CRITERIA-1D

Technical manual

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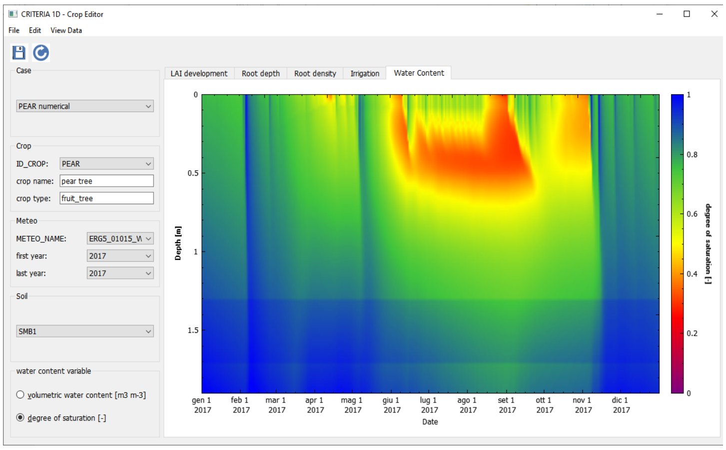

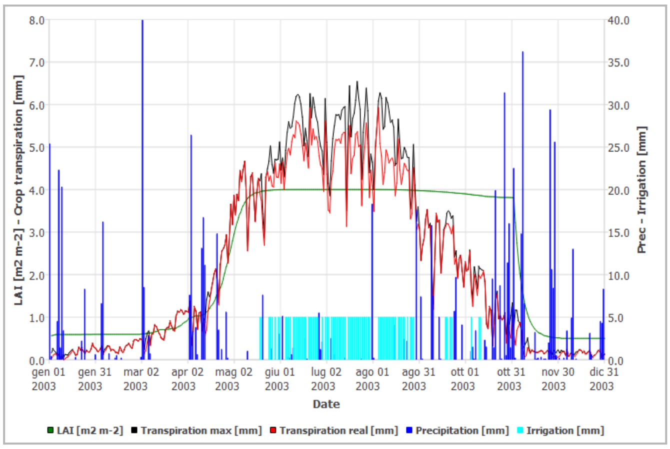

SUMMARY

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0. INTRODUCTION

CRITERIA-1D is an agro-hydrological model that simulates one-dimensional water flow in variable saturation soils, crop development, root water extraction and irrigation water needs. Soil water flow can be simulated with two different approaches depending on the user's choice: a physically based numerical model or a layer-based conceptual model. Soil and crop parameters can be defined at different levels of detail.

It requires daily agro-meteorological data as input: minimum and maximum air temperature, total precipitation and, if available, water table depth data to estimate capillary rise.

The software is written in C++ using Qt libraries, so cross-platform building is possible (Windows, Linux, Mac OS).

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

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.

Projects can be opened by loading the corresponding project.ini in the **CRITERIA1D_PRO** graphical user interface (*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 in a command shell passing the .ini file as parameter to the **CRITERIA1D** executable (e.g. Bash shell in Linux, DOS shell in Windows).

The project.ini file must contain the following information:

- [project] section: the location referring to the input input/output data
- [output] section: additional output that the user requires, which will be added to the default output of the model.

The file path of input/output data can be absolute or relative to the location of the project.ini file. If the *db_output directory* is missing, it will be created at the first project run.

Below is an example of the structure of a settings file (**test.ini**). 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_comp_units="./data/comp_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*

A **template_meteo.db** is available 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 contains the locations and properties of the meteo points or the cells of a gridded meteorological dataset. The table contains the following fields:

- *id_meteo*: point/cell identifier;

- *table_name*: name of the table, for example composed by "GRD_" followed by the grid cell identifier;
- *meteo_name*: location name;
- *longitude*: longitude of the cell center in the WGS84 geographic reference system (decimal degrees);
- *latitude*: latitude of the cell center in the WGS84 geographic reference system (decimal degrees);
- *height* (optional): height of the cell center (meters);

id_meteo	table_name	meteo_name	longitude	latitude	height
Filter	Filter	Filter	Filter	Filter	Filter
01878	GRD_01878	VALSAVIGNONE	12.033825	43.7325	816.26
01918	GRD_01918	MONTE DELLA ZUCCA	12.096875	43.7325	915.44
01958	GRD_01958	SAN PATRIGNANO	12.159925	43.7325	781.15
01998	GRD_01998	POGGIO DELLE CAMPANE	12.222975	43.7325	575.14
01797	GRD_01797	BADIA PRATAGLIA	11.907725	43.7775	979.62
01837	GRD_01837	VERGHERETO	11.970775	43.7775	844.81

*Example of **meteo_locations** table*

1.2.2 Weather data tables

The other tables of the **meteo** database contain the meteorological 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 **meteo_locations**.

The meteorological data are organized according to the following format:

- *date*: ISO8601 format (YYYY-MM-DD) *
- *tmin*: daily minimum air temperature (°C) *
- *tmax*: daily maximum air temperature (°C) *
- *tavg* (optional): daily average air temperature (°C)
- *prec*: daily total precipitation (mm) *
- *et0* (optional): reference evapotranspiration (mm)
- *watertable* (optional): water table depth (m)

* required data

date	tmin	tmax	tavg	prec	et0	watertable
Filtro	Filtro	Filtro	Filtro	Filtro	Filtro	Filtro
2012-01-01	1.9	7.9	4.6	0	NULL	NULL
2012-01-02	2.8	7.2	4.6	8.4	NULL	NULL
2012-01-03	2.6	6.9	4.9	0	NULL	NULL
2012-01-04	2.1	3.9	2.7	0	NULL	NULL
2012-01-05	1.5	10.8	5.6	2.6	NULL	NULL
2012-01-06	5.4	9.7	6.9	0	NULL	NULL
2012-01-07	5.2	11.4	7.7	0	NULL	NULL

Example of a weather data table

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

1.3 db_soil

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

A **template_soil.db** is available in the directory DATA/TEMPLATE of the distribution while two examples of soil databases are 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.

Table: soils

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

*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 determine the shape of the soil water retention curve in the model.

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

- *soil_code*: unique alphanumeric code to identify the soil *
- *horizon_nr*: horizon number *
- *upper_depth*: horizon upper depth[cm] *
- *lower_depth*: horizon lower depth [cm] *
- *coarse_fragment*: percentage of soil particles > 2 mm [%]
- *organic_matter*: percentage of organic matter [%]
- *sand*: percentage of sand [%] *
- *silt*: percentage of silt [%] *
- *clay*: percentage 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}]

* required data

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.

A **crop_default.db** is available in the directory DATA/TEMPLATE and an example is 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.
By convention, *id_crop* must be in uppercase (for example: POTATO) while for *id_class* you can use both lowercase and uppercase.

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 ALFALFA is not irrigated the *irri_ratio will be set to* 0, whereas if it is irrigated or partially irrigated the *irri_ratio* will be set to a value between 0 and 1.

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.

Some crops (e.g. apple) are not yet simulated by CRITERIA, so they are not included in the **crop**. Here are two possible solutions for simulating a new crop:

1) the user can choose a crop that can be considered similar for development and water needs (e.g. pear could be used to simulate apple);

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. By convention, *id_crop* must be in uppercase (for example: POTATO).

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

Crop development		
Parameter name	**Description**	**Unit**
plant_cycle_max_duration	Crop cycle max duration	days
thermal_threshold	Development thermal threshold	°C
degree_days_lai_ increase	Degree days sum for LAI increase stage	°C
degree_days_lai_decrease	Degree days sum for LAI decrease stage	°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* for LAI increase stage	[-]
lai_curve_factor_b	Factor *b* for LAI increase stage	[-]
kc_max	Crop coefficient (Kc) corresponding to the maximum LAI	[-]
Roots		
Parameter name	**Description**	**Unit**
root_depth_zero	Beginning depth of rooting system	m
root_depth_max	Maximum depth of rooting system	m
degree_days_root_increase	Degree days sum for the maximum development of the rooting system	°C

root_shape	Root shape factor (gamma function, cardioid, cylinder, ellipsoid)	[-]
psi_leaf	Leaf resistance	hPa
Water demand and irrigation		
Parameter name	**Description**	**Unit**
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 since the last irrigation	days
irrigation_volume	Crop irrigation volume	mm/day
stress_tolerance	Threshold of Tr/Tmax ratio (actual transpiration/maximum transpiration) above which stress is tolerated 0 = any water stress is tolerated 1 = no water stress is tolerated	[-]
raw_fraction	Fraction of readily available water	[-]
max_height_surface_puddle	Maximum height of the surface puddle (i.e. 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 must define in the *thermal_threshold* field.

The degree days sum 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*) must be set.

upper_thermal_threshold field defines the maximum cardinal temperature, which is the maximum temperature value at which the crop could develop.

The leaf area index development is simulated by using the following parameters: minimum leaf area index at the beginning of the crop cycle (*lai_min*), maximum leaf area index reached during the season (*lai_max*) and, especially for fruit trees with a grass cover, leaf area index of the grass (*lai_grass*).

The maximum crop coefficient (*kc_max*) is used to compute actual evapotranspiration.

The crop rooting system development is simulated by using the following parameters: depth of the beginning of roots with respect to the ground (*root_depth_zero) e.g.* the depth of the root collar, the maximum depth of the roots (*root_depth_max*), the degree days sum for the full development of the rooting system (*degree_days_ root_increase*) and the shape of the roots (*root_shape*). Currently, three shape factors codes are considered:

1 → cylinder
4 → cardioid
5 → gamma distribution

In addition, a coefficient of deformation (*root_shape_deformation*), expressed as a value ranging from 0 to 2, can be used to adapt the selected shape to the actual shape of the crop (only for cylinder and cardioid, it does not affect the gamma distribution).

The *max_height_surface_puddle* is the amount of water that surface can retain without runoff, typically a few millimeters of water, except for some crops (such as rice) where the surface is shaped specifically 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 and allows rapid runoff (for example on hills).

In order to assess the crop water demand, the irrigation process is controlled by the parameters listed in the table: *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 0 means that any water stress is tolerated and 1 that no water stress is tolerated by the crop.

1.5 db_comp_units

The comp_units database contains only one table (**computational_units**) that lists the computational units of the project, with the specific options for each unit. A computational unit (*ID_CASE*) is a unique combination of one crop class (*ID_CROP*), one meteo (*ID_METEO*) and one soil (*ID_SOIL*).

WARNING: *ID_CROP* in the table **computational_units** must correspond to the *id_class* of the **crop_class** table in the crop database. [TODO fix inconsistency]

A **template_comp_units.db** is available in the directory DATA/TEMPLATE and an example is available in the test project DATA/PROJECT/test/data

ID_CASE	TEXT
ID_CROP	TEXT
ID_METEO	TEXT
ID_SOIL	NUMERIC
hectares	NUMERIC
numerical_solution	INTEGER
use_water_table	INTEGER
water_retention_fitting	INTEGER
optimal_irrigation	INTEGER
slope	REAL

*Structure of the **computational_units** table*

Several model parameters for each computational unit can be defined:

- *hectares* [ha] of the unit, used only in geographical version of the model;
- *numerical_solution:* (1: true, 0: false, default: 0) if true, use the soil water flux numerical algorithm, otherwise a simplified conceptual algorithm;
- *use_water_table:* (1: true, 0: false, default: 1) if true, the model computes the capillary rise from water table; 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) if true, the soil parameters will be fitted using data in **water_retention** table, if available;
- *optimal_irrigation:* (1: true, 0: false, default: 0) if true, use ideal subirrigation to restore field capacity in the root zone without losses;
- *slope:* [m m-1] slope of the unit, used only in the numerical solution to compute the flow in the lateral boundaries.

ID_CASE	ID_CROP	ID_METEO	ID_SOIL	umerical_solutic	use_water_table	vater_retention_fittin	ptimal_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 **computational_units** table in the project test*

1.6 db_output

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

Default output variables 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	Actual crop transpiration [mm]
EVAP_MAX	Maximum evaporation [mm]
EVAP	Actual evaporation [mm]

LAI	Leaf area index [m2 m-2]
ROOT_DEPTH	Root depth [m]
BALANCE	Water balance error (for numerical solution) [mm]

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

waterContent	Volumetric water content at specific depth [m3 m-3]
waterPotential	Water potential at specific depth [kPa]
waterDeficit	Sum of water deficit (FC - water content) from zero to user defined depth [mm]
awc	Sum of Available Water Capacity (FC-WP) from zero to user defined 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 depths and the sum of the water deficit in the first meter of soil:

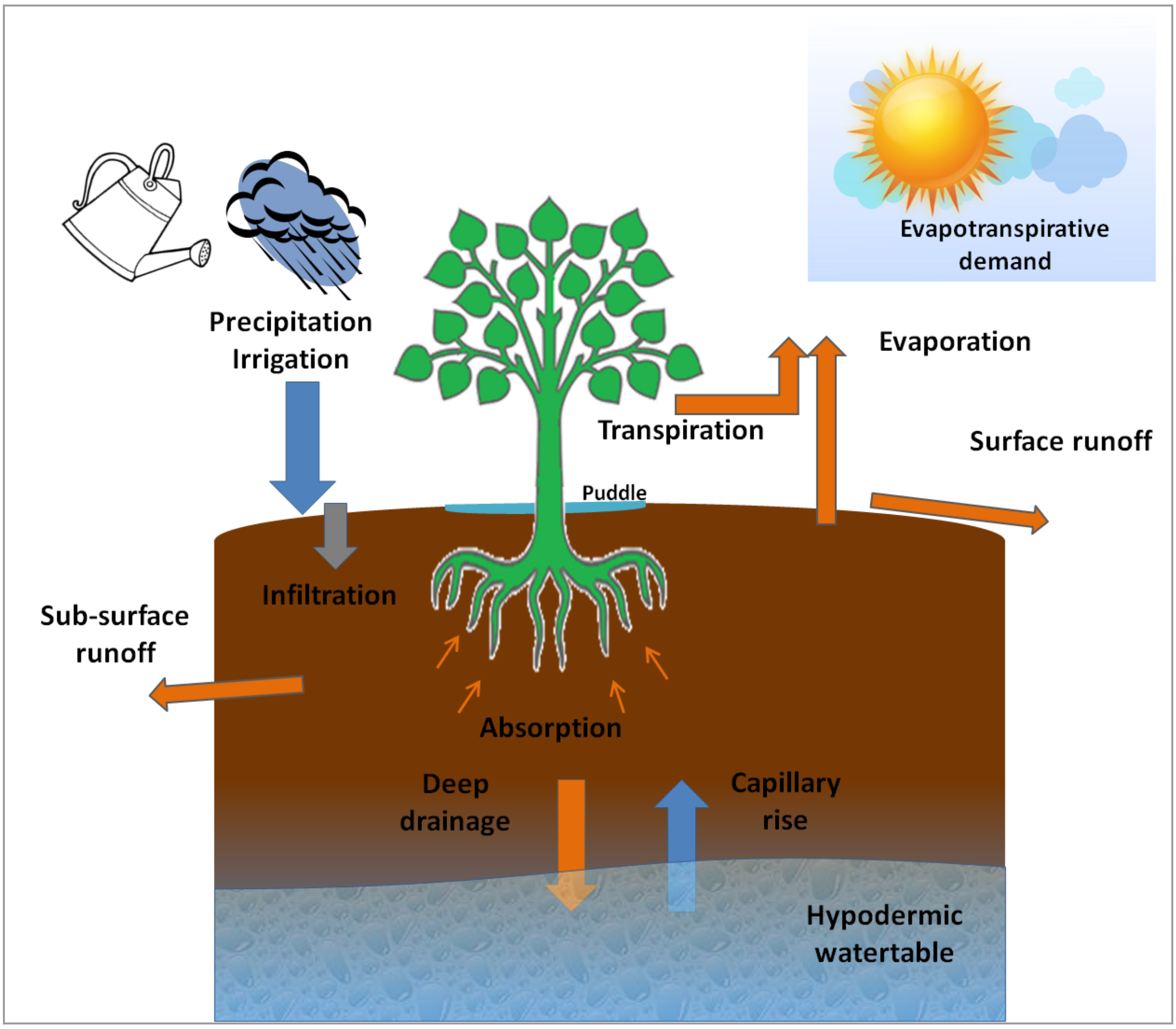
```
[output]
waterContent=15,30,50
waterPotential=15,30,50
waterDeficit=100
```

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 all the hydrological processes occurring between soil, vegetation 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 could not infiltrate into 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 hold water or transfer it to the layer below. In the presence of a water table, there may also be a supply of water to the soil deeper layers because of capillary rise.

The presence of a crop produces water loss in the root zone through root absorption, 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.

Once the crop parameters are properly set, it is possible by means of the SWB to estimate 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. Water flows can be simulated with two different approaches depending on the user's choice: a numerical physically-based model or a layer-based conceptual model.

2.1 Water

In a 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 below which the plant is not able to withdraw water;
- 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"; the generic 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 is 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 αh_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+(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 in the [CRITERIA_2016 Technical Manual] (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 the following advantages: a higher computational speed, which facilitates their use in applications designed for simulations at larger scales; lower need of parameters and input data, which could be required in case of more complex models.

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:

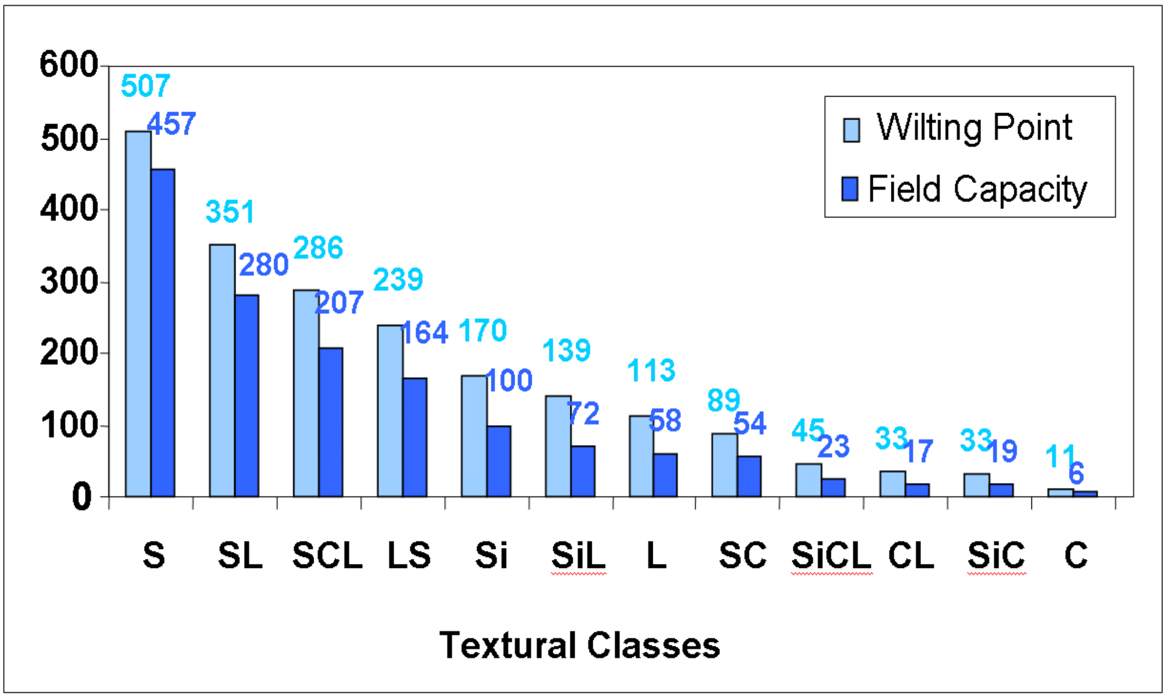
I_{max}	maximum infiltration	[mm d^{-1}]
S_0	standard sorptivity	[cm d^{-1}]
θ	volumetric water content of the layer	[m^3 m^{-3}]
θ_{sat}	volumetric water content at saturation	[m^3 m^{-3}]
A	hydraulic conductivity at the wetting front	[cm d^{-1}]

The sorptivity represents the infiltration rate determined by the single matric potential, the standard sorptivity S_0 being defined for a completely dry soil. 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 different soil 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.

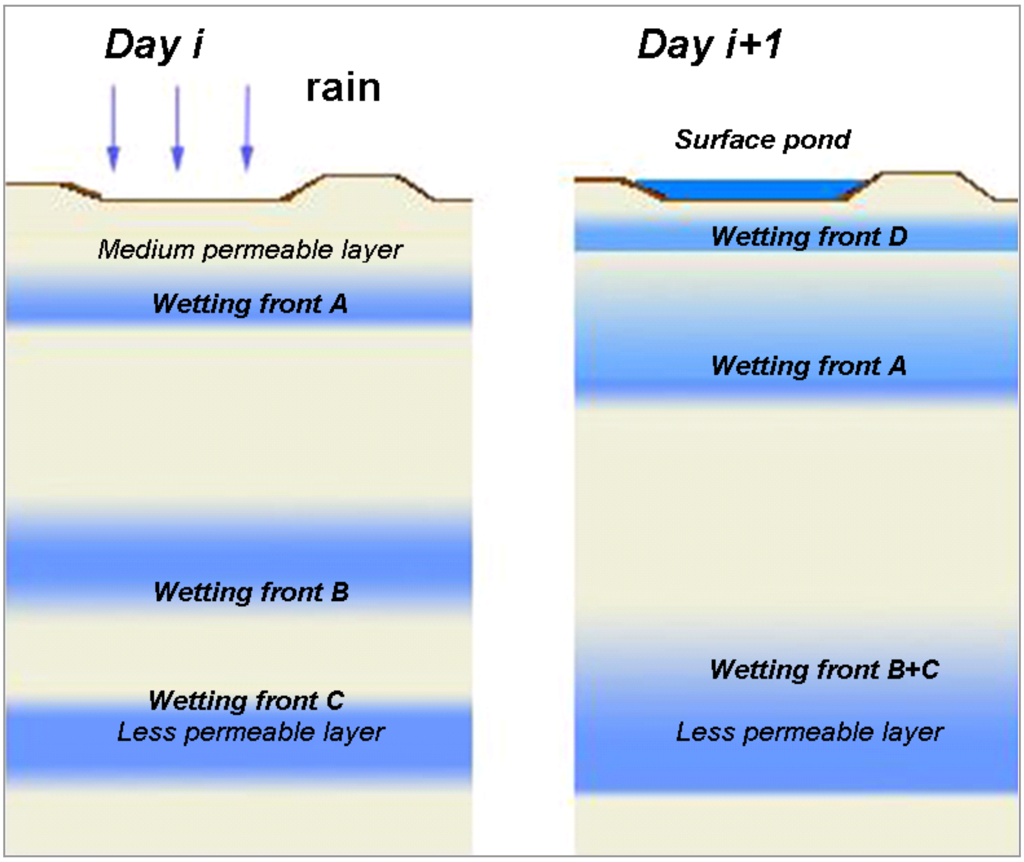
Each layer is characterized by an infiltration of the maximum daily amount (Imax). To estimate the maximum displacement of the waterfront, the maximum infiltration of the underlying layer at the waterfront is calculated. If the water content of the layer exceeds the field capacity, the amount in excess is transferred 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 that is lower than *FC*, then the waterfront is stopped.

Two conditions have to be satisfied:

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

2. in case the waterfront meets a saturated layer, the front stops at the layer above the saturated layer.

The first condition limits the passage of water in case of clay layers with low maximum daily infiltration: in this case it forms a suspended water table.
The second condition 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 figure above, 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 less permeable layer;
- the rain partially infiltrates creating a new front D;
- The water in excess with respect to surface I_{max} 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 higher puddle 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):

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

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 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 the layer 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 can be computed by the steady state solution of Darcy's equation as:

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

Where:

CR is the capillary rise (cm d-1)

h is the matric suction (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 three main root shapes: cylinder, cardioid and gamma distribution.

LAI drives 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 on the crop physiological parameters.

TODO

Crop processes are detailed in the CRITERIA_2016 Technical Manual (section 3).

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 evapotranspiration rate increases until water is available. 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. ET_0 represent the water demand by the atmosphere, and it depends on atmospheric and surface conditions (temperature, solar radiation, wind speed, air water content, leaf water content).

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 reference evapotranspiration.
The Hargreaves method needs only latitude of the computation area and daily maximum and minimum temperature for the estimation:

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

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 portion of soil explored by 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:
$H_2O_{available}$ 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 $H_2O_{available}$ is below zero.

In more detail, an irrigation is performed in the model if all the following conditions are fulfilled:

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

The irrigation amount is computed as the minimum value among the predefined irrigation quantity for the crop and the maximum quantity of water that can infiltrate daily without runoff.

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