CRITERIA-1D

Technical manual

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Fausto Tomei ftomei@arpae.it
Gabriele Antolini gantolini@arpae.it
Giulia Villani gvillani@arpae.it
Marco Bittelli marco.bittelli@unibo.it

1. DATA

CRITERIA-1D input and output data are stored in SQLite databases (.db files) that can be easily managed by open source software on main platforms (Windows, Linux or MacOS), such as **sqlitebrowser**.

1.1 Meteo database

Weather dataset is organized in a SQLite database with a **meteo_locations** table and several weather data tables.

Nome	Tipo	Schema
Tabelle (2)		
data_example		CREATE TABLE "data_example" ("date" TEXT, "tmin" REAL, "tmax"
date	TEXT	"date" TEXT
tmin	REAL	"tmin" REAL
tmax	REAL	"tmax" REAL
tavg	REAL	"tavg" REAL
prec	REAL	"prec" REAL
etp	REAL	"etp" REAL
watertable	REAL	"watertable" REAL
meteo_locations		CREATE TABLE "meteo_locations" ("id_meteo" TEXT, "table_name"
id_meteo	TEXT	"id_meteo" TEXT
table_name	TEXT	"table_name" TEXT
meteo_name	TEXT	"meteo_name" TEXT
longitude	REAL	"longitude" REAL
latitude	REAL	"latitude" REAL
height	REAL	"height" REAL

*Example of **meteo.db** structure*

You can see the **template_meteo.db** in the directory DATA/TEMPLATE of the distribution, and an example of **meteo.db** in the test project: DATA/PROJECT/test/data

1.1.1 Table meteo_locations

meteo_locations table identifies the location of the meteo point or the cells of a meteo analysis grid.
In the **meteo_locations** table, the following fields are listed:

- *id_meteo*: identifier of the point/cell;
- *table_name*: name of the table, for example composed by "GRD_" followed by the identifier of the grid cell;
- *meteo_name*: toponym of the location;
- *longitude*: longitude of the center of the cell for the WGS82 system coordinates, unit of measure: decimal degree;
- *latitude*: latitude of the center of the cell for the WGS82 system coordinates, unit of measure: decimal degree;

- *height* (optional): height of the center of the cell, unit of measure: meters;

Table: meteo_locations

	id_meteo	table_name	meteo_name	longitude	latitude	height
	Filter	Filter	Filter	Filter	Filter	Filter
1	01878	GRD_01878	VALSAVIGNONE	12.033825	43.7325	816.26
2	01918	GRD_01918	MONTE DELLA ZUCCA	12.096875	43.7325	915.44
3	01958	GRD_01958	SAN PATRIGNANO	12.159925	43.7325	781.15
4	01998	GRD_01998	POGGIO DELLE CAMPANE	12.222975	43.7325	575.14
5	01797	GRD_01797	BADIA PRATAGLIA	11.907725	43.7775	979.62
6	01837	GRD_01837	VERGHERETO	11.970775	43.7775	844.81
7	01877	GRD_01877	MONTECORONARO	12.033825	43.7775	922.14
8	01917	GRD_01917	MONTE FUMAIOLO	12.096875	43.7775	1052.27
9	01957	GRD_01957	CASTELDELCI	12.159925	43.7775	758.5
10	01997	GRD_01997	MIRATOIO	12.222975	43.7775	621.36

*Example of **meteo_locations** table*

1.1.2 Weather data tables

The other tables of the **meteo** database store the weather data, one table for each meteo point or for each cell of the analysis grid. The name of each table corresponds to the *table_name* field in the **meteo_locations**.

The weather data are organized according to the following format:

- *date*: ISO8601 format (YYYY-MM-DD);
- *tmin*: daily minimum air temperature, unit of measure: °C;
- *tmax*: daily maximum air temperature, unit of measure: °C;
- *tavg* (optional): daily average air temperature, unit of measure: °C;
- *prec*: daily total precipitation, unit of measure: mm;
- *etp* (optional): potential evapotranspiration, unit of measure: mm;
- *watertable* (optional): water table depth, unit of measure: m.

Table: GRD_01785

	date	tmin	tmax	tavg	prec	etp	watertable
	Filter	Filter	Filter	Filter	Filter	Filter	Filter
1	2018-07-19	22.5	35.4	28.7	0.0		
2	2018-07-20	22.9	35.4	28.8	0.0		
3	2018-07-21	22.9	36.0	29.1	0.0		
4	2018-07-22	19.6	28.7	23.8	3.3		
5	2018-07-23	19.8	26.0	22.9	2.7		
6	2018-07-24	21.8	31.8	26.7	0.1		

Example of weather data table

If potential evapotranspiration is not available, the SWB will compute the variable by means of the Hargreaves-Samani equation using temperatures and latitude of the meteo point. If water table depth is missing the SWB model will simulate free drainage at the soil bottom.

1.2 Soil database

The database for the soil parameters is organized in two tables: **soils** and **horizons**.

Name	Type	Schema
Tables (2)		
horizons		CREATE TABLE "horizons" (\`soil_code\` TEXT, \`horizon_nr\` INTEGER, \`upper_depth\` INTEGER, \`lower_depth\` INTEGER, \`coarse_fragment\` REAL, \`organic_matter\` REAL, \`sand\` REAL, \`silt\` REAL, \`clay\` REAL, \`bulk_density\` REAL, \`theta_sat\` REAL, \`ksat\` REAL)
soils		CREATE TABLE "soils" (\`id_soil\` INTEGER, \`soil_code\` TEXT, PRIMARY KEY(id_soil))

*Example of **soil.db** structure*

You can see the **template_soil.db** in the directory DATA/TEMPLATE of the distribution and two examples of soil database in the directory DATA/SOIL

1.2.1 Table soils

The table **soils** is an identifier table where each soil has to be defined by an alphanumeric code (*soil_code*) linked to an integer field *id_soil*. Typically this numeric field refers to a soil map shapefile for a geographical project.

Table: soils

	id_soil	soil_code
	Filter	Filter
1	1	AGO1
2	2	AGOz
3	3	ARC1
4	4	ARC2
5	5	BAD

*example of **soils** table*

1.2.2 Table horizons

Each soil is typically composed of several pedological horizons, described in the **horizons** table, where each record describes the horizon in terms of pedological features as texture, structure, and organic matter content, that determines the shape of the soil water retention curve in the Soil Water Balance model.

In more details, each record of the **horizons** table contains:

- *soil_code*: univocal alphanumeric code to identify the soil *
- *horizon_nr*: number of horizon *
- *upper_depth*: upper depth of the horizon, [cm] *
- *lower_depth*: lower depth of the horizon, [cm] *
- *coarse_fragment*: percentage of soil particles > 2 mm
- *organic_matter*: percentage of organic matter
- *sand*: fraction of sand, [-] *
- *silt*: fraction of silt, [-] *
- *clay*: fraction of clay, [-] *
- *bulk_density*: bulk density, [g cm^{-3}]
- *theta_sat*: water content at saturation, [m^3 m^{-3}]
- *ksat*: water conductivity at saturation, [cm day^{-1}]

***** The data marked with a star are mandatory.

soil_code	horizon_nr	upper_depth	lower_depth	coarse_fragment	organic_matter	sand	silt	clay	bulk_density	theta_sat	ksat
Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter
AGO1	1	0	60	0.0	32.4	0.66	0.25	0.09	0.6		
AGO1	2	60	80	0.0	8.6	0.23	0.49	0.28	0.8		
AGO1	3	80	110	0.0	2.0	0.44	0.46	0.1	1.42		
AGO1	4	110	150	0.0	0.8	0.83	0.13	0.04	1.76		
AGOz	1	0	50	0.0	11.96	0.426	0.334	0.24	0.7		
AGOz	2	50	65	0.0	6.08	0.252	0.35	0.398	0.9		
AGOz	3	65	74	0.0	24.35	0.722	0.198	0.08	0.7		
AGOz	4	74	85	0.0	10.42	0.668	0.262	0.07	0.8		
AGOz	5	85	150	0.0	2.46	0.778	0.149	0.073	1.76		
ARC1	1	0	50	10.0	1.2	0.189	0.414	0.397	1.35		
ARC1	2	50	75	0.0	0.1	0.189	0.417	0.394	1.4		
ARC1	3	75	150	0.0	0.1	0.116	0.48	0.404	1.45		
ARC2	1	0	50	10.0	1.2	0.189	0.414	0.397	1.35		
ARC2	2	50	75	0.0	0.1	0.189	0.417	0.394	1.4		
ARC2	3	75	150	0.0	0.1	0.116	0.48	0.404	1.45		
BAD	1	0	35	10.0	1.2	0.48	0.3	0.22	1.35		
BAD	2	35	125	80.0	0.5	0.67	0.22	0.11			

*Example of **horizons** table*

TODO: **van_genuchten** and **water retention** tables

1.3 Crop database

The *Crop* database is a SQLite file organized in two tables (**crop_class** and **crop**) containing crop classification and parameters.
You can see the **crop_default.db** in the directory DATA/TEMPLATE of the distribution and an example of crop database in the test project DATA/PROJECT/test/data

1.3.1 Table crop_class

crop_class is a table where each crop classification (*id_class*) is linked to a prevalent crop (*id_crop*) described in the **crop** table.

Tabella: crop_class

	id_class	type	id_crop	irri_ratio
	Filtro	Filtro	Filtro	Filtro
1	SUMMER_HERBACEOUS	Summer herbaceous generic	CORN	0.6
2	FALLOW	Fallow (spontaneous natural growth)	FALLOW	0.0
3	KIWIFRUIT	Kiwifruit orchard	KIWIFRUIT	1.0
4	CORN	Corn	CORN	1.0
5	TOMATO	Tomato	TOMATO	1.0
6	PERENNIAL_HERBACEOUS	Perennial herbaceous generic	ALFALFA	0.0
7	WINTER_HERBACEOUS	Winter herbaceous generic	RAINFEDWHEAT	0.0
8	IRRI_WHEAT	Irrigated wheat	IRRIWHEAT	1.0
9	IRRI_ALFALFA	Irrigated Alfalfa	ALFALFA	1.0
10	PEAR	Pear orchard	PEAR	1.0
11	POTATO	Potato	POTATO	1.0
12	GRAPEVINE	Irrigated grapevine	GRAPEVINE	1.0
13	PEACH	Peach orchard	PEACH	1.0
14	SPARSE_FALLOW	Sparse fallow	SPARSEFALLOW	0.0

*Example of **crop_class** table*

The field *type* is a description of the crop class and the field *irri_ratio* [-] defines the irrigated percentage of the class. For instance, if in a study area the ALFALFA is not irrigated the *irri_ratio* has to be set to 0, whereas if it is irrigated or partially irrigated the *irri_ratio* has to be set to a value greater than zero.

If in a pilot area the class *summer herbaceous* includes both irrigated and not irrigated crops, *irri_ratio* has to be set to the ratio between the two categories. For example *irri_ratio*=0.6 means that the irrigated area is 60% of the total area covered by summer herbaceous.

Warning: in some cases the required crop for a specific class can be not defined in the **crop** table. This means that this crop is not set at all in the model (e.g. the cotton). There are two possible solutions about this:

1) the user can choose a crop that can be considered similar for development and water needs: for example pear is used to simulate the apple tree that is missing in the model;

2) a new crop can be added in the **crop** table, following the instructions explained in the following paragraphs.

1.3.2 Table crop

Each crop is typically characterized by several parameters, described in the **crop** table, where each record describes the crop in terms of phenological characteristics, water needs and irrigation parameters.

In the table below, key parameters of the table (crop development, roots and irrigation water needs) are listed.

Parameter name	**Description**	**Unit**
Crop development		
plant_cycle_max_duration	Crop cycle max duration	days
thermal_threshold	Thermal threshold	°C
degree_days_lai_ increase	Degree days sum for LAI increase	°C
degree_days_lai_decrease	Degree days sum for LAI decrease	°C
lai_min	Minimum value of LAI	$m^2\ m^{-2}$
lai_max	Maximum value of LAI	$m^2\ m^{-2}$
lai_curve_factor_a	Factor *a* of exponential curve of LAI increase	[-]
lai_curve_factor_b	Factor *b* of exponential curve of LAI increase	[-]
kc_max	Value of crop coefficient (Kc) corresponding to the maximum LAI	[-]
Roots		
root_depth_zero	Start of rooting system depth	m
root_depth_max	Max root depth	m

degree_days_root_increase	Degree days sum for the maximum development of the rooting system	°C
root_shape	Root shape (gamma function, cardioid, cylinder, ellipsoid)	[-]
psi_leaf	Leaf resistance	hPa
Water demand and irrigation		
degree_days_start_irrigation	Degree days sum for the start of the irrigation period	°C
degree_days_end_irrigation	Degree days sum for the end of the irrigation period	°C
irrigation_shift	Minimum number of days from the last irrigation	days
irrigation_volume	Crop irrigation volume	mm/day
stress_tolerance	Tolerated threshold on the ratio Tr/Tmax (real transpiration vs maximum transpiration) 1 = no stress is tolerated	[-]
raw_fraction	Fraction of Readily Available Water	[-]
max_height_surface_puddle	Maximum height of the surface puddle, that is the amount of water that surface can retain without runoff	mm

*Parameters in the **crop** table*

1.3.3 Crop parameters description

To define the crop cycle, key parameters to set are *sowing_doy* (the day of the year in which usually the crop is seeded) and *plant_cycle_max_duration* (the maximum length of the crop cycle in days). The computation of the phenological stages is carried out on the basis of the thermal threshold that the user has to define in the *thermal_threshold* field.

From this data, the degree days needed by the crop for the emergence (*degree_days_emergence*), for the maximum leaf area index development (*degree_days_lai_increase*) and for the leaf area index senescence (*degree_days_lai_decrease*) have to be set.

Moreover the *upper_thermal_threshold* field defines the threshold above which the crop stops to grow.

The leaf area index development is calculated on the basis of these parameters: the minimum leaf area index at the beginning of the crop cycle (*lai_min*), the maximum lai reached during the season (*lai_max*) and, especially for fruit trees, if the orchards have a grass cover, the user has to define the leaf area index of the grass (*lai_grass*).

The maximum crop coefficient (*kc_max*) has to be defined in order to compute actual evapotranspiration.

In order to describe the rooting system of the crop, the user has to set how much is the depth of the beginning of roots with respect to the ground (*root_depth_zero,* in other words the height of the root collar) the maximum reachable depth of the roots (*root_depth_max*), and the degree days sum for the full development of the rooting system (*degree_days_ root_increase*).

For the computation of the root density It is important the definition of the shape of the roots (*root_shape*), selecting the following codes:

1 ⟶ cylinder
4 ⟶ cardioids
5 ⟶ gamma distribution

In addition, the coefficient of deformation (*root_shape_deformation*), expressed as percentage ranging from 1 to 2, can be used to adapt the selected shape to the actual shape of the crop.

The *max_height_surface_puddle* is the amount of water that surface can retain without runoff, typically it is a few millimeters of water, except for some crops (such as rice) where the surface is excavated on purpose to retain water. This parameter can be increased if the field is worked (the clods retain water) or decreased if the field is not flat (for example on hills).

In order to assess the crop water demand, the irrigation process is controlled by the parameters listed in the table such as *irrigation_shift* (the number of days between two irrigations) and *irrigation_volume* (the maximum volume of water distributed for each irrigation during the crop cycle in mm).

These parameters allow the user to define the irrigation methods (i.e. micro irrigation, sprinkler irrigation) depending on time shifts and maximum volumes for each irrigation.

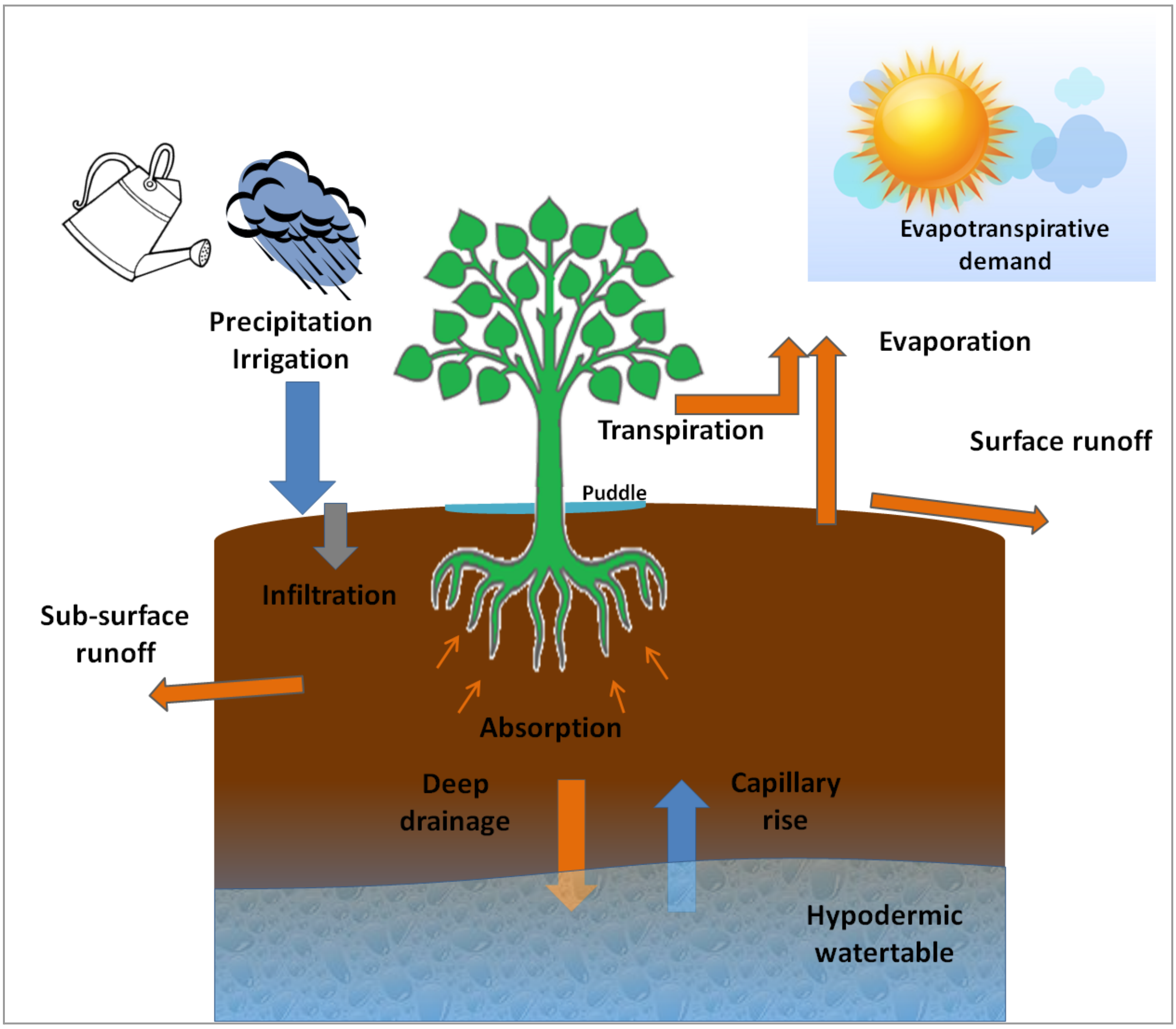
The irrigation season length is controlled by *degree_days_start_irrigation* and *degree_days_end_irrigation* parameters: the actual irrigation period starts and stops according to a degree days sum, taking into account the weather conditions of every specific year, anticipating it in warm years and delaying it in cold ones.

The water stress sensitivity specific for the crop is expressed by the *raw_fraction*, i.e. the fraction of readily available water between the wilting point and the field capacity.

Another parameter useful to calibrate the irrigation needs for the crop is *stress_tolerance*: it expresses the tolerance of the crop to water stress as the ratio between actual transpiration and maximum transpiration, where 1 means that no water stress is tolerated by the crop.

2. ALGORITHMS

The Soil Water Balance (SWB) is the result of interactions of hydrological processes occurring between soil, crop and atmosphere.



SWB conceptual scheme

The amount of water from rain or irrigation that infiltrates into the ground depends on surface conditions, on the hydrological characteristics of the first layer of soil and its water content. The water that cannot be absorbed from the soil is collected in puddles formed by surface roughness. Once puddles are filled, surface runoff occurs.

The processes of storage and infiltration are governed by soil water potential differences. Each soil horizon is characterized by its water retention curve. 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 because of capillary rise.

The presence of a crop produces water loss in the root zone through transpiration, and simultaneously reduces evaporation loss in the surface layers. 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.
So that, once the crop parameters are properly set, it is possible by means of the SWB to forecast the crop water needs not fulfilled by the soil water content that have to be provided by irrigations.

CRITERIA-1D model follows the approach of Driessen (1986), Driessen, and Konijn (1992) but it assumes a multilayered soil and explicitly computes approximate values of daily actual evaporation and transpiration, water flows between layers, deep drainage, surface and subsurface runoff and capillary rise. The software is written in C++ language with QT libraries, thus it can be compiled on several platforms.

2.1 Water

In the soil water balance model the following concepts play a key role:

- Field Capacity (FC): the presumed water content at which internal drainage ceases.
- Wilting Point (WP): the minimal water content the plant requires not wilting.
- Soil texture classification: soil is classified by the fractions of specific ranges of particle sizes (typically sand, silt, and clay). Classifications are named for the primary constituent particle size or a combination of the most abundant particles sizes, e.g. "sandy clay"; a fourth term, “loam” is used to describe a roughly equal concentration of sand, silt, and clay
- 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.
- Conceptual models: approximation of the physical processes through simplified schemes adapted to describe reality by means of semi-empirical models.

2.1.1 Water retention curve

The soil water retention in the model is described by the van Genuchten equation (van Genuchten, 1980), modified by Ippish et al. (2006). The original van Genuchten equation is:

$$\theta(h) = \theta_r + (\theta_s - \theta_r)\left(\frac{1}{[1 + (\alpha h)^n]^m}\right)$$

where $\theta(h)$ is the volumetric water content at the water potential h, θ_s and θ_r are the saturated and residual water contents, α is the coordinate of the inflexion point of the retention curve, m and n are dimensionless factors related to the pore-size distribution.
We used the typical restriction $m = 1 - 1/n$

The hydraulic conductivity was calculated by the equation of Mualem (1976):

$$K(h) = \frac{K_s\left(1-(\alpha h)^{mn}\left[1+(\alpha h)^n\right]^{-m}\right)^2}{\left[1+(\alpha h)^n\right]^{ml}}$$

where K_s is the saturated hydraulic conductivity, and l is an empirical parameter that accounts for pore tortuosity.

Ippisch et al. (2006) pointed out that the van Genuchten-Mualem model, under certain conditions, is problematic when water retention data are used to predict the hydraulic conductivities and they demonstrated that if $n< 2$ or $\alpha h_e> 1$ (where h_e is the air-entry value of the soil, corresponding to the largest pore radius), the van Genuchten-Mualem predicts erroneous hydraulic conductivities. In these cases, an explicit air-entry value h_e has to be included, leading to a modified van Genuchten-Mualem model (Ippisch et al., 2006):

$$S_e = \begin{cases} \frac{1}{S_c}\left[1+(\alpha h)^n\right]^{-m} & \text{if } (h > h_e) \\ 1 & \text{if } (h \leq h_e) \end{cases}$$

where S_e is the degree of saturation and S_c = [1+(αh_e)n]−m is the water saturation at the air-entry potential h_e.

The resulting hydraulic conductivity using the Mualem model is:

$$K = \begin{cases} K_s S_e^l \left[\frac{1-(1-(S_e S_c)^{1/m})^m}{1-(1-S_c^{1/m})^m}\right]^2 & \text{if } (S_e < 1) \\ K_s & \text{if } (S_e \geq 1) \end{cases}$$

where l is the same parameter as in the original Mualem equation.
The following table lists the parameters used in the model for the USDA texture classification.

texture	alpha	n	he	theta_r	theta_s	k_sat	l
Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter
sand	0.39	1.7	0.07	0.01	0.38	192.0	0.5
loamy sand	0.35	1.5	0.1	0.02	0.39	96.0	0.5
sandy loam	0.29	1.4	0.15	0.02	0.4	48.0	0.5
silt loam	0.13	1.2	0.26	0.03	0.44	9.6	0.5
loam	0.17	1.21	0.23	0.03	0.42	12.0	0.5
silt	0.1	1.24	0.27	0.03	0.44	2.4	0.5
sandy clayloam	0.22	1.22	0.2	0.03	0.41	12.0	0.5
silty clayloam	0.13	1.2	0.31	0.03	0.46	2.4	0.5
clayloam	0.18	1.18	0.27	0.04	0.45	4.8	0.5
sandy clay	0.21	1.18	0.25	0.04	0.44	3.6	0.5
silty clay	0.17	1.16	0.33	0.05	0.48	1.2	0.5
clay	0.16	1.16	0.33	0.05	0.48	0.8	0.5

Soil parameters for USDA texture classes

The values of the table were produced by a comparison of data presented in several papers on this subject (Wösten et al., 1998; Simota and Mayr, 1996; Carsel and Parrish, 1988; Schaap, Leji and van Geuchten, 2001).

2.2 Water flow numerical model

TODO
Numerical solution of water flow is detailed at the following address (section 1.1.2)

2.3 Layer-based empirical model

Conceptual models 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.

2.3.1 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):

$$I_{max} = 10\left[S_0\left(1 - \theta/\theta_{sat}\right) + A\right]$$

Where:

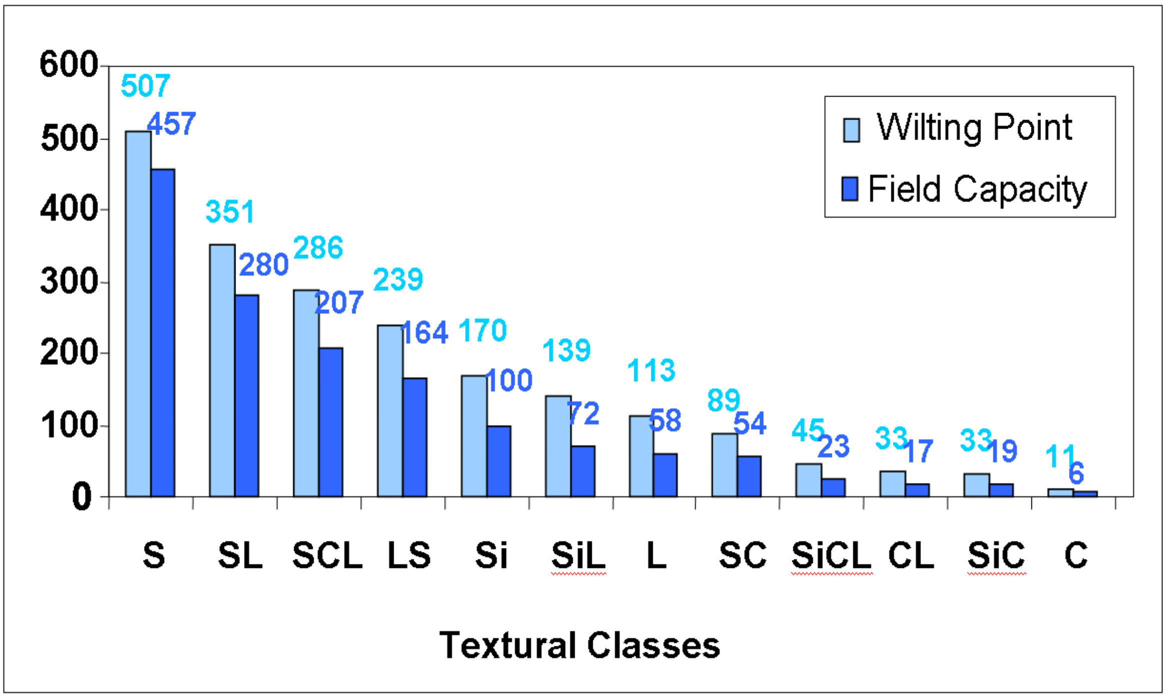
I_{max}	maximum infiltration	[mm d^{-1}]
S_0	standard sorptivity	[cm d^{-1}]
θ	volumetric water content of the layer	[m^3 m^{-3}]
θ_{sat}	volumetric water content at saturation	[m^3 m^{-3}]
A	hydraulic conductivity at the wetting front	[cm d^{-1}]

The sorptivity represents the infiltration rate determined by the single matrix potential, the standard sorptivity S_0 is defined for a completely dry matrix. Reference values for these parameters, depending on the different soil textural classes, are reported in the following table:

Textural classes	**A [cm d-1]**	**S_0 [cm d-1]**	**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	3.98	1.3
Clay (C)	0.15	1.93	0.5

Reference values of infiltration speed of the wetting front (A), of the standard sorptivity (S_0) and the saturated conductivity (K_0) depending on the different textural classes (Driessen, 1986).

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



Maximum daily infiltration (Imax) after a rain at field capacity and wilting point for the different textures (S=Sand, Si=Silt, C=Clay, L=Loam).

2.3.2 Infiltration and redistribution

The soil profile is divided by the model into a number of thin computational layers (usually 2 cm of thickness), and the computation of water flow by layer starts from the bottom of the profile, depending on soil maximum depth.
A wetting front is determined when a layer has water content 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. 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.

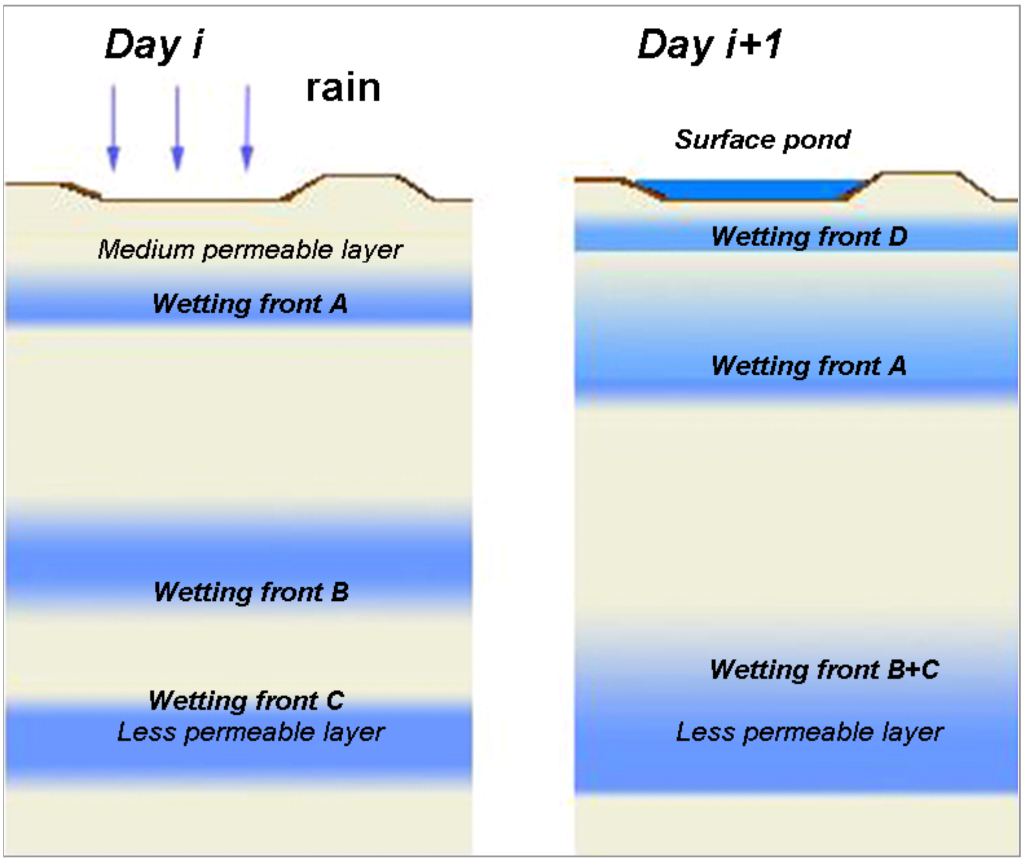
Each layer is characterized by an infiltration of the maximum daily amount (Imax). To estimate the maximum displacement of the waterfront the maximum infiltration of the underlying layer at the waterfront is calculated. If the water content of the layer exceeds the field capacity it passes to the next one. This computation continues until the waterfront 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:

1. the sum of the flows previously passed through a layer cannot exceed its maximum daily infiltration;

2. In the case the waterfront 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 clay with 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 saturation condition: the waterfront that is arriving lays on the previous one.



Infiltration into the soil profile of moisture fronts A, B, C and D

In the previous figure, the infiltration of several wetting fronts in different conditions of permeability is shown:

- the front A, crossing through medium permeable layers, moves downwards while remaining separate from the other fronts;
- the front B crosses the same permeable layers and merges with front 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 cases where the free water reaches the last layer, it leaves the system as deep drainage.

2.3.3 Surface and subsurface runoff

The agricultural fields are usually delimited by drains and ditches, therefore surface and sub-surface runoff can be assumed as outflow from the system through these means.

The surface runoff occurs when the soil surface roughness cannot hold puddle water. The process is simulated considering the maximum height of storage surface, which depends on:

- crop species; for instance *Oryza sativa* (rice) has typically a puddle higher to other cereals.
- crop type, i.e. annual and perennial. Annual crops are typically herbaceous crops that need tillages and thus a default value of 5-10 mm of clod height is simulated. For perennial crops (trees) usually tillages are not performed.

Maximum sub-surface runoff is estimated by the following equation, which solves the universal flow equation as a function of distance and radius of drains (Driessen, 1986):

$$D_{max} = 10 \cdot k_0 \cdot \psi / \left(\psi + L_d / \pi \cdot ln\left(L_d / r_d \pi\right)\right)$$

where:

D_{max} is maximum subsurface runoff (lateral drainage) [mm]

k_0 is saturated hydraulic conductivity (see table in maximum infiltration paragraph) [cm/day]

ψ is hydraulic head midway between drains [m]

L_d is drain spacing [m]; default: 100 m

r_d is drain radius [m]M default: 0.25 m

2.3.4 Capillary rise

Capillary rise is computed by the steady state solution of Darcy's equation.

The vertical water flow between two arbitrary points follows Darcy's law:

$$F = k_h \,.\, dH/dL$$

where:

F	is the flow rate (cm d^{-1})
dH	is the difference in hydraulic head (cm)
dL	is the distance of flow (cm)
k_h	is the hydraulic conductivity at matric suction *h* (cm d^{-1})

The total hydraulic head *H* is composed of both gravity forces and matric suction:

$$H = h + g$$

Where *h* is the matric suction at soil layer *n* and *g* the gravity head, equal to the vertical distance (cm) between soil layer and the groundwater level.

The total hydraulic head *H* is positive if the matric suction *h* exceeds the vertical distance between point n and the groundwater. A positive hydraulic head allows positive water flow from the groundwater to the point with matric suction *h*. This water flow is called capillary rise.

Therefore capillary rise at soil layer *n* can be computed by the steady state solution of Darcy's equation:

$$CR = k_h \,.\, (dh/dz \text{ -}1)$$

Where:

CR is the capillary rise (cm d-1)

h is the matric suction at soil layer n (cm)

z is the distance between the soil layer and the groundwater level.

2.4 Crop

Crop development in the SWB model is computed by means of daily minimum and maximum temperature, driving the leaf area index (LAI) curve in three stages: emergence, increase and senescence (LAI decrease). In addition, the root development is driven by temperatures and the root density follows two main root shapes: cylinder and cardioid.
The LAI values drive the partitioning of the evapotranspiration in potential evaporation and transpiration. Potential evaporation is assigned to the surface layer (if it is wet) and to the first soil layers (up to 15 cm), while potential transpiration is assigned to the rooting system, subdivided depending on the root density.
The actual evaporation and transpiration can be lower than the potential, depending on the actual soil water content and to the crop physiological parameters.

TODO
All processes are described by a set of equations that are detailed at the following address

2.4.1 Potential evapotranspiration

The term evapotranspiration refers to the total water that is moved from the soil to the atmosphere by evaporation from surface and soil and by transpiration from plants.
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* (ET_m) and is defined as the amount of water evapotranspirated per unit time from a uniform crop that has full water availability.
The *reference evapotranspiration* (ET_0) 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 of water availability.

The ET_0 estimation methods proposed in literature are many, characterized by different input variables and made for different time scales integration. In CRITERIA-1D, **Hargreaves and Samani equation** (1985) is used to calculate daily potential evapotranspiration.
The Hargreaves method needs only latitude of the computation area and daily maximum and minimum temperature for the estimation; in more details, the equation is:

$$ET_0 = 0.0023 \cdot \frac{Rad_{ext}}{2.456} \cdot (T_{avg} + 17.78) \cdot (T_{max} - T_{min})^{0.5}$$

Where:
ET_0 is reference evapotranspiration [mm d^{-1}];
Rad_{ext} is extraterrestrial radiation [MJ m^{-2} d^{-1}];
T_{max} and T_{min} are daily maximum and minimum temperature of the air [°C];
T_{avg} is the daily average temperature, computed as $T_{avg} = (T_{max}+T_{min})/2$

Rad_{ext} is the potential radiation that would reach Earth's surface in the absence of the atmosphere and it can be computed by:

$$Rad_{ext} = 24 \cdot 4.921 \cdot d_r / \pi \cdot (\Omega sin(lat) \cdot sin(\delta) + cos(lat) \cdot cos(\delta) \cdot sin(\Omega))$$

where:
4.921 is the hourly solar constant [MJ m^{-2} h^{-1}];
lat is the latitude of the computation area [rad];
doy is the day of the year;
d_r is the inverse Earth-Sun relative distance, compute by:

$$d_r = 1 + 0.033 \cdot cos(2 \cdot \pi \cdot doy / 365)$$

$\Omega$is the sunset hour angle [rad] computed by:

$$\Omega = arccos(- tg(lat) * tg(\delta))$$

Finally $\delta$is the solar declination [rad], computed by:

$$\delta = 0.4093 \cdot sin((2\pi/365) \cdot doy - 1.39)$$

2.5 Irrigation

Every crop has its own sensitivity to water stress, defined by the ability to use the water present in the rooting system. This value is defined by the fraction of readily available water by the root.
The amount of water that can be easily available in the root profile is calculated using this function, which integrates the height of water that can be easily used on the layer of ground affected by the roots:

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

where:
H_2O_{avb} is the easily available water content [mm]
fRAW is the fraction of readily available water [-]

WC_l , FC_l and WP_l are the water content, field capacity and wilting point of the layer [mm]

The easily available water is used to assess when to irrigate the crop: the model defines the irrigation time when H_2O_{avb} has value less than zero.

In more detail, the irrigation algorithm can be summarized in this sequence of checks:

1. if the current day of simulation is included in the irrigation season;
2. if the number of days from the last irrigation is higher than the irrigation shift;
3. If the forecast rain is lower than 5 mm;
4. if the actual ratio between actual transpiration and potential transpiration is lower than the tolerated stress percentage for the crop;
5. if the easily available water is lower than zero.

If all the previous conditions are true, an irrigation volume is distributed. This is computed as the minimum between the predefined irrigation quantity for the crop and the maximum quantity of water that can daily infiltrate without runoff, so an irrigation without losses is computed.

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