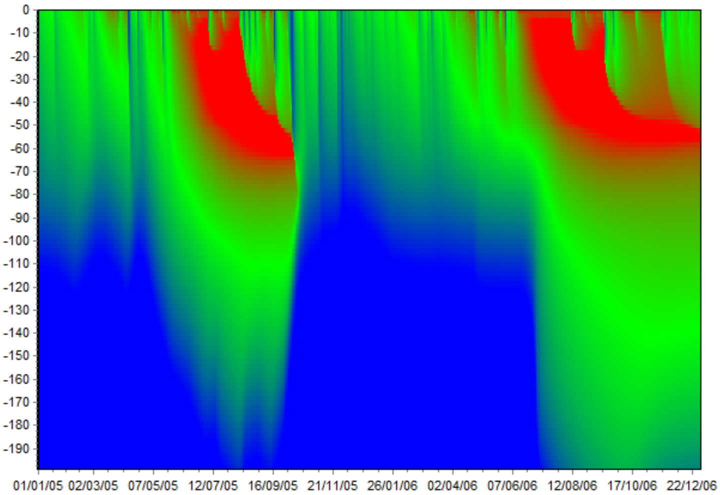
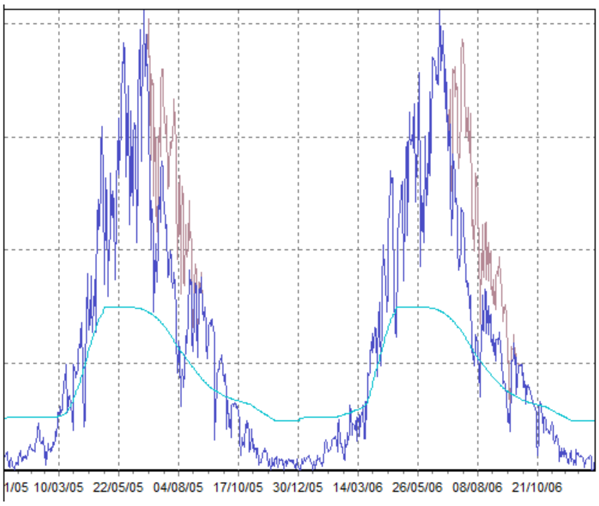
Arpae Emilia-Romagna - Hydro-Meteo-Climate Service
Agrometeorology Area and Territory

CRITERIA

Technical manual





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January 2016

Introduction

This manual is a reference guide to scientific theories and algorithms used within the model CRITERIA, therefore this is not an explanation for users of the practical operations of the program. For a complete description of the interface commands, see the "User Manual".

CRITERIA, developed by the Agrometeorology Area and Hydrometeorological Service Territory of Arpae Emilia-Romagna, is the result of a collective effort that began in the nineties, directed by Franco Zinoni and Vittorio Marletto. The interface is the work of Gabriele Antolini, Fausto Tomei, Tomaso Tonelli and the modeling code is by Gabriele Antolini, Fausto Tomei, Vittorio Marletto, Franco Zinoni, Giorgio Ducco, Margot Van Soetendael, Luca Criscuolo and Marco Bittelli.

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The water balance

To assess the water balance of cultivated or fallow ground, all the contributions and loss of water along the vertical profile of soil have to be computed.

The amount of water from rain or irrigation that infiltrates into the ground depends on surface conditions (fouling, crevasses), on the hydrological characteristics of the first layer of soil and its water content. The water that cannot be absorbed from the soil collects in ponds formed by surface roughness. Once they are filled they cause surface runoff.

The processes of storage and infiltration are governed by soil water potential differences. Each soil horizon is characterized by its water retention curve, described by some characteristic water potential points - such as moisture saturation (SAT), the field capacity (FC) and the wilting point (WP). Depending on the water content, the layer can absorb water or transfer it to the layer below. In the presence of a water table there may also be a supply of water to deeper layers as a result of capillary rise.

The presence of a crop or natural vegetation produces water loss in the root zone through transpiration, and simultaneously reduces evaporation loss in the surface layers covering the soil surface. Depending on the type of soil, its water content and the phenological stage of the crop, the water in the soil is more or less available to plants, thus affecting its transpiration rate.

Together, all these phenomena constitute the soil water balance. The following sections describe in detail all the processes by which these phenomena are simulated in the Criteria model.

1.1 Infiltration and redistribution

Infiltration is the process of transferring water from the soil surface into the soil, where it becomes *soil water content* and originates redistribution processes such as *subsurface flow* in the unsaturated zone and *groundwater flow* in the saturated zone. As already mentioned, the processes of transferring water within the soil are determined by soil water potential differences. Factors such as texture, structure, and organic matter content of a soil horizon, all determine the shape of the soil water retention curve, and the location of the soil saturation point (SAT), the field capacity (FC), and the wilting point (WP). Depending on the water content, the layer can absorb water or transfer it to the underlying layer: free flow of water does not occur if the layer's water content is between wilting point and field capacity (the soil holds all the water it receives until it reaches FC). Over the FC value, water is considered free and will move downwards depending on the infiltration rate and water content of the soil layers that are crossed, eventually reaching the aquifer.

In Criteria, infiltration and redistribution can be simulated with two different approaches depending on the user's choice: a layer-based, semi-empirical conceptual and a numerical physically-based model.

1.1.1 Layer-based empirical model

Conceptual models, such as the one present in CRITERIA, approximate the physical processes through simplified schemes adapted to describe reality by means of semi-empirical models.

While conceptual models are not able to describe the processes with the same precision of physically-based models, they present some advantages with respect to the latter, in particular the greater computational speed, which facilitates their use in computer models designed for simulations at the regional (or territorial) scale. Moreover, a simple modeling approach is mandatory in many cases because of the lack of the necessary parameters needed for a more detailed representation of the phenomena.

The following paragraphs will describe all the components of the layer-based empirical model implemented in CRITERIA.

1.1.1.1 Maximum infiltration

The amount of water that can flow through the layer depends on its water content and the permeability of the same and is estimated using the following equation (Driessen, 1986):

$$I_{Max} = 10 * S_O * \left(1 - \frac{\theta}{\theta_{sat}}\right) + 10 * A_a \qquad \textbf{(0-1)}$$

Where:			
	I_{Max}	maximum infiltration (Driessen, 1986)	[mm d^{-1}]
	S_O	standard sorptivity (reference values for texture)	[cm $d^{-0.5}$]
	θ	volumetric water content of the layer	[m^3 m^{-3}]
	θ_{sat}	volumetric water content at saturation	[m^3 m^{-3}]
	A_A	hydraulic conductivity at the wetting front (reference values for texture)	[cm d^{-1}]

The sorptivity S_0 represents the infiltration rate determined by the single matrix potential. The standard sorptivity is defined for soil with zero water content, whose values are reported in

Table 0-1.

Textural classes	**A_A [cm d-1]**	**S_0 [cm d-0.5]**	**K_0 [cm d-1]**
Sand (S)	30.33	21.44	50
Sandy Loam (SL)	17.80	19.20	26.5
Loamy Sand (LS)	9.36	17.57	12
Silt Loam (SiL)	5.32	14.46	6.5
Loam (L)	3.97	11.73	5
Silt (Si)	8.88	13.05	14.5
Sandy Clay Loam (SCL)	16.51	19.05	23.5
Silty Clay Loam (SiCL)	1.18	6.15	1.5
Clay Loam (CL)	0.76	4.70	0.98
Sandy Clay (SC)	2.94	10.74	3.5
Silty Clay (SiC)	0.80	4.98	1.3
Clay (C)	0.15	1.93	0.5

Table 0-1. Reference values of infiltration speed of the wetting front (A_A), of the sorptivity (S_0) and the saturated conductivity (K_0) depending on the different textural classes (Driessen, 1986).

In equation (0-1) three input parameters are identified (S_O, θ_{sat} and A_A) and two state variables (θ and T_{dp}). In this CRITERIA version, the parameter P_{it} (the simulation time step) is equal to 1.

Figure 0-1 shows the effect of the parameters S_0 and A_A on the total value of I_{max} of contained water to WP and FC for all textural classes. At saturation the effect of sorptivity S_0 is equal to zero and I_{max} depends only on A_A. For clay textures the effect of S_0 greatly increases to the highest potential (WP), for the sand textures the effect of S_0 is less sensitive.

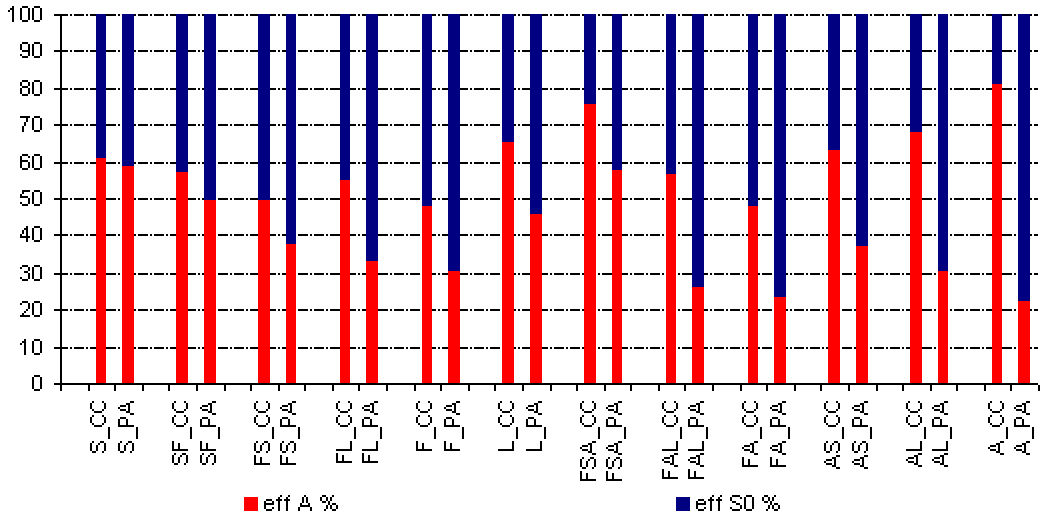

Figure 0-1. Effect of S_0 and A_A on maximum infiltration (I_{max}) at field capacity (FC) and wilting point (WP) for the different textures (Tdp=1, S=sandy, SL=Sandy Loam, LS=Loamy Sand, SiL= Silty Loam, L=Loam, Si=Silty, SCL=Sandy Clay Loam, SiCL=Silty Clay Loam, CL=Clay Loam, SC= Sandy Clay, SiC= Silty Clay, C=Clay).

The absolute values of I_{max} vary by several orders of magnitude as function of textural class (Figure 1-2): in particular, maximum infiltration is greatly reduced in both dry and wet conditions by increasing the clay content. Figure 0-2, shows the effect of soil moisture on I_{max} values.

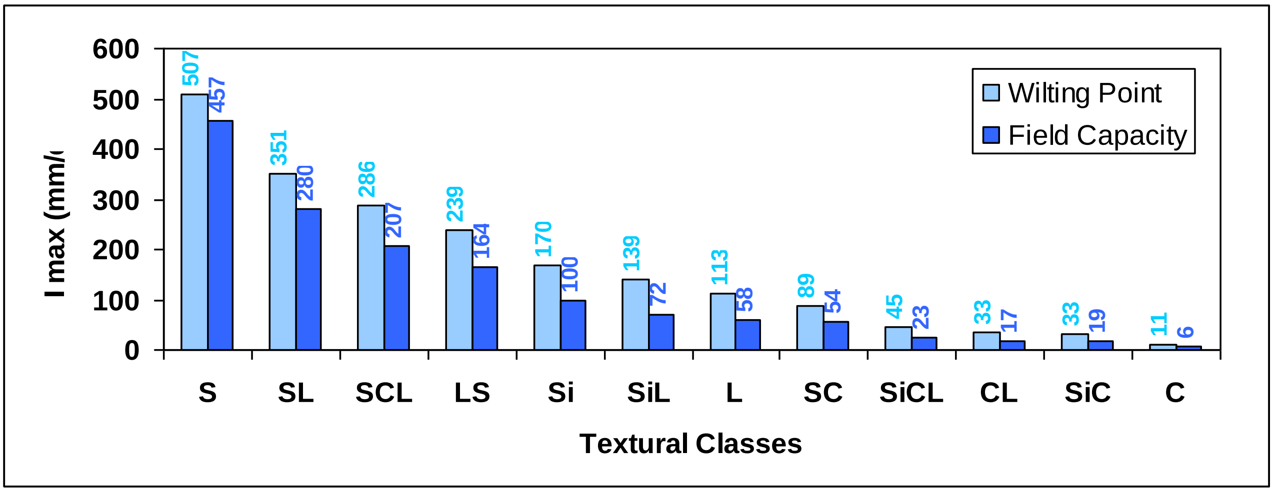

Figure 0-2. Maximum infiltration (I_{max}) after a day of rain at field capacity (FC) and wilting point (WP) for the different textures (S=sandy, SL=Sandy Loam, LS=Loamy Sand, SiL= Silty Loam, L=Loam, Si=Silty, SCL=Sandy Clay Loam, SiCL=Silty Clay Loam, CL=Clay Loam, SC= Sandy Clay, SiC= Silty Clay, C=Clay).

The influence of the temporal variable of days since last rain (T_{dp}) is modest in both absolute terms and in comparison to the changes made by other variables (Figure 0-3).

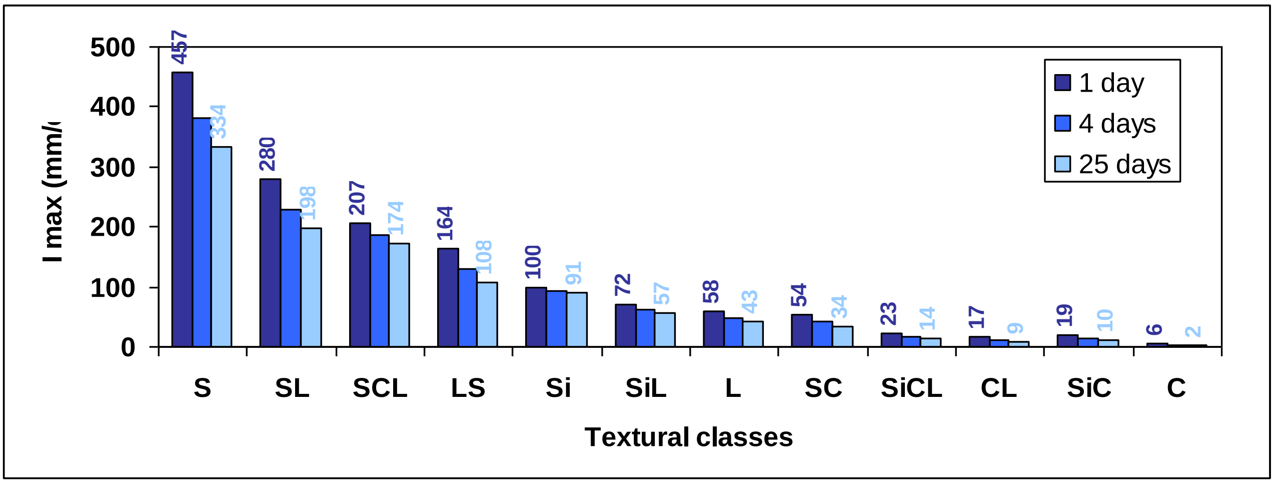

Figure 0-3. Maximum infiltration (I_{max}) consequently to the number of days since last rain (Water content = field capacity).

1.1.1.2 Infiltration and redistribution

The soil profile is divided into a number of thin computational layers (usually 2 cm), and the computation of water flow by layer starts from the bottom of the profile, which in the CRITERIA simulations is usually located at 2 m depth. However, the user can select any depth for the soil profile. A wetting front is determined when a layer has water content (θ) greater than its field capacity (FC), and an initial flow is defined considering the amount of water that can be moved and by the difference between the actual water content and the field capacity (θ-FC). The amount of water that actually moves and the length of the downward shift depends on the water content and the texture of the underlying layers.

As described in Section 1.1.1.1, each layer is characterized by an infiltration of the maximum daily amount (I_{max}). To estimate the maximum displacement of the waterfront the maximum infiltration of the underlying layer at the waterfront is calculated. If the water content of layer exceeds the field capacity it passes to the next one. This computation continues until the water front encounters a layer in which the amount of incoming water determines a total water content of that layer that is less than *FC*, then the waterfront is stopped.

Two conditions have to be satisfied: the sum of the flows previously passed through a layer cannot exceed its maximum daily infiltration, and in the case it meets a saturated layer, the front stops at the layer above the saturated layer. The first condition restricts the passage of water in the case that it meets a layer of clayey and low maximum daily infiltration. In this case it forms a suspended water table. The second condition instead simulates the slowing down of the waterfront when it approaches a situation of saturation: the waterfront that is arriving relies on the previous one (Figure 0-4).

In cases where the free water reaches the last layer, it leaves the system as deep drainage.

On the surface, the infiltration of rainwater is strongly limited by I_{max} of the first layer: in the case of rainfall, excess puddles can form and possibly sub surface lateral flow (the latter in the presence of drains), as represented by the diagram in Figure 0-4. Once the amount of water that enters the first layer of the soil is defined, we proceed similarly as described in general for the other layers of the profile.

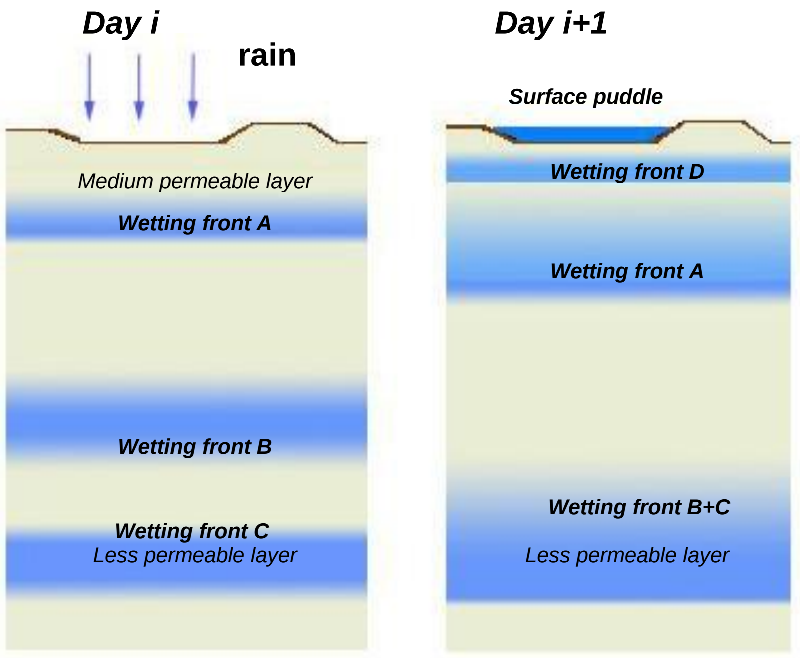

Figure 0-4. infiltration into the soil profile of moisture fronts A,B,C,D.

- **A, crossing through medium permeable layers, moves downwards while remaining separate from the other fronts;**
- **B crosses more permeable layers and merges with C, whose infiltration is slowed by the presence of a not very permeable layer.**
- **The rain partially infiltrates creating a new front D; the water in excess of the I_{max} of the surface layer creates a puddle on the ground.**

In Figure 0-5 the results are compared to the same event of rain (50 mm) on three soil types (SL loamy-sand, CL clay loam, C clay), along the time:

- LS: the rain water seeps directly into the soil without forming puddles and without causing surface runoff. Three days later it already passed through the profile and a drainage event of almost 45 mm occurs.
- CL: some of the water stagnates on the surface for several days without causing a surface runoff. In the profile, the front is divided into several smaller fronts: the first drainage events occurring after 20 days, ending at about ten days after.
- C: some of the water stagnates on the surface for nearly two weeks but there is a surface runoff of 15 mm on the day of rain. In the profile, the front is divided into many small fronts. The first drainage events occur after 20 days and last for several weeks.

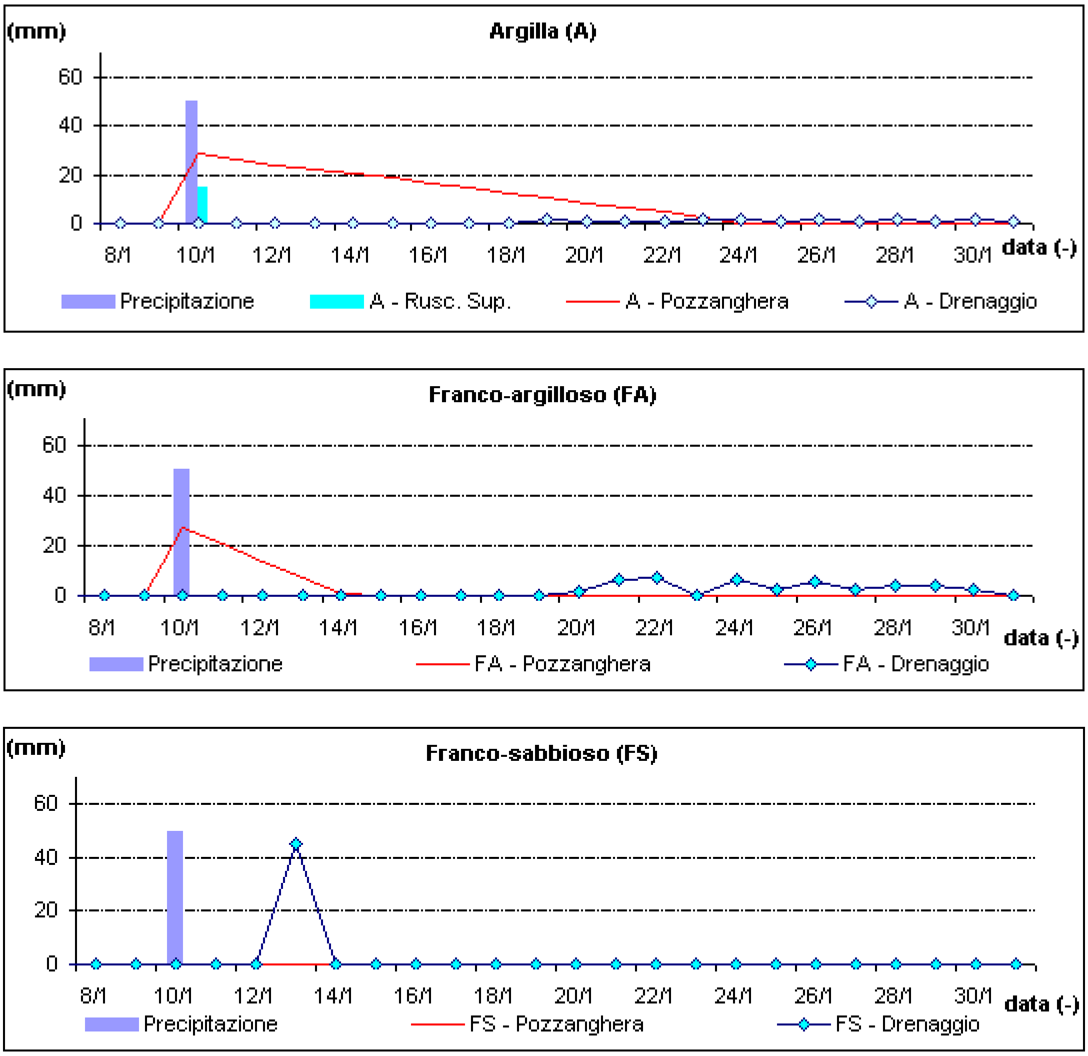

Figure 0-5. **Time trends in the pond, surface runoff and deep drainage after a rain event of 50 mm (10 January) for three types of soil (C clay, CL loamy-clay, LS loamy-sand).**

The water applied during an irrigation event does not infiltrate the soil with the procedure described above, but rather brings the layers back to field capacity, regardless of I_{max}, starting from the surface and continuing until the irrigation water is all utilized. If the volume of irrigation assigned for the event is greater than the volume of water required to bring the entire soil profile to field capacity, the excess is added to the daily water to drain.

1.1.2 The numerical model

Physically- based hydrological models develop a description of the phenomena through classical physics equations (which essentially led back to the equation of mass conservation and quantity of motion).

A characteristic of these models is their ability to describe a single set of differential equations and with little or no contribution of a variety of corrective empirical phenomena that are often physically contiguous in nature: infiltration and redistribution, drainage, capillary rise, runoff and accumulation of surface and hypodermic runoff. This unified treatment involves the use of coupled equations of motion on the surface and soil through appropriate formulation of the equation of continuity of mass. The physically-based models are also interesting for ability to describe physical systems based on theoretically-measurable quantities.

The numerical model of CRITERIA uses a restriction of one-dimensional hydrological model CRITERIA3D (*Bittelli et al., 2010*), inserted in CRITERIA environment by a dll (dynamic link library). The 3D model describes all phenomena related to the soil hydrologic balance, and phenomena such as surface runoff, infiltration, redistribution, drainage and capillary rise in a three-dimensional domain. The one-dimensional restriction contained in CRITERIA is able to calculate only phenomena related to infiltration but not the surface runoff.

1.1.2.1 Numerical formulation

The model solves the accurate equation of continuity.

$$\mathrm{div}\,(u) + \frac{\partial(W\theta)}{\partial t} = q \qquad \textbf{(0-2)}$$

Where:	*u*	flux density	[m/s]
	W	total volume available	[m^3]
	ϑ	volume fraction occupied by water (volumetric water content)	[m^3/m^3]
	q	water flow incoming or outgoing	[m^3/s]

This general equation is solved using two different expressions to describe the flow within the matrix of the soil and the soil surface. In the first case we obtain the equation of Richards:

$$\frac{d\theta}{dH}\frac{\partial H}{\partial t} = \mathrm{div}\,\left[K(h) \bullet \mathrm{grad}\,(H)\right] + q \qquad \textbf{(0-3)}$$

Where:	*K*(*h*)	hydraulic conductivity	[m/s]
	H	total hydraulic load	[m]

H is the sum of the share *z* (or gravity term) and the hydraulic term (hydraulic matric component) $h = p/\rho_w$, where ρ_w is the density of water, *p* is the soil matric potential and *t* is the time. For the flow in a saturated mean the equation (0-3) is reduced to the Laplace equation for the underground water flow.

The solution of the governing equations is based on the integrated finite difference method, which is integration of the differential equation of continuity (0-2) within a finite domain *D,* as described by *de Marsily* (1986), obtaining the integral equation (limited to the one-dimensional case):

$$\int div\,(u)\; dz + \int \frac{\partial (W\theta)}{\partial t} dz = \int q\; dz \tag{0-4}$$

The mass balance is calculated into the space domain D of the model. According to the properties of the integral, equation (0-4) can be written as:

$$\int_{\Gamma_D} u \bullet n\; dS + \int \frac{\partial (W\theta)}{\partial t} dz = \int q\; dz \tag{0-5}$$

Where:	Γ_D	surface of the computational domain D	[m^2]
	N	unit vector normal to it	[-]
	H	total hydraulic load	[m]

Equation (0-4) can be applied on a volume of simulation in which the material properties are constant.

If the simulation domain is approximated by a three-dimensional grid of nodes (or one-dimensional), the equation (0-5) is equivalent to the equation of mass balance for the volume around each node.

$$\frac{\partial V_i}{\partial t} = \sum_{j=1}^{n} Q_{ij} + q_i \qquad \forall\, \mathrm{i} \neq \mathrm{j} \tag{0-6}$$

Where:	V_i	water content is the volume around the node i-th	[m^3]
	Q_{ij}	flow between nodes *i*-th and *j*-th,	[m^3/s]
	q_i	inflow in the *i*-th node	[m^3/s]

You can write a system of equations for all nodes, where the unknowns are the values of potential hydraulic *H*. The flow Q_{ij} is described by Darcy's law in the form of finite differences:

$$Q_{ij} = -K_{ij} S_{ij} \frac{(H_i - H_j)}{L_{ij}} \tag{0-7}$$

Where:	S_{ij}	interface area between nodes *i*-th and *j*-th	[m^2]
	L_{ij}	distance between two nodes	[m]
	H_i	hydraulic potential on node *i*	[m]
	K_{ij}	conductivity between the two nodes	[m/s]

The conductivity of inter-node K_{ij} is calculated as a geometric or harmonic mean:

$$K_{ij} = mean(K(H)_i, K(H)_j) \tag{0-8}$$

Where:	$K_i(H_i)$	Hydraulic conductivity on the node i-th	[m/s]

The model uses the approach proposed by *van Genuchten* (1980), *Mualem* (1976) and modified van Genuchten-Mualem, as proposed by *Ippisch et al.* (2006), for the characterization of soil water retention curve (SWR) and hydraulic conductivity curves (*K*).

1.1.2.2 Boundary conditions

The model allows you to specify boundary conditions that vary over time and space for each node.

1. nodes with a fixed hydraulic head (H = constant), Dirichlet boundary condition;
2. node set to atmospheric boundary conditions, Neumann boundary condition;
3. node with a default flow, Neumann boundary condition;
4. nodes without flow in all directions, Neumann boundary condition.

The boundary conditions of type 1 can be used to represent a variety of conditions such as deep drainage to the lower limit of the domain, or loads imposed by the presence of ponds, lakes or other water bodies. Atmospheric boundary conditions (2) allow you to assign fixed values of precipitation and evapotranspiration. Precipitation is assigned to a unit area of land equivalent to the boundary area of a volume surface. As for the coupling between surface runoff and hypodermic, precipitation is applied to the surface nodes and coupling takes place through the application of Richards' equation among the surface layer and the first sub-surface layer. Details about the coupling are provided by *Bittelli et al*., (2010).

The numerical formulation of the model produces a strongly non-linear system that is solved by successive approximations. Each time step corresponds to the calculation of more than approximations, each of which solves a linear system through a resolution method. It can be shown that the matrix produced by the model is defined as positive therefore, the principle iterative methods of resolution are convergent. In particular, the Gauss-Seidel algorithm was selected because its computational cost has been found optimal for the matrix produced by the model (*Tomei*, 2005).

It is noted that there is still the necessity to develop an adaptive algorithm that varies the time step according to the conditions of the system. The main reference for monitoring the status of the system is given by mass balance, which is assessed on the basis of *mass balance ratio* (MBR). This is calculated in time step as the ratio between the change in soil water storage (*storage*) and the sum of the flows (*flux*) inflow (rainfall) and outflows (surface and underground runoff, evapotranspiration).

$$MBR = \frac{\Delta storage}{flux_{in} - flux_{out}} \qquad \textbf{(0-9)}$$

The two values represent the same phenomenon, thus an algorithm should be fully conservative and should be MBR = 1. If the inflows and outflows are very low or equate the equation might produce overflow, so we prefer to use the expression:

$$MBR = \frac{storage_{t+\Delta t}}{storage_t + flux_{in} - flux_{out}} \quad \textbf{(0-10)}$$

that does not cause numerical problems, because the water content can never reach zero. The error in mass balance is then defined as

$$ERR_{MBR} = 1 - MBR \quad \textbf{(0-11)}$$

that can easily be used as a parameter for evaluating the quality of the solution of the system produced by each approximation, setting a tolerance threshold ε, under which the balance is considered correct and time step accepted.

The coupling of the *dll* numerical model with the program CRITERIA is by daily time steps. The dll receives the stratigraphy of the soils, the boundary conditions (impermeable base or height of water table), the initial conditions of humidity and the daily precipitation data. The *dll* calculates the humidity in the profile and returns it to CRITERIA, which allows for simulation of the evaporation and transpiration, crop and radical growth. At this point the cycle begins again with the data of the following day.

1.2 Surface runoff

As described in Chapter 1, the surface runoff occurs when the soil surface roughness cannot hold excess pond water. The process is simulated considering the maximum height of storage surface (the volume that reproduces the actual height or volume of puddles). The storage capacity depends on the tillage according to the following expressions:

$$SSmax = \frac{1}{2} * \frac{Clod}{\cos(\varphi) * \cos(\psi)} * \frac{\left(sin(\varphi - \psi)\right)^2}{2 * sin(\varphi)} * \left[\frac{1}{\tan(\varphi + \psi)} + \frac{1}{\tan(\varphi - \psi)}\right] + CropWaterStorage \quad \textbf{(0-12)}$$

Where:	*SSmax*	maximum height of Surface water Storage	[mm]
	Clod	actual height of the clod, calculated by the equation (0-13)	[mm]
	CropWaterStorage	height of the crop water storage	[mm]
	ϕ	angle processing, tabulation for each type of processing	[Rad]
	ψ	slope of the plots	[°]

Some crops have a certain storage capacity that is added to the soil and protects the soil itself by surface runoff. This capacity is considered by the parameter *CropWaterStorage*.

$$Clod = \min\left[DiMin0 + DiMin, \left(Clod - Cost*(DataA - DataL)\right)\right] \tag{0-13}$$

where:	Clod	actual height of the clod	[mm]
	Cost	daily rate of decline of the clod, tabulated for each type of processing	[-]
	DataA	actual date of the simulation	[-]
	DataL	date of the last tillage	[-]
	DiMin0 e *DiMin*	minimal roughness of bare soil and tillage (tabulated)	[mm]

The initial value of height of storage *SSmax* varies from 80 mm for deep plowing to few millimeters for rolling. To the minimum value of roughness of the tillage (DiMin) is added a minimum value of roughness of bare soil.

If there is no tillage, the roughness of the soil decreases with time, Figura 0-6 shows an example of the height of storage surface after a deep plowing: increasing the slope of the ground the initial height of storage decreases, after 52 days the effect of plowing disappears and the storage height backs up to the minimum roughness.

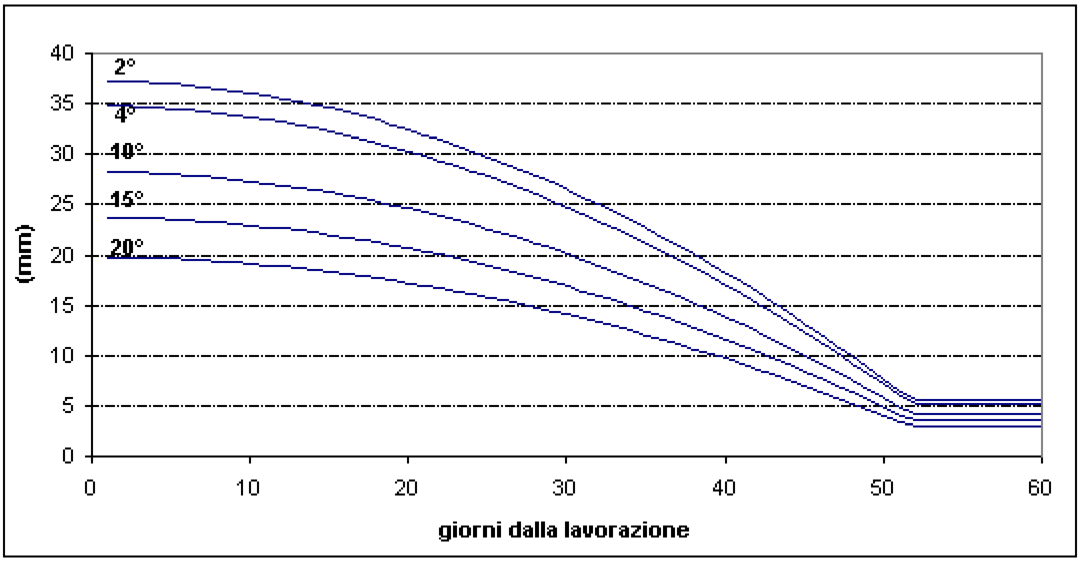

Figura 0-6. Height of storage surface: effect of the surface slope.

The calculation of the amount of surface water runoff is a simple comparison between the height of the surface storage ability and the amount of water left on the surface after the process of infiltration.

1.3 Deep drainage

The daily deep drainage can be defined as the height of water passing through the top layer of the soil profile that is simulated. In the case of capillary rise simulation from groundwater, this height of water is not added to the height of the water (read as daily data incoming or attached to a certain depth). Along with the deep drainage, it is possible that leaching of nitrogen, phosphorus and pesticides may occur.

In the model code the deep drainage is calculated at the end of the process of infiltration.

1.4 Capillary rise

The phenomenon of capillary rise is simulated in CRITERIA with both infiltration models available. In the semi-empirical model, a separate algorithm is used, based on simplified equations that are described in the following section (1.4.1); In the numerical model, however, the process is simulated by the same equations that regulate the infiltration, already described in section 1.1.2.

1.4.1 Capillary rise in the semi-empirical model

The contribution of water from the aquifer is calculated daily according to the type of soil present, the average potential of the layer affected by the roots and the distance of this layer from the surface of groundwater.

The approach adopted derives from that of Rijtema (presented by van Keulen and Wolf, 1986). The capillary rise is calculated by the distance between the free surface of the water (z_t) and the last layer affected by the roots (RD).

The general expression of the capillary rise can be written as:

$$CR = k_\psi \left(\frac{d\psi}{dz} - 1 \right) \tag{0-14}$$

Where:	*CR*	capillary rise, general expression (van Keulen e Wolf, 1986)	[cm d^{-1}]
	k_ψ	hydraulic conductivity as a function of the potential ψ	[cm d^{-1}]
	ψ	matric potential	[cm]
	z	Depth	[cm]

Rijtema (1986) proposed two equations for the solution of this equation, one for potential values below the limit of a typical potential for each soil (ψ_{max}) ψ max) of the form:

$$CR = \frac{k_0 \left(e^{-\alpha\psi} - e^{-\alpha(z_t - RD)} \right)}{e^{-\alpha(z_t - RD)} - 1} \tag{0-15}$$

Where:	*CR*	capillary rise (Rijtema, 1986)	[cm d^{-1}]
	k_0	saturated hydraulic conductivity	[cm d^{-1}]
	α	characteristic parameter of each soil	[cm^{-1}]
	ψ	matric tension of the soil	[cm]
	z_t	depth to groundwater (to ground level to the free surface of the water)	[cm]
	RD	depth of the root system	[cm]

Table 0-2 shows the values of k_0 and α used in CRITERIA.

Table 0-2. Values of ψ_{max}, α e k_0 for different granulometric types.

Soil	ψ_{max} [cm]	α [cm^{-1}]	K_0 [cm^{-1}]
Sand (S)	70	0.2240	1120
Sandy Loam (SL)	175	0.0500	50
Loamy Sand (LS)	200	0.0398	26.5
Silt Loam (SiL)	290	0.0248	12
Loam (L)	300	0.0200	6.5
Silt (Si)	300	0.0231	5
Sandy Clay Loam (SCL)	130	0.0490	14.5
Silty Clay Loam (SiCL)	200	0.0353	23.5
Clay Loam (CL)	170	0.0237	1.5
Sandy Clay (SC)	300	0.0248	0.98
Silty Clay (SiC)	300	0.0174	3.5
Clay (C)	50	0.0480	1.3

For values of ψ higher than ψ_{max} it is necessary to calculate the relationships between CR, ψ and (z_t - RD) through numerical integrations of the equation:

$$CR = k_{\overline{\psi}} \left(\frac{\overline{\psi}}{\Delta(z_t - RD)} - 1 \right) \qquad \textbf{(0-16)}$$

Where:

CR	capillary rise for potential higher than ψ_{max} (Rijtema, 1986)	[cm d^{-1}]
k_{φ}	hydraulic conductivity for the average potential φ	[cm d^{-1}]
α	characteristic parameter of each soil	[cm^{-1}]
ψ	matric water potential of the soil	[cm]
z_t	depth to groundwater (to ground level to the free surface of the water)	[cm]
RD	depth of the root system	[cm]

To avoid numerical integrations that are sometimes very expensive, as well as to maintain consistency with the general approach, the mentioned authors propose two entries tables for each type of soil. These tables relate the vertical distance of capillary flow (the maximum distance at which it is possible to have capillary flow), capillary flow itself and the matric potential that allows the same flow. In these tables, therefore, a minimum and a maximum distance is given within which there is the phenomenon of capillary rise. All combinations of triplets CR, z_t and ψ present in the tables were treated statistically by *Marletto and Zinoni* (2001) in order to obtain the functional relations valid for the entire voltage range and for each soil type. These relationships were expressed by two equations, one for voltages lower than 250 cm and the other for higher voltages. The first equation is the following:

$$CR = a + \frac{\psi}{1000} * b + \left(\frac{\psi}{1000}\right)^2 * c + \left(\frac{\psi}{1000}\right)^3 * d + Dist * \left(e + \frac{f}{\psi / 1000} \right) \quad \textbf{(0-17)}$$

Dove: *CR* capillary rise for potential lower than 250 cm [cm d^{-1}]

ψ matric tension [cm]

Dist distance between the free surface of the water and the last layer of soil with roots [cm]

a, b, c, d, e,f parameters obtained by statistical procedure, typical for each class of soil. [-]

the second equation is:

$$CR = g + h * \ln(\psi) + i * \left(\frac{Dist}{100}\right)^2 + l * \left[\ln\left(\left[\frac{Dist}{100}\right] * Ln(\psi) \right) \right]^2 \quad \textbf{(0-18)}$$

Where: *CR* capillary rise for potential higher than 250 cm [cm d^{-1}]

ψ matric tension [cm]

Dist distance between the free surface of the water and the last layer of soil with roots [cm]

g, h, i and *l* parameters obtained by statistical procedure, typical for each class of soil. [-]

Table 0-3 shows the values of the parameters of equations (0-17) and (0-18) for all textural classes.

Table 0-3. List of parameters used to calculate capillary rise in CRITERIA.

Suolo	a	b	c	d	e	f	g	h	i	l
Coarse sand	21.38	490.30	-6640.72	18340.71	-0.0174	-0.0023	18.49	3.77	0.2448	-3.895
Fine sand	2.25	151.34	-1626.39	4197.03	-0.0022	-0.0007	3.79	0.64	0.0523	-0.717
Silty sand	61.82	-175.23	-586.47	1771.60	0.0190	-0.0060	13.88	1.71	0.0107	-1.240
Loamy sand	85.67	-289.71	-254.95	870.07	0.0290	-0.0085	14.72	1.68	0.0051	-1.101
Silty loam	48.52	-332.85	-374.46	4385.57	0.0021	-0.0017	10.16	1.29	0.0023	-0.742
Loamy	34.93	-104.68	-149.44	551.86	0.0097	-0.0034	12.92	1.45	0.0078	-1.057
Loess	29.93	-52.00	-793.76	2507.50	0.0072	-0.0029	8.16	1.14	0.0067	-0.789
Sandy clay	70.75	-214.63	-557.81	1721.43	0.0230	-0.0070	10.53	1.36	0.0042	-0.858
Silty clay	14.57	-32.58	-99.42	360.31	0.0020	-0.0014	5.75	0.88	0.0031	-0.537
Loamy clay	11.14	-21.61	-79.24	287.72	0.0006	-0.0011	7.63	0.94	0.0196	-0.853
Light clay	31.00	-90.73	-58.18	257.00	0.0083	-0.0031	8.40	1.14	0.0017	-0.622
Clayey silt	11.51	-57.01	109.03	28.37	0.0010	-0.0011	4.14	0.70	0.0036	-0.443
Heavy clay	5.60	-10.38	-26.86	162.17	-0.0031	-0.0006	2.97	0.53	0.0336	-0.563

If the soil profile affected by the capillary rise is composed of layers of varying texture, the values of the dominant textural class are used. By using the equations presented it is possible to calculate matric tension values for capillary rise flow.

Once the height of capillary rise *CR* is calculated, the recharging mechanism of the soil layer occurs from the computational layer above the last layer calculation (starting from the height of water table) to field capacity *FC. A*fter having calculated the water deficit, the layer is brought to *FC* while *CR* is decreased by a corresponding amount, the value $CR_{(i+1)}$ to be used for the following layer is given by the equation:

$$CR(i+1) = \min\left(CR(i) * 0.95; CR(i) - deficit(i)\right) \quad \textbf{(0-19)}$$

Where:	$CR_{(i+1)}$	capillary rise available to the layer *i+1*	[mm]
	$CR_{(i)}$	capillary rise available to the layer *i*	[mm]
	$deficit_{(i)}$	Water deficit in the layer *i*, calculated as the difference between the initial water content contained at field capacity	[mm]

The water content θ_z of a layer included in the soil thickness between the height of the groundwater and the last layer at *FC* is assigned by the following equation:

$$\theta(z) = \theta_{FC} + (\theta_S - \theta_{FC}) * d_{rel}^2 \quad \textbf{(0-20)}$$

Where:	d_{rel}	$= (z - z_{FC}) / (z_S - z_{FC})$ relative distance of the layer under consideration from the last layer at *FC*	[cm/cm]
	θ_z	Water content of the layer under consideration	[mm]
	Z	Depth of the layer under consideration	[cm]
	θ_{FC}	Water content at field capacity	[mm]
	Z_{FC}	Depth of the layer at field capacity	[cm]
	θ_S	Water content at saturation	[mm]
	Z_S	Depth of groundwater level	[cm]

The resulting trend of the soil water content profile is shown in the figure below.

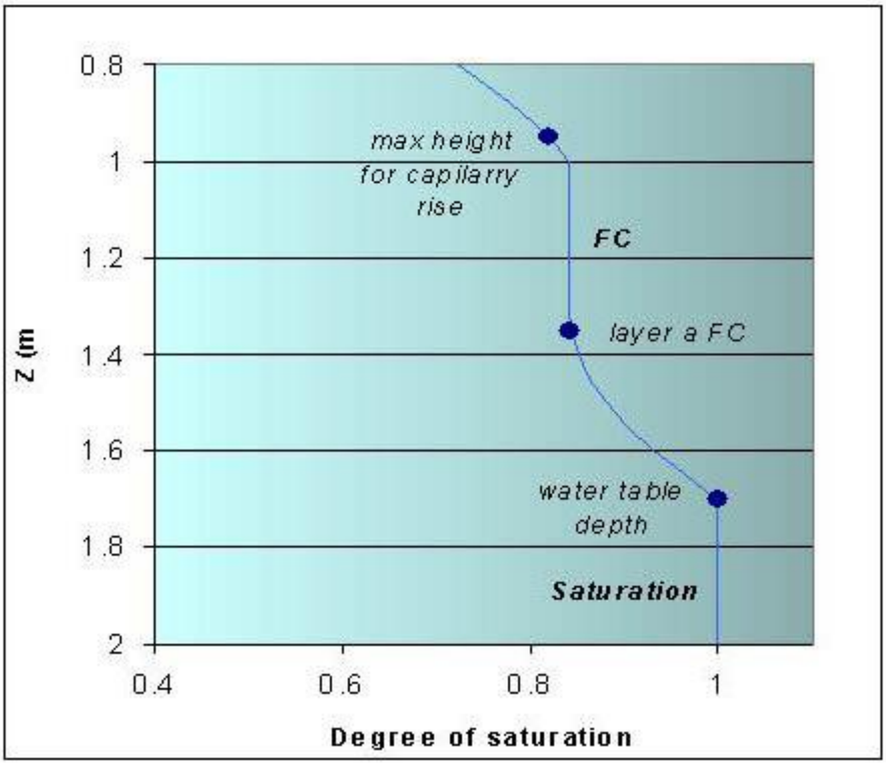

Figure 0-7. Trend of the relative humidity of the soil values (θ/θ_S) in the presence of water. The capillary rise takes effect from the deepest layer to field capacity: profile of soil affected by the rise is brought to *FC*.

1.5 Potential evapotranspiration

The term evapotranspiration refers to the total water that is moved from the soil to the atmosphere by evaporation from bodies of water and soil and by transpiration from plants.

Equal to other conditions, with increasing water availability in the soil, the value of 'evapotranspiration increases until a limit value that cannot be exceeded for more availability of water. The limit is called the *maximum evapotranspiration* (*ETm*) and is defined as the amount of water evapotranspirated per unit time from a uniform and compact crop that has full water availability.

The *reference evapotranspiration* (*ET0*) however is the amount of water evapotranspirated from a reference crop (*Festuca arundinacea* Schreb., multispecies grass) maintained between 8 and 15 cm height, completely covering the ground with plenty water availability.

ET0 depends on the following factors:

- solar radiation (about 80%);
- wind (16%);
- relative humidity (4%).

The *real evapotranspiration* (*ETr*) is the amount of water actually lost from the soil-crop-atmosphere system and depends on:

- the size of the plant (LAI);

- the phenological stage of the crop (different evapotranspiration needs for the different phases);
- the nutritional and phytosanitary conditions of the crop;
- soil water conditions (for example, in situations of dry soil, the plant draws water from the soil with greater difficulty and perspiration decreases).

The formulas used in CRITERIA for the calculation of *Etr* are detailed in paragraphs 1.6.2 and 1.6.3.

Lysimeters are normally used to perform field measurements of evapotranspiration in the field: they are high volume containers filled with natural soil and vegetation in the surface, located in open country, and equipped with drainage system that allows maintaining the desired humidity conditions in the soil and measure the volume drained at the bottom of the container.

Due to the complexity of this system, more simply methods or mathematical formulas are normally used for estimating evapotranspiration. The estimation methods proposed in literature are many, characterized by different input variables and made for different time scales estimates. In Table 0-4 1 most frequently methods and equations used are shown:

Table 0-4. Data entry of some methods to estimate potential evapotranspiration.

Method	T [°]	RH [ ]	Wind int. [ ]	Solar rad. [ ]	E_{pan} [mm d^{-1}]	Meteo [ ]
Blaney-Criddle	*	+	+			+
Radiation	*	+	+	*		+
Evaporimeter		+	+		*	*
Thornthwaite	*					
Hargreaves	*			+		
Priestley-Taylor	*	*		*		*
Penman-Montheith	*	*	*	*		+

*** measured; + estimated; E_{pan} = amount of water evaporated from evaporimeter [mm d^{-1}]**;

In the CRITERIA model there are two formulas for calculating evapotranspiration:

- **Hargreaves and Samani** (1985), chosen for its wide diffusion and for the small number of parameters required;
- **Penman-Monteith**, as submitted in the latest FAO review made by Allen et al. (1994), is the equation at the global level and requires more data.

1.5.1 Hargreaves and Samani

Hargreaves and Samani equation (1985) is calibrated to obtain estimates of cumulative weekly evapotranspiration. However, it is a formula widely used for the daily estimates, and recent field studies in the Mediterranean (Ventura et al., 1998) show that it fits very well with a lower time scale.

The Hargreaves method uses data from daily maximum and minimum temperature with the function:

$$ETO_{H\&S} = 0.0023 \frac{Rad_{pot}}{2.456}\left(\frac{T_{\max} + T_{\min}}{2} + 17.8\right)\left(T_{\max} - T_{\min}\right)^{1/2} \qquad \textbf{(0-21)}$$

Where: *$ETO_{H\&S}$* ET0 of Hargreaves and Samani [mm d^{-1}]

Rad_{pot} potential radiation in the absence of atmosphere [MJ m^{-2} d^{-1}]

T_{max} and *T_{min}* daily maximum and minimum temperature of the air [°C]

The magnitude defined Rad_{pot} is the potential radiation that would reach Earth's surface in the absence of the atmosphere. The variables to be included in the calculation are the latitude and the day of the year:

$$\mathrm{Rad}_{pot} = \frac{24*60}{\pi} R_{sc} D_R \left(O_{MS} \sin\left(F_L\right) \sin\left(d_d\right) + \cos\left(F_L\right) \cos\left(d_d\right) \sin\left(O_{MS}\right)\right) \qquad \textbf{(0-22)}$$

Where: *Rad_{pot}* potential radiation for the estimation of the ETP with Hargreaves and Samani (1985) [MJ m^{-2} d^{-1}]

R_{sc} 0.082 [MJ m^{-2} d^{-1}]

F_l Latitude [rad]

G day of the year [d]

other variables depend on the following expressions:

$$d_d = 0.409 \sin(0.0712\ g - 1.39) \qquad \textbf{(0-23)}$$

$$D_r = 1 + 0.033 \cos(0.0712\ g) \qquad \textbf{(0-24)}$$

$$O_{MS} = \mathrm{A}r\mathrm{ctan}\ g\left(\frac{-N_N}{\left(1 - N_N^2\right)^{0.5}}\right) + 1.5708 \qquad \textbf{(0-25)}$$

$$N_N = -\tan\left(F_L\right)\tan\left(D_d\right) \qquad \textbf{(0-26)}$$

1.5.2 Penman-Monteith

The Penman-Monteith equation is the modified version of the original equation proposed by Penman (1948). There have been several modified versions over the years and in the FAO head office has been accepted and defined as a reference equation for estimating evapotranspiration. In CRITERIA, the most recently updated available version is used, presented in the work of Allen et al. (1994):

$$ETO_{P\&M} = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{900}{T_{ave} + 273} u\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u\right)} \qquad \textbf{(0-27).}$$

Where: *$ETO_{P\&M}$* ET0 of Penman [mm],

R_n net radiation [MJ m^{-2} d^{-1}]

G	net heat flow from the ground	[MJ m^{-2} d^{-1}]
Δ	slope of the function of saturated vapor	[kPa °C^{-1}]
γ	psichometric constant	[kPa °C^{-1}]
u	daily average wind speed at 2 meters height	[m s^{-1}]
e_s	average pressure of vapor in air saturation (eq. (0-28))	[kPa]
e_a	average pressure of vapor	[kPa]

The saturated vapor pressure is calculated by the equation:

$$e_s = 0.6108 \cdot e^{\frac{17.27\, T_{med}}{T_{med}+237.3}} \tag{0-28}$$

Where: e_s average pressure of vapor in air saturation at the average air temperature [kPa]
T_{ave} average air temperature [°C]

1.6 Evaporation and transpiration

1.6.1 The maximum evapotranspiration

To calculate the maximum evapotranspiration from the potential one and the subsequent division into maximum evaporation and transpiration, the approach of Driessen (1986) and Driessen and Konijn (1992) is used, with some modifications. With no crop or before the emergence, the maximum evaporation (ETM) is set equal to potential evapotranspiration (ET0), while transpiration is zero.

After crop emergence, maximum evaporation and maximum transpiration are determined as follows:

$$E_M = (1 - K_c) \cdot ET_0 \tag{0-29}$$

$$T_M = K_c \cdot TC \cdot ET_0 \tag{0-30}$$

Where: E_M maximum evaporation [mm]
T_M maximum transpiration
K_c crop coefficient (equation (0-31)) [-]
TC turbulence coefficient (equation (0-32))

$$K_c = 1 - e^{-k_e LAI} \tag{0-31}$$

Where: K_c crop coefficient [-]
k_e extinction factor (equal to 0.5) [-]
LAI leaf area index [-]

K_{Cref} refers to a hypothetical crop, short and compact enough not to be affected by the air turbulence in the process of transpiration. The effect of turbulence on a real crop which is expressed using the actual TC coefficient is calculated using the following formula:

$$TC = 1 + \left(K_{CM} - 1\right) \cdot K_C \quad \textbf{(0-32)}$$

Where: *TC* turbulence coefficient [-]

K_{CM} Highest level of TC, depending on the crop and basically corresponding to the maximum value of K_c as proposed by Doorenbos and Kassam (1979) [-]

K_C crop coefficient [-]

Figure 0-8 shows the trends of LAI and coefficients K_c and *TC*.

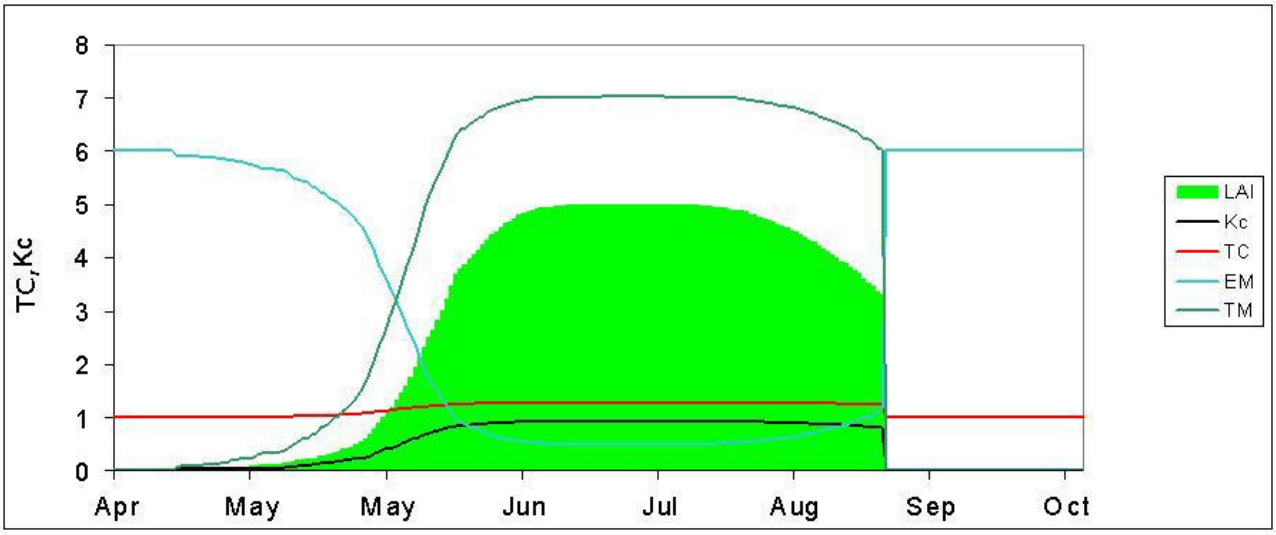

Figure 0-8. Trend of LAI, K_c and *TC* for the corn crop (K_{cm} = 3, k_e = 0.5).

The graph in Figure 0-9 illustrates the trend of maximum evaporation and transpiration with increasing of LAI.

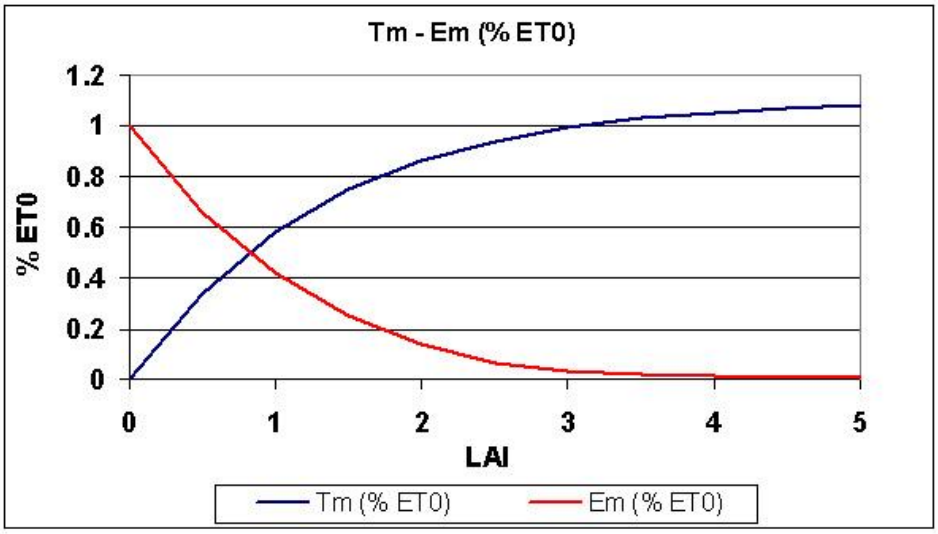

Figure 0-9. Trend for values of maximum Transpiration and maximum Evaporation, as a percentage of ET0, according to LAI, with kc_M = 1.1

1.6.2 Actual transpiration

The water removed by plant transpiration from the soil profile is calculated as the sum of the actual transpiration of all rooted layers, using their radical densities as weights.

The calculation of actual transpiration of the i-th layer of $T_{e,i}$ depends on its moisture content: $T_{e,i}$ nothing is taken in case of saturated soil, while in conditions of high humidity (over a threshold currently placed for all crops in the middle of the interval between field capacity and saturation), but lower than the saturation, the total maximum transpiration T_M reduces linearly, according to the following expressions:

$$T_{e,i} = 0 \qquad \text{for} \qquad \theta_i = \theta_{sat} \tag{0-33}$$

$$T_{e,i} = T_M * DensRad_i * \frac{\theta_{sat} - \theta_i}{\left[\frac{1}{2} * (\theta_{sat} - \theta_{cc})\right]} \qquad \text{per} \qquad \theta_i \geq \theta_{sat} - \frac{1}{2}(\theta_{sat} - \theta_{cc}) \tag{0-34}$$

Where:	$T_{e,i}$	actual transpiration of layer *i* (Driessen e Konijn, 1992)	[mm/d]
	T_M	Maximum transpiration.	[mm/d]
	θ_{sat} e θ_{FC}	Water content of root zone at saturation and at field capacity	[mm]
	θ_i	actual water content of layer *i*	[mm]
	$DensRad_i$	radical density of the layer *i*	[m^3 m^{-3}]

If the water content is lower, the maximum values of transpiration and water uptake of roots are compared, according to the Driessen and Konijn (1992) treatment, soon reported below.

The amount of water that the roots of a plant can extract from the soil is determined by the difference in potential between the ground and root tissue:

$$MUR = \frac{(PSI_{root} - PSI)}{R_{root}} \tag{0-35}$$

Where:	MUR	maximum uptake rate	[cm/d]
	PSI_{root}	water potential of root tissue	[cm]
	PSI	water potential derived from the conditions of soil moisture through the water retention curve	[cm]
	R_{root}	root resistance	[d]

The water is absorbed by the plant flows to the leaves, where it is transpired. The flow is originated from the potential difference between the points of transpiration (leaves) and absorption (roots) according to the formula:

$$Te = \frac{(PSI_{leaf} - PSI_{root})}{R_{plant}} \tag{0-36}$$

Where:	Te	actual transpiration rate	[cm/d]
	PSI_{leaf}	water potential in leaf tissue	[cm]
	PSI_{root}	water potential in root tissue	[cm]

R_{plant} resistance of plant tissues to the flow of water [d]

Since the water accumulated in the tissues of the plant is a small fraction of water absorbed, you can match the rate of absorption to that of transpiration, by combining equations (0-35) and (0-36) we obtain:

$$MUR = \frac{(PSI_{Leaf} - PSI)}{(R_{plant} + R_{root})} \quad \textbf{(0-37)}$$

PSI_{Leaf} corresponds to the wilting point of a crop, since if $PSI = PSI_{Leaf}$ we have $MUR = 0$; la Table 0-5 shows the values of crops in Criteria.

R_{root} e R_{plant} represent the specific resistance to the flow [cm/d] along the whole flow distance [cm], and are calculated using equations (0-39) and (0-40) later described in this section.

Table 0-5. values of *PSIleaf* by crop.

Crop (herbaceous and horticultural)	**PSIleaf (cm)**	**Crop** (grassland and tree)	**PSIleaf (cm)**
Corn	17000	Alfalfa	13000
Spring sugar beet	12000	Undesowing grass	14000
Soybean	15000	Gramineae grass	11000
Wheat	14000	Fallow	20000
Barley	14000	Fallow sparse	20000
Tranplanted tomato	12000	Grapevine	18000
Sorghum	20000	Peach tree	10000
Sunflower	14000	Pear tree	15000
Potato	7000	Kiwifruit	8000
Onion	9000		

Thus, under conditions of limited humidity, the actual transpiration of layer of soil $T_{e,i}$, coincides with the maximum value T_M until the maximum uptake rate *MUR* is greater than or equal to T_M, otherwise it is limited by the value MUR. We then have:

$$T_{e,i} = T_M * RootDens_i \quad \text{if } MUR \geq T_M \quad \left(\text{for } \theta_i \leq \theta_{sat} - \frac{1}{2}(\theta_{sat} - \theta_{cc})\right) \quad \textbf{(0-38)}$$

$$T_{e,i} = MUR * RootDens_i \quad \text{if } MUR < T_M$$

Where: $T_{e,i}$ actual transpiration of layer *i* [mm/d]

$RootDens_i$ radical density of the layer *i* [$m^3\ m^{-3}$]

R_{plant} depends on physiological plant resistance to drought, and is calculated according to PSI_{Leaf} using the equation (derived empirically):

$$R_{plant} = 680 + 0.53 * PSI_{Leaf} \tag{0-39}$$

R_{root} is estimated using the "average" hydraulic conductivity and the rooted in the soil profile according to the equation:

$$R_{root} = \frac{10}{(P_{rad}) * K_{ave}} \tag{0-40}$$

Where:	K_{ave}	average hydraulic conductivity in the rooted profile	[cm d^{-1}]
	φ	Potential	[cm]
	P_{rad}	rooting depht	[cm]

The calculation of K_{ave} is done with the following expressions[1]:

$$\begin{aligned} K(\varphi) &= K_0 e^{-(\alpha\varphi)} \qquad \varphi \le \varphi_{\max} \\ K(\varphi) &= ak\,\varphi^{-1.4} \qquad \varphi > \varphi_{\max} \end{aligned} \tag{0-41}$$

Where:	$K(\varphi)$	hydraulic conductivity	[cm d^{-1}]
	φ	Potential	[cm]
	φ_{max}	threshold potentials tabulated by type of soil	[cm]
	K_0	saturated hydraulic conductivity	[cm d^{-1}]
	α	exponent depending on the type of soil	[cm^{-1}]
	Ak	Coefficient depending on the type of soil	[$cm^{2.4}$ d^{-1}]

$$K_{medio} = \exp\left((\sum_{i}^{NSR} \log\ k(\varphi_i)) / NSR \right) \tag{0-42}$$

Where:	$K(\varphi_i)$	hydraulic conductivity of layer *i*	[cm d^{-1}]
Dove:	*NSR*	Total number of layers with roots	[-]

The actual transpiration of all the rooted profile is then calculated as follows:

$$T_E = \sum_{i}^{NSR} T_{e,i} \tag{0-43}$$

The hydraulic conductivity is highly dependent on soil texture and the potential (Figure 0-10); For values of soil water content between saturation at field capacity, sandy soils are more permeable, while with increasing potential clay soils have higher values *K*. In Figure 0-11 and Figure 0-12 values of R_{root} and *MUR* are shown depending on water potential for some types of soil. Then in Figure 0-13 and Figure 0-14 are represented the curves of the coefficient *MUR* in a loamy soil all crops present in Criteria.

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[1] H. van Keulen, J.Wolf, 1986. Modelling of agricultural production: weather, soils and crops. Pp 84

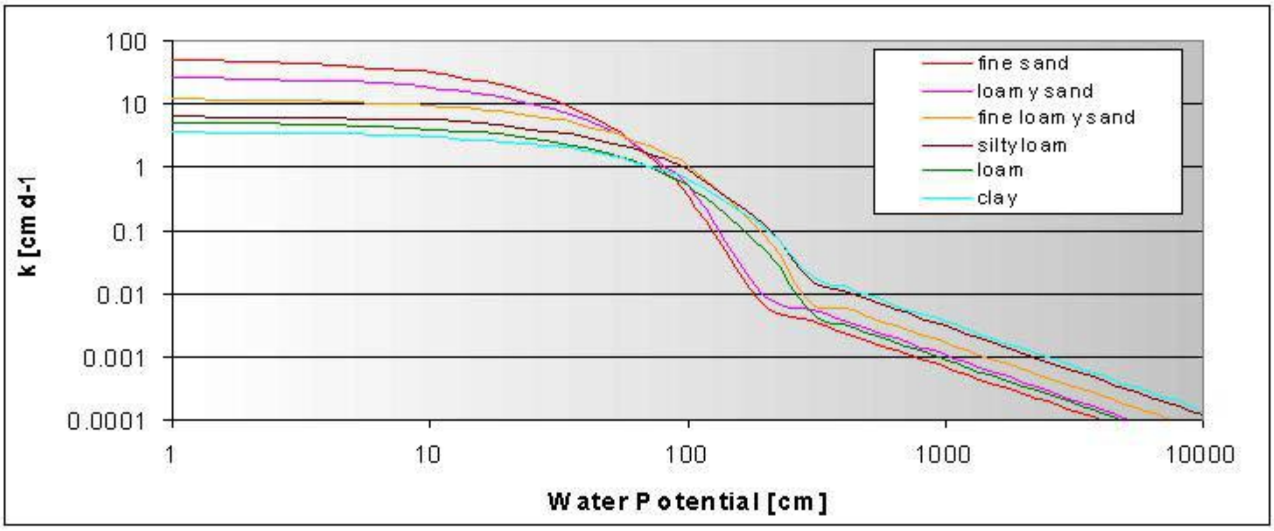

Figure 0-10. hydraulic conductivity (K, cm d^{-1}) for soils with uniform texture.

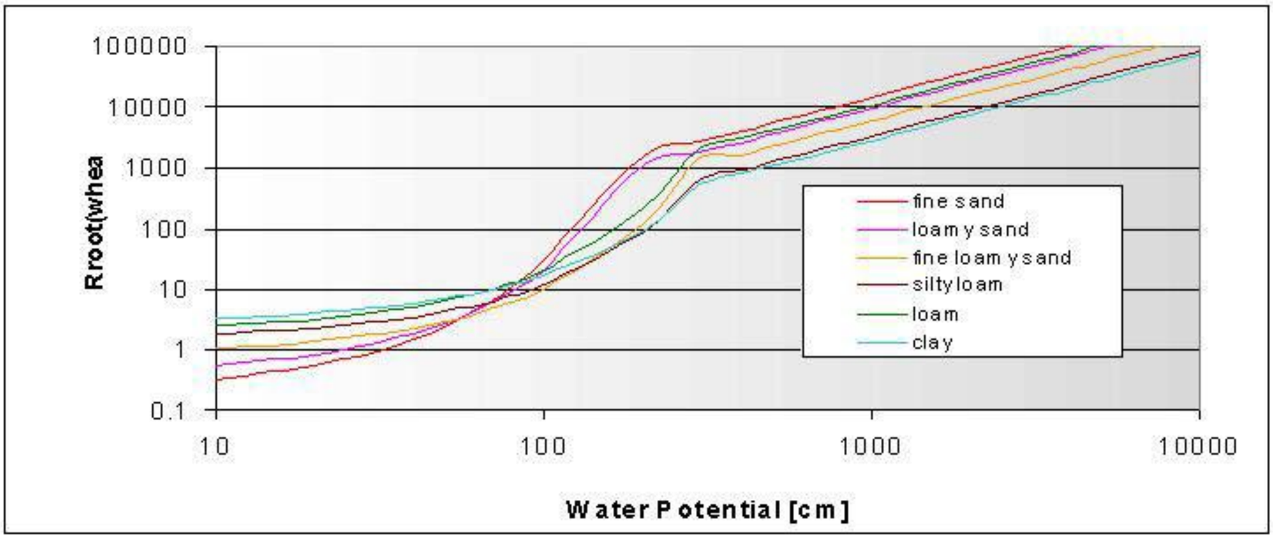

Figure 0-11. Values of the variable R*root* as a function of the potential in uniform soils cultivated with wheat.

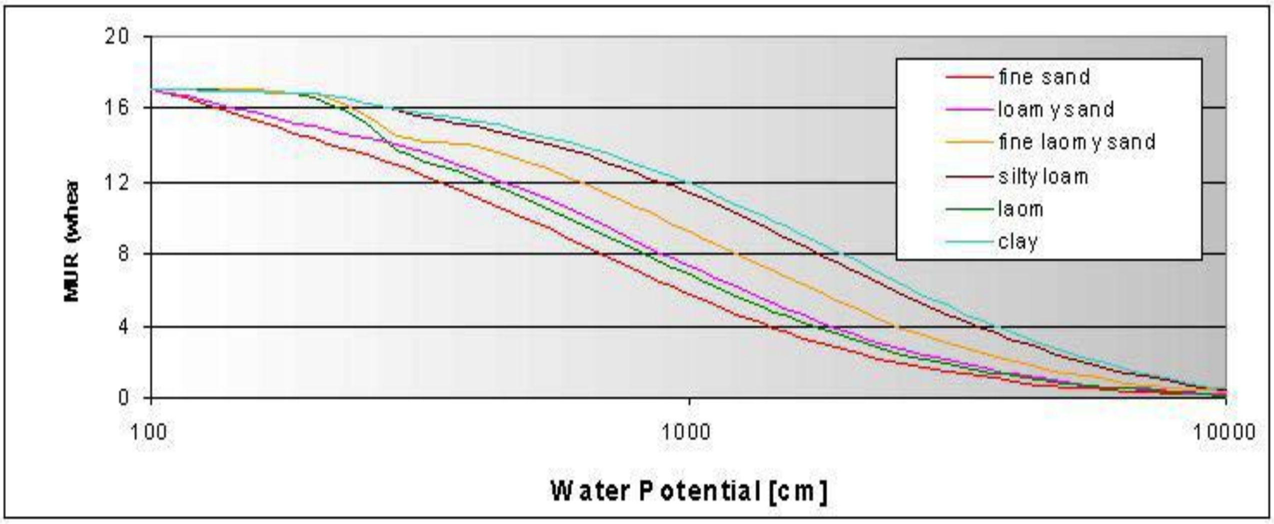

Figure 0-12. Levels of MUR (maximum uptake rate) in for a uniform soil profile of 1 m, under wheat crop.

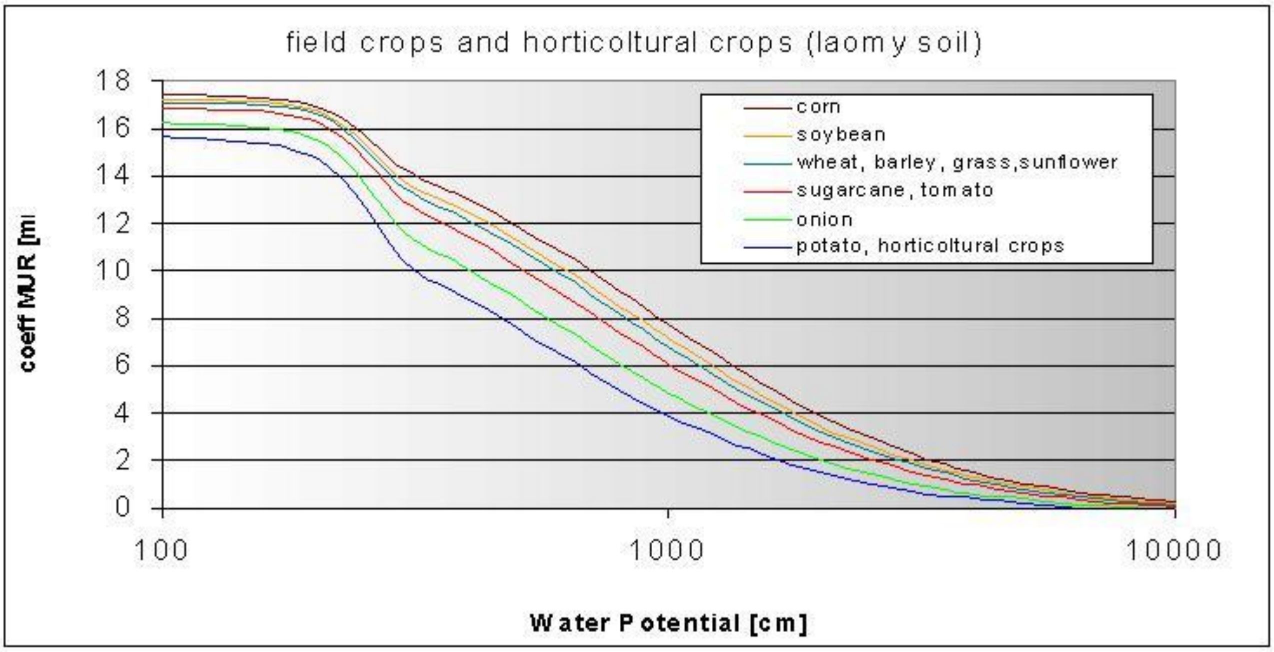

Figure 0-13. Levels of MUR (maximum uptake rate) for herbaceous and horticultural crops present in Criteria, calculated in a uniform loamy soil profile of 1 m.

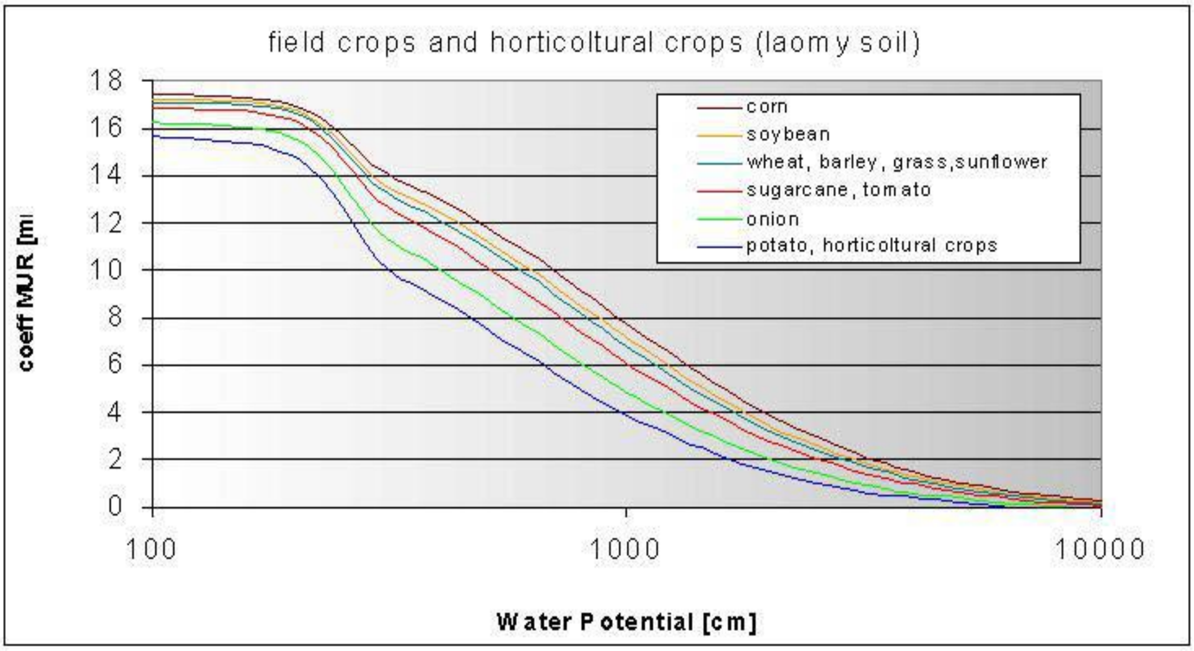

Figure 0-14. Levels of MUR (maximum uptake rate) for grassland and tree crops present in Criteria, calculated in a uniform loamy soil profile of 1 m.

1.6.3 The actual evaporation

- In the presence of a puddle high enough to meet the demand for maximum evaporation (E_M), the actual evaporation (E_E) is equal to the maximum;
- In the presence of a puddle not high enough to meet the demand for maximum evaporation (E_M), the remaining evaporation rate (E_M-puddle height) will be determined by the water content of the top 20 cm of the soil ($E_E \leq E_M$);
- in the absence of a puddle, the actual evaporation will be determined by the water content of the top 20 cm of the soil ($E_E \leq E_M$).

Evaporation takes place in a layer only if the humidity is above a certain threshold value, calculated using the following expression.

$$ThrEvap_{layer} = WC_{FC} - CoeffEvapRed * (WC_{FC} - WC_{WP}) \quad \textbf{(0-44)}$$

Where:	*SogliaEvapStrato*	threshold for evaporation for layer	[mm]
	WC_{FC}	water content at field capacity of the layer	[mm]
	WC_{WP}	water content at permament wilting point	[mm]
	CoeffEvapRed	evaporation reduction coefficient, calculated according to equation (0-45)	[-]

Figure 0-15 shows, for any type of soil, the minimum amount of water that must be present in the soil to be able to evaporate.

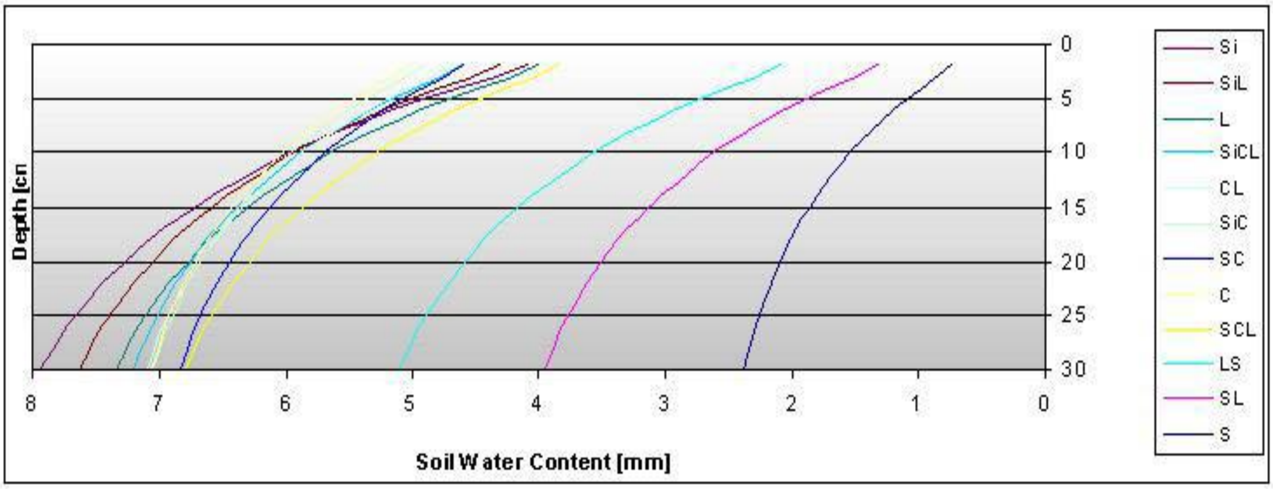

Figure 0-15. Threshold of evaporation in the first 30 cm of the profile for all textual classes. (S=sandy, SL=Sandy Loam, LS=Loamy Sand, SiL= Silty Loam, L=Loam, Si=Silty, SCL=Sandy Clay Loam, SiCL=Silty Clay Loam, CL=Clay Loam, SC= Sandy Clay, SiC= Silty Clay, C=Clay).

The maximum threshold of evaporation decreases with depth exponentially decreasing according to the following equation:

$$CoeffEvap\,Red = e^{-2\cdot(depth/\max depth)} \qquad \textbf{(0-45)}$$

Where:	*CoeffEvapRed*	evaporation reduction coefficient	[mm]
	Prof	depth in the middle of the layer	[m]
	Profmax	maximum depth of the layer	[m]

Figure 0-16 shows the decrease of evaporation with depth.

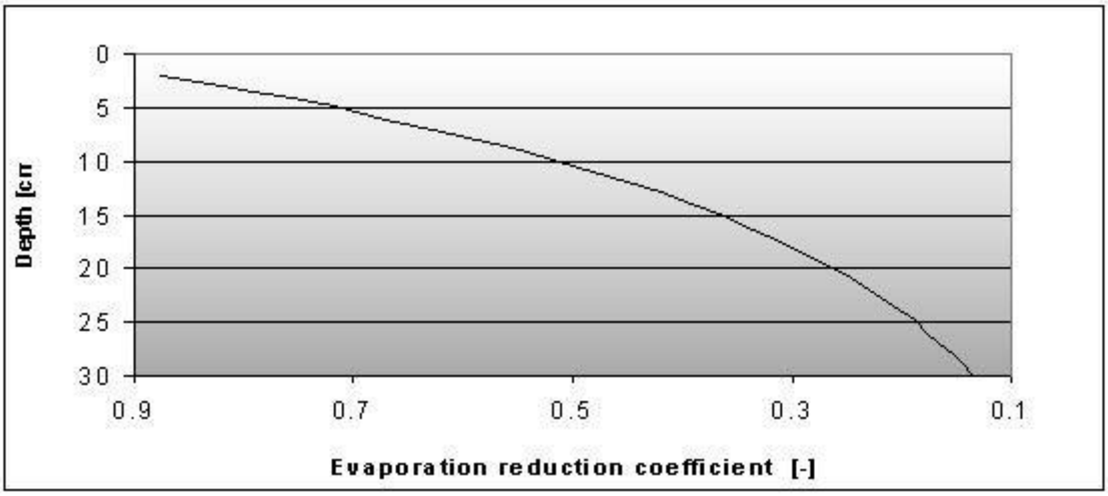

Figure 0-16. Reduction of evaporation in the first 30 cm of the profile for all textual classes.

1.7 Water balance

Once calculated, all the components CRITERIA calculate the total water content of the soil profile as the sum of moisture in all the layers. This value is then compared with the water content of the previous day, to which the contributions and losses of water occurred during present day are added. The difference between the two terms shows the error in the calculation of water balance made by CRITERIA. Control of the balance is therefore:

$$Balance = WCProfile_{today} - (WCProfile_{today-1} - Prec + Dren + Runoff + SubLatFlow + Er + Tr - Irri - CapRise) \qquad \textbf{(0-46)}$$

Where:	*Balance*	Error in the calculation of water balance	[mm]
	$WCProfile_{today}$	Total water content of the profile in present day	[mm]
	$WCProfile_{today-1}$	Total water content in the profile of the previous day	[mm]
	Prec.	Daily rainfall	[mm]
	Dren.	Daily deep drainage	[mm]
	Runoff	Daily surface runoff	[mm]
	SubLatFlow	Daily hipodermic runoff	[mm]

Er	Actual daily evaporation	[mm]
Tr	Actual daily transpiration	[mm]
Irri.	Daily irrigation	[mm]
CapRise	Daily capillary rise	[mm]

If the error is too high compared to the maximum tolerated value the model indicates this problem in the log file. This can occur with the numerical model in case of intense rains.

2 The pedotransfer functions and water retention curves

As illustrated in the chapter on water balance, the study of infiltration requires characterizing each soil horizon through its water retention curve (or soil water characteristic curve), which defines the potential-water content relationship and thus the soil's ability to retain or release water. Currently in CRITERIA model the water retention curve of Campbell, van Genuchten and modified van Genuchten (Ippisch et al., 2006) are used. Formulas and pedotransfer functions linked to them in the model are illustrated in the following chapters.

In Table 2-1 a number of points of particular importance in the retention curve are defined and some important definitions concerning the hydrological characteristics of the soil are listed.

Table 2-1

Property name	**Description**
WATER CONTENT	it is the amount of water present in the soil. Can be expressed as the ratio between the volume of water contained in the sample and the volume of soil sample [cm^3 cm^{-3}], or as the ratio between the weight of the water contained in the sample and the dry weight of the same sample [g g^{-1}].
WATER POTENTIAL	it is the strength with which water is retained in the soil. For each type of soil there is a unique relationship between soil water content and its potential, expressed by the retention curve. It has theoretical potential zero on a free surface of distilled water, in practice assumes potential equal zero that of a ground completely saturated with water.
RETENTION CURVE	describes the patterns of water potential in relation to the percentage of water. It is commonly used to determine the water content at field capacity and wilting point.
SATURATION, SAT	indicates the maximum amount of water that the soil can hold. Also called maximum water capacity.
FIELD CAPACITY, FC	expresses the content of moisture in the soil at the upper limit of drainage, in other words, FC indicates the water content that the soil can retain, after that value water is considered free and it will seep into the lower horizons of soil. Roughly corresponds to a matric potential of -30 kPa (-0.3 bar) in most soils and to -10 kPa (-0.1 bar) in sandy soils, corresponding to a pF value of 1.
WILTING POING, WP	a land is at the wilting point when most of the plants are no longer able to extract the water. Usually for herbaceous crops a land is called at the wilting with a matric potential of -1500 kPa (-15 bar). or pF of 4.2. Roughly corresponds to the lower limit of water available. In CRITERIA WP was set to the value of 1600 kPa
PLANT AVAILABLE WATER, PAW	Corresponds to the difference between field capacity and permanent wilting point AD = (FC - WP).

SAT, FC, WP and PAW can be expressed in weight (water grams/soil grams [g g^{-1}], kilograms of water per cubic meter of soil [kg m^{-3}]) or in volume (water volume/soil volume [cm^3 cm^{-3}], or water millimeters /meter of soil [mm m^{-1}]).

In Figure 2-1 are represented the different levels of water content of the soil with their types and limits of water availability to the crop.

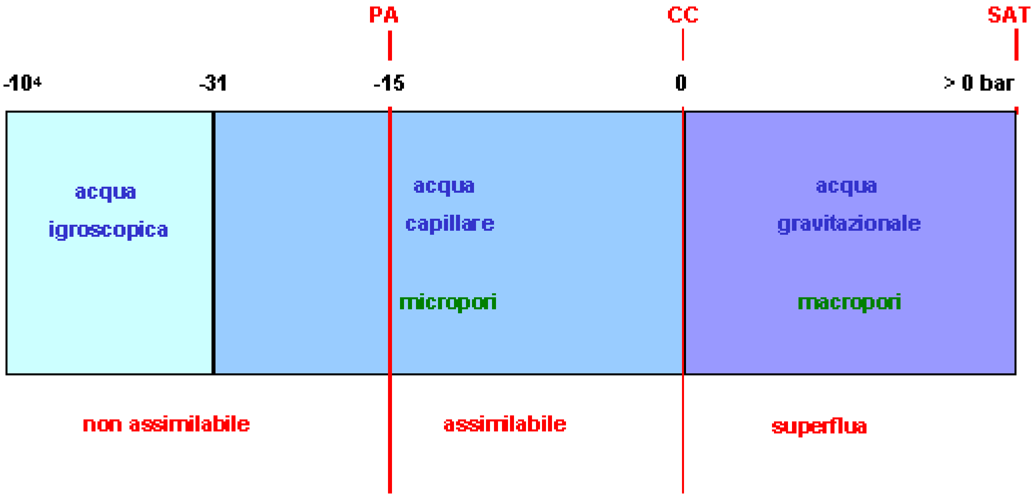

Figure 2-1. **Characteristic levels of the water retention curve with their types and levels of water availability for crop**

It should be noted that the concepts of field capacity, permanent wilting point and water available are not very strict with regard to the complex dynamics of the soil-plant-atmosphere system; however, these concepts provide a useful reference for a schematic and simplified processes description.

The relative availability of water depends basically on the texture of the soil. The sandy soils are rich in macropores and thus much of the water content is gravitational water, superfluous from the point of view of crop as subject to rapid percolation to the deeper horizons. At the other extreme clay soils are rich in micropores and thus much of the water content is made up of water held back by ties to ground voltages to -15 bar and then unassimilable by plants.

Here below are some conversion factors between units of measure usually used to indicate the tension:

1 mbar	=	1hPa	=	1cm
1 bar	=	100 kPa	=	0.987 atm

2.1 The water retention curve and the Campbell pedo-transfer function

Campbell (1974) proposes a formula to describe the relation moisture-tension split into two equations:

$$\psi = \psi_a \left(\frac{\theta}{\theta_S} \right)^{-b} \qquad \text{or the inverse:} \qquad \theta = \theta_S \left(\frac{\psi}{\psi_a} \right)^{\left(-1/b\right)} \quad \text{for } \psi < \psi_a \tag{2-1}$$

while: $$\theta = \theta_S \qquad \text{for } \psi \geq \psi_a$$

Where:	θ *and* θ_S	water content (ψ) and water content at saturation	[m^3m^{-3}]
	ψ	matric potential	[kPa]
	ψ_a	air entry potential	[kPa]
	b	empirical coefficient	[-]

We use the following formula if in the soil database there is an experimental value of the water content at saturation, otherwise θ_{sat}, is calculated as a function of bulk density and organic matter content using the following formula (Driessen, Konijn 1992):

$$\theta_{sat} = 1 - \frac{BD}{2.6} \text{ if } OM = 0 \qquad \textbf{(2-2)}$$

$$\theta_{sat} = 1 - \frac{BD}{\left(\frac{1}{0.38 + 0.57 * (OM\ /100)}\right)} \text{ if } OM > 0 \qquad \textbf{(2-3)}$$

Where:	θ_{sat}	Water content at saturation	[m^3m^{-3}]
	BD	bulk density, tabulated in the database of soils	[$t\ m^{-3}$]
	OM	Organic matter content	[m^3m^{-3}]

If the database does not have an experimental value of *BD* for the land in question, it refers to the typical value for the textural class contained in the CRITERIA settings.

Careful consideration must be given to the estimation of water content at saturation: The experimental data that is used in MVA must be sufficiently reliable, otherwise you can get θ_{sat} values that do not correspond to reality; to overcome this problem, the resulting θ_{sat} from equations (2-2) and (2-3) (2 3) is compared with the reference value of the textural class of soil horizon under consideration (contained in the CRITERIA settings), if the variance is too high (greater than 33%) an average of the two values is used.

As is clear from equation (2-1), in the Campbell soil water retention curve from value ψ_a to saturation value is considered constant and equal to the saturation water content itself. Figure 2-2 shows an example of the curve trend with low values of matric potential. It is thus emphasized the discontinuity due to the hypothesis that moisture does not vary from the potential value 0 at the value of entry of water into the soil.

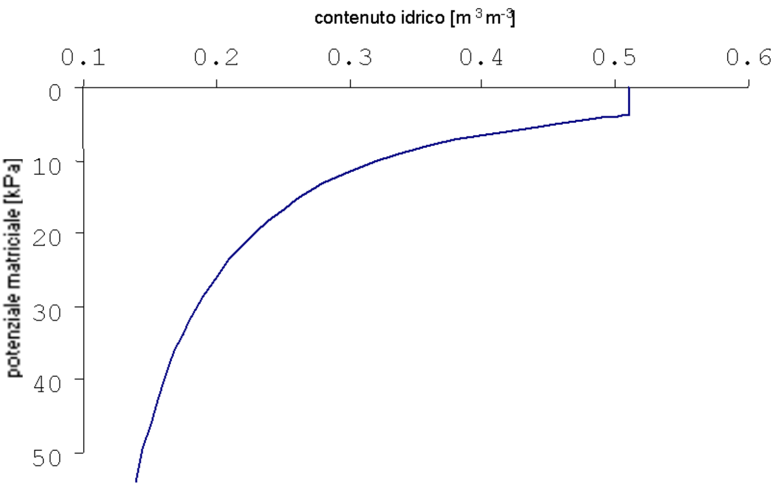

Figure 2-2. Example Campbell soil water retention curve near saturation.

2.1.1 Pedotransfer functions for parameter estimation

To estimate parameters ψ_a e b of the water retention curve, Shiozawa and Campbell (1985) present interdependence relations between granulometric physical parameters and geometric mean diameter (dg) and its standard deviation (σg).

Parameters estimates are given by:

$$\psi_a = \frac{-5}{\sqrt{dg}} \quad \text{and} \quad b = \frac{10}{\sqrt{dg}} + 0.2\sigma g \tag{2-4}$$

Where:

	ψ_a	value of incoming air tension (parameter of the functional curve of Campbell)	[kPa]
	b	empirical coefficient (parameter of the functional curve of Campbell)	[-]
	dg	geometric mean diameter	[µm]
	σg	standard deviation of *dg*	[µm]

dg and σg, both expressed in µm, can be estimated (Shiozawa *et al.*, 1991) by:

$$dg = e^{\left(5.756 - 3.454 m_t - 7.712 m_y\right)}$$

$$\sigma g = e^{\sqrt{33.14 - 27 - 84 m_t - 29.31 m_y - (\ln dg)^2}} \tag{2-5}$$

Where:

	dg	geometric mean diameter	[µm]
	σg	standard deviation of *dg*	[µm]
	m_t and m_y	Fraction of mass of silt and clay fractions of soil under consideration	[%]

The data required for using of the pedotransfer function and the water retention curve of Campbell are only three: bulk density to estimate the water content at saturation, and content of silt and clay of the horizon for the estimation of parameters a and b. For this reason, these functions are widely used in mapping applications where the geographic availability of soil data is often limited. It should be noted however, that the pedotransfer function ignores the content of organic matter, an important factor that influences the hydrological characteristics of the soil.

If for the horizon of soil are available test data of potential - moisture, the parameters of the water retention curve are calibrated in terms of these data through a fitting procedure.

2.2 The water retention curve of van Genuchten

The other water retention curve used in Criteria is expressed by the equation proposed by van Genuchten (1980), widely used in soil physics modelling. The equation has the following form:

$$\frac{\theta - \theta_R}{\theta_S - \theta_R} = \left[\frac{1}{1 + \left(\alpha \left| \psi \right| \right)^n} \right]^m \tag{2-6}$$

Where:	*θ, θ_R e θ_S*	water contain at water potential h, residual and at saturation	$[m^3m^{-3}]$
	α, m e n	empirical parameters with α>0, *n*>1, 0<*m*<1 and *m*=1-1/*n*;	[-]
	ψ	matric potental with | ψ |≥0	[cm]

The left side of the equation can be summarized in the term θ_E to make it easier for clarification of the term of the matric potential. The equation can therefore be also presented in the following form:

$$\psi = \frac{\left(\theta_E^{-1/m} - 1 \right)^{1/n}}{\alpha} \quad \text{where} \quad \theta_E = \left(\frac{\theta - \theta_R}{\theta_S - \theta_R} \right)^m \tag{2-7}$$

The parameters to be estimated in equations (2-6) and (2-2) are 4: α, *m*, *n* and θ_S, and θ_R (parameter *m* can depend on *n* if the restriction *m*=1-1/*n* is applied). If for the horizon of soil test data of potential-water content are available, the parameters of the water retention curve are calibrated in terms of these data through a procedure of fitting. Otherwise, their values are read in the general settings of CRITERIA (listed in Tabella 2-2), where they are tabulated according to textural class.

In Criteria, also the van Genuchten curve modified by Ippish (2006) has been developed; in the numeric solution of water fluxes in the soil only the modified van Genuchten can be applied because it solves numeric problems due to the conducibility curve.

Tabella 2-2: parametri caratteristici delle classi tessiturali USDA

texture	Alfa	N	he	Thetar	Thetas	Ksat
sand	0.39	1.7	0.07	0.01	0.38	192
loamy sand	0.35	1.5	0.1	0.02	0.39	96

texture	Alfa	N	he	Thetar	Thetas	Ksat
sandy loam	0.29	1.4	0.15	0.02	0.4	48
silt loam	0.13	1.2	0.26	0.03	0.44	9.6
loam	0.17	1.21	0.23	0.03	0.42	12
silt	0.1	1.24	0.27	0.03	0.44	2.4
sandy clay loam	0.22	1.22	0.2	0.03	0.41	12
silty clay loam	0.13	1.2	0.31	0.03	0.46	2.4
clay loam	0.18	1.18	0.27	0.04	0.45	4.8
sandy clay	0.21	1.18	0.25	0.04	0.44	3.6
silty clay	0.17	1.16	0.33	0.05	0.48	1.2
clay	0.16	1.16	0.33	0.05	0.48	0.8

In addition to the Van Genuchten parameters in Tabella 2-2 are also present:

- Ksat [cm/d]: saturated hydraulic conductivity
- he [kPa]: air entry point for the modified Van Genuchten curve (see Ippisch et al. 2006)

The values of this table were produced from the data presented in a serie of papers of the subject (Wösten, Lilly, Nemes, Le Bas, 1998; Simota, Mayr, 1996; Carsel, Parrish, 1988; Schaap, Leji, van Geuchten, 2001).

3 The crop: growth and development simulation

The development of the crop in CRITERIA can be simulated using two models:

- a standard model, based on the degree day sum;
- the growth model WOFOST.

For the standard model have been implemented five classes of crop: herbaceous, horticultural, tree (with grass or not), grass and fallow. Table 3-1 lists all the crops present in the database.

Table 3-1. Crops in the standard model implemented by CRITERIA

Class	Crop
Herbaceous crop	corn, spring sugar beet, soybean, wheat, barley, sunflower, tomato
Fruit tree crops	grapevine, peach tree, pear tree, kiwifruit
Horticultural crops	potato, onion
Grass and fallow crops	alfalfa, meadow grass, fallow, sparse fallow

The growth model WOFOST currently allows simulating corn and wheat crops.

3.1 The standard model in CRITERIA

In the standard model, the crops are treated as fictitious elements that interact in the water balance of the system. There shall be no estimates of biomass growth. The variables of interest are therefore the development of the leaf system (expressed by parameter LAI, *Leaf Area Index*) for the epigeal part and development, understood as the growth rate and spatial distribution of the root system. The sum of degree days is the factor that determines the development of the crop. The reduction in development caused by water stress or lack of nutrients is not considered in the standard model.

3.1.1 The degree day sum

The standard function for calculating the sum of degree days is the following:

$$SumDegreeDays = \frac{(T_{\min} + T_{\max})}{2} - Threshold \tag{3-1}$$

Where:	*SumDegreeDays*	sum degree days	[°C d]
	T_{min} and T_{max}	daily maximum and minimum temperature	[°C]
	Threshold	minimum temperature depending on the crop that must be overcome to start the development of roots and leaves	[°C]

For tree, grassland and uncultivated crops, the calculation of the sum degree days begins January 1 and is reset December 31 of each year. For herbaceous and horticultural crops, however, the calculation starts from sowing date of the crop.

As long as the function result is negative (the threshold was not reached), the calculation of LAI and roots will not start. Then a further check on the value of the daily maximum temperature (T_{max}) is made to avoid unrealistic growth curve in the very hot days. In this case, T_{max} is replaced by a threshold value depending on the crop.

3.1.2 The development of the epigeal part

In the standard crop model of CRITERIA development of LAI is approximated assuming 4 phenological stages (5 for herbaceous crops), each with its own growth rate:

- emergency phase: present only in the herbaceous crops
- phase 1: exponential growth of LAI
- phase 2: linear growth of LAI
- phase 3: decreasing growth rate of LAI
- phase 4: decrease of LAI

The length of each phase varies from crop to crop. At the end of phase 4 there is the harvest for herbaceous, horticultural and tree crops.

In the model code, the calculation function of LAI is divided into two steps: the growth phase up to the maximum LAI (which includes the first three stages), and the decreasing phase until harvest or at the end of the leaves fall.

The development of the LAI in the early growth stages is calculated as follows:

$$LAI = \frac{LAI_{MAX} - LAI_{MIN}}{1 + e^{\left(a_{LAI} + b_{LAI} * SumDegreeDay\right)}} + LAI_{MIN} \tag{3-2}$$

Where:	*LAI*	*Leaf Area Index* during the exponential growth phase	[-]
	LAI_{MAX}	maximum value of LAI for the crop	[-]
	LAI_{MIN}	minimum value of LAI for the crop	[-]
	a_{LAI} e b_{LAI}	coefficients of the linear regression log*LAI* –SumDegreeDays	[-]
	SumDegreeDays	sum degree days, calculated with equation (3-1).	[°C d]

For grass crops a cutting procedure is included: for every time there is a default value of the degree day sum (corresponding to the maximum value of LAI), the variable *SommaGG* is reset and LAI is brought to the minimum value.

For tree with grass covered ground the LAI of the herbaceous cover (LAI_{grass}) is added to the LAI calculated by crop.

The decreasing phase of LAI is handled differently, depending on the type of crop:

- **herbaceous** and **horticultural** crops:

For herbaceous and horticultural crops, during the decreasing phase LAI is calculated as follows:

$$LAI = \frac{LAI_{MAX} - LAI_{MIN}}{1 + \left(\dfrac{10 * \left(\text{SumDegreeDays} - Sumphase3\right)}{Sumphase4 * C4_{LAI}}\right)^{N4_{LAI}}} + LAI_{MIN} \tag{3-3}$$

Where:	*LAI*	*Leaf Area Index*	[-]
	LAI_{MAX}	maximum value of LAI for the crop	[-]
	LAI_{MIN}	minimum value of LAI for the crop	[-]
	Sumphase3	sum degree days of the first three phenological phases	[°C d]
	Sumphase4	sum degree days between phase 3 and phase 4	
	$N4_{LAI}$ e $C4_{LAI}$	specific coefficients for the crop	[-]
	SumDegreeDays	sum degree days calculated with equation (3-1)	[°C d]

When the sum degree days exceeds the phase 4, which corresponds to the harvest for these crops, the LAI of herbaceous and horticultural crops is set equal to LAI_{MIN}.

- **tree** crops:

For tree crops, once the fourth phase is exceeded LAI decreases exponentially, reaching its minimum value of on November 15.

- **grass** crops:

For grass crops phenological stages are not considered and LAI follows a growing trend repeated after each mowing. Starting from November 1 of each year begins to decrease linearly to reach the minimum value of LAI at the last day of the year.

- **fallow:**

For fallow, phenological stages are not considered and LAI, once reached its maximum value remains stable until November 1 of each year when it begins, like the grassland and tree crops, the exponentially decrease until reaching the minimum value of LAI at the last day of the year.

3.1.3 The development of the hypogeal part

The root development is simulated for annual crops (herbaceous and horticultural) as a function of growth in CRITERIA (logarithmic, linear, asymptotic, and exponential), up to a maximum depth value typical of the crop. Radical density is calculated daily in each layer of the soil affected by roots, according to a radical density profile present in CRITERIA (cylindrical, ellipsoid, ovoid, and cardioid)

For the uncultivated, tree and grassland crops, the rooting depth is always equal to the maximum rooting depth. Once defined the shape of the root system the radical density in each layer of the soil remains always the same. An exception is the alfalfa in the first year, which is managed as herbaceous crop to simulate the development of the rooting depth.

3.1.3.1 Computing of the parameters of the function of growth

First, the creep factor is calculated by the root system, depending on the function of growth typical of the crop, with a logistic growth, parameter is calculated as:

$$FatDef = \frac{\log_{MAX} - \log_{MIN}}{PRad_{MAX} - PRad_{INI}} \tag{3-4}$$

Where:

$$\log_{MAX} = \frac{PRad_{MAX}}{1 + \exp(-b - k * ciclo)} \qquad \log_{MIN} = \frac{PRad_{MAX}}{1 + \exp(-b)} \tag{3-5), (3-6}$$

$$k = \frac{ini_{\log} - fin_{\log}}{G_{F1} - rootCycle} \qquad b = -(fin_{\log} + k * ciclo) \tag{3-7), (3-8}$$

$$ini_{\log} = \log(1/(ini - 1)) \qquad fin_{\log} = \log(1/(fin - 1)) \tag{3-9), (3-10}$$

Where:	*FatDef*	creep factor of the root system	[-]
	Ini	fractional depth at the end of the slow growth phase	[m]
	fin	fractional depth at the end of the growing cycle	[m]
	$PRad_{MAX}$	maximum rooting depth	[m]
	$Prad_{INI}$	initial rooting depth	[m]
	rootCycle	Length of growth cycle of roots	[d]
	G_{F1}	Length of the first phase of the slow growth	[d]

In the case of asymptotic or exponential growth the creep factor is calculated as:

$$FatDef = \frac{PRad_{MAX} - PRad_{INI}}{1 - \exp(ciclo \ / G_{75})} \text{ asymptotic growth} \quad (3\text{-}11)$$

$$fatDef = \frac{PRad_{MAX} - PRad_{INI}}{\exp(-1 / k_2 * ciclo) - 1} \text{ exponential growth} \quad (3\text{-}12)$$

$$K_2 = ciclo - G_{F1} \quad (3\text{-}13)$$

Where:	*FatDef*	creep factor of the root system	[-]
	$PRad_{MAX}$	maximum rooting depth	[m]
	$Prad_{INI}$	initial rooting depth	[m]
	Ciclo	Length of growth cycle of roots	[d]
	G_{F1}	Length of the first phase of the slow growth	[d]
	G_{75}	number of days to reach 75% of the maximum rooting depth	[d]
	K_2	Length of the second growth phase	[d]

In case of linear growth the creep factor is not used.

3.1.3.2 Computing of rooting depth

In annual crops the depth reached by the roots day by day is evaluated based on the sum degree days. Depending on the function of growth of the crop, rooting depth is calculated as:

$$PRad = PRad_{INI} + \frac{1}{FatDef * \left(\frac{PRad_{MAX}}{1 + \exp(-b - k * sGG)} \right) - \log_{min}} \text{ logistic growth} \quad (3\text{-}14)$$

$$PRad = PRad_{INI} + \frac{PRad_{MAX} - PRad_{INI}}{ciclo} * sGG \qquad \text{linear growth} \quad (3\text{-}15)$$

$$PRad = PRad_{INI} + FatDef * (1 - \exp(-sGG \ / G_{75})) \qquad \text{asymptotic growth} \quad (3\text{-}16)$$

$$PRad = PRad_{INI} + FatDef * (\exp(1 / k_2 * sGG) - 1) \qquad \text{exponential growth} \quad (3\text{-}17)$$

Where:	*Prad*	rooting depth at the relevant date	
	$PRad_{MAX}$	maximum rooting depth	[m]
	$Prad_{INI}$	initial rooting depth	[m]
	FatDef	creep factor of the root system	[-]
	b	Growth factor, calculated with the equation (3-7), **(3-8)**	[-]
	k	Growth factor, calculated with the equation (3-7), **(3-8)**	[-]
	Log_{min}	Growth factor, calculated with the equation (3-5), **(3-6)**	[-]
	sGG	sum degree days at the relevant date	[°C d]
	ciclo	Length of growth cycle of roots	[d]
	K_2	Length of the second growth phase	[d]

G_{75}	number of days to reach 75% of the maximum rooting depth	[d]

As already mentioned, for the uncultivated, tree and grassland crops rooting depth is always equal to the maximum rooting depth.

3.1.3.3 Root density

In CRITERIA root density is calculated using a basic geometric shape (cylindrical or spherical), on which a deformation is applied that reproduces the actual configuration of the crop root system.

In the model calculations the density is expressed as a fraction of the root mass density so that the sum of the densities of all layers is equal to one. Considering the projection of solid three-dimensional plane by the system, the model initially assumes that the roots are distributed uniformly in a rectangle (for the cylindrical shape), or in a circle (for spherical shape) whose center is half of the rooting depth and whose radius has the same value. The identified area is divided into parts of equal thickness parallel to the surface and equal to the number of layers, the density is then obtained by the ratio between the surface of the part and the total one. Depending on the crop, to the resulting initial density is applied a deformation present in the model: ellipsoid, ovoid, and cardioid.

The elliptical deformation of the basic spherical structure takes place by applying increasing linearly deformation coefficients from the first layer (i = 1) to the central (i = n) which has the maximum deformation provided by the user. So the modified density of the i-th layer is given by:

$$RootDens_i = RootDensC_i * \left(def - \frac{def - 1}{n - 1} \right) \tag{3-18}$$

Where:	$RootDens_i$	modified radical density of the i-th layer, with i: $n \rightarrow 1$	[-]
	$RootDensC_i$	Base radical density of the i-th layer (spherical)	[-]
	def	parameter of elliptical geometric deformation of the root system (for *def* = 1 spherical shape is preserved)	[-]

Due to the symmetry of this type of deformation, for the layers of the lower half density is set equal to that of the corresponding upper layer.

The ovoid deformation, which also applies to cylindrical systems to bring them to conical, consists in the application of a coefficient to the density of each layer that varies linearly from the first layer (i = 1) to the last one (i = 2n).

$$RootDens_i = RootDensC_i * \left(def - \frac{def - 1}{n} \right) \tag{3-19}$$

Where:	$RootDens_i$	modified radical density of the i-th layer, with i: $1 \rightarrow 2n$	[-]
	$RootDensC_i$	base radical density of the i-th layer (spherical or cylindrical)	[-]
	def	parameter of ovoid geometric deformation (for *def* = 1 spherical shape is preserved)	[-]

The cardioid deformation is obtained by applying a exponentially decreasing coefficient to the density of the layers with speed conditioned on the value of deformation provided by the user.

$$RootDens_i = RootDensC_i * e^{(-k*(i-0.5))} \quad \textbf{(3-20)}$$

where: $k = LiMin + (LiMax - LiMin)(def - 1)$ **(3-21)**

where: $LiMin = -\log(0.2)/n$ and: $LiMax = -\log(0.05)/n$ **(3-22), (3-23)**

Where:	*RootDens_i*	modified radical density of the i-th layer, with *i*: 1 → 2*n*	[-]
	RootDensC_i	base radical density of the i-th layer (spherical)	[-]
	def	parameter of cardioid geometric deformation	[-]

3.1.4 Irrigation management

Every crop has its own sensitivity to water stress, defined by the ability to use the water present in the root layer. The formula used in Criteria for computing is the function of Landsberg, the sensitivity, calculated as a function of phenological stage, represents the fraction of water readily available to use under which the plant goes into stress.

$$fRAW = \frac{(fRAW_{smax} + fRAW_{smin})}{2} - \frac{(fRAW_{smax} - fRAW_{\mathrm{smin}})}{2} * cos\left[6.28 * \frac{(sumDegreeDays - DD_{smax})}{sumDD_{cycle}}\right] \quad \textbf{(3-24)}$$

Where:	*fRAW*	fraction of readily available water according to Landsberg	[-]
	$fRAW_{smax}$	fraction of readily available water during the maximum sensitivity to water stress	[-]
	$fRAW_{smin}$	fraction of readily available water during the minimum sensitivity to water stress	
	sumDegreeDays	sum degree days calculated with equation (3-1).	[°C d]
	DD_{smax}	threshold of degree days of maximum sensitivity to water stress	[°C d]
	$sumDD_{cycle}$	sum of the degree days of the 4 phenological phases	[°C d]

The function of computing the fraction of useful water compared to the available water (equal to *FC-WP*) determines a minimum point corresponding to the phase of maximum sensitivity of the crop, as shown in in Figure 3-1.

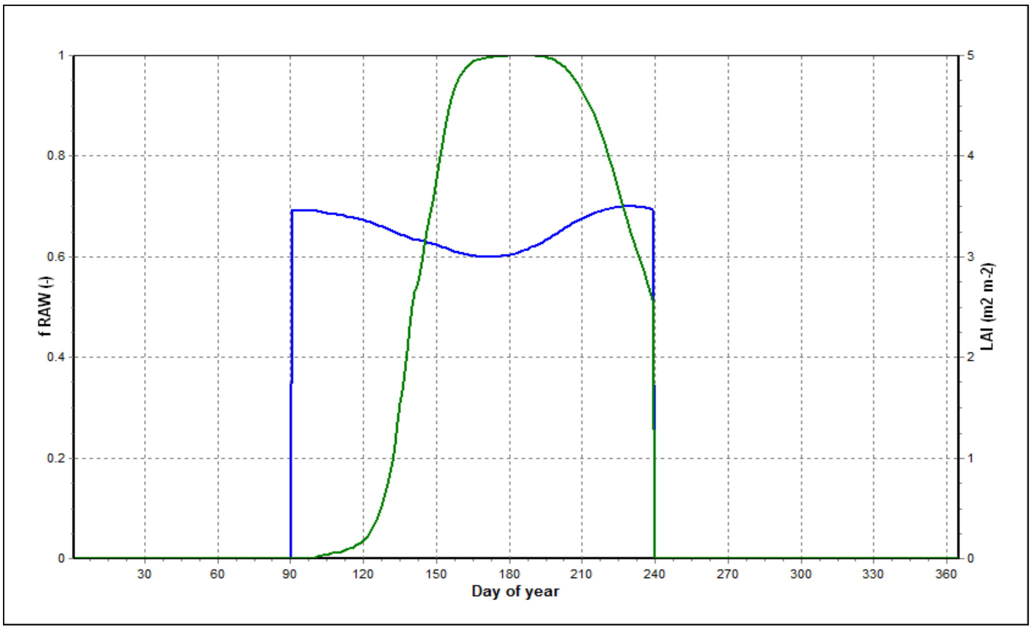

Figure 3-1. Fraction of readily available water (fRAW) depending on the crop development (simulated crop: corn)

Once fRAW value is defined, the amount of water that can be easily used in the root profile is calculated using the function:

$$H_2O_{available} = \sum_{l=iniRootDepth}^{rootDepth} \left(WC_l - \left(FC_l - fRAW * (FC_l - WP_l)\right)\right) \qquad \textbf{(3-25)}$$

Where:	$H_2O_{available}$	easily available water in the root profile	[mm]
	fRAW	fraction of readily available water according to Landsberg, calculated with equation (3-24)	[-]
	WC_l, FC_l, WP_l	respectively water content, field capacity and wilting point of the layer	[mm]

The variable $H_2O_{available}$ is used to assess when to irrigate the crop if it is on the automatic irrigation mode. The model defines the irrigation time when $H_2O_{available}$, that integrates the height of water that can be easily used on the layer of ground affected by the roots, takes values less than 0. In the databases of Criteria a range of water volume values are present, typical for each crop, depending on the method of irrigation.

To prevent unrealistic automatic irrigation, controls were placed on the beginning and the end of the irrigation period and on the frequency of irrigation events. If $H_2O_{available}$ assumes a value less than zero in a date outside the irrigation period or too close to the last watering event, it does not apply any irrigation.

If the automating irrigation mode is off, the magnitudes *fRAW* and $H_2O_{available}$ are calculated but not used, since the irrigation events are set by the user. The time, the volume and type of irrigation are read by the crop history, and carried out regardless the conditions of water stress of the crop.

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