the area and they would be found instead of the riparian plants if there were no water flow and, therefore, the water table was found at a greater depth under the soil surface.

Model inputs definition

Different institutions services, as the National Climatic Data Bank of the State Agency of Meteorology (AEMET), the Centre for Hydrographical Studies (CEH-CEDEX), and the Valencian Institute for Agricultural Research (IVIA), supplied the data needed to obtain the hydro-meteorological inputs for the *RibAV* model simulations: daily precipitation (P), daily potential evapotranspiration (E_0), and daily river flow (Q).

These supplied data series required an adjustment to each site location. Seven meteorological stations were considered to interpolate the precipitation data for the Terde reach; five in the case of the Lorcha reach. The inverse distance weighting method was applied for this purpose.

Temperature series were employed for the E_0 data estimation. For the Terde reach the temperature data came from the meteorological station of Sarrión (AEMET), and was corrected for elevation (6.5 ºC/1000m). In the Lorcha reach the temperature series came from different surrounding meteorological stations (AEMET, IVIA) due to their lack of information in different periods along the series. Available data of E_0 obtained by Penman-Monteith equation (Planes station, IVIA) were taken as reference to calibrate by regression the simplified Hargreaves equation (Allen *et al.*, 1998). Finally the calibration resulted in the reduction of the default correction factor to a value of 0.001887 (R^2=0.883). The following modified Hargreaves equation was applied in the in-site E_0 data series estimation:

$$E_0(t) = 0.001887\cdot(T_{med}(t)+17.78)\cdot R_a(t)\cdot(T_{\max}(t)-T_{\min}(t))^{0.5} \tag{19}$$

where, T_{med}, T_{max} and T_{min} are the medium, maximum and minimum daily temperatures respectively, and R_a is the daily extraterrestrial radiation tabulated for each month (Allen *et al.*, 1998).

The daily river flow data series needed no corrections. In the Terde reach these data were available from the gauging station named 'Río Mijares en Terde' (CEDEX) which is located 550 m downstream of the study site. The watershed area is very similar and there are no tributaries or springs between them. The same occurred in the Lorcha reach. The gauging station named 'Villalonga' (CEDEX) is located 3.12 km downstream of the reach and there are not important contributions or withdrawals between both points. The periods in which all the hydro-meteorological data were available were from January 1st, 1949 to December 31st, 2009 in the Terde reach and from January 1st, 1999 to December 31st, 2009 in the Lorcha reach. Monthly averaged values and coefficient of variation of these hydro-meteorological data are shown in **¡Error! No se encuentra el origen de la referencia.** 4.

In addition, soil and vegetation maps were required for the model implementation. All these maps had a pixel size of 1 m. The soil maps, containing the different soil types, allowed the selection of the corresponding set of parameters in each cell during the model simulation (Table 1.). On the other hand, the vegetation maps that contained the observed PFTs in each study site were only

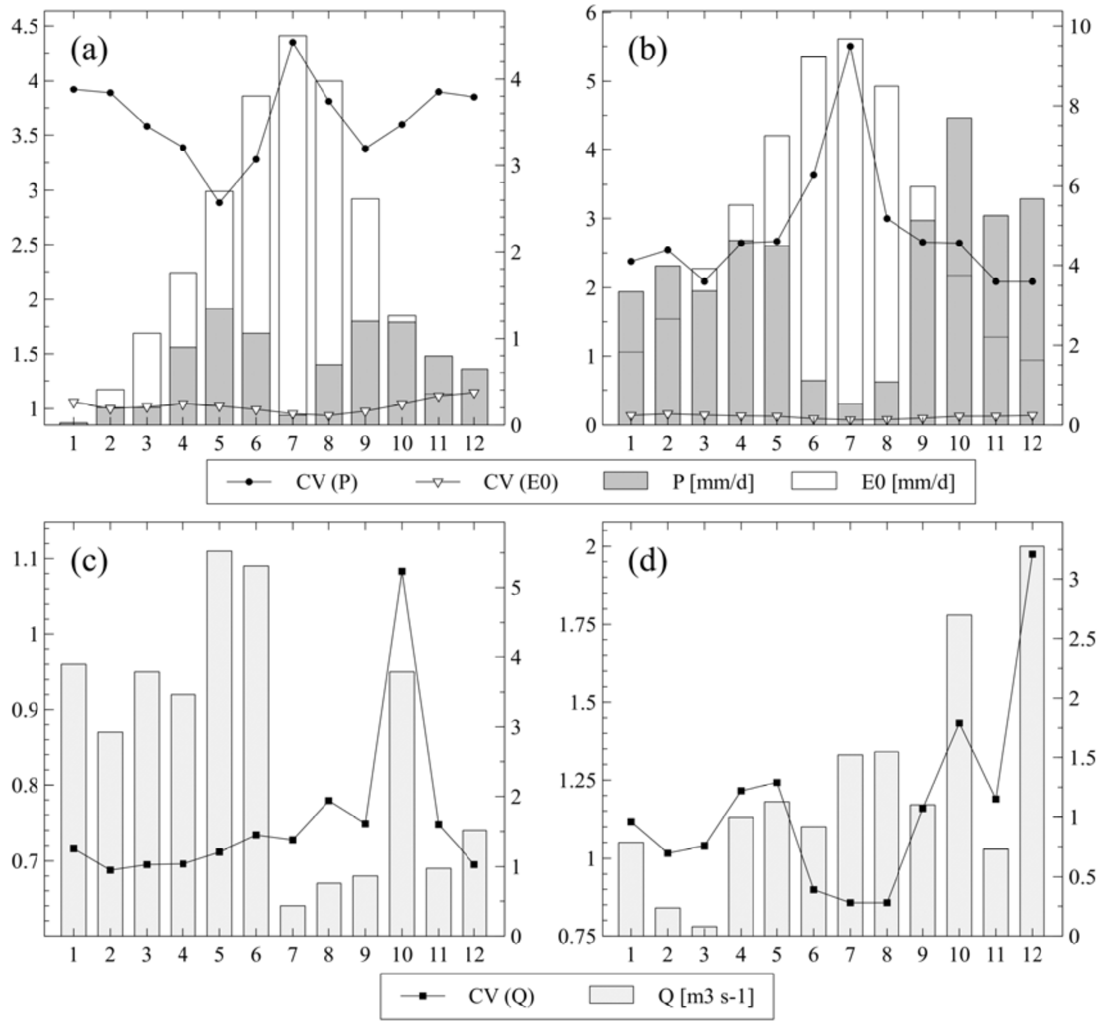

Figure 4. Monthly average data (left axes) and coefficient of variation (right axes) of the daily precipitation (P) and daily potential evapotranspiration (E_0) from the Terde (a) and Lorcha reaches (b); monthly average data (left axes) and coefficient of variation (right axes) of the daily mean river discharge (Q) from the Terde (c) and Lorcha reaches (d).

used for comparison issues during the calibration and the validation processes in the model performance evaluation.

For the soil parameters establishment, ten soil samples (extracted at 30-60 cm soil depth) from each reach were analyzed in one of the soil laboratories of the Universitat Politècnica de València (Spain). The percentages of gravel, sand, silt, clay and organic matter were introduced in the model "Soil Water Characteristics" (Saxton and Rawls, 2006), which provided for each soil type the water retention curves, defined by the following parameters: the soil moisture at field capacity, the porosity, the saturated hydraulic conductivity, the bubble pressure, and the porosity index. The D_c values were established considering the texture of the soils (Brouwer *et al.*, 1985), and a Ψ_{fc} of 33 kPa was considered.

The reference maps of water table elevation ($Z_{wt,\ j}$) were obtained using the Guad-2D software, which includes the finite volume based two-dimensional model of the same name for the numerical simulation of transient flows over

Table 1. Basic parameters of the soil types present in the Terde reach and in the Lorcha reach.

	ID	Φ	λ	Ψ_b	K_s	D_c	Soil type description
Terde reach (Mijares River, Spain)	1	0.397	0.530	3.848	56.24	4.0	Light coloured soil mainly composed of sand and gravel. Large blocks and bedrock outcrops are present.
	2	0.436	0.209	0.342	22.65	6.0	Dark soil with great boulders present on the surface; silt and gravel dominate in depth.
	3	0.441	0.226	2.625	19.91	7.0	Similar to soil 2 but with a higher presence of gravel and a lighter colour.
	4	0.406	0.277	1.037	42.76	8.0	Fine textured soil with a silt-clay main composition. The absence of gravel is characteristic.
	5	0.412	0.220	0.057	28.19	4.0	Soil that consists of coarse sand and gravel. Surface has boulders which presence decrease in depth.
	6	0.432	0.184	0.246	37.09	4.0	Soil that mainly consists of coarse sand and gravel. It contains some silt conglomerates.
	7	0.414	0.251	0.024	97.96	4.0	Sandy and loose soil without plasticity.
	8	0.423	0.231	0.056	34.45	5.0	Black loamy soil with a strong presence of gravel and boulders.
	9	0.398	0.278	2.370	26.83	6.0	Light coloured soil composed mainly of sand and silt.
	10	0.403	0.207	0.045	25.06	5.5	Soil with medium particle size. Its composition is mainly gravel with a matrix of very coarse sand.
Lorcha reach (Serpis River, Spain)	1	0.401	0.456	5.837	36.78	6.0	Soil composed of sand and silt.
	2	0.412	0.315	4.403	22.62	7.0	Soil composed mostly of silt.
	3	0.407	0.266	2.475	32.00	6.0	Sand and silt are the textures that dominate this soil.
	4	0.450	0.238	4.343	15.81	8.0	Soil mainly composed of silt and without gravel.
	5	0.502	0.233	1.253	46.38	5.0	A soil with two marked horizons, the upper one with organic matter predominance and the lower one with gravel.
	6	0.458	0.206	1.196	14.32	4.0	Soil mainly composed of sand and gravel.
	7	0.441	0.215	0.187	30.53	4.0	Soil composed of sand and gravel.
	8	0.435	0.238	0.984	40.39	6.0	Composed mainly of sand and silt.
	9	0.412	0.209	0.021	38.82	4.0	Soil mainly composed of gravel but also of sand.
	10	0.486	0.260	0.516	40.02	6.0	Soil composed of gravel and sand, with an important presence of organic matter.

The specific meaning of the symbol representing each parameter can be found in the Appendix section.

irregular topography, under the shallow water equations hypothesis (Murillo *et al*., 2008). The digital elevation model and a Manning roughness map (roughness estimated according to Cowan's procedure) were included as input of this model. Sixteen reference flows (Q_j) for the Terde reach ranging from 0 to 150 $m^3 s^{-1}$ and other thirteen for the Lorcha reach ranging from 0.1 to 75 $m^3 s^{-1}$ were modeled. Once the water surface elevation maps were obtained, they were interpolated horizontally by the Thiessen proximity algorithm to represent the Z_{wt} under the banks along the reaches. The same pixel size of 1 m was maintained for all the input maps, also the same surface extension for each specific study site.

Calibration and validation methodology

The model was calibrated in the Terde reach (Mijares River, Spain) considering a time period of 61 years (1949-2009). The calibration process required iterative variations of the vegetation parameters values followed by the comparison between the simulated map (obtained using the E_{idx} as conclusive index for the distribution of the PFTs) and the map corresponding to the observed vegetation. This comparison did not consider those cells in which the observed vegetation was almost inexistent, for example, those areas where bare sediment was observed, because they are mainly gravel bars caused by sediment deposition processes that could not be simulated through the model.

The value of 0.97 $mm\,MPa^{-1}\,h^{-1}$ reported in the literature (Ryel *et al.*, 2002; Zhen and Wang, 2007) for *Cr* was selected for all the analyzed PFTs. Regarding the pressures, Ψ^* were set as 500 KPa (Eagleson, 2002), while Ψ_{wp} were set as 1500 KPa for riparian PFTs (e.g., Kramer and Boyer, 1995) and 3000 KPa for the adapted to semi-arid conditions terrestrial vegetation (Laio *et al*., 2001). Finally, several assumptions conditioned the establishment of the parameters related to the vegetal coverage fraction (*Cv*). The riparian vegetation is typically lush due to the high contribution of resources (water, nutrients, sediments, etc.) by the river. Through aerial photographs and field observations this fact was verified and we decided to consider complete the soil coverage by the riparian vegetation in the vegetated patches. The terrestrial vegetation in Mediterranean semi-arid environments is usually more scattered than most of the riparian vegetation, which was corroborated especially in the reach used for the calibration of the model (Terde). In consequence, values of 1 to HRV and WRV, and 0.8 to TV were assigned.

The remaining vegetation parameters needed to be calibrated. Values from 0.5 to 1.3 m were attempted for the establishment of D_r in HRV. Those values were related to D_e values ranging between 0.3 and 0.9 m, avoiding incoherent combinations in which the D_e values were higher than D_r. The D_r values for WRV ranged between 3.0 and 6.0 m; these values were related to D_e values between 0.5 and 3.0 m. The r_u value for HRV was forced to be the lowest, between 0.3 and 0.7, and r_s the highest, between 0.6 and 0.9. In addition, D_{sat} was forced to be the highest considering values between 0.5 and 1 m above the soil surface. The calibration of r_u and r_s considered a rank of 0.3-0.8 for WRV. TV was supposed to obtain a maximum value of r_u (0.9-1.0), an approximately null value of r_s (0.0-0.1), and a critical D_{sat} located under the soil surface, just below the effective root depth. After these parameters were considered to be correctly calibrated, the model was spatially validated in the Lorcha reach (Serpis River, Spain) considering a time period of 11 years (1999-2009).

Objective functions

The confusion matrix that resulted from the comparison between the observed and the simulated maps allowed the calculation of the correctly classified instances (*CCI*), the kappa (*k*) coefficient of agreement (Cohen, 1960), and the weighted kappa (*k**) coefficient (Cohen, 1968). These coefficients, which maximum value is 1 representing a perfect agreement, were employed in the model performance analyses comparing one to one the distribution of all the PFTs present in the maps.

Additionally, other criteria were analyzed in terms of the presence/absence of each PFT: the area under the curve (*AUC*), the *sensitivity* as correctly predicted positive fraction, the *specificity* as correctly predicted negative fraction, the *omission rate* as falsely predicted negative fraction, the *commission rate* as falsely predicted positive fraction, and the accuracy (*ACC*) understood as the proportion of the presence and absence records correctly identified.

RESULTS

The model was considered calibrated for the prediction of the PFTs distribution in the Terde reach with the vegetation parameters shown in Table 2. Root depths resulted on values under a meter for HRV, and approximately two meters for TV. In both PFTs the distance between D_r and D_e was very small, only 20-30 cm. WRV obtained higher values for D_r (3.2 m) that contrasted with a reduced value of D_e (0.8 m), very similar to the value established for HRV (0.6 m).

Table 2. Vegetation basic parameters for the plant functional types considered in the *RibAV* model implementation.

PFTs	D_r	D_e	D_{sat}	r_u	r_s	Ψ^*	Ψ_{wp}	Cv
HRV	0.8	0.6	-0.7	0.5	0.6	500	1500	1
WRV	3.2	0.8	-0.3	0.7	0.3	500	1500	1
TV	1.9	1.6	1.59	1	0	500	3000	0.8

The specific meaning of the symbol representing each parameter can be found in the Appendix section.
HRV, herbaceous riparian vegetation; PFTs, plant functional types; TV, terrestrial vegetation; WRV, woody riparian vegetation.

The phreatophytic character of the riparian plants is expressed through the negative values of D_{sat}. The more negative the value for asphyxia by saturation root depth is the greater is the flood elevation resistance of the PFT. Taking this into account, HRV was forced to be the more resistant obtaining a D_{sat} value of 0.7 meters above the soil surface elevation; half a meter less was assigned to WRV (0.3 m above the soil surface), and just under the D_e was assigned to TV because this PFT groups non-phreatophytic species.

The phreatophytic or non-phreatophytic character of the different species included in each PFT was also emphasized through the transpiration factors (r_u and r_s). The more phreatophytic the PFT is the higher r_s value must be assigned. Following the previous consideration, a high r_s value of 0.6 was assigned to HRV and lower values were assigned to WRV; TV obtained a null value for this parameter. On the other hand, a maximum r_u value of 1 was assigned to TV while the riparian PFTs obtained lower values due to the disadvantage on the transpiration from this zone compared to the terrestrials. Indeed, HRV obtained a lower r_u value than r_s.

The objective functions results (Table 3) represent the quality performance of the calibration and validation from two points of view: considering simultaneously all the PFTs and comparing each PFT presence/absence simulation agreement.

Table 3. Indices of the *RibAV* model calibration and validation performance using E_{idx} as conclusive index for PFTs distribution.

CALIBRATION CASE STUDY: Terde reach (Mijares River, Spain)				
Three PFTs confusion matrix	CCI		0.675	
	k		0.460	
	k*		0.670	
			Plant Functional Type	
		HRV	*WRV*	*TV*
PFTs absence/presence confusion matrices	AUC	0.584	0.648	0.673
	Sensitivity	0.525	0.492	0.846
	Specificity	0.306	0.212	0.501
	Omission rate	0.163	0.598	0.240
	Commission rate	0.914	0.722	0.365
	ACC	0.331	0.319	0.676
VALIDATION CASE STUDY: Lorcha reach (Serpis River, Spain)				
Three PFTs confusion matrix	CCI		0.750	
	k		0.510	
	k*		0.645	
			Plant Functional Type	
		HRV	*WRV*	*TV*
Each PFT presence/absence confusion matrix	AUC	0.580	0.778	0.765
	Sensitivity	0.906	0.423	0.983
	Specificity	0.254	0.021	0.548
	Omission rate	0.010	0.951	0.040
	Commission rate	0.968	0.768	0.264
	ACC	0.271	0.186	0.792

CCI, kappa (K) and weighted kappa (k*) indices resulted from confusion matrices that compare every PFT. The other indices were obtained through the absence/presence matrices of each PFT.

ACC, accuracy; CCI, correctly classified instances; HRV, herbaceous riparian vegetation; PFTs, plant functional types; TV, terrestrial vegetation; WRV, woody riparian vegetation.

Confusion matrices that compared the three analyzed PFTs were characterized by *CCI*, *k* and *k** coefficients of agreement. *CCI* achieved a value of approximately 0.68 in calibration being higher in the validation case study (0.75). In both cases, the *k** values (0.67 in calibration and 0.65 in validation) were considerably better than the *k* values (0.46 and 0.51, respectively) proving that *RibAV* makes not only very few but also reasonable mistakes between PFTs distributions. In both case studies, when the absence/presence of each PFT was studied, values between 0.58 and 0.78 were obtained in terms of AUC for each PFT absence/presence confusion matrix. Sensitivity values higher than 0.42 and good ACC results up to 0.79, were obtained in addition.

The static comparison and hierarchical organization of the E_{idx} values obtained for each observed PFT (Figure 5), resulted to be a good criterion for the prediction of the riparian zonation in the long term, since the actual observed PFT was considered correctly simulated when a higher value of E_{idx} for the observed PFT was obtained respect to the other PFTs. Consequently, the E_{idx} was validated as a good indicator for PFTs response/adaptation to the variable environmental conditions of each unit area.

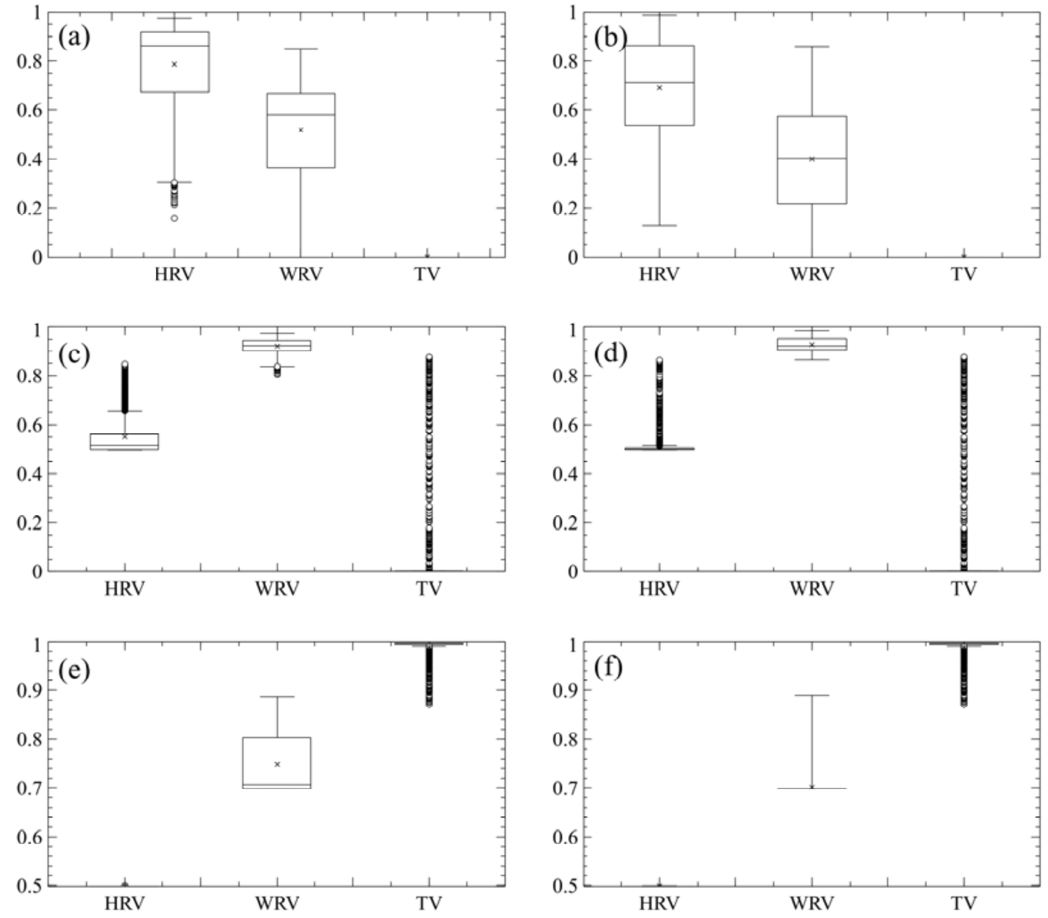

Figure 5. *RibAV* evapotranspiration index (E_{idx}) values obtained for the different plant functional types (PFTs) analysed in the cases when the actual observed PFT was herbaceous riparian vegetation (HRV) in Terde (a) and in Lorcha (b), woody riparian vegetation (WRV) in Terde (c) and in Lorcha (d) and terrestrial vegetation (TV) in Terde (e) and in Lorcha (f).

Finally, the model reproduced correctly the transverse distribution of the riparian vegetation at reach scale (Figure 6). The distinction between the terrestrial vegetation and the riparian PFTs was remarkable, with no cells simulated as terrestrial vegetation in typical riparian areas (areas adjacent to the water course, islands, etc.). In the same way, the herbaceous riparian vegetation was located in very wet areas and did not appear in typical terrestrial areas (areas located far from the aquatic zone with lower soil moisture content and considerably deep water table).

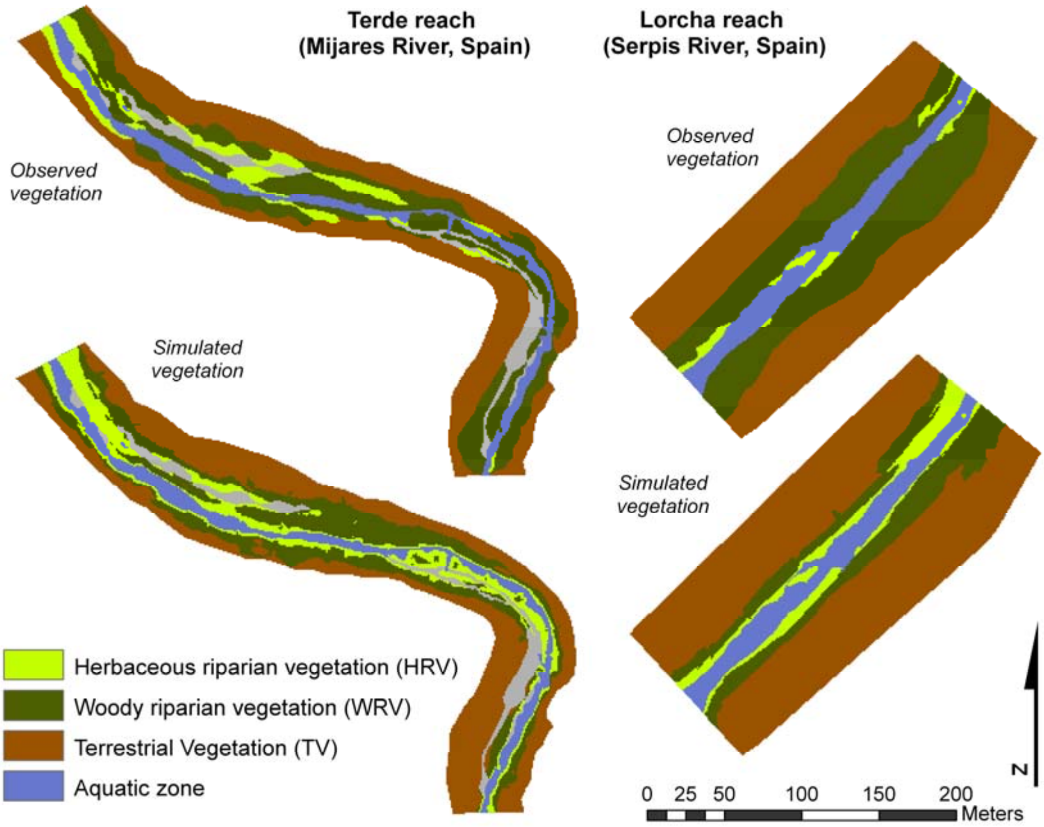

Figure 6. Observed and simulated vegetation maps at both study sites where the *RibAV* model was calibrated and validated. The plant functional types appear with different colours, whereas bared areas appear in grey.

DISCUSSION AND CONCLUSIONS

An ecohydrological model for evapotranspiration and vegetation distribution modelling in riparian zones, the *RibAV* model, is presented. By including the knowledge of many disciplines, this model considers the plant growth from two perspectives of water availability: the static storage and the saturated zone. The *RibAV* model incorporates the strengths of quantifying and analyzing the evapotranspiration of the riparian vegetation from the perspective of the groundwater (Stromberg *et al.,* 1996; Horton and Clark, 2001; Mac Nish *et al.,* 2000; Horton *et al.,* 2001; Maddock III and Baird, 2003; Baird and Maddock III, 2005; Lamontagne *et al.,* 2005; Lautz, 2008; Schilling and Kiniry, 2007) and the water availability in the unsaturated zone both when there are shallow water tables and when they are far from the surface (Lowrance *et al.,* 1998; Inamdar *et al.,* 1999; Goodrich *et al.,* 2000; Lowrance *et al.,* 2000; Scott *et al.,* 2000; Altier *et al.,* 2002; Dahm *et al.,* 2002). The modelling of water fluxes from the saturated zone, as the hydraulic lift from the saturated zone, means an important milestone developed in *RibAV*. Through this paper, the mathematical conceptualization of this static tank flow model is described.

The *RibAV* model is also an innovative tool for water management since the generated rates of evapotranspiration of the different PFTs can determine by themselves how the riparian zone is affecting the water balance. In addition, it can be useful in the riverine ecosystems management since it predicts in an efficient manner the different PFTs present in these ecosystems of semi-arid Mediterranean environments. The *RibAV* model, through its E_{idx} calculation, allows not only the presence/absence determination of each riparian PFT but also the goodness of their situation, representing a major improvement respect to other models. Thereby, *RibAV* provides the scientific community with a tool that frequently has been pointed out as necessary (e.g., Schaeffer and Williams, 1998; Mac Nish *et al.,* 2000; Scott *et al.,* 2000; Snyder and Williams, 2000; Tabacchi *et al.* 2000; Hughes *et al.,* 2003; Lamontagne, 2005; Lautz, 2008). To accomplish the necessities stated by the European Water Framework Directive (WFD 2000/60/EC), the model required in addition to be spatially distributed, objective that has been accomplished in this paper. In addition, although regarding the habitat characterization protocols available in Europe, many of them include the riparian vegetation structure (Fernandez *et al*., 2011) no other indexes in use integrate the complex interactions occurring among the soil, water and vegetation, like the E_{idx} does.

To implement plant distribution models correctly, it is necessary to count on reliable procedures for their calibration and performance evaluation based on efficiency indexes (Manel *et al.*, 2001; Mouton *et al.*, 2010). For the performance analysis of the *RibAV* model as a PFTs spatial distribution simulation tool, the riparian zones of two semi-arid Mediterranean reaches from different rivers were selected. The model was calibrated in a natural reach called the Terde reach (Mijares River), and then spatially validated in a second study site with flow regulation, the Lorcha reach (Serpis River). A confusion matrix was obtained as a result of the comparison of the observed and the simulated PFTs distribution maps. Then, different criteria based on the confusion matrix were selected to evaluate the model performance and its efficiency in the simulation of the PFTs distribution. The model performed in a good manner under the different discharge regimes of the two case studies. The use of time series with different lengths between study sites demonstrated that is not necessary to analyze extremely long periods in order to obtain good results. In addition, the selected pixel size of 1 m was a good choice and it is recommended for further applications of the model.

The model set-up involved an important effort in the estimation of the basic parameters. These estimations were based on expert knowledge, field data and calibration techniques. Each group of parameters could be established by one or more of those techniques, increasing the versatility of the model implementation. Other parameters could be established with complementary models (i.e. Saxton and Rawls, 2006). For some vegetation parameters, it was considered recommendable to take into account specific ranks based in the scarce but valuable literature available (i.e., Schenk and Jackson, 2002; González *et al*., 2012) and the eco-physiological characteristics of each PFT, to delimit the options in the calibration.

RibAV was considered to be correctly implemented once the parameters were calibrated and validated. Several indices were selected in order to combine their potential benefits in the performance evaluation. Although some opinions are against the use of kappa coefficient, it has been considered as a useful tool, better than overall accuracy. Kappa is a simple and standardized tool, effective to establish the agreement between nominal data comparison, and it considers and corrects the agreement achieved by chance (Hagen, 2002; Hanberry *et al*., 2012, Manel *et al*., 2001). Apart from CCI and kappa, AUC was calculated because it is considered to be independent of prevalence despite its high correlation with kappa (Manel *et al*., 2001). These indices are widely used and are considered as adequate criteria for the categorical evaluation of a model performance (Mouton *et al*., 2010). The calculation of other absence/presence indices was additionally helpful in the decision making during the calibration process.

The calibration and validation results showed in this paper demonstrate that the model is able to simulate different PFTs distribution satisfactorily through the E_{idx} comparison in the riparian zone of Mediterranean river reaches. CCI values of approximately 0.7, kappa values close to 0.4 and weighted kappa values of 0.6 proved the quality of the *RibAV* model for predicting PFTs distribution. The capabilities of the model in terms of each PFT absence/presence were also tested, obtaining average AUC values of 0.7, and ACC values close to 0.4 in riparian PFTs and almost 0.9 in the terrestrial vegetation. The obtained results, E_{idx} values for each PFT and the simulated maps (Figures 5 and 6), revealed the model capabilities to reproduce correctly the typical transverse distribution of the riparian vegetation in both study sites. This transverse distribution of the vegetation in the riverine areas has been related to the hydrological periods, the topography, the sediment types and the competition between species (Hupp and Osterkamp, 1985, 1996; Naiman *et al*., 2005).

In summary, the hydrological regime of the rivers in semi-arid environments determine the riparian vegetation distribution and represent the main source of water during the dry season, controlling the local water table elevation. In Mediterranean climates, typically semi-arid, the presence/absence of different PFTs is controlled by their response and adaptation capacity under stress conditions, such as water scarcity periods during the dry season alternated with periods in which the soil is saturated causing root asphyxia. In this sense, it has been demonstrated that the *RibAV* model, with its base in a soil-plant-atmosphere continuum schema, and its E_{idx}, can be applied as an indicator of the vegetation response to fluctuations on saturated and unsaturated water availability. Through this technique, the limitations of analysing the evapotranspiration from the saturated zone and the static storage separately are suppressed, implying that *RibAV* provides an innovative tool pointed out as necessary. Considering that the natural variability of water sources is not only temporal but also spatial, it is not surprising the frequent adaptation of the riparian vegetation to each river dynamics and variable conditions. The potential use of the described methodology, not only allows the simulation of the vegetation distribution, but also the analysis of the plant well-being in the riparian zones and the exploitation of the different water sources in a combined manner. Since in Mediterranean semi-arid environments the water is a scarce resource, human impacts over the river systems have been traditionally important (e.g., Salinas *et al.,* 2000; Aguiar and Ferreira, 2005). Currently, new threats related to global change impacts make indispensable to have available tools for a responsible management of the environment. *RibAV* is in addition a useful tool for restoration initiatives and global change scenarios analyses such as climate change scenarios, discharge regulation alternatives, or changes in the land use, since the analyses of different hydrological and meteorological scenarios can be accomplished easily, once the *RibAV* model is implemented in a study site.

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APENDIX. LIST OF SYMBOLS

Symbol	**Description**	**Usual units**	**Type (*)**
Cv	Plant coverage factor	dimensionless	BP
Cr	Maximum water conductivity in root-soil interface	$mmMPa^{-1}h^{-1}$	BP
$Cwf(t)$	Upward capillary water flow	mmd^{-1}	SV
D_c	Maximum depth to consider capillary rise flow from the water table to the static storage	m	BP
D_e	Effective root depth	m	BP
D_r	Maximum root depth	m	BP
D_a	Asphyxia root depth	m	BP
$E_0(t)$	Potential evapotranspiration	mmd^{-1}	IV
$E(t)$	Actual evapotranspiration	mmd^{-1}	SV
$E_s(t)$	Actual evapotranspiration from the saturated zone of the soil	mmd^{-1}	SV
$E_u(t)$	Actual evapotranspiration from the static storage of the soil	mmd^{-1}	SV
E_{idx}	*RibAV* evapotranspiration index	dimensionless	SV
H_{fc}	Water content equivalent to field capacity	mm	DP
H^*	Water content equivalent to the optimum plant transpiration point	mm	DP
$H_{rel}(t)$	Relative water content	mm	SV
$H(t)$	Water content in the static storage (ending day *t*)	mm	SV
H_{wp}	Water content equivalent to the permanent wilting point	mm	DP
$I(t)$	Water inputs to the static storage	mmd^{-1}	SV
$K_u(t)$	Hydraulic conductivity of the unsaturated soil	mmh^{-1}	SV
K_s	Hydraulic conductivity of the saturated soil	mmh^{-1}	BP
θ_{fc}	Moisture content at field capacity	dimensionless	DP
θ^*	Optimum plant transpiration point moisture	dimensionless	DP
θ_{wp}	Wilting point moisture	dimensionless	DP
λ	Pore size distribution index	dimensionless	BP
$P(t)$	Precipitation	mmd^{-1}	IV
$Pe(t)$	Percolation	mmd^{-1}	SV
Ψ_{50}	Midpoint saturation pressure (corresponding to relative soil moisture of 50%)	kPa	DP
Ψ_b	Bubbling pressure	kPa	BP
Ψ_{fc}	Field capacity point pressure	kPa	BP
$\Psi(t)$	Capillary pressure of the soil	kPa	SV
Ψ^*	Optimum plant transpiration pressure	kPa	BP
Ψ_{wp}	Permanent wilting point pressure	kPa	BP
Φ	Soil porosity	dimensionless	BP
Q_j	Immediately higher reference flow	m^3s^{-1}	AV
Q_{j-1}	Immediately lower reference flow	m^3s^{-1}	AV
$Q(t)$	River flow	m^3s^{-1}	IV
r_u	Transpiration factor from the unsaturated zone	dimensionless	BP
r_s	Transpiration factor from the saturated zone	dimensionless	BP
$Sr(t)$	Surface runoff	m^3s^{-1}	SV
$U(t)$	Hydraulic lift or root water uptake	mmd^{-1}	SV
$X(t)$	Excess water	mmd^{-1}	SV
Z_a	Asphyxia by saturation root depth elevation	m	DP
Z_c	Minimum elevation to consider capillary rise flow from the	m	DP

	water table to the static storage		
Z_e	Effective root depth elevation	m	DP
Z_r	Maximum root depth elevation	m	DP
Z_s	Soil surface elevation	m	DP
$Z_{wt,\,j}$	Water table elevation maps associated to the Q_j	m	AV
$Z_{wt,\,j-1}$	Water table elevation maps associated to the Q_{j-1}	m	AV
$Z_{wt}(t)$	Water table elevation calculated by the model	m	SV

BP: Basic parameter, DP: Derived parameter, IV: Input variable, SV: State variable, AV: Auxiliary variable

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