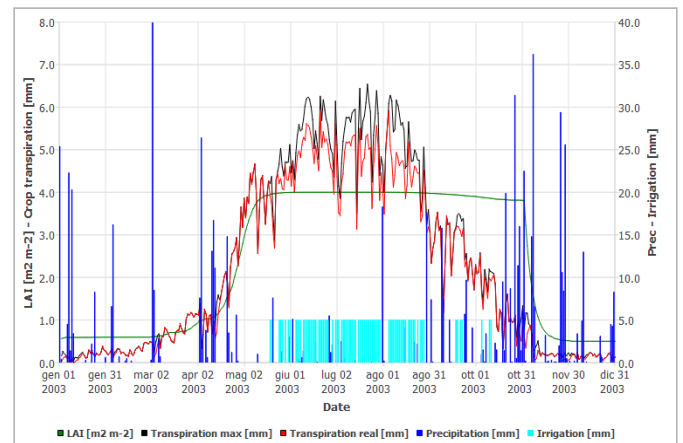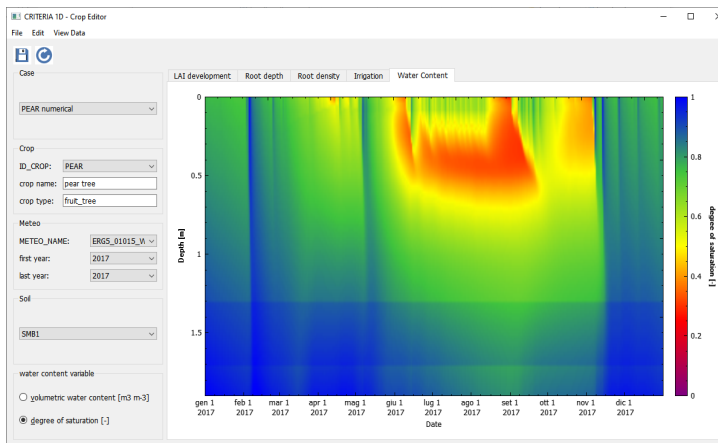# CRITERIA-1D

Technical manual

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SUMMARY

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 Projects

The data are typically organized in projects (/DATA/PROJECT/projectName), with a directory for each project, containing a settings file *projectName.ini* and a subdirectory *data.* You can see the test project in the distribution as an example.

The projects can be opened by loading the corresponding project.ini in the graphical user interface of **CRITERIA1D_PRO** (menu *File–>Open Project*). With the same interface it is possible to create a new project (*File–>New Project*) and execute a single case of the project (*File–>Execute Case*). All cases of a project can be executed on shell passing the .ini file as parameter to the **CRITERIA1D** executable in the Linux bash or Windows shell commands.

The project.ini file must contain information about the location of data input/output in the [*project*] section and additional output that the user requires, which will be added to the default output of the model, in the [*output*] section. The file path of input/output data can be absolute or relative to the location of the project.ini file. The directory for the *db_output* can be not existing, in this case it will be created at the first run of the project.

You can see an example of the structure of a settings file (**test.ini**) in the text listed below. In the following section, the structure of each input and output file will be described.

```
[software]
software="CRITERIA1D"

[project]
path="./"
name="test"
db_meteo="./data/meteo.db"
db_soil="./data/soil_ER_2002.db"
db_crop="./data/crop.db"
db_units="./data/units.db"
db_output="./output/test.db"

[output]
waterContent=15,30,50
waterPotential=15,30,50
```

1.2 db_meteo

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 and an example of **meteo.db** in the test project DATA/PROJECT/test/data

1.2.1 Table meteo_locations

meteo_locations table identifies the location of the meteo points or the cells of a meteo analysis grid. The table contains the following fields:

- *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;

*Example of **meteo_locations** table*

1.2.2 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 must correspond to the field *table_name* 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.

Example of a weather data table

If potential evapotranspiration is not available, the model 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 model will simulate a free drainage condition at the bottom of the soil.

1.3 db_soil

Soil data and parameters are organized in several tables: **soils**, **horizons**, **driessen**, **van_genuchten** and **water_retention**. Furthermore the table UNITS lists the unit of measure of each field in the soil database.

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

1.3.1 Table soils

soils is a registry table where each soil is defined by an alphanumeric *soil_code* linked to an integer *id_soil*. Typically this numeric field refers to a soil map shapefile in a geographical project and it is the id used to identify the computational unit in the **unit** database.

*example of **soils** table*

1.3.2 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 such as texture, structure and organic matter content, that determines the shape of the soil water retention curve in the 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		

*Example of **horizons** table*

TODO describe **van genuchten**, **driessen** and **water retention** tables

1.4 db_crop

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

1.4.1 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.

	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 the class *summer herbaceous* in the study area 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 class.

In some cases the required crop can be not defined in the **crop** table. This means that this crop is not set at all in the model (e.g. the apple). 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.

1.4.2 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*

1.4.3 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.

1.5 db_unit

The Unit database contains only one table (**units**) that list the computational units of the project and related model options. A computational unit (*ID_CASE*) is a unique combination of one crop (*ID_CROP*), one meteo (*ID_METEO*) and one soil (*ID_SOIL*).

WARNING: despite its name, *ID_CROP* in the table **units** must correspond to the *id_class* of the **crop_class** table in the crop database. (TODO fix inconsistency).

*Structure of the **units** table*

Tt is possible to define several model parameters for each computational unit:
- *hectares* [ha] of the unit, used only in geographical version of the model;
- *numerical_solution* (1: true, 0: false, default: 0) it defines if the numerical solution has to be performed;
- *use_water_table* (1: true, 0: false, default: 1) it defines if capillary rise from water table has to be computed; in case of lack of water table data a condition of free drainage at the bottom of the soil will be simulated;
- *water_retention_fitting* (1: true, 0: false, default: 1) it defines if soil parameters have to be fitted using data in **water_retention** table, when they are available;
- *optimal_irrigation* (1: true, 0: false, default: 0) it assign a ideal subirrigation to restore field capacity in the root zone without losses;
- *slope* [-] slope of the unit, it is used only in the numerical solution to compute the flow in the lateral boundary.

You can see the **template_units.db** in the directory DATA/TEMPLATE of the distribution and an example of units.db in the test project DATA/PROJECT/test/data

ID_CASE	ID_CROP	ID_METEO	ID_SOIL	imerical_solutic	use_water_table	ater_retention_fittin	›timal_irrigatic	slope
Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro
PEAR	PEAR	ERG5_01015...	267	0	1	0	0	0.01
PEAR numerical	PEAR	ERG5_01015...	267	1	1	0	0	0.01
PEAR numerical no ...	PEAR	ERG5_01015...	267	1	0	0	0	0.01
KIWI	KIWIFRUIT	ZATTAGLIA	97	0	0	0	0	0.02
KIWI numerical	KIWIFRUIT	ZATTAGLIA	97	1	0	0	0	0.02
RAVONE	SPARSE_FALLOW	ERG5_01422	104	0	0	0	0	0.04
RAVONE numerical	SPARSE_FALLOW	ERG5_01422	104	1	0	0	0	0.04
POTATO	POTATO	ERG5_01015	268	0	0	0	0	0.01
POTATO numerical	POTATO	ERG5_01015	268	1	1	0	0	0.01

*Example of the **units** table*

1.6 db_output

Model output is stored in a multi-table database, one table is created for each case in the **units** table, naming it with the corresponding ID_CASE.

Default output variables that Criteria-1D automatically saves are listed in the following table:

DATE	date (yyyy-mm-dd)
PREC	Precipitation [mm]
IRRIGATION	Irrigation water needs [mm]
WATER_CONTENT	Soil water content in the first meter [mm]
SURFACE_WC	Surface water content [mm]
AVAILABLE_WATER	Available water (water content - wilting point) in the first meter [mm]
FRACTION_AW	Fraction of available water with respect to AWC (field capacity - wilting point) in the first meter [mm]
READILY_AW	Readily available water in the rooting zone [mm]
RUNOFF	Surface Runoff [mm]
DRAINAGE	Soil deep drainage [mm]
LATERAL_DRAINAGE	Soil lateral drainage [mm]
CAPILLARY RISE	Capillary rise from watertable [mm]
ET0	Reference evapotranspiration [mm]
TRANSP_MAX	Maximum crop transpiration [mm]
TRANSP	Current crop transpiration [mm]
EVAP_MAX	Maximum Evaporation [mm]

EVAP	Current evaporation [mm]
LAI	Leaf area Index [-]
ROOT_DEPTH	Root depth [m]
BALANCE	Water balance (for numerical solution) [mm]

Additional output and specific computation depth can be added by user, defining it in the project.ini file. The possibly additional output are:

waterContent	Volumetric water content at specific depth [-]
waterPotential	Water potential at specific depth [kPa]
waterDeficit	Sum of water deficit (FC - water content) from zero to depth [mm]
awc	Sum of Available Water Capacity (FC-WP) from zero to depth [mm]

The calculation depth can be set in the project.ini as a depth list in [cm]. the following example saves the water content and water potential at 15, 30 and 50 centimeters of soil depth and the sum of the water deficit in the first meter of soil:

```
[output]
waterContent=15,30,50
waterPotential=15,30,50
waterDeficit=100
```

The corresponding fields in the db output will be named:

```
SWC_15,  SWC_30, SWC_50
WP_15, WP_30, WP_50
DEFICIT_100
```

2. ALGORITHMS

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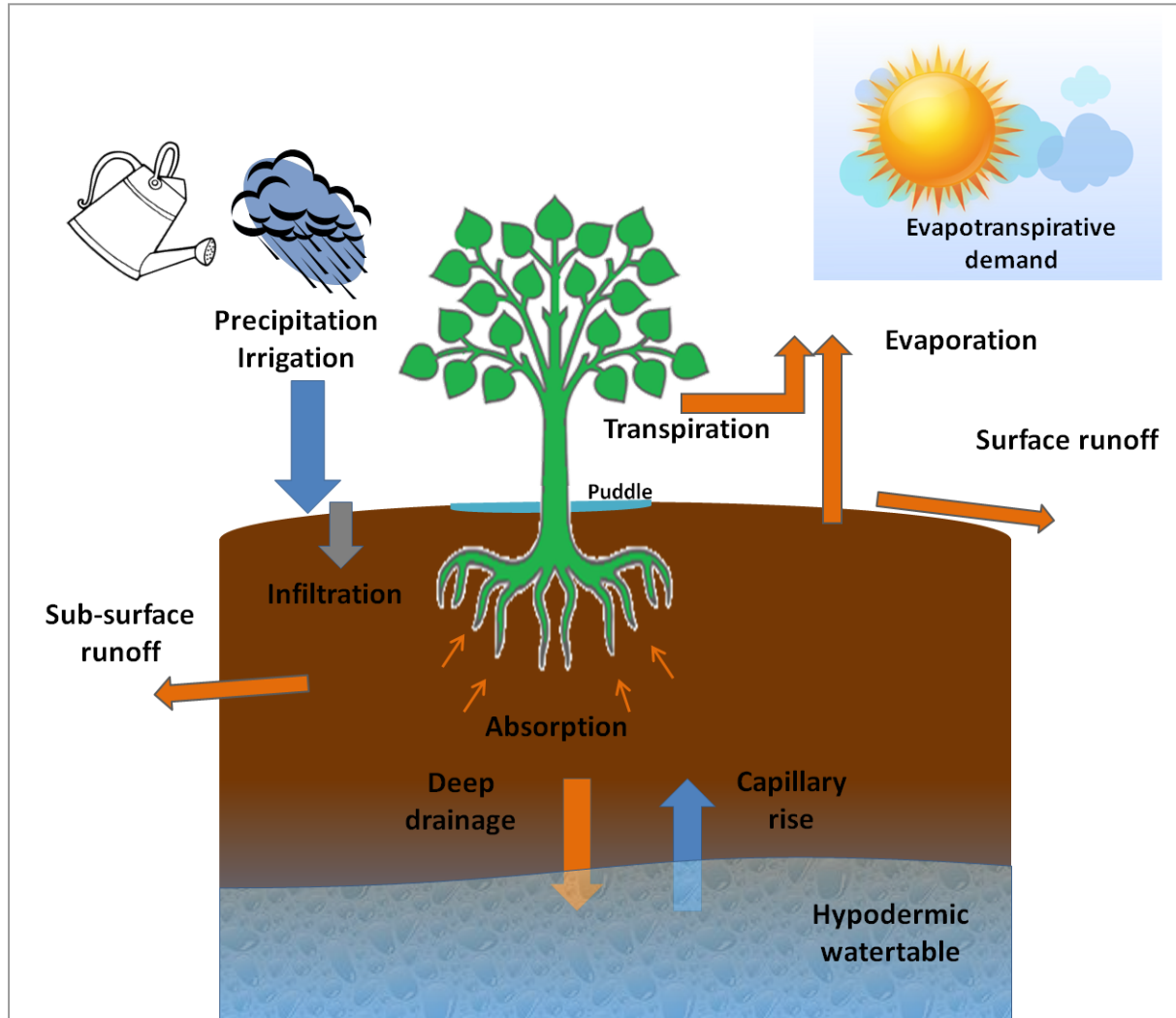
SWB conceptual scheme

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 use of 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:

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

where S_e is the degree of saturation and $S_c = [1+(\alpha h_e)n]-m$ 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.
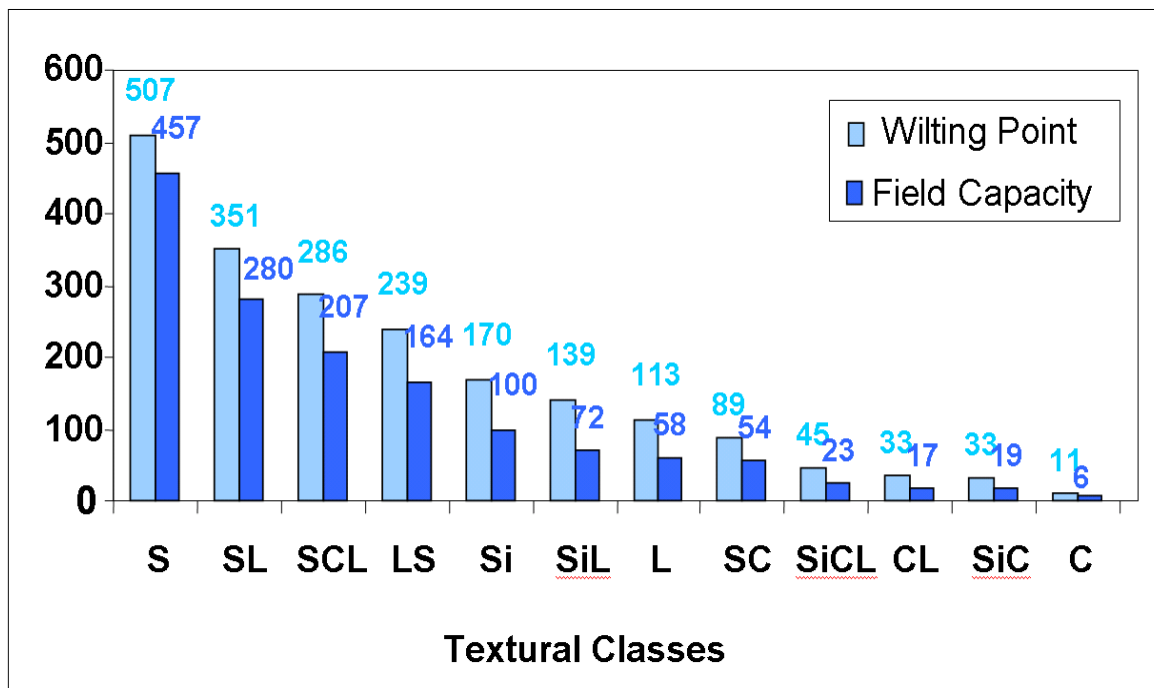
Maximum daily infiltration (Imax) after a rain at field capacity and wilting point for the different textures (S=Sand, Si=Silt, C=Clay, L=Loam).

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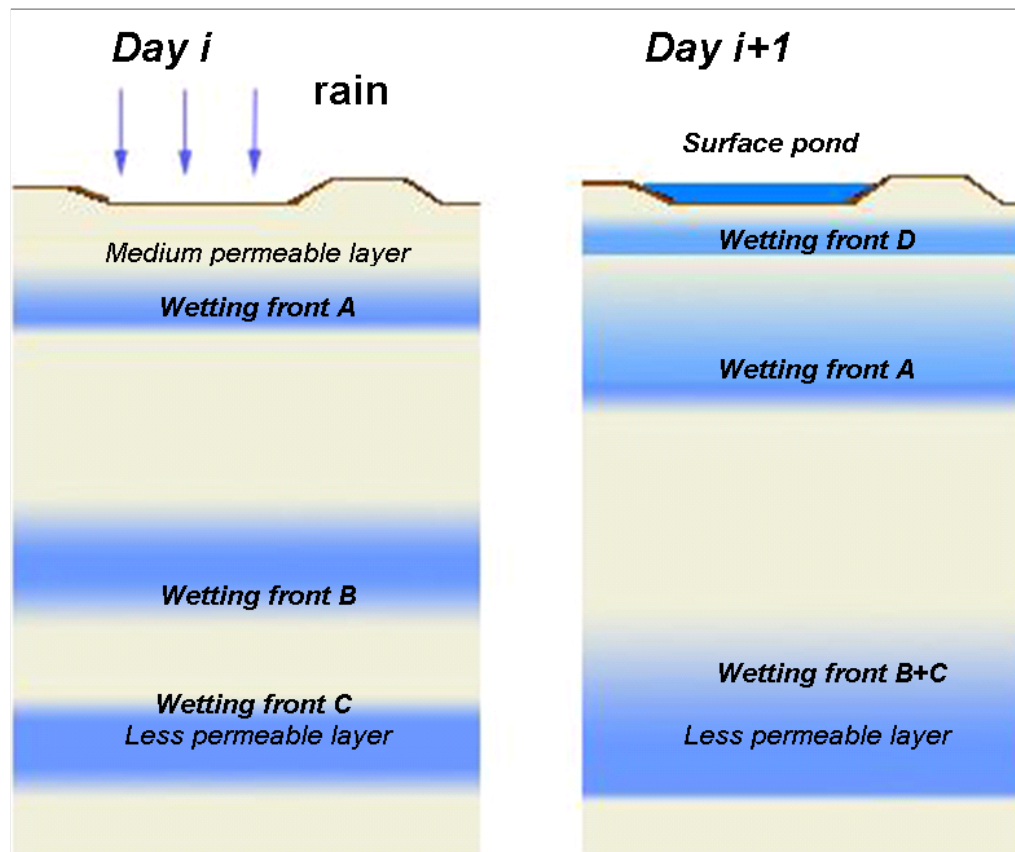
Infiltration into the soil profile of moisture fronts A, B, C and D

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 than 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):

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

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:

$$F = k_h \cdot dH/dL$$

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:

$$CR = k_h \cdot (dh/dz - 1)$$

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
Crop processes are 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 evapotranspired per unit time from a uniform crop that has full water availability.
The *reference evapotranspiration* (ET_0) is the amount of water evapotranspired 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:

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

Ω is the sunset hour angle [rad] computed by:

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

Finally δ 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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