IdgRA

Technical manual

version 2.0

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DiSAA – Department of Agricultural and Environmental Sciences

University of Milan

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List of principal symbols

Symbol	Meaning [unit]
a_I	empirical coefficient to compute interception [mm]
a_{irr_met}	parameter that accounts for irrigation method [-]
$a_{irr\_met}^{inf}$	minimum value of a_{irr_met} for the considered irrigation method [-]
$a_{irr\_met}^{sup}$	maximum value of a_{irr_met} for the considered irrigation method [-]
$a_{rc,1}$	$a_{rc,1} = W_{FC}$, soil water storage to 1.0 m depth at field capacity [mm]
$a_{rc,2}$	$a_{rc,2} = 1.1\frac{W_{fc}-W_{wp}}{2}$, storage above the average between those at field capacity and the wilting point [mm]
$a_{rc,3}$	empirical parameter to estimate critical groundwater depth that depends on soil type [-]
$a_{rc,4}$	empirical parameter to estimate potential capillary flux that depends on soil type [-]
b_I	soil cover fraction to compute interception, estimated by $b_I = \min\left(\frac{LAI}{3}, 1\right)$ [-]
$b_{rc,1}$	empirical parameter to estimate critical soil water storage that depends on soil type [-]
$b_{rc,2}$	empirical parameter to estimate steady soil water storage that depends on soil type [-]
$b_{rc,3}$	empirical parameter to estimate critical groundwater depth that depends on soil type [-]
$b_{rc,4}$	empirical parameter to estimate potential capillary flux that depends on soil type [-]
CGD_t	accumulated thermal time since planting for the day t [°C d]
CN	curve number [-]
CN_x	curve number adjusted for moisture condition and slope [-]
CN_1	moisture condition I curve number [-]
CN_2	moisture condition II curve number [-]
CN_{2s}	moisture condition II curve number adjusted for slope [-]
CN_3	moisture condition III curve number [-]
CN_4	moisture condition at saturation, equal to 95 [-]

$(CN_x)_{crop}$	curve number adjusted for moisture condition and slope, for a crop [-]
$(CN_x)_{fallow}$	curve number adjusted for moisture condition and slope, for fallow land use, crop residue cover treatment [-]
c_p	specific heat of air at constant pressure $[kJ\ kg^{-1}C^{-1}]$
$D_{e,i-1}$	cumulative depth of evaporation from the soil surface layer the end of the previous day [mm]
$d_{i,j}^{-2}$	inverse-square distance weight between the point (i,j) and each n meteorological station $[-]$
d_g	groundwater depth [m]
d_{gc}	critical groundwater depth for capillary rise estimation [m]
d_r	inverse relative distance Earth-Sun [-]
d_s	maximum number of day shift in crop parameters series [-] (see § par. 3.6.2)
dlh	daylight hours of day t [d]
dlh_{if}	daylight hours to inhibit flowering, day length threshold below (for long-day crops) or above (for short-day crops) which no accumulation of physiological time occurs [d]
dlh_{ins}	daylight hours for insensitivity, day length threshold above (for long-day crops) or below (for short-day crops) which maximum physiological time accumulation occurs [d]
E	evaporation rate [mm d^{-1}]
e_a	actual vapour pressure [kPa]
$e^0(\mathrm{T}_{air})$	saturation vapour pressure at the air temperature T_{air} [kPa]
e_s	saturation vapour pressure [kPa]
ET_0	reference evapotranspiration [mm d^{-1}]
ET_c	crop evapotranspiration under standard conditions [mm d^{-1}]
$ET_{c\ adj}$	crop adjusted evapotranspiration [mm d^{-1}]
f_c	average fraction of soil surface covered by vegetation $[0 - 0.99]$ [-]
f_{ew}	soil surface from which most evaporation occurs [-]
f_w	average fraction of soil surface wetted by irrigation or precipitation $[0.01 - 1]$ [-]
$f_{w,1}, f_{w,2}, f_{w,3}$	well flow shares [-] [0-1]

G	soil heat flux density [MJ m^{-2} d^{-1}]
g	days elapsed since last irrigation [d]
GD_t	thermal time of the day t [°C d]
G_{max}	potential capillary flux rate [mm d^{-1}]
G_{sc}	solar constant, equal to $0.0820\ MJ\ m^{-2}\ min^{-1}$
h	counter of hourly time steps
h_{crop}	crop height [m]
h_{irr}	fixed irrigation amount to the field [mm]
I	canopy rainfall interception [mm d^{-1}]
I_a	initial abstractions including surface storage, interception and infiltration before runoff inception [mm d^{-1}]
J	Julian day: number of the day in the year between 1 (January 1st) and 365 or 366 (December 31st) [-]
K_c	crop coefficient [-]
K_{c_max}	maximum value of K_c following rainfall or irrigation [-]
K_{c_min}	minimum value of K_c for dry bare soil with no ground cover [$K_{c\_min} \approx 0.15 - 0.20$]
K_{cb}	basal crop coefficient [-]
$K_{cb\ ini}$	basal crop coefficient for the initial stage [-]
$K_{cb\ mid}$	basal crop coefficient for the mid-season stage [-]
$K_{cb\ end}$	basal crop coefficient at the of the late season stage [-]
K_e	soil water evaporation coefficient [-]
K_E	unsaturated hydraulic conductivity of the evaporative layer [cm h^{-1}]
K_r	evaporation reduction coefficient dependent on the cumulative depth of water depleted from the topsoil [-]
$K_{s,E}$	saturated hydraulic conductivity of the evaporative layer [cm h^{-1}]

$K_{s,T}$	saturated hydraulic conductivity of the transpirative layer [cm h^{-1}]
K_T	unsaturated hydraulic conductivity of the transpirative layer [cm h^{-1}]
LAI	Leaf Area Index [-]
n	number of interpolating points [-]
n_E	Brooks-Corey exponent for the evaporative layer [-]
n_T	Brooks-Corey exponent for the transpirative layer [-]
N_s	number of irrigation sources for which timeseries of daily flows are available
P	rainfall rate [mm d^{-1}]
p	average fraction of Total Available Soil Water that can be depleted from the root zone before moisture stress occurs $[0-1]$ [-]
p_{tab}	tabulated values of average fraction of Total Available Soil Water that can be depleted from the root zone before moisture stress occurs [-]
P_{atm}	atmospheric pressure [kPa]
P_{eff}	effective rainfall [mm d^{-1}]
PF	photoperiod factor [0-1] [-]
$P_{i,k}$	normalized weight of the k-th data point on the point estimated (i,j) [-]
Q_e	outflow from the evaporative to the transpirative layer, accounting for irrigation management [mm d^{-1}]
$Q_{e,nc}$	outflow from the evaporative to the transpirative layer, not accounting for irrigation management [mm]
Q_g	Capillary flux into the root zone [mm d^{-1}]
Q_{irr}	irrigation application to an individual cell [mm d^{-1}]
$Q_{j,t}$	total water supply to the j^{th} irrigation unit (IU) on day t $(mm \cdot d^{-1})$,
Q_{inf}	infiltration [mm d^{-1}]
Q_p	percolation flux out of the root zone [mm d^{-1}]

Q_s	outflow from the root zone to the deeper subsoil, accounting for irrigation management, ($Q_s > 0$) or capillary rise rate ($Q_s < 0$) [mm d^{-1}]
$Q_{s,nc}$	outflow from the root zone to the deeper subsoil, not accounting for irrigation management [mm]
Q_u	net runoff from the cell [mm d^{-1}]
R_a	extra-terrestrial radiation [MJ m^{-2} d^{-1}]
RAW	readily available soil water in the root zone [mm]
REW	cumulative depth of evaporation at the end of first stage (readily evaporable water) [mm]
RH_{max}	maximum relative humidity [%]
RH_{min}	minimum relative humidity [%]
R_n	net radiation at the crop surface [MJ m^{-2} d^{-1}]
R_{nl}	net outgoing longwave radiation [MJ m^{-2} d^{-1}]
R_{ns}	net solar or shortwave radiation [MJ m^{-2} d^{-1}]
R_s	incoming solar radiation [MJ m^{-2} d^{-1}]
R_{so}	clear-sky solar radiation [MJ m^{-2} d^{-1}]
S	retention parameter [mm d^{-1}]
slp	average fraction slope of the cell [%]
t	counter of daily time steps
T	transpiration rate [mm d^{-1}]
T_{air}	air temperature at $2\ m$ height [°C]
TAW	total available soil water in the root zone [mm]
T_p	potential crop transpiration rate [mm d^{-1}]
$\mathrm{T}_{\mathrm{cutoff}}$	maximum temperature for viable crop development [°C]
$\mathrm{T}_{\mathrm{daybase}}$	minimum temperature for viable crop development [°C]
TEW	total evaporable water, equal to the maximum depth of water that can be evaporated from the soil when the topsoil has been initially completely wetted [mm]

T_{max}	daily maximum temperature at $2\,m$ height [°C]
$\mathrm{T}_{max,K}$	maximum daily absolute temperature $\mathrm{T}_{max,K} = \mathrm{T}_{max} + 273.16$ [K]
T_{ave}	mean daily air temperature at $2\,m$ height [°C]
T_{min}	daily minimum temperature at $2\,m$ height [°C]
$\mathrm{T}_{min,K}$	minimum daily absolute temperature $\mathrm{T}_{min,K} = \mathrm{T}_{min} + 273.16$ [K]
$\mathrm{T}V_{A}$	parameter for not optimum vernalisation [°C]
$\mathrm{T}V_{max}$	high end temperature threshold for optimum vernalisation [°C]
$T\mathrm{V}_{\mathrm{min}}$	low end temperature threshold for optimum vernalisation [°C]
T_{sow}	sowing temperature threshold [°C]
u_2	wind speed at $2\,m$ height [m s-1]
$\overline{U_{cr}}$	weighted mean value of readily available soil water in the root zone of the ensemble cells supplied by a collective runtime source [mm]
$\overline{U_{cr}^{MAX}}$	weighted maximum value of readily available soil water in the root zone of the ensemble cells supplied by a collective runtime source [mm]
VD_{end}	required sum to complete vernalisation (at which VF reaches a value of 1.0) [d]
VD_{start}	accumulated vernalisation days at which VF is set equal to VF_{min} [d]
VD_{sum}	sum of the currently accumulated vernalisation days, equal to $\sum_{j=i}^{d} V_{eff}$ [d]
V_{E}	water content of the evaporative layer per unit surface area of the cell [mm]
V_{eff}	vernalisation contribution of day d [d]
V_p	ponded volume on the cell surface [mm]
V_T	water content of the transpirative layer per unit surface area of the cell [mm]
$V_{T,r}$	residual soil water content of the transpirative layer [mm]
$V_{T,c}$	critical water storage in the transpirative zone [mm]
VF	vernalisation factor [0-1] [-]
VF_{min}	minimum vernalisation factor value at the beginning of the vernalisation process [0-1] [-]

W	daily water withdrawal from a collective source supplying the study area
W^{MAX}	maximum admissible daily water withdrawal from a collective source [mm d^{-1}]
(X_i, Y_i)	coordinates of the i-th cell center [m]
(X_k, Y_k)	coordinates of the k-th data point [m]
z	elevation above sea level [m]
z_E	depth of the evaporative layer [m]
z_T	depth of the transpirative layer [m]
z_r	total root depth [m]
α	albedo, which is 0.23 for the hypothetical grass reference crop [-]
α_i	coefficient for the activation of irrigation [-]
α_w	coefficient for well activation [-] [0-1]
$\alpha_{w,1}, \alpha_{w,2}$	well activation thresholds [-] [0-1]
γ	psychrometric constant [kPa °C^{-1}]
δ	solar declination [rad]
Δ	slope vapour pressure curve [kPa °C^{-1}]
ε	ratio molecular weight of water vapour/dry air 0.622
θ	soil water content of the entire profile [m^3 m^{-3}]
θ_E	volumetric water content of the evaporative layer [m^3 m^{-3}]
θ_{fc}	field capacity soil profile water content [m^3 m^{-3}]
$\theta_{fc,E}$	soil water content of the evaporating layer at field capacity [m^3 m^{-3}]
$\theta_{fc,T}$	soil water content of the transpirative layer at field capacity [m^3 m^{-3}]
$\theta_{fc,wp}$	Antecedent Moisture Condition II soil profile water content, equal to $\theta_{fc,wp} = \theta_{wp} + \frac{2}{3}(\theta_{fc} - \theta_{wp})$ [m^3 m^{-3}]
$\theta_{r,E}$	residual water content of the evaporative layer [m^3 m^{-3}]

$\theta_{r,T}$	residual water content of the transpirative layer [m^3 m^{-3}]
$\theta_{RAW,T}$	water content corresponding to RAW for the transpirative layer, equal to $\theta_{FC,T} - p \cdot (\theta_{FC,T} - \theta_{WP,T})$ [m^3 m^{-3}]
θ_s	saturation soil profile water content [m^3 m^{-3}]
$\theta_{s,E}$	saturated water content of the evaporative layer [m^3 m^{-3}]
$\theta_{s,T}$	saturated water content of the transpirative layer [m^3 m^{-3}]
θ_T	volumetric water content of the transpirative layer [m^3 m^{-3}]
$\theta_{Tc,h}$	critical soil water content of the transpirative layer for capillary rise estimation (-)
$\theta_{Ts,h}$	steady-state soil water content of the transpirative layer for capillary rise estimation (-)
θ_{wp}	wilting point soil profile water content [m^3 m^{-3}]
$\theta_{wp,E}$	soil water content of the evaporating layer at wilting point [m^3 m^{-3}]
$\theta_{wp,T}$	soil water content of the transpirative layer at wilting point [m^3 m^{-3}]
σ	Stefan-Boltzmann constant, $\sigma = 4.903 \cdot 10^{-9}$ MJ K^{-4} m^{-2} d^{-1}
φ	latitude [rad]
$\varphi_{degrees}$	latitude [decimal degrees]
ξ_{conv}	conveyance efficiency [0.01-0.99] [-]
ξ_{field}	field application efficiency [0.01-0.99] [-]
λ	latent heat of vaporization, $\lambda = 2.45\ MJ\ kg^{-1}$
η_{irr}	application efficiency of the cell irrigation method (-)
η_{ij}	conveyance efficiency from the i^{th} source to the j^{th} IU, (-)
ω_s	sunset hour angle [rad]

Nomenclature

Study area: the spatial domain where the IdrAgra simulation is run.

Simulation horizon: time period between a starting date and a final date where the IdrAgra simulation is run on a daily basis; for scenario analysis it may include several years.

Discretization mesh: the regular mesh used to discretize the spatial domain of the study area; the size of the mesh is defined by the user.

Cell: a volume of soil of the study area delimited at the surface by one of the square cells of the discretization mesh and extending to the depth where the roots of the cell vegetation can reach to extract water and nutrients.

Water source: any source of irrigation water, either from surface water or from groundwater, where water can be diverted or withdrawn and conveyed to specific zones (command area of the source) within the study area; the study area can include one or more command areas and each of them receive water supply from multiple sources.

Irrigation Unit (IU): the command area of a specific delivery point along the conveyance and distribution network originating from a water source; an IU can be linked to more than one water source.

Allocation rule: the vector of weights associated with each water source defining the share of the total flowrate at the source that is allocated to each IU of its command area.

Conveyance and distribution efficiency: the ratio between the flowrate at the delivery point of an IU and the flowrate at the source under steady state hydraulic conditions; each IU has its own value of efficiency that accounts for seepage losses along the hydraulic path from the source to the IU.

Distribution rule: the operating rule according to which the water conveyed to an IU is distributed among the cells of the IU itself; a typical operating rule is on turn, where water is allocated to the cells of the IU with a rotation criterion.

Irrigation practice: a combination of the irrigation method (e.g., border irrigation, rain gun, central pivot, surface drip irrigation) and of the operating rule of irrigation application (e.g., soil water content threshold for irrigation activation, depth and duration of the irrigation applications).

Water sources: IdrAgra can deal with the following types of water sources:

- <u>MONITORED sources</u>. The first type includes any source for which the daily value of the water supply can provided in input. This is typically the case, for example, of surface water diversions where a license fixes the amount of flow that can be diverted during the irrigation season, possibly according to water availability in the water body, but independently from the actual conditions of the irrigated area. For these sources the timeseries of daily irrigation volumes during the whole simulation period and for each source must be provided as input files (see Installation & Use manual for the input file format specifications). They represent any type of diversion/withdrawal, either from surface or ground waters, for which are available:
    - the timeseries of observed daily discharge for the whole simulation horizon;

- the list of IUs supplied by the source;
- the share of the total discharge of each IU.

▪ RUNTIME sources. The second type include all the sources where the daily irrigation volume is not available. For these sources, the daily value of irrigation volume is computed runtime by the IdrAgra model, according to a set of parameters that the user needs to provide, specifying the constraints on daily water availability (if applicable) and the operating rule according to which the desired amount of supply is determined based on the soil water status of the command area of each source. Moreover, RUNTIME sources can belong to two different categories:
  - Collective: the source provides water supply to one or more IUs and the operating rules are known. This is typically the case of diversions, either from surface or groundwater, that provide irrigation supply to an area including multiple farms, where water is pumped and that are typically managed by an irrigation agency or consortium;
  - Private: the source provides water supply to an individual farm (group of cells within an irrigation unit) and its characteristics are unknown. This is typically the case of irrigation wells or small diversions from surface water by pumping that are owned and managed by farmers, that can be present in large numbers in irrigated areas and for which it is often difficult to obtain precise information on the plant characteristics and operation.

In both cases, it is supposed that water can be unlimitedly diverted/pumped, thus satisfying the irrigation need of the cell or cells supplied by the well.

▪ INTERNAL reuse. It represents the amount of water potentially available for irrigation use that originates within the study area due the accumulation of surplus and tailwaters (i.e., the portion of water supplied to irrigation units by monitored or runtime sources that is not applied to the fields of an IU because the volume delivered to the IU exceeds the crop irrigation needs); the daily value of the discharge is computed online by IdrAgra based on:
  - the list of IUs producing surplus and tailwaters that can be supplied to other units in the study area;
  - the list of irrigation units supplied by the reuse water;
  - the share of the total reusable volume of each of these irrigation units.

The daily amount of reusable flow is estimated on runtime by IdrAgra, based on the crop irrigation requirements of the irrigation units supplied by the diversion, accounting for conveyance and distribution efficiency.

1 Introduction

IdrAgra is a distributed-parameter conceptual model, which allows the simulation of the irrigation water distribution in agricultural areas and the estimation of the hydrological balance on a daily basis. IdrAgra includes **four modules** devoted to specific tasks (Figure 1):

- crop phenology,
- soil-crop water balance,
- irrigation,
- crop yield.

Each module will be described in detail in the next chapters.

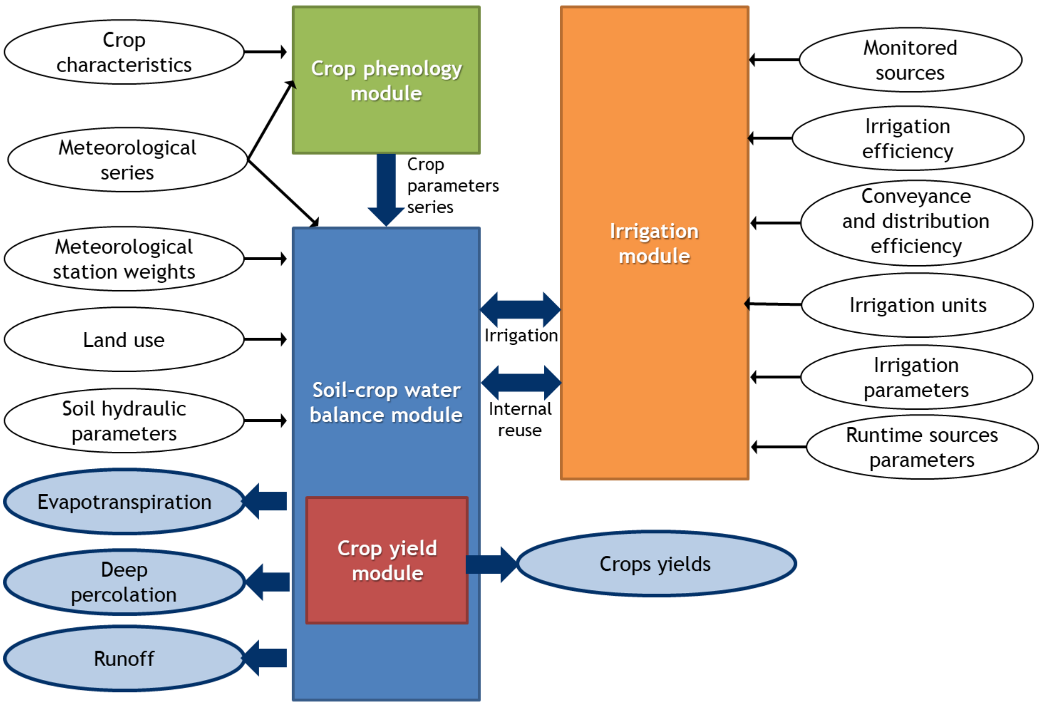


Figure 1: Flowchart of the IdrAgra simulation model: modules are represented as colored boxes, inputs in white background ellipses, outputs in light blue background ellipses.

IdrAgra operates in **two modes:**

- NEED mode, for the estimation of the crop water needs of an irrigated area,
- USE mode, for the simulation of irrigation water uses and the estimation of the crop productions of an irrigated area.

NEED mode. The first mode can be used to estimate the crop water requirements of a study area over a user defined time horizon, accounting for the space variability soil and crop characteristics, for the efficiency of irrigation application at the field scale. If conveyance and distribution network characteristics are provided, the model can estimate the cumulative daily flow diversion requirement from each of the irrigation water sources, accounting for the conveyance and distribution efficiency. Figure 2shows a schematic of the modelling approach, consisting of the following steps:

- identification of the study area,
- selection of the meteorological stations,
- collection of the meteorological input series of each station over the selected simulation horizon,
- discretization of the area with a regular spatial mesh,
- setting land use and soil hydraulic parameters of each cell,
- setting irrigation method and management criterion for each cell,
- running the simulation of the daily water balance for each cell of the mesh over the simulation horizon.

Optionally the user can provide a list of water sources feeding the study area and eventually a value of the conveyance efficiency from each source to each cell. In this case, daily values of the flowrate of each source that need to be supplied to the study area to satisfy the crop water requirements can be computed by the model. Moreover, according to the characteristics of the conveyance and distribution network, the study area can be split into irrigation units, each receiving water supply through a delivery point of the network. Irrigation units include multiple cells, sharing the same water supply with a unique value of the conveyance efficiency (Figure 3).

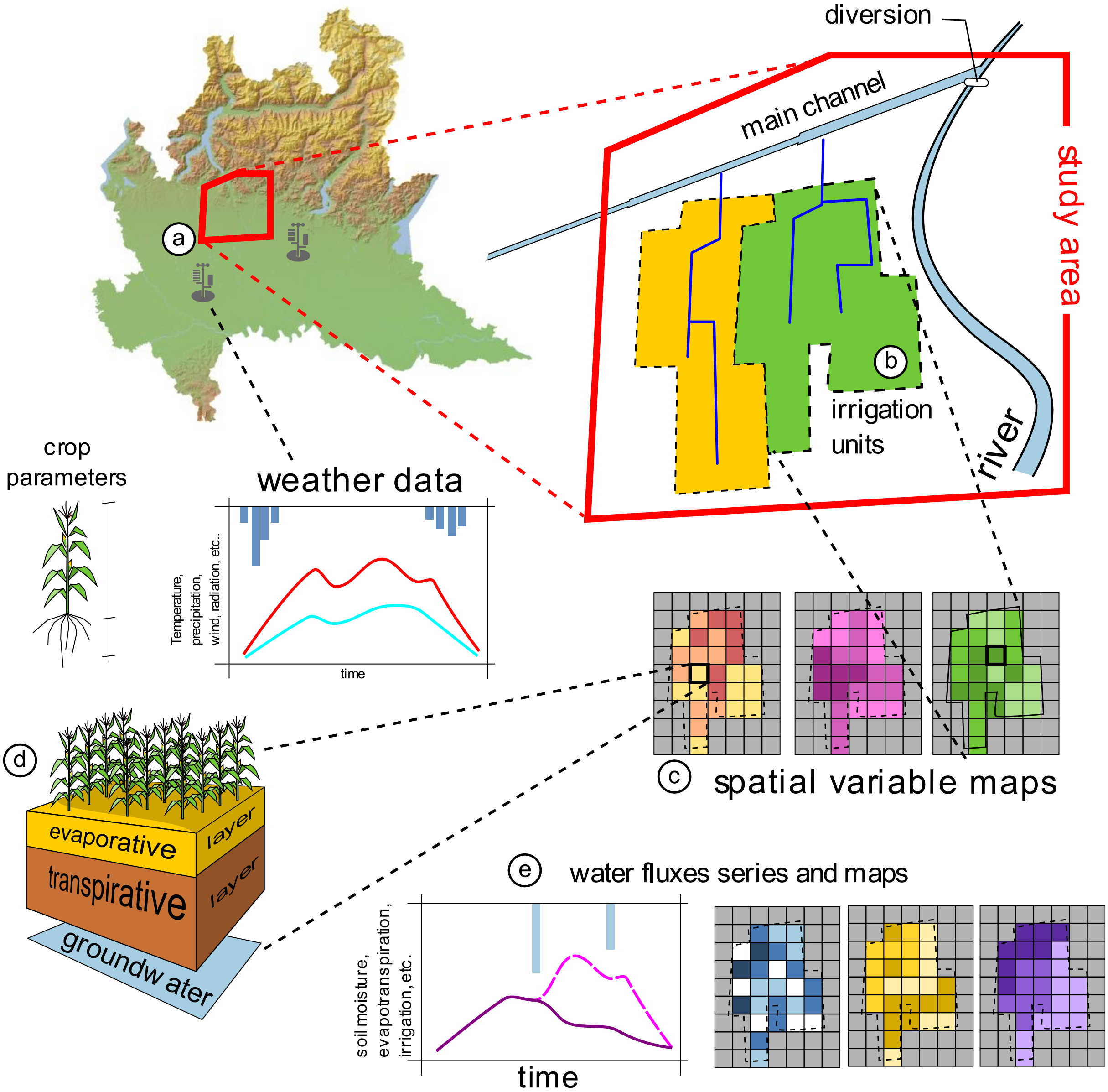


Figure 2: Schematic of the NEED mode operation: a) identification of the study area, selection of the meteorological stations and crop types; b) identification of the Irrigation Units (optional); c) space discretization with a regular mesh; d) computation of the daily hydrological balance for each cell of the mesh; e) simulation results (potential and actual ET, rainfall, irrigation, etc.) in one cell and distributed over study area

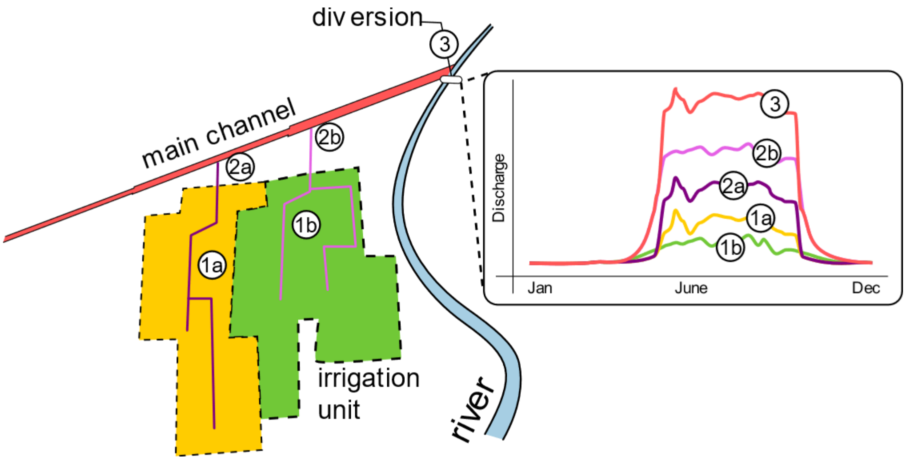


Figure 3: Graphical representation of the hydraulic connection between an Irrigation Unit (or a cell) and the water source where irrigation water supplied to the cell originates; the NEED model allows combining all the IU (or cells) linked to a source to compute the total daily flowrate that is needed to feed the irrigated area

USE mode. The second mode is designed for the actual simulation of all the phases of water use in irrigation systems, particularly suited for areas where water conveyance takes place through open channels and water distribution to the individual farms is on rotation or continuous. Multiple sources with different characteristics can be considered (see § 4.1.1 and Installation & Use manual) and a great deal of flexibility is provided in defining different irrigation methods (see § 4). The USE mode requires further steps, in addition to those of the NEED mode:

- identification of the study area,
- selection of the meteorological stations,
- collection of the daily meteorological input series of each station over the selected simulation horizon,
- selection of the irrigation water sources,
- collection of the daily hydrometric input series of each station over the selected simulation horizon,
- discretization of the area with a regular spatial mesh,
- setting land use and soil hydraulic parameters of each cell,
- setting irrigation method and management criterion for each cell,
- subdividing the study area into irrigation units,
- defining conveyance efficiencies from each water source to the served areas (individual cells or irrigation units),
- running the simulation of the water conveyance, distribution, application and of the daily water balance for each cell of the mesh over the simulation horizon.

The USE mode computes the space-variable values of all terms of the soil water balance of each cell on a daily basis and provides an estimate of the potential and actual crop yields.

Finally, the USE mode also allows for the computation of tailwater amounts generated in the study area and can account for their reuse within the area itself (see § 4.1.1.3).

In both modes the size of the cells of the regular discretization mesh is defined by the user.

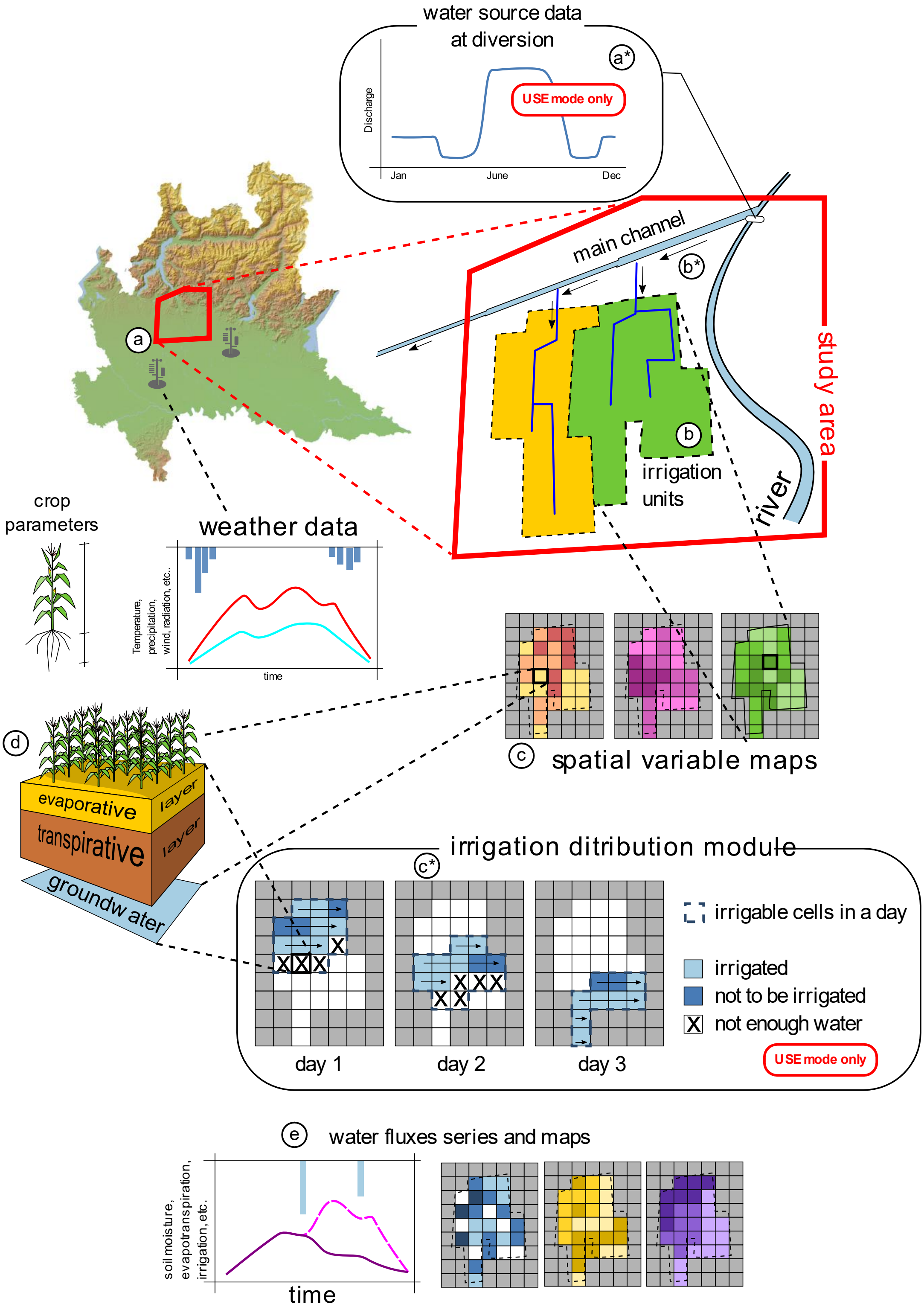


Figure 4: Schematic of the USE mode operation: in addition to the steps of the NEED mode (Figure 2) the USE mode requires a*) identification of the water sources, collection of the daily input series of withdrawals; b*) definition of the conveyance path from each source to each IU (or cell); c*) distribution of the flow delivered to a IU within the IU itself (not needed if the flow is delivered to individual cells)

2 Crop phenology module

The crop phenology module (CropCoef in the following) calculates the length of growth stages of different crops based on a thermal sum model (see, e.g., Stockle and Nelson, 2000), requiring input of minimum and maximum temperatures recorded at one or more weather stations. The code also generates specific input files to the other IdrAgra modules. The characteristics and functions of CropCoef are described in detail in the following sections.

2.1 Sowing date

Crops are sowed based on the satisfaction of temperature requirements. The model calculates a forward moving average of the daily average temperature (window of 5 days, from t to $t+4$) from the minimum sowing date (*SowingDate_min*) for a number of days defined by *SowingDelay_max* and select feasible sowing dates with respect to temperature (

Figure 5, panels a and b) based on Eq. 2.1:

$$\frac{\sum_{i=t}^{t+4} \mathrm{T}_{ave}}{5} \geq \mathrm{T}_{sowing} \tag{2.1}$$

where t (d) is the daily time step, T_{ave} $(°C)$ is the daily average temperature at 2 m height and T_{sowing} $(°C)$ is the sowing temperature threshold defined in the crop parameters file. If no feasible sowing dates are found, sowing date is set equal to *SowingDate_min* for winter crops and equal to *SowingDate_min* + *SowingDelay_max* for summer crops (

Figure 5, panel c). On the other hand, if some feasible sowing dates are identified, the model checks if the previous crop in the crop sequence has already been harvested to avoid overlapping of crops. If there is no crop in the field (

Figure 5, panel d), sowing is set on the first feasible date; otherwise, the model selects a sowing date so that there are a number of days equal to *CropsOverlap* between harvest of the previous crop and sowing of the next one (

Figure 5, panel e). If harvest of the previous crop is too delayed, then the model sets the sowing date on the last feasible date (

Figure 5, panel f).

Eventually, once selected the sowing date, the model anticipates the harvest of the previous crop to allow *CropsOverlap* days without any crops and returns a warning message.

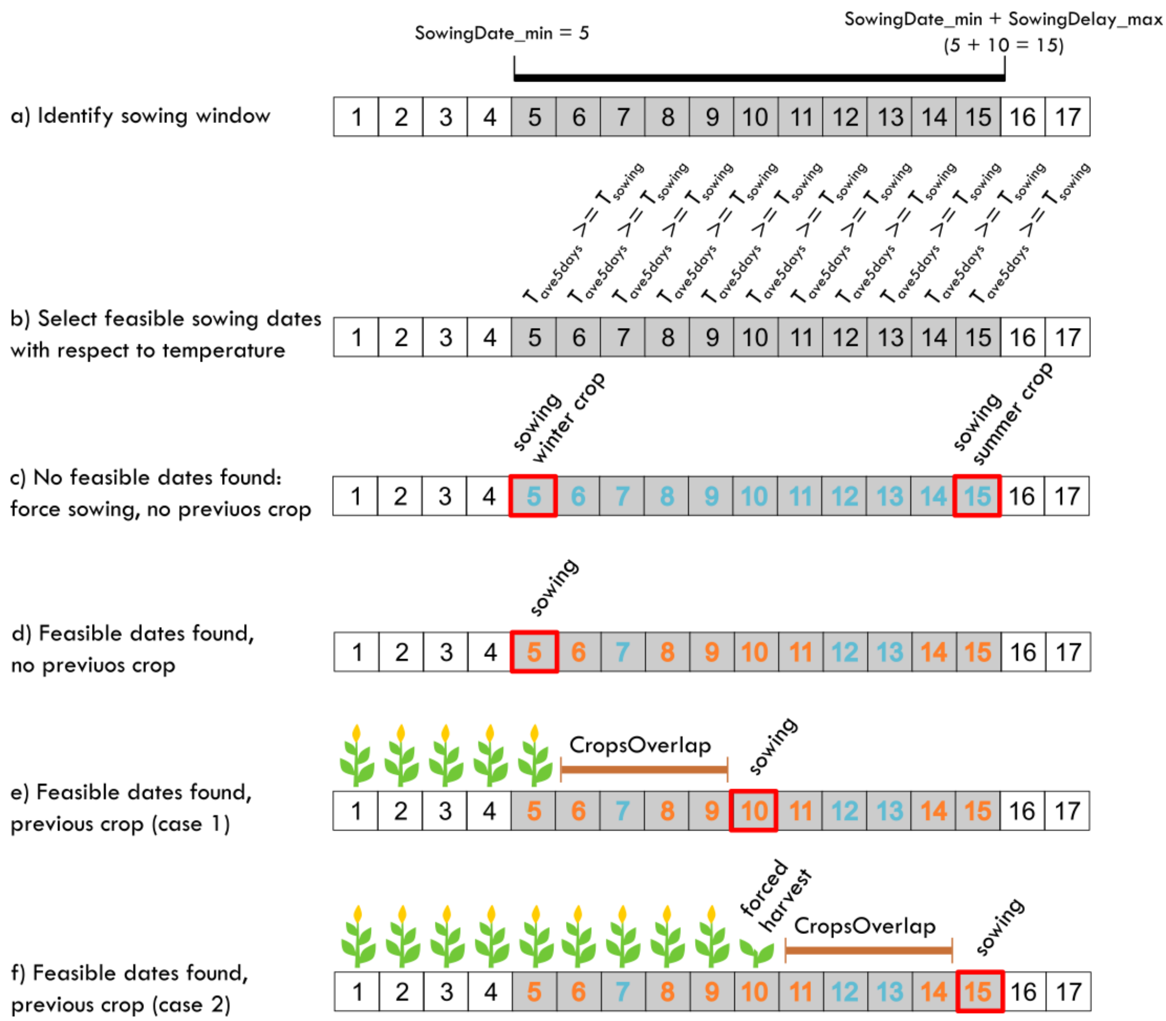


Figure 5: Scheme of the routine to select sowing dates (bold numbered cells represent dates when temperature requirements for sowing are satisfied, dark grey cells represent dates with previous crop in the field)

2.2 Thermal contribution of the day

Crop parameters are based on thermal time accumulated throughout the growing season (Growing degree-days, Stöckle & Nelson, 2003, McMaster & Wilhelm, 1997). For perennial crops, such as hays and trees, the growing season is assumed starting January 1st and ending December 31st; whereas the computation of thermal time for annual crops starts on sowing date and ends at harvesting. A crop enters the next stage of development when the thermal time reaches the thermal time requirement for the respective stage. Thermal time is computed according to Eq. 2.2 (Snyder, 1985):

$$
GD_t = \begin{cases} 0 & T_{max} < T_{base} \\ T_{ave} - T_{base} & T_{base} \le T_{min} < T_{max} \le T_c \\ \frac{(T_{ave}-T_{base})\left(\frac{\pi}{2}-\theta\right)+W\cos(\theta)}{\pi} & T_{min} < T_{base} < T_{max} \le T_c \\ (T_{ave} - T_{base}) - \frac{(T_{ave}-T_c)\left(\frac{\pi}{2}-\varphi\right)+W\cos(\varphi)}{\pi} & T_{base} \le T_{min} < T_c < T_{max} \\ \frac{(T_{ave}-T_{base})\left(\frac{\pi}{2}-\theta\right)+W\cos(\theta)}{\pi} - \frac{(T_{ave}-T_c)\left(\frac{\pi}{2}-\varphi\right)+W\cos(\varphi)}{\pi} & T_{min} < T_{base} < T_c < T_{max} \\ T_c - T_{base} & T_c \le T_{min} \end{cases} \tag{2.2}
$$

where t (d) is the daily time step, GD_t $(°C\ d)$ is the thermal time of the day t, T_{min} $(°C)$ and T_{max} $(°C)$ are the daily minimum and maximum temperatures, T_{base} $(°C)$ and T_c $(°C)$ are the minimum and maximum temperatures for crop development (corresponding, respectively, to the parameters $T_{daybase}$ and T_{cutoff} described in Installation & Use manual) and the remaining terms are calculated as follows:

$$T_{ave} = (T_{max} + T_{min})/2 \tag{2.2.1}$$

$$W = (T_{max} - T_{min})/2 \tag{2.2.2}$$

$$\theta = arcsin[(T_{base} - T_{ave})/W] \tag{2.2.3}$$

$$\varphi = arcsin[(T_c - T_{ave})/W] \tag{2.2.4}$$

2.3 Vernalisation

Vernalisation of crops can be defined as the low temperature promotion of flowering. Winter crops require a period of exposure to temperatures between approximately 0 to 12 °C for a period of time from 10 to 60 days from germination to proceed into the reproductive phase. Vernalisation is simulated by defining a vernalisation factor, VF, which fluctuates from 0 to 1 depending on the accumulation of vernalisation days:

$$VF = VF_{min} + \frac{(1-VF_{min})(VD_{sum}-V_{start})}{V_{end}-V_{start}} \tag{2.3}$$

where VF (-) is the vernalisation factor [0-1], VF_{min} (-) is the minimum vernalisation factor value at the beginning of the vernalisation process [0-1, usually 0], VD_{sum} (d) is the sum of the currently accumulated vernalisation days, equal to $\sum_{j=i}^{t} V_{eff}$, V_{start} (d) is the accumulated vernalisation days at which VF is set equal to VF_{min}, V_{end} (d) is the required sum to complete vernalisation (at which VF reaches a value of 1), t (d) is the daily time step, i (-) is the day number of the growing season.

V_{eff}, required to compute VD_{sum}, is the vernalisation contribution of day t (Figure 6) and is calculated from the average air temperature according to Eq. 2.4:

$$V_{eff} = \begin{cases} 0 & \mathrm{T}_{ave} < \mathrm{TV}_{min} - V_{slope} \\ 1 - \frac{\mathrm{TV}_{min} - \mathrm{T}_{ave}}{V_{slope}} & \mathrm{TV}_{min} - V_{slope} \le \mathrm{T}_{ave} < \mathrm{TV}_{min} \\ 1 & TV_{min} \le \mathrm{T}_{ave} < TV_{max} \\ 1 - \frac{\mathrm{T}_{ave} - \mathrm{TV}_{max}}{V_{slope}} & TV_{max} \le \mathrm{T}_{ave} < \mathrm{TV}_{max} + V_{slope} \\ 0 & \mathrm{T}_{ave} \ge \mathrm{TV}_{max} + V_{slope} \end{cases} \tag{2.4}$$

where V_{eff} (d) is the vernalisation contribution of day *t*, TV_{min} $(°C)$ and TV_{max} $(°C)$ are respectively the low end and high end temperature thresholds for optimum vernalisation, V_{slope} (°C) is a parameter usually set equal to 7.0 and T_{ave} $(°C)$ is the daily average air temperature at 2 m height.

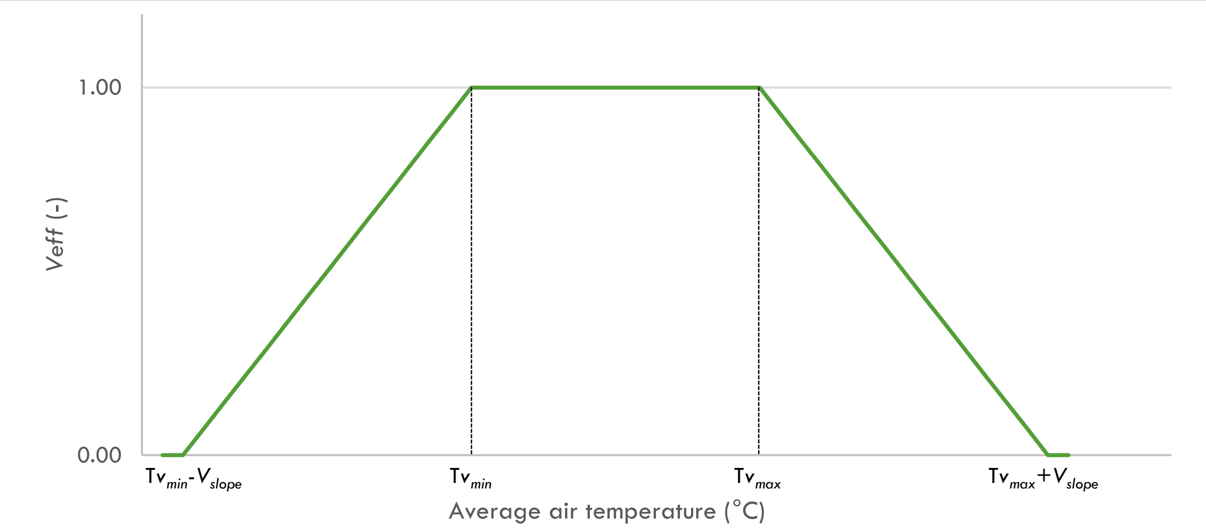


Figure 6: Pattern of the vernalisation contribution, V_{eff}, in response to temperature

2.4 Photoperiod impact

Plant development may respond to the relative lengths of days and nights. Some crops accumulate thermal time towards flowering when the day length exceeds a threshold (long-day crops); others accumulate thermal time towards flowering when the day length is less than a minimum threshold value (short-day crops). Eventually, some crops are insensitive to day length.

The photoperiod impact is simulated by defining a photoperiod factor, PF, which fluctuates between 0 and 1, computed according to a linear function (Figure 7).

For long-day crops, the relation is:

$$PF = \begin{cases} 0 & dlh < dlh_{if} \\ \frac{dlh - dlh_{if}}{dlh_{ins} - dlh_{if}} & dlh_{if} \le dlh \le dlh_{ins} \\ 1 & dlh > dlh_{ins} \end{cases} \tag{2.5}$$

where PF (-) is the photoperiod factor [0-1], dlh (h) is the number of daylight hours of the day t, dlh_{ins} (h) is the number of daylight hours for insensitivity (i.e. the day length threshold above which maximum physiological time accumulation occurs) and dlh_{if} (h) is the number of daylight hours to inhibit flowering (i.e. the day length threshold below which no accumulation of physiological time occurs).

For short-day crops, the relation is:

$$PF = \begin{cases} 1 & dlh < dlh_{ins} \\ \frac{dlh_{if}-dlh}{dlh_{if}-dlh_{ins}} & dlh_{ins} \leq dlh \leq dlh_{if} \\ 0 & dlh > dlh_{if} \end{cases} \quad (2.6)$$

where PF (-) is the photoperiod factor [0-1], dlh (h) is the number of daylight hours of the day t, dlh_{ins} (h) is the number of daylight hours for insensitivity (i.e. the day length threshold below which maximum physiological time accumulation occurs) and dlh_{if} (h) is the number of daylight hours to inhibit flowering (i.e. the day length threshold above which no accumulation of physiological time occurs).

The daylight hours, dlh, are given by Eq. 2.7:

$$dlh = \frac{24}{\pi} \omega_s \quad (2.7)$$

where dlh (h) is the number of daylight hours and ω_s (rad) is the sunset hour angle.

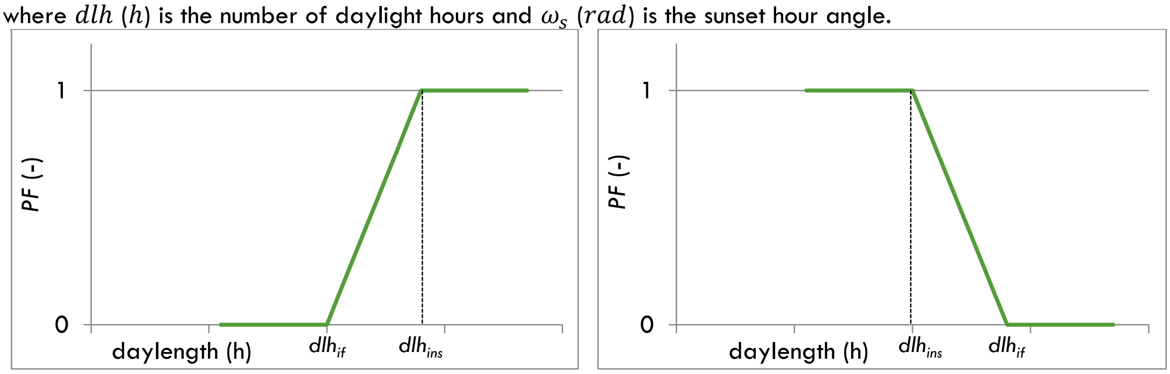


Figure 7: Pattern of the photoperiod factor, PF, in response to daylight hours in long-day plants (a) and short-day plants (b)

2.5 Thermal sum

Each day, the thermal time calculated from temperature according to Eq. 2.2 is multiplied by the minimum between the vernalisation and photoperiod factors to determine the actual amount of degree-days accumulated for the day. Then, the cumulated thermal time at day t is given by Eq. 2.8:

$$CGD_t = \sum_{j=i}^{t} GD_j \min\left(PF_j, VF_j\right) \quad (2.8)$$

where CGD_t $(°C)$ is cumulated thermal time at day t (calculated from seeding), i (-) is the day number within the growing season, GD_j $(°C\ d)$ is the thermal time computed for the day j, PF_j (-) is the photoperiod factor for the day j [0-1] and VF_j (-) is the vernalisation factor for the day j [0-1].

2.6 Adjustment of canopy resistance

Modified leaf conductance $g_{l,CO2}$ $(m\ s^{-1})$ is calculated to reflect the effects of higher concentration levels of CO_2 in the atmosphere according to Easterling et al., 1992:

$$g_{l,CO_2} = g_l * \left[1.4 - 0.4 * \left(\frac{C_{a,i}}{330}\right)\right] \tag{2.9}$$

where g_l $(m\ s^{-1})$ is the effective leaf conductance and $C_{a,i}$ (ppm) is the atmospheric concentration of carbon dioxide in the atmosphere for year *i*. The modified leaf resistance, r_{l,CO_2} $(s\ m^{-1})$, is calculated from the modified leaf conductance as $1/g_{l,CO2}$ and the modified canopy (surface) resistance, r_{s,CO_2}, is computed according to Allen at al., 1998:

$$r_{s,CO_2} = \frac{r_{s,CO_2}}{LAI_{active}} \tag{2.10}$$

where r_{s,CO_2} $(s\ m^{-1})$ is the (bulk) canopy/surface resistance for a grass reference crop and LAI_{active} $(m^2\ m^{-2})$ is obtained as $0.5 \cdot 24 \cdot 0.12$.

2.7 Adjustment of basal crop coefficient K_{cb}

Values of basal crop coefficient K_{cb} greater than 0.45 are adjusted considering corrections for climates with minimum relative humidity different from 45% or with wind speed larger or smaller than 2 m/s as proposed in Allen et al., 1998:

$$K_{cb} = K_{cb(Tab)} + [0.04(\overline{u_2} - 2) - 0.004(RH_{min} - 45)]\left(\frac{\overline{h}}{3}\right)^{0.3} \tag{2.11}$$

where $K_{cb(Tab)}$ (-) is the value for $K_{cb\ mid}$ or $K_{cb\ end}$ (if $>\ 0.45$) taken form the tables reported in Allen et al. (1998), $\overline{u_2}$ $(m\ s^{-1})$ is the mean value of wind speed at 2 m height over grass during the mid or late season growth stage for $1\ m\ s^{-1} < u_2 < 6\ m\ s^{-1}$, RH_{min} (%) is the mean value for daily minimum relative humidity during the mid or late season growth stage for $20\% < RH_{min} < 80\%$, $\overline{h}$ (m) is the mean plant height during the mid or late season stage for $0.1\ m < h < 10\ m$.

2.8 Potential dry above ground biomass

The normalized biomass water productivity WP^*_{adj} is calculated as:

$$WP^*_{adj} = [1 + f_{type}(f_{CO_2} - 1)]WP^*] \tag{2.12}$$

where f_{type} (-) is the crop type coefficient computed according to following Eq. 2.14, f_{CO_2} (-) is correction coefficient for CO_2 and WP^* $(t\ ha^{-1})$ is the crop biomass water productivity (reference values are $0.30 - 0.35\ t\ ha^{-1}$ for C4 crops, $0.15 - 0.20\ t\ ha^{-1}$ for C3 crops and values lower than $0.15\ t\ ha^{-1}$ for some leguminous crops). The crop type coefficient f_{CO2} is computed as:

$$f_{CO2} = \frac{(C_{a,i}/C_{a,o})}{1 + (C_{a,i} - C_{a,o})[(1-w)b_{Sted} + w(f_{sink}b_{Sted} + (1-f_{sink})b_{FACE}]} \tag{2.13}$$

where $C_{a,i}$ (ppm) is atmospheric CO_2 concentration for year i, $C_{a,o}$ (ppm) is the reference atmospheric CO_2 concentration equal to $369.41\ ppm$, b_{Sted} (-) is equal to 0.000138, b_{FACE} (-) is equal to 0.001165, w (-) is a weighing factor calculated according to Eq. 2.15 and f_{sink} is the crop sink strength coefficient.

$$0 \leq f_{type} = \frac{40-WP^{*}}{40-20} \leq 1 \tag{2.14}$$

$$0 \leq w = 1 - \frac{(550-C_{a,i})}{(550-C_{a,o})} \leq 1 \tag{2.15}$$

2.9 Harvest date

For all crops with just one cut per year (parameter *HarvNum_max* = 1, Installation & Use manual), harvest date generally corresponds to the day t where the cumulated thermal time computed according to Eq. 2.8 is equal to the highest GDD threshold entered in the crop parameter file. In case of crops with multiple cuts (e.g. fodder crops, *HarvNum_max* > 1), the model restarts to cumulate thermal units after the first harvest for a number of times equal to *HarvNum_max*. If any crops do not reach full maturation by the date defined by *HarvestDate_max* (see Installation & Use manual), harvest date is forced at *HarvestDate_max*. In case of double cropping, the model verifies if the next crop has already been sown and, if so, harvest date is anticipated to allow a number of days equal to *CropsOverlap* without any crops. When this condition occurs, the model returns a warning message.

3 Soil-crop water balance module

The core of the IdrAgra model is the soil-crop water balance module, which accounts for the space variability of soils, crops, meteorological and irrigation inputs by dividing the irrigation district with a regular mesh. Soil and crop characteristics, meteorological inputs, and irrigation supply are assumed to be homogeneous in each cell but may vary from cell to cell.

The soil volume of each cell is subdivided into two layers (Figure 8): the top one (evaporative layer) includes the upper few centimetres of the soil, i.e. the surface soil portion that is subject to drying by way of evaporation, while the bottom one (transpirative layer) represents the soil zone where water uptakes by crop roots predominantly takes place and has a time-varying depth, following roots growth. The two layers are modelled as two non-linear reservoirs in cascade.

The soil water balance equation is applied to the evaporative and transpirative soil layers through the equations described in the following sections.

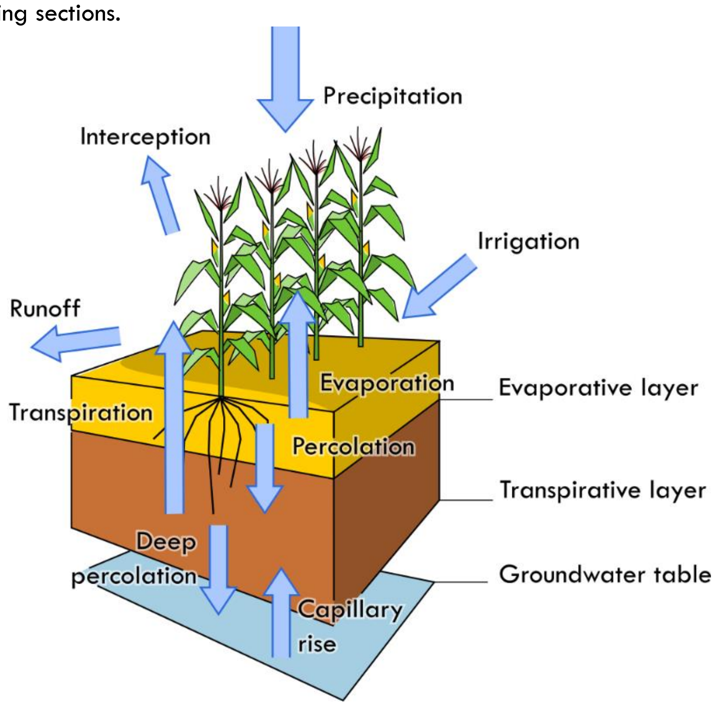


Figure 8: Scheme of the IdrAgra soil crop water balance module.

3.1 Evaporative layer

Water balance equation of the evaporative layer has the following form:

$$V_{E,h}^{*} = \begin{cases} V_{E,h}^{**} = V_{E,h-1} + Q_{inf,h}^{**} - E_h - Q_{E,h}^{*} & V_{E,h}^{**} \le V_{E,max} \\ V_{E,max} & V_{E,h}^{**} > V_{E,max} \end{cases} \quad (3.1)$$

where $V_{E,h}^{*}$ (mm) is the first estimate of the value of the soil water content of the evaporative layer at the end of time step h, $V_{E,h}^{**}$ is a service variable, $Q_{inf,h}^{**}$ $(mm \cdot h^{-1})$ is the amount of water for infiltration during time step h,

E_h $(mm \cdot h^{-1})$ is the evaporation depth (provided by the FAO-Penman-Monteith equation, see § 3.4.1) and $Q^*_{E,h}$ $(mm \cdot h^{-1})$ is the percolation flux to the transpirative layer. For numerical reasons the discretization time step adopted in eq. (3.1) is hourly, as indicated by the subscript h; the integration time step can be further reduced automatically by the model, if necessary for numerical accuracy. Therefore, the variables that are available on a daily basis (rainfall, runoff, evaporation and transpiration) are uniformly distributed over the 24 hours of each day; the hourly distribution of irrigation application, $Q_{i,h}$, can be specified for each cell in the irrigation method input file (see Installation & Use Manual).

The amount of water available for infiltration, $Q^*_{inf,h}$, is given by:

$$Q^*_{inf,h} = \frac{P_t - P_{e,t} - I_t + V_{P,t-1}}{24} + Q_{irr,h} \tag{3.2}$$

where $Q_{irr,h}$ $(mm \cdot h^{-1})$ is the irrigation depth on time step h of day t, P_t is the rainfall depth on day t, $P_{e,t}$ is the rate of direct surface runoff provided by the SCS-CN model application (see § 3.5) on the same day, $V_{P,t-1}$ is the ponded volume at the end of the previous day, and I_t $(mm \cdot d^{-1})$ is the canopy rainfall interception, computed following Von Hoyningen-Hüne (1983) and Braden (1985) as:

$$I_t = a_I \cdot LAI_t \left(1 - \frac{1}{1 + \frac{b_I \cdot P_t}{a_I \cdot LAI_t}}\right) \tag{3.3}$$

where, LAI_t $(m^2 \cdot m^{-2})$ is the Leaf Area Index, a_I (mm) is an empirical coefficient, b_I (-) is the soil cover fraction, estimated by $b_I = \min\left(\frac{LAI}{3}, 1\right)$.

Assuming that the percolation flux is predominantly gravity-driven, $Q^*_{E,h}$ can be assumed equal to the unsaturated hydraulic conductivity of the evaporative layer, K_E $(mm \cdot h^{-1})$, i.e.:

$$Q^*_{E,h} = K_{E,h} \tag{3.4}$$

The Brooks-Corey (1964) equation is used to evaluate the unsaturated hydraulic conductivity:

$$K_E = K_{s,E} \left(\frac{\theta_{E,h} - \theta_{r,E}}{\theta_{s,E} - \theta_{r,E}}\right)^{n_E} \tag{3.5}$$

where $K_{s,E}$ $(cm \cdot h^{-1})$ is the saturated hydraulic conductivity of the evaporative layer, $\theta_{E,h}$ $(m^3 \cdot m^{-3})$ is the volumetric water content of the evaporative layer, $\theta_{r,E}$ $(m^3 \cdot m^{-3})$ is the residual water content of the evaporative layer, $\theta_{s,E}$ $(m^3 \cdot m^{-3})$ is the saturated water content of the evaporative layer, and n_E (-) is the Brooks-Corey exponent of the evaporative layer.

When $V^{**}_{E,h} > V_{E,max}$ in Eq. 3.1 the infiltration flux is limited, and its actual value is derived as:

$$Q^*_{inf,h} = Q^{**}_{inf,h} - \max(0; V^{**}_{E,h} - V_{E,max}) \tag{3.6}$$

The ponded water volume is then updated:

$$V^*_{p,h} = \max(0; V^{**}_{E,h} - V_{E,max}) \tag{3.7}$$

Otherwise, when $V_{E,h}^{**} \leq V_{E,max}$

$$Q_{inf,h}^{*} = Q_{inf,h}^{**} \tag{3.8}$$

and the ponded water volume becomes:

$$V_{p,h}^{*} = 0 \tag{3.9}$$

3.2 Transpirative layer

Water balance equation of the transpirative layer has the following form:

$$V_{T,h} = \begin{cases} V_{T,h}^{*} = V_{T,h-1} + Q_{E,h} - T_h - Q_{T,h} & V_{T,h}^{*} \leq V_{T,max} \\ V_{T,max} & V_{T,h}^{*} > V_{T,max} \end{cases} \tag{3.10}$$

where $V_{T,h}$ (mm) is the water content of the transpirative layer at the end of time step h, $V_{T,h}^{*}$ is a service variable, $Q_{T,h}$ $(mm \cdot h^{-1})$ is the flux at the bottom of the layer. This flux can be either of percolation or capillary rise, depending on the soil water content, the depth to the saturated surface and the soil characteristics. It is computed by the following equation:

$$Q_{T,h} = \begin{cases} -Q_{g,h} & Q_{g,h} > 0 \\ Q_{p,h} & Q_{g,h} \leq 0 \end{cases} \tag{3.11}$$

where $Q_{g,h}$ and $Q_{p,h}$ are, respectively, the capillary flux and the percolation flux at the bottom of the transpirative layer.

Percolation prevails in free drainage conditions, when the flux is predominantly gravity-driven and it is assumed equal to the unsaturated hydraulic conductivity of the transpirative layer$K_{T,h}$ $(mm \cdot h^{-1})$, i.e.:

$$Q_{p,h} = K_{T,h} \tag{3.12}$$

The Brooks-Corey (1964) equation is used to evaluate the unsaturated hydraulic conductivity:

$$K_{T,h} = K_{s,T} \left(\frac{\theta_{T,h} - \theta_{r,T}}{\theta_{s,T} - \theta_{r,T}} \right)^{n_T} \tag{3.13}$$

where $K_{s,T}$ $(cm \cdot h^{-1})$ is the saturated hydraulic conductivity of the transpirative layer, $\theta_{T,h}$ $(m^3 \cdot m^{-3})$ is the volumetric water content of the transpirative layer, $\theta_{r,T}$ $(m^3 \cdot m^{-3})$ is the residual water content of the transpirative layer, $\theta_{s,T}$ $(m^3 \cdot m^{-3})$ is the saturated water content of the transpirative layer, and n_T (-) is the Brooks-Corey exponent of the transpirative layer.

When the groundwater table is shallow, the percolation fluxes are inhibited and upward fluxes into the root zone may occur due to capillary rise. This process depends upon the soil characteristics, the actual water storage in the root zone and the actual evapotranspiration. The model proposed by Liu et al. (2006) is adopted to estimate the capillary flux. The model assumes the capillary flux, Q_g $(mm \cdot h^{-1})$, occurs only when the water content in the transpirative layer falls below a threshold value, $V_{T,c}$ (mm), and that it cannot exceed a maximum value, $Q_{g,max}$ $(mm \cdot h^{-1})$, that depends upon the groundwater depth and the evapotranspiration demand. Liu et al. (2006)

consider a fixed rooting depth of 1 m; therefore, the equations accounting for the influence of groundwater depth on capillary fluxes are adapted to account for a generic rooting depth z_r (sum of the evaporative and transpirative layers depths in IdrAgra).

The critical soil water storage $V_{T,c}$ (mm), is estimated by:

$$V_{Tc} = \theta_{fc,T} \cdot \left(d_{g,h} - z_r + 1\right)^{b_{rc,1}} \tag{3.14}$$

where $\theta_{fc,T}$ $(m^3 \cdot m^{-3})$ is the soil water content of the transpirative layer at field capacity, $d_{g,h}$ (m) is groundwater depth, $b_{rc,1}$ $(-)$ is an empirical parameter that depends on soil type.

The critical groundwater depth, d_{gc} (m), which is the threshold value for groundwater depth above which the potential capillary flux does not increase anymore, is estimated by:

$$d_{gc,h} = \begin{cases} a_{rc,3}(E_h + T_{p,h}) + b_{rc,3} & (E_h + T_{p,h}) \leq 4/24\ mm \cdot h^{-1} \\ z_r + 0.4 & (E_h + T_{p,h}) > 4/24\ mm \cdot h^{-1} \end{cases} \tag{3.15}$$

where is the critical groundwater depth, $a_{rc,3}$ (-) and $b_{rc,3}$ (-) are empirical parameters that depend on soil type, E_h $(mm \cdot h^{-1})$ is the evaporation rate, and $T_{p,h}$ $(mm \cdot h^{-1})$ is the potential crop transpiration rate and z_r (m) is the depth of the rooted layer.

The potential capillary, $Q_{g,max}$ $(mm \cdot h^{-1})$, flux is estimated by:

$$Q_{gmax,h} \begin{cases} T_{p,h} & d_{g,h} \leq d_{gc,h} \\ \frac{a_{rc,4} \cdot (d_{g,h} - z_r + 1)^{b_{rc,4}}}{24} & d_{g,h} > d_{gc,h} \end{cases} \tag{3.16}$$

where $d_{g,h}$ (m) is the groundwater depth, $d_{gc,h}$ (m) is the critical groundwater depth, $a_{rc,4}$ $(-)$ and $b_{rc,4}$ $(-)$ are empirical parameters that depend on soil type.

The flux is then provided by the following equation:

$$Q_{g,h} = \begin{cases} Q_{gmax,h} & \theta_{T,h} < \theta_{Ts,h} \\ Q_{gmax,h}\left(\frac{\theta_{Tc,h} - \theta_{T,h}}{\theta_{Tc,h} - \theta_{Ts,h}}\right) & \theta_{Ts,h} \leq \theta_{T,h} \leq \theta_{Tc,h} \\ 0 & \theta_{T,h} > \theta_{Tc,h} \end{cases} \tag{3.17}$$

where $Q_{g,h}$ $(mm \cdot h^{-1})$ is the capillary rise, $\theta_{T,h}$ $(-)$ is the actual average soil water content in the transpirative zone, $Q_{gmax,h}$ $(mm \cdot h^{-1})$ is the potential groundwater contribution, $\theta_{Tc,h}$ $(-)$ is the critical soil water content, and $\theta_{Ts,h}$ $(-)$ is the so-called steady state soil water content, i.e. the value of the soil water content below which the flux remains constant at its maximum. The critical soil water content is given by:

$$\theta_{Tc,h} = a_{rc,2} \cdot \left(d_{g,h} - z_r + 1\right)^{b_{rc,2}} \tag{3.18}$$

where $b_{rc,2}$ $(-)$ is an empirical parameter that depends on soil type and $a_{rc,2}$ $(-)$ is a reference soil water content, above the average between field capacity and wilting point:

$$a_{rc,2} = 1.1\frac{(\theta_{fcT} - \theta_{wpT})}{2} \tag{3.19}$$

The parameters for the equations, as reported in Liu *et al.* (2006), are listed in Table 1.

Table 1: Parameters of the groundwater contribution semi-empirical equations for different soil types. Source: Liu *et al.*, 2006.

Parameter	Silt loam soil	Sandy loam soil	Clay loam soil
$b_{rc,1}$	-0.17	-0.16	-0.32
$b_{rc,2}$	-0.27	-0.54	-0.16
$a_{rc,3}$	-1.3	-0.15	-1.4
$b_{rc,3}$	6.6	2.1	6.8
$a_{rc,4}$	4.6	7.55	1.11
$b_{rc,4}$	-0.65	-2.03	-0.98

Once the water balance of the transpirative layer has been determined, the excess of water $\Delta V_{T,h} = V_{T,h}^{*} - V_{T,max}$ that occurs when $V_{T,h}^{*} > V_{T,max}$ in Eq. (3.10) and cannot be stored in the transpirative layer, needs to be allocated. This volume, or part of it, is therefore transferred back into in the free capacity of the evaporative layer, if there is any:

$$V_{E,h} = \min(V_{E,h}^{*} + \Delta V_{T,h}; V_{E,max}) \tag{3.20}$$

The possible residual adds up to the ponded volume:

$$V_{P,h} = V_{P,h}^{*} + \max(0; V_{E,h}^{*} + \Delta V_{T,h} - V_{E,max}) \tag{3.21}$$

and the actual value of the flux through the bottom of the evaporative layer is finally obtained as:

$$Q_{E,h} = Q_{E,h}^{*} - \Delta V_{T,h} \tag{3.22}$$

Otherwise, when $V_{T,h}^{*} \leq V_{T,max}$

$$V_{E,h} = V_{E,h}^{*} \tag{3.23}$$

$$V_{P,h} = V_{P,h}^{*} \tag{3.24}$$

$$Q_{E,h} = Q_{E,h}^{*} \tag{3.25}$$

3.3 Percolation of irrigation application

The percolation model expressed by the equations (3.4) and (3.12) has been modified to account for percolation during and after irrigation events. In fact, due to the non-uniformity of irrigation application over the fields – which is particularly high with surface irrigation but can be significant also with other irrigation methods – and the non-linearity of the percolation dynamics, percolation fluxes can be under-estimated by a lumped representation of the cell processes. When combined with the spatial variability of soil characteristics and water content within the cell, this effect can be magnified and cause a significant difference of the percolation flux compared to the lumped representation adopted in the model. To account for this, the following correction can be used in IdrAgra:

$$Q_{E,irr} = (1 + a_E e^{-t \cdot b_E}) Q_E \tag{26}$$

$$Q_{T,irr} = (1 + a_T e^{-t \cdot b_E}) Q_T \tag{27}$$

where $Q_{E,irr}$ (mm) and $Q_{T,irr}$ (mm) are the outflows from the evaporative to the transpirative layer and from the root zone to the deeper subsoil accounting for irrigation management, Q_E (mm) and Q_T (mm) are the outflows from the evaporative to the transpirative layer and from the root zone to the deeper subsoil computed as described in the previous paragraph, t (d) is the time elapsed since the start of the irrigation, a_E (-), a_T (-), b_E (-) and b_T (-) are calibration parameters that vary with the irrigation method and the soil characteristics.

When the IdrAgra model is applied to an irrigated area including a number of cells sufficiently large to estimate values basic statistics of the distribution of the saturated hydraulic conductivity values, like percentiles, the following relationships can be applied in order to reduce the number of parameters that need to be estimated:

$$a_x = \begin{cases} a_M & K_x \leq K_l \\ \frac{a_M - a_m}{K_l - K - h}(K_x - K_h) + a_m & K_l < K_x < K_h \\ a_m & K_x \geq K_h \end{cases} \tag{3.28}$$

$$b_x = \begin{cases} b_M & K_x \leq K_l \\ \frac{b_M - b_m}{K_l - K - h}(K_x - K_h) + b_m & K_l < K_x < K_h \\ b_m & K_x \geq K_h \end{cases} \tag{3.29}$$

where a_m, a_M, b_m and b_M, (-), are the parameters that need to be determined for each irrigation method and represent, respectively, the maximum and minimum values of a_E, a_T, b_E and b_T for the considered irrigation method, K_x $(cm \cdot h^{-1})$ is the saturated hydraulic conductivity of the considered layer, K_l $(cm \cdot h^{-1})$ and K_h $(cm \cdot h^{-1})$ are two values representative, respectively, of the lower and of the higher tails of the saturated hydraulic conductivity distribution for the considered layer, e.g. the 10th and 90th percentile. In this way only four parameters - a_m, a_M, b_m and b_M - need be estimated for the whole study area.

3.4 Crop transpiration and soil evaporation

The daily crop evapotranspiration under standard conditions (ET_c), is calculated, according to Allen et al. (1998), referring to crops grown in large fields under excellent agronomic and soil water conditions. Crop evapotranspiration is therefore calculated by:

$$ET_c = (K_{cb} + K_e) ET_0 \tag{3.30}$$

where ET_c $(mm \cdot d^{-1})$ is the crop evapotranspiration under standard conditions, K_{cb} (-) is the basal crop coefficient, K_e (-) is the soil water evaporation coefficient and ET_0 $(mm \cdot d^{-1})$ is the reference crop evapotranspiration.

3.4.1 **Reference crop evapotranspiration**

Reference crop evapotranspriation ET_0, i.e. the evapotranspiration calculated from a hypothetical grass reference crop with an assumed crop height of $0.12\ m$, a fixed surface resistance of $70\ s \cdot m^{-1}$ and an albedo of 0.23, is computed from meteorological data using the FAO Penman-Monteith method as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{\mathrm{T}_{mean}+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \tag{3.31}$$

where ET_0 $(mm \cdot d^{-1})$ is the reference evapotranspiration, R_n $(MJ \cdot m^{-2} \cdot d^{-1})$ is the net radiation at the crop surface, G $(MJ \cdot m^{-2} \cdot d^{-1})$ is the soil heat flux density, T_{mean} $(°C)$ and u_2 $(m \cdot s^{-1})$ are respectively the mean daily air temperature and the wind speed at $2\ m$ height, e_s (kPa) and e_a (kPa) are respectively the saturation and the actual vapour pressure, Δ $(kPa \cdot °C^{-1})$ is the slope vapour pressure curve and γ $(kPa \cdot °C^{-1})$ is the psychrometric constant.

The approach used to estimate equation (3.31) terms is described in Allen et al. (1998) and transcribed in the sequel for completeness.

3.4.1.1 Atmospheric parameters

The atmospheric pressure is calculated employing a simplification of the ideal gas law, assuming $20°C$ for a standard atmosphere, as:

$$P_{atm} = 101.3 \left(\frac{293 - 0.0065z}{293}\right)^{5.26} \tag{3.32}$$

where P_{atm} (kPa) is the atmospheric pressure and z (m) is the elevation above sea level.

The latent heat of vaporization, λ is calculated as:

$$\gamma = \frac{c_p P_{atm}}{\varepsilon \lambda} = 0.665 \cdot 10^{-3} P_{atm} \tag{3.33}$$

where γ $(kPa \cdot °C^{-1})$ is the psychrometric constant, P_{atm} (kPa) is the atmospheric pressure, λ is the latent heat of vaporization, assumed equal to $2.45\ MJ\ kg^{-1}$, c_p is the specific heat at constant pressure, equal to $1.013 \cdot 10^{-3}\ MJ\ kg^{-1} C^{-1}$, and ε $(-)$ is the ratio molecular weight of water vapour/dry air, equal to 0.622.

The mean daily air temperature is defined as the mean of the daily maximum and minimum temperatures:

$$\mathrm{T}_{mean} = \frac{\mathrm{T}_{max} + \mathrm{T}_{min}}{2} \tag{3.34}$$

where T_{mean} $(°C)$, T_{max} $(°C)$ and T_{min} $(°C)$ are the daily mean, maximum and minimum temperatures, respectively, at $2\ m$ height.

The saturation vapour pressure is calculated as:

$$e^0(\mathrm{T}_{air}) = 0.6108 e^{\frac{17.27 \mathrm{T}_{air}}{\mathrm{T}_{air}+237.3}} \tag{3.35}$$

where $e^0(\mathrm{T}_{air})$ (kPa) is the saturation vapour pressure at the air temperature T_{air} $(°C)$, measured at $2\ m$ height.

Due to the non-linearity of equation (3.35), the mean saturation vapour pressure is computed as the mean between the saturation vapour pressure at the mean daily maximum and minimum air temperatures for that period:

$$e_s = \frac{e^0(\mathrm{T}_{max}) + e^0(\mathrm{T}_{min})}{2} \tag{3.36}$$

where e_s (kPa) is the mean saturation vapour pressure and T_{max} $(°C)$ and T_{min} $(°C)$ are respectively the daily maximum and minimum temperatures at $2\ m$ height.

The slope of the relationship between saturation vapour pressure and temperature, Δ, at a temperature T_{air} $(°C)$, is given by:

$$\Delta = \frac{4098\left(0.6108 e^{\frac{17.27\mathrm{T}_{air}}{\mathrm{T}_{air}+237.3}}\right)}{(\mathrm{T}_{air}+237.3)^2} \tag{3.37}$$

The actual vapour pressure is calculated form the relative humidity by:

$$e_a = \frac{e^0(\mathrm{T}_{min})\frac{RH_{max}}{100} + e^0(\mathrm{T}_{max})\frac{RH_{min}}{100}}{2} \tag{3.38}$$

where e_a (kPa) is the actual vapour pressure, $e^0(\mathrm{T}_{min})$ (kPa) and $e^0(\mathrm{T}_{max})$ (kPa) are respectively the saturation vapour pressures at daily minimum (T_{min}) and maximum temperature (T_{max}), and RH_{max} (%) and RH_{min} (%) are respectively the maximum and minimum relative humidity.

3.4.1.2 Radiation

The extra-terrestrial radiation is estimated by:

$$R_a = \frac{24 \cdot 60}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \tag{3.39}$$

where R_a $(MJ \cdot m^{-2} \cdot d^{-1})$ is the extraterrestrial radiation, G_{sc} is the solar constant, equal to $0.0820\ MJ\ m^{-2}\ min^{-1}$, d_r $(-)$ is the inverse relative distance between Earth and Sun, ω_s (rad) is the sunset hour angle, φ (rad) is the latitude and δ (rad) is the solar declination.

The inverse relative distance between Earth and Sun, d_r, and the solar declination, δ, are given by:

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365} day\right) \tag{3.40}$$

$$\delta = 0.409\sin\left(\frac{2\pi}{365} J - 1.39\right) \tag{3.41}$$

where d_r $(-)$ is the inverse relative distance between Earth and Sun, δ (rad) is the solar declination and J $(-)$ is the Julian day (i.e., the number of the day in the year between 1, January 1st and 365 or 366, December 31st).

The sunset hour angle is given by:

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \tag{3.42}$$

where ω_s (rad) is the sunset hour angle, φ (rad) is the latitude and δ (rad) is the solar declination.

The clear-sky radiation, R_{so}, is calculated with the Ångström formula:

$$R_{so} = (0.75 + 2 \cdot 10^{-5} z) R_a \tag{3.43}$$

where R_{so} $(MJ \cdot m^{-2} \cdot d^{-1})$ is the clear-sky solar radiation, z (m) is the elevation above sea level and R_a $(MJ \cdot m^{-2} \cdot d^{-1})$ is the extra-terrestrial radiation.

The net shortwave radiation R_{ns} $(MJ \cdot m^{-2} \cdot d^{-1})$ is given by:

$$R_{ns} = (1 - \alpha) R_s \tag{3.44}$$

where α (-) is the albedo, which is 0.23 for the hypothetical grass reference crop, and R_s $(MJ \cdot m^{-2} \cdot d^{-1})$ is the incoming solar radiation.

The rate of longwave energy emission R_{nl} $(MJ \cdot m^{-2} \cdot d^{-1})$ is given by:

$$R_{nl} = \sigma \left(\frac{\mathrm{T}_{max,K}^4 + \mathrm{T}_{min,K}^4}{2} \right) \left(0.34 - 0.14\sqrt{e_a} \right) \left(1.35 \frac{R_s}{R_{so}} - 0.35 \right) \tag{3.45}$$

where σ is the Stefan-Boltzmann constant, equal to $4.903 \cdot 10^{-9}$ $MJ \cdot K^{-4} \cdot m^{-2} \cdot d^{-1}$, $\mathrm{T}_{max,K}$ (K) and $\mathrm{T}_{min,K}$ (K) are respectively the maximum ($\mathrm{T}_{max,K} = \mathrm{T}_{max} + 273.16$) and minimum ($\mathrm{T}_{min,K} = \mathrm{T}_{min} + 273.16$) daily absolute temperatures, e_a (kPa) is the actual vapour pressure, and R_s $(MJ \cdot m^{-2} \cdot d^{-1})$ and R_{so} $(MJ \cdot m^{-2} \cdot d^{-1})$ are respectively the incoming solar radiation and the clear-sky radiation. The relative shortwave radiation is limited so that $\frac{R_s}{R_{so}} \leq 1.0$.

The net radiation R_n $(MJ \cdot m^{-2} \cdot d^{-1})$ is the difference between the incoming net shortwave radiation R_{nl} $(MJ \cdot m^{-2} \cdot d^{-1})$ and the outgoing net longwave radiation R_{ns} $(MJ \cdot m^{-2} \cdot d^{-1})$:

$$R_n = R_{ns} - R_{nl} \tag{3.46}$$

The soil heat flux, G, can be considered negligible compared to the other fluxes, thus $G \approx 0$.

3.4.2 **Basal crop coefficient**

The basal crop coefficient (K_{cb}), that is the ratio of the crop evapotranspiration over the reference transpiration (ET_c/ET_0) when the soil surface is dry, but transpiration is occurring at a potential rate (i.e. water is not limiting transpiration), is calculated by interpolating its values at the initial stage ($K_{cb\,ini}$), the mid-season stage ($K_{cb\,mid}$) and at the end of the late season stage ($K_{cb\,end}$) (Figure 9). Horizontal lines are drawn through $K_{cb\,ini}$ in the initial stage and through $K_{cb\,mid}$ in the mid-season stage. Diagonal lines are drawn from $K_{cb\,ini}$ to $K_{cb\,mid}$ within the course of the crop development stage and from $K_{cb\,mid}$ to $K_{cb\,end}$ within the course of the late season stage. For forage crops harvested several times during the growing season, each harvest essentially terminates a growing 'sub-season' and associated K_{cb} curve and initiates a new growing sub-season and associated K_{cb} curve.

The numerical determination of the K_{cb} for any period of the growing season can be derived by:

$$K_{cb,t} = K_{cb\,prev} + \left[\frac{GD - \sum(L_{prev})}{L_{stage}} \right] (K_{cb\,next} - K_{cb\,prev}) \tag{3.47}$$

where GD (-) is the growing day counter from the start of the season, $K_{cb,t}$ (-) is the crop coefficient of day t, L_{stage} (d) is the length of the stage under consideration, $\sum(L_{prev})$ (d) is the sum of the lengths of all previous stages, and $K_{cb\ prev}$ (-) and $K_{cb\ next}$ (-) are the crop coefficients of the previous and the next stage respectively.

Figure 9: Crop coefficient curve for annual crops. Source: Allen *et al.*, 1998.

3.4.3 Soil evaporation coefficient

The soil evaporation coefficient $K_{e,t}$ is expressed according to Allen *et al.* (1998) as:

$$K_{e,t} = \min\left(K_{r,t}\left(K_{c\_max,t} - K_{cb,t}\right), f_{ew}K_{c\_max,t}\right) \tag{3.48}$$

where $K_{cb,t}$ $(-)$ is the basal crop coefficient for day t, $K_{c\_max,t}$ $(-)$ is the maximum value of K_c following rain or irrigation, related to the energy available for evapotranspiration at the soil surface, $K_{r,t}$ $(-)$ is the evaporation reduction coefficient dependent on the cumulative depth of water depleted from the topsoil and f_{ew} $(-)$ is the soil surface from which evaporation mostly occurs. K_{c_max} is calculated as:

$$K_{c\_max} = \max\left(\left\{1.2 + \left[0.04\left(u_{2,t} - 2\right) - 0.004\left(RH_{min,t} - 45\right)\right]\left(\frac{h_{crop,t}}{3}\right)^{0.3}\right\}, \left\{K_{cb,t} + 0.05\right\}\right) \tag{3.49}$$

where $u_{2,t}$ $(m \cdot s^{-1})$ is the average wind speed at $2\ m$ height on day t, $RH_{min,t}$ (%) is the daily minimum relative humidity, $h_{crop,t}$ (m) is the crop height and $K_{cb,t}$ $(-)$ is the basal crop coefficient. Equation 3.49 ensures that $K_{c\_max,t}$ is always greater or equal to the sum $K_{cb,t} + 0.05$.

The evaporation reduction coefficient $K_{r,t}$ of day t depends on the water content of the evaporative layer at the end of the previous day $\theta_{e,t-1}$ (mm), and can be computed as:

$$K_{r,t} = \begin{cases} 1 & \theta_{e,t-1} \geq \theta_{REW} \\ \frac{\theta_{e,t-1} - 0.5\theta_{wp,E}}{\theta_{REW} - 0.5\theta_{wp,E}} & \theta_{wp,E} \leq \theta_{e,t-1} < \theta_{REW} \\ 0 & \theta_{e,t-1} < \theta_{wp,E} \end{cases} \tag{3.50}$$

where $\theta_{e,t-1}$ is water content of the evaporative layer at the end of the previous day, θ_{REW} (mm) is the water content of the evaporative layer when the readily evaporative water has been removed, and $\theta_{wp,E}$ (mm) is the soil water contents of the evaporating layer at wilting point.

In equation (3.50), θ_{REW} is calculated as:

$$\theta_{REW} = 0.4 \cdot \left(\theta_{fc,E} - 0.5\theta_{wp,E}\right) \cdot 1000 \cdot z_E \tag{3.51}$$

where $\theta_{fc,E}$ $(-)$ and $\theta_{wp,E}$ $(-)$ are respectively the soil water content of the evaporative layer at field capacity and at wilting point, and z_E (m) is the depth of the evaporative layer, i.e. of the surface soil layer that is subject to drying by way of evaporation (defined by the user, generally ca. 10 cm).

3.4.4 Exposed and wetted soil fraction

Where the complete soil surface is wetted, as by precipitation or by surface irrigation, then the fraction of soil surface from which most evaporation occurs, f_{ew}, is essentially defined as $(1 - f_c)$, where f_c is the average fraction of soil surface covered by vegetation. However, for irrigation systems where only a fraction of the ground surface is wetted, f_{ew} is limited to the fraction of the soil surface wetted by irrigation:

$$f_{ew} = \min(1 - f_c, f_w) \tag{3.52}$$

where f_{ew} $(-)$ is the exposed and wetted soil fraction, f_c $(-)$ is the effective fraction of soil surface covered by vegetation $[0 - 0.99]$ and f_w $(-)$ is the average fraction of soil surface wetted by irrigation or precipitation $[0.01 - 1]$.

f_c is estimated using the relationship:

$$f_c = \left(\frac{K_{cb} - K_{c\,min}}{K_{c\,max} - K_{c\,min}}\right)^{(1+0.5h)} \tag{3.53}$$

where K_{cb} $(-)$ is the basal crop coefficient for the particular day, $K_{c\,min}$ $(-)$ is the minimum K_c for dry bare soil with no ground cover $[\approx 0.15 - 0.20]$, $K_{c\,max}$ $(-)$ is the maximum K_{cb} immediately following wetting (equation 3.49) and h (m) is the mean plant height.

3.4.5 Crop transpiration under water stress

The transpiration reduction factor coefficient K_s is calculated by taking into account water content of the transpirative layer as:

$$K_s = \begin{cases} 1 & V_{T,h} \geq V_{RAW} \\ \frac{V_{T,h} - V_{wp,T}}{V_{RAW} - V_{wp,T}} & V_{wp,T} \leq V_{T,h} < V_{RAW} \\ 0 & V_{T,h} < V_{wp,T} \end{cases} \tag{3.54}$$

where $V_{T,h}$ (mm) is water content of the transpirative layer, V_{RAW} (mm) is the water content of the transpirative layer when the readily available water has been depleted, and $V_{wp,T}$ (mm) is the soil water content of the transpirative layer at wilting point.

In equation (3.54), V is calculated as:

$$V_{RAW} = V_{fc,T} - \left(V_{fc,T} - V_{wp,T}\right) \cdot p \tag{3.55}$$

where $V_{fc,T}$ (mm) is the soil water volume of the transpirative layer at field capacity and p (-) is the adjusted mean fraction of total available water (TAW) that can be depleted from the root zone before moisture stress occurs.

The fraction p in Eq. (3.55) is calculated from its tabulated value p_{tab} as:

$$p = p_{tab} + 0.04 \cdot (5 - ET_c) \tag{3.56}$$

where ET_c (mm) is the potential crop evapotranspiration. p is limited between $[0.1 - 0.8]$ as in Allen *et al.* (1998).

The effects of soil water stress on crop evapotranspiration are described by reducing the value for the crop coefficient. This is accomplished by multiplying the crop coefficient by the water stress coefficient, K_s.

Water depletion in the transpirative layer can be expressed as $\theta_{fc,T} \cdot Z_r - V_T$, that is the water shortage relative to field capacity. When soil water is extracted by evapotranspiration, the depletion increases, and stress will be induced when water content drops under RAW (Figure 10).

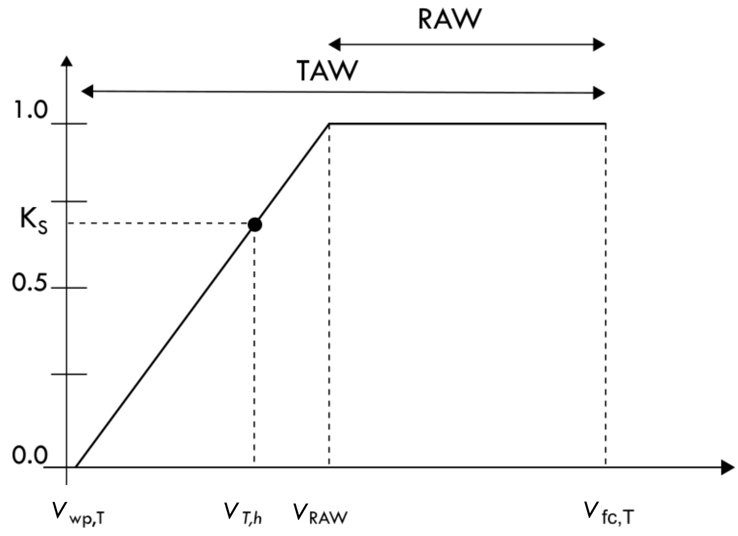


Figure 10: Water stress coefficient, K_s. Source: Allen *et al.*, 1998.

3.5 Surface runoff

IdrAgra computes daily surface runoff volume using a modification of the Soil Conservation Service curve number method (SCS, 1972). The SCS runoff equation is an empirical model that has become of common use since the 1950s. The model was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types (Rallison and Miller, 1981) and is also used in many hydrological models (see, e.g., the SWAT model, Neitsch et al., 2011).

The SCS curve number equation is:

$$P_{e,t} = \frac{(P_t - I_a)^2}{P_t - I_a + S} \tag{3.57}$$

where $P_{e,t}$ $(mm \cdot d^{-1})$ is the superficial rainfall excess in day *t*, P_t $(mm \cdot d^{-1})$ is the rainfall rate for the same day, I_a $(mm \cdot d^{-1})$ are the initial abstractions which include surface storage, interception and infiltration prior to runoff, and S $(mm \cdot d^{-1})$ is the soil retention parameter. The retention parameter represents the potential maximum water volume that can be stored in the soil and varies spatially due to changes in soil characteristics, land use, management and slope, and temporally due to changes in soil water content. It is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{3.58}$$

where CN (-) is the Curve Number. In equation 3.58, the number 25.4 is a conversion factor from inches to millimetres. The initial abstractions, I_a, is approximated as $I_a = \lambda_{CN} \cdot S$, and equation 3.57 becomes:

$$P_e = \frac{(P - \lambda_{\mathrm{CN}} \cdot S)^2}{P + 0.8S} \tag{3.59}$$

Runoff will only occur when $P > I_a$, or, substituting I_a by $\lambda_{CN} \cdot S$, when $P > \lambda_{CN} \cdot S$. The value 0.2 is assumed for λ_{CN} as default by IdrAgra, but the user has the option to set a different value.

Typical reference values of the curve number are listed in Table 2 for different land uses (SCS Engineering Division, 1986). Tabled values are appropriate for a 5% slope.

Treatment is a cover type modifier to describe the management of cultivated agricultural lands. It includes mechanical practices, such as contouring and terracing, and management practices, such as crop rotations and reduced or no tillage.

Hydrologic condition indicates the effects of cover type and treatment on infiltration and runoff. Good hydrologic condition indicates that the soil usually has a low runoff potential for that specific hydrologic soil group, cover type, and treatment. Affecting factors are canopy or density of lawns, crops, or other vegetative areas, amount of year-round cover, amount of grass or close-seeded legumes in rotations, percent of residue cover and degree of surface roughness.

Finally, Hydrologic soil group refers to the classification of soils into four groups, based on soil infiltration and storage characteristics. A hydrologic group is a group of soils having similar runoff potential under similar storm and cover conditions (NRCS Soil Survey Staff, 1996). Soil properties that influence runoff potential are those that impact the minimum rate of infiltration for a bare soil after prolonged wetting and when not frozen. These properties are depth to water table, saturated hydraulic conductivity, and depth to a very slowly permeable layer. Soil may be placed in one of four classes:

A. (Low runoff potential). The soils have a high infiltration rate even thoroughly wetted. They chiefly consist of deep, well drained to excessively drained sands or gravels. They have a high rate of water transmission.

B. (Moderately low runoff potential). The soils have a moderate infiltration rate when thoroughly wetted. They chiefly are moderately deep to deep, moderately well-drained to well-drained soils that have moderately fine to moderately coarse textures. They have a moderate rate of water transmission.

C. (Moderately high runoff potential). The soils have a slow infiltration rate when thoroughly wetted. They chiefly have a layer that impedes downward movement of water or have moderately fine to fine texture. They have a slow rate of water transmission.

D. (High runoff potential). The soils have a very slow infiltration rate when thoroughly wetted. They chiefly consist of clay soils that have a high swelling potential, soils that have a permanent water table, soils that have a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. They have a very slow rate of water transmission.

Table 2: Runoff curve numbers for antecedent moisture condition II for agricultural lands; values for a 5% slope. Selection for study area. Source: SCS Engineering Division, 1986.

Cover			Hydrologic Soil Group			
Land use	Treatment or practice	Hydrologic condition	A	B	C	D
Fallow	Bare soil	---	77	89	91	94
	Crop residue cover[1]	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
Small grains	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
Close-seeded or broadcast legumes or rotation	Straight row	Poor	66	77	85	89
		Good	58	72	81	85
Meadow – continuous grass, protected from grazing and generally mowed for hay	---	---	30	58	71	78
Woods – grass combination (orchard or tree farm)	---	Poor	57	73	82	86
		Fair	43	65	76	82
		Good	32	58	72	79

[1] Crop residue cover applies only if residue is on at least 5% of the surface.

3.5.1 Antecedent soil moisture condition

The reference values of CN, that are listed in Table 2, are valid for average soil moisture conditions antecedent to the event (AMC II). The SCS considers two additional antecedent moisture conditions, defined as follows:

- AMC I (Dry). The moisture condition I curve number is the lowest value the daily curve number can assume in dry conditions (at wilting point).
- AMC III (Wet). The moisture condition III curve number is the higher value the daily curve number can assume in wet conditions (at field capacity).

The curve numbers for moisture conditions I and III are calculated with the equations (Neitsch et al., 2011):

$$CN_1 = CN_2 - \frac{20\cdot(100-CN_2)}{100-CN_2+e^{2.533-0.0636\cdot(100-CN_2)}} \tag{3.60}$$

$$CN_3 = CN_2 \cdot e^{0.0673\cdot(100-CN_2)} \tag{3.61}$$

where CN_1 $(-)$, CN_2 $(-)$ and CN_3 $(-)$ are the moisture condition I, II and III curve numbers respectively.

The curve number varies with soil water profile content by linear interpolation:

$$CN_x = \begin{cases} CN_1 & \theta \geq \theta_{wp} \\ \frac{CN_2-CN_1}{\theta_{fc,wp}-\theta_{wp}}\left(\theta-\theta_{wp}\right)+CN_1 & \theta_{wp} < \theta < \theta_{fc,wp} \\ CN_2 & \theta = \theta_{fc,wp} \\ \frac{CN_3-CN_2}{\theta_{fc}-\theta_{fc,wp}}\left(\theta-\theta_{fc,wp}\right)+CN_2 & \theta_{fc,wp} < \theta < \theta_{fc} \\ CN_3 & \theta = \theta_{fc} \\ \frac{CN_4-CN_3}{\theta_s-\theta_{fc}}\left(\theta-\theta_{fc}\right)+CN_3 & \theta_{fc} < \theta < \theta_s \\ CN_4 & \theta \geq \theta_s \end{cases} \tag{3.62}$$

where CN_1 $(-)$, CN_2 $(-)$ and CN_3 $(-)$ are the moisture condition I, II and III curve numbers respectively, CN_4 $(-)$ is the moisture condition at saturation, equal to 95, θ $(m^3 \cdot m^{-3})$ is the soil water content of the entire profile, θ_{wp} $(m^3 \cdot m^{-3})$, θ_{fc} $(m^3 \cdot m^{-3})$ and θ_s $(m^3 \cdot m^{-3})$ are the soil water contents at wilting point, at field capacity and at saturation respectively, and $\theta_{fc,wp}$ $(m^3 \cdot m^{-3})$ is the soil water content at Antecedent Moisture Condition II, equal to $\theta_{fc,wp} = \theta_{wp} + \frac{2}{3}(\theta_{fc} - \theta_{wp})$.

3.5.2 Slope adjustment

The moisture condition II curve numbers provided in Table 2 are assumed appropriate for ground slope of 5%. Williams (1995) developed an equation to adjust the curve number to a different slope:

$$\begin{aligned} CN_{2s} &= \frac{CN_3-CN_2}{3}\cdot\left(1-2\cdot e^{-13.86\cdot slp}\right)+CN_2 = \\ &= \frac{CN_2\cdot\left(e^{0.0673\cdot(100-CN_2)}-1\right)}{3}\cdot\left(1-2\cdot e^{-13.86\cdot slp}\right)+CN_2 \end{aligned} \tag{3.63}$$

where CN_{2s} $(-)$ is the moisture condition II curve number adjusted for slope, CN_2 $(-)$ and CN_3 $(-)$ are the moisture condition II and III curve numbers, respectively, for the default 5% slope, and slp $(-)$ is the average fraction slope of the cell.

3.5.3 Seasonal variations

The average CN in Table 2 apply to average crop conditions for a growing season. To account for seasonal variations of the CN, IdrAgra considers the stages of growth of crops following the indications in USDA (1985); the curve number adjusted for moisture condition and slope, CN_x, is corrected according to the growth stage as follows:

$$CN_x = \begin{cases} (CN)_{fallow} & before\ plowing \\ (CN)_{crop} & between\ plowing\ and\ normal\ peak\ height \\ 2(CN)_{crop} - (CN)_{fallow} & between\ normal\ peak\ height\ and\ harvest\ time \\ (CN)_{fallow} & after\ harvesting \end{cases} \tag{3.64}$$

where $(CN_x)_{fallow}$ $(-)$ is the curve number for fallow land use and crop residue cover treatment, and $(CN_x)_{crop}$ $(-)$ is the curve number for the considered crop, both adjusted for moisture condition and slope.

3.5.4 Specifications for paddy fields

Paddy fields are assumed to be able to store the precipitation during the flooding period; therefore, surface runoff is considered equal to 0. Before emergence and after harvest, surface runoff is calculated as described in the precedent paragraphs.

3.6 Spatial interpolation of meteorological and crop datasets

As IdrAgra needs local values of meteorological variables and crop variables (K_{cb}, LAI, crop height, root depth, cover fraction, harvest index, water stress coefficients, biomass water productivity, CN class) for each cell of the domain, a built-in spatial interpolation algorithm allows the creation of a continuous field of the variables from the point values that are available at the location of the meteorological stations (timeseries of meteorological variables must be provided in input by the user, while those of the crop variables are obtained by the preliminary run of CropCoeff).

3.6.1 Spatial interpolation of meteorological data

The spatial interpolation of the agro-meteorological data applies the inverse-square distance weighting (IDW). The method assumes that in any given cell with (x, y) coordinates, the value of a generic meteorological variable z can be approximated by a combination of the values observed at the n closest stations weighted by the inverse-squared of the distance between the point (x, y) and the meteorological station:

$$z_{x,y} = \frac{\sum_{i=1}^{n} z_i d_{x,y,i}^{-2}}{\sum_{i=1}^{n} d_{x,y,i}^{-2}} \tag{4.65}$$

where $z_{x,y}$ is the value of the variable at cell (x, y), z_i is the value of the observed variable at the meteorological station i, and $d_{x,y,i}$ is the distance between (x, y) and i (Bartier & Keller, 1996).

3.6.2 Spatial interpolation of the crop variables

Each cell of the modelled domain is assigned to a cluster (region of influence), according to the nearest meteorological stations. To assure that the spatial variability of the crop parameters inside the same cluster is maintained, the series computed for each cell is randomly shifted for a maximum of $\pm d_s$ days, with d_s defined in the simulation parameters (e.g., 10 days).

For each cell, the series are computed taking into account the emergence dates and the total crop growing cycle length computed on the n nearest meteorological stations, as the inverse weighting average of these vales.

Thus, if tab is the series of a phenological parameter of a crop, on a day d its value is:

$$tab_d = tab[g_{x,y}^e + (d - g_{x,y}^e)d_{x,y} - iran_{x,y}] \tag{4.66}$$

where $g_{x,y}^e$ $(-)$ is the emergence date in the (x, y) cell, d $(-)$ is the day of the simulation, $d_{x,y}$ $(-)$ is the weighting length factor in the (x, y) cell, $iran_{x,y}$ $(-)$ is the random shifting of the emergence date, equal to

$$iran_{x,y} = \delta_{x,y}^s + \delta_{x,y}^e \tag{4.67}$$

where $\delta_{x,y}^s$ (-) is the random shift $[-d_s, d_s]$ and $d_{x,y}^e$ (-) is the difference between the emergence date $g_{x,y}^e$ in the (x, y) cel and the emergence date g_1^e at the nearest meteorological station.

4 Irrigation module

The irrigation module is devoted to the determination of the irrigation term $Q_{irr,t}$ in the cell water balance equation (3.1). In the NEED mode the irrigation applications for each cell are obtained directly by solving the hydrological balance equation of the two layers with the user-defined irrigation practice (see § 4.1.4); then the daily irrigation requirements of the individual cells can be aggregated at the IU level and at the water source level, accounting for conveyance losses. In the USE mode the rationale is similar, but the calculation steps are in reverse order: daily time series of water diverted for irrigation use, possibly from multiple sources, and information about conveyance and distribution are fed into the model, that simulates the behaviour of the irrigation schemes, from sources to IUs and individual cells; irrigation applications are again determined based on the cell hydrological balances and on the irrigation practice, but in this case the satisfaction of the cell irrigation demand depends on the actual water availability and crop water stress may occur. The module can also deal with water sources where diverted flows are unknown, for which the module computes an estimate of the daily withdrawals, based on the simulated irrigation need and the irrigation practices in the command area of the source.

4.1 USE simulation

In this type of simulation, irrigation water availability in each day of the simulation horizon depends on the amount of water diverted or withdrawn from the different sources feeding the study, on the conveyance and distribution from the source to the IU and to the individual cells, and on the irrigation practices.

4.1.1 Water sources

In the USE mode IdrAgra considers three different types of irrigation water sources.

- MONITORED sources.
- RUNTIME sources.
- INTERNAL reuse.

4.1.1.1 MONITORED sources

MONITORED sources include any source for which the daily value of the water supply can provided in input. This is typically the case, for example, of surface water diversions where a license fixes the amount of flow that can be diverted during the irrigation season, possibly according to water availability in the water body, but independently from the actual conditions of the irrigated area. For these sources the timeseries of daily irrigation volumes during the whole simulation period and for each source must be provided as input files (see Installation & Use manual for the input file format specifications).

4.1.1.2 RUNTIME sources

RUNTIME sources include all the sources where the daily irrigation volume depends on the conditions of the area which is supplied by the source itself, computed runtime by IdrAgra. This is typically the case of surface or groundwater sources where the withdrawal is through pumping. For these sources, the daily value of irrigation volume is computed runtime by the IdrAgra model, according to a set of parameters that the user needs to provide, specifying the constraints on daily water availability (if applicable) and the operating rule according to which the desired amount of supply is determined based on the soil water status of the command area of each source.

The model distinguishes between two different types of RUNTIME sources:

- **Collective**: the source provides water supply to one or more irrigation units and the operating rules are known. This is typically the case of diversions, either from surface or groundwater, that provide irrigation supply to an area including multiple farms, where water is pumped and that are typically managed by an irrigation agency or consortium;
- **Private**: the source provides water supply to an individual farm (group of cells within an irrigation unit) and its characteristics are unknown. This is typically the case of irrigation wells or small diversions from surface water by pumping that are owned and managed by farmers, that can be present in large numbers in irrigated areas and for which it is often difficult to obtain precise information on the plant characteristics and operation. In both cases, it is supposed that water can be unlimitedly pumped, thus satisfying the irrigation need of the cell or cells supplied by the well.

In the case of **Collective RUNTIME sources**, it is assumed that the decision on the daily amount of water uptake is taken based on the soil moisture conditions of the grid cells supplied by the source. Specifically, the weighted mean value of the volumes of available water in the cell ensemble, where the weights are proportional to the transpiration rate of each cell, is taken as an indicator of the soil moisture conditions. For each day of the irrigation season this weighted mean, $\overline{U_{cr}}$ (mm), is calculated as:

$$\overline{U_{cr}} = \frac{\sum_{i=1}^{N}\{V_{T,i} - [\theta_{fc,T,i} - (\theta_{fc,T,i} - \theta_{wp,T,i}) p_i] Z_{r,i} \cdot 1000\} \cdot T_{c,i}}{\sum_{i=1}^{N} T_{c,i}} \tag{4.1}$$

where N is the number of cells in the ensemble, $V_{T,i}$ (mm) is the water content of the transpirative layer per unit surface area of the i^{th} cell of the ensemble, $\theta_{fc,T,i}$ $(m^3 \cdot m^{-3})$ and $\theta_{wp,T,i}$ $(m^3 \cdot m^{-3})$ are respectively the soil water contents of the transpirative layer of the i^{th} cell, respectively at field capacity and at wilting point, p_i $[0-1]$ $(-)$ is the average fraction of TAW that can be depleted from the root zone before moisture stress occurs, $z_{r,i}$ (m) is the depth of the transpirative layer of the i^{th} cell, and $T_{p,i}$ $(mm \cdot d^{-1})$ is the potential crop transpiration rate for the i^{th} cell.

The withdrawal from the source is activated only if the $\overline{U_{cr}}$ drops below a ratio, α_w, of its maximum value $\overline{U_{cr}^{MAX}}$

$$\overline{U_{cr}^{MAX}} = \frac{\sum_{i=1}^{N}(\theta_{fc,T,i} - \theta_{wp,T,i}) p_i Z_{r,i} \cdot 1000 \cdot T_{p,i}}{\sum_{i=1}^{N} T_{p,i}} \tag{4.2}$$

Every source can be activated partially or totally, depending on the ratio between $\overline{U_i}$ and $\overline{U_i^{MAX}}$:

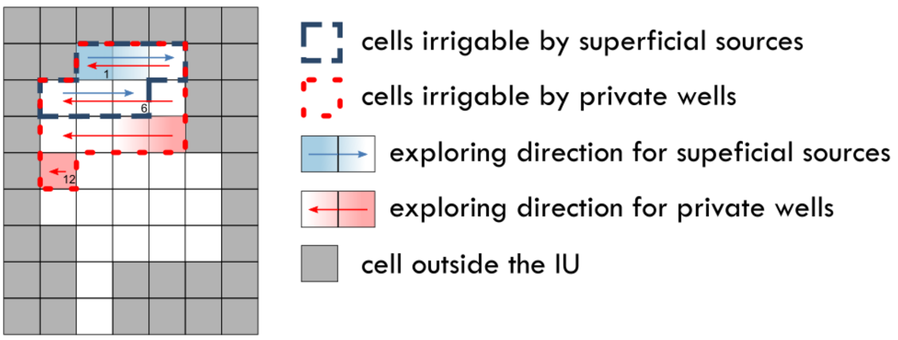
$$W = \begin{cases} f_{w,1} Q_w^{MAX} & \alpha_{w,2}\overline{U_i^{MAX}} < \overline{U_i} \leq \alpha_{w,1}\overline{U_i^{MAX}} \\ f_{w,2} Q_w^{MAX} & \alpha_{w,3}\overline{U_i^{MAX}} < \overline{U_i} \leq \alpha_{w,2}\overline{U_i^{MAX}} \\ f_{w,3} Q_w^{MAX} & \overline{U_i} \leq \alpha_{w,3}\overline{U_i^{MAX}} \end{cases} \quad (4.3)$$

where W $(mm \cdot d^{-1})$ is the actual daily water withdrawal, W^{MAX} $(mm \cdot d^{-1})$ is the maximum admissible daily withdrawal, $f_{w,1}$, $f_{w,2}$ and $f_{w,3}$ are degree of activation of the source $[0-1]$, $\alpha_{w,1}$ $(-)$, $\alpha_{w,2}$ $(-)$ and $\alpha_{w,3}$ $(-)$ are the corresponding activation thresholds $[0-1]$.

Water withdrawals from **Private RUNTIME sources** is estimated by first identifying the cells that are supplied by these sources. The withdrawal is then determined independently for each cell based on two conditions: (1) the cell would not be irrigated from superficial sources in a short time period (i.e. it does not fall into the cells potentially irrigable within a number of days in the future specified for each sub-district; Figure 11), and (2) the water content of the transpirative layer of the cell satisfies the equation:

$$V_{T,i} - \left[\theta_{fc,T,i} - \left(\theta_{fc,T,i} - \theta_{wp,T,i}\right)p_i\right]Z_{r,i} \cdot 1000 < \alpha_a\left(\theta_{fc,T,i} - \theta_{wp,T,i}\right)p_i Z_{r,i} \cdot 1000 \quad (4.4)$$

If both conditions are met, the water withdrawal is equal to irrigation water depth set for the cell, according to the irrigation method.



Number of cells irrigable by private wells = 2 x number of cells irrigable by superficial sources

Figure 11: Irrigation from private wells: check for irrigation from superficial sources.

4.1.1.3 INTERNAL reuse

Internal reuse is the amount of water potentially available for irrigation use that originates within the study area due the accumulation of surplus and tailwaters (i.e., the portion of water supplied to irrigation units by monitored or unmonitored diversions that is not applied to the fields of an IU because the volume delivered to the IU exceeds the crop irrigation needs); the daily value of the discharge is computed online by IdrAgra based on:

- the list of IUs producing surplus and tailwaters (surplus-IUs) that can be supplied to other units in the study area;
- the list of irrigation units supplied by this water (reuse-IUs);
- the share of the total reusable volume of each of these irrigation units.

The daily amount of reusable flow is estimated in a first run of IdrAgra involving only the portion of the study area covered by the surplus-IUs. The surplus is then treated as an additional source in a second run of the model for the whole study area. The process is completely transparent to the user, who only needs to provide the information listed above.

4.1.2 **Conveyance and distribution water losses**

The irrigated area is subdivided into **Irrigation Units (IU)**, each receiving its irrigation water supply from one or more sources. The total water supply, $Q_{j,t}$ $(m^3 \cdot d^{-1})$, to the j^{th} IU on day t is calculated as:

$$Q_{j,t} = \sum_{i=1}^{N_s} \varepsilon_{i,j} \eta_{i,j} W_{i,t} \tag{4.5}$$

where N_s is the total number of sources supplying the IU, $W_{i,t}$ $(m^3 \cdot d^{-1})$ is water volume diverted from the i^{th}source, $\varepsilon_{i,j}$ $(-)$ is the share of $W_{i,t}$ to which the j^{th} IU is entitled, and $\eta_{i,j}$ (-) is the conveyance efficiency from the i^{th} source to the j^{th} IU, assumed equal to the ratio between the volume actually delivered to the IU, till the inlet of the individual cells (i.e. it accounts also for seepage losses of the canals within the IU), and the volume $\varepsilon_{ij} Q_{i,t}$ supplied by the source.

4.1.3 **Distribution criterion**

The internal distribution of the water delivered to each IU takes place according to the following criterion that replicates the mechanism of distribution on rotation to the individual farms within the IU (Figure 12). If the rotation period is provided by the user, then in each day of the simulation horizon a number of cells (**target cells**) equal to the total number of irrigable cells in the IU divided by the rotation period is explored and irrigation is applied to those that actually require irrigation (Figure 12) according to the local irrigation practice (see next section). If there remains water at the end of the target cells exploration, the surplus can be accounted for by the model as potentially usable in downstream IUs; these destination IUs must be specified by the user in input. A buffer can also be defined by the user, to account for possible reallocation of the surplus within the IU, meaning that the number of target cells explored daily can be expanded by user defined multiplying factor greater than 1.

If the value of the rotation period is 1 day, all the irrigable cells of the IU can be explored in sequence daily, if there is enough water to satisfy all needs, reproducing an allocation criterion that is close to on demand distribution. ~~An option is also available that allocates the daily available water volume to the cells of the IU according to their current water stress conditions (as expressed by the stress coefficient K_s), starting from the highest.~~

When the value of the rotation period is not specified by the user, it is assumed equal to 1 by the model.

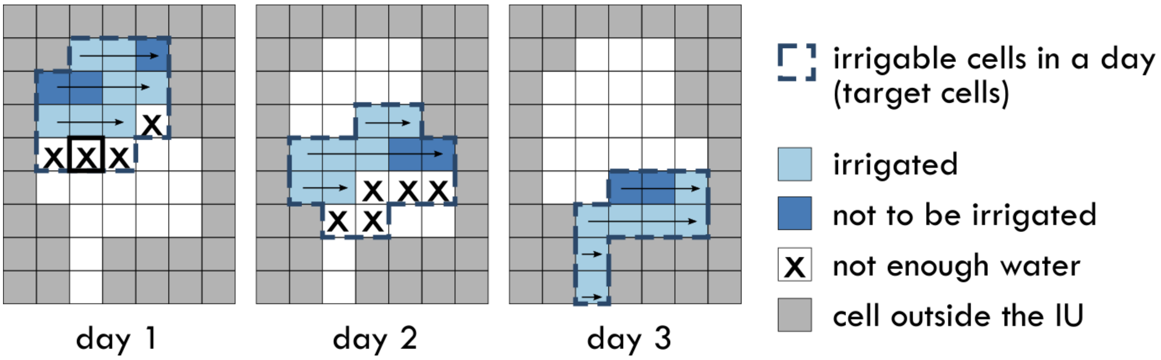


Figure 12: IdrAgra simulation of irrigation water distribution in a subdistrict in two consecutive days.

4.1.4 Irrigation practice

The irrigation practice consists of two main elements: application method and irrigation scheduling criterion.

The scheduling criterion is expressed by the rule according to which irrigation is applied or not to a target cell. In IdrAgra a target cell is actually irrigated when the soil water content in the root zone, computed by the soil water balance model, is at risk of limiting crop growth, i.e. when:

$$\left(V_{T,i,t} - V_{Tr,i,t}\right) - \left(TAW_{i,t} - RAW_{i,t}\right) < \alpha_i RAW_{i,t} \tag{4.6}$$

where $V_{T,i,t}$ (mm) is the total water content of the transpirative layer of cell *i* in day *t*, $V_{Tr,i,t}$ (mm), $TAW_{i,t}$ (mm) and $RAW_{i,t}$ (mm) are, respectively, the residual water content, the total available water and the readily available water of the same cell layer; finally, α_i (-) is a user-defined threshold coefficient for the activation of irrigation.

The irrigation method defines the characteristics of water application to the field, among which irrigation depth Q_{irr} can be provided as a fixed value (e.g., 30 mm), or in the form of irrigation "efficiency"; in the latter case the irrigation depth may vary in time and is computed as the value of the soil water content deficit in the rooted layer divided by the efficiency:

$$Q_{irr,t} = \frac{(\theta_{fc,E} - \theta_{E,t}) z_e + (\theta_{fc,T} - \theta_{T,t}) z_{T,t}}{\eta_{irr}} \tag{4.7}$$

where $\theta_{fc,E}$ $(m^3 \cdot m^{-3})$ and $\theta_{fc,T}$ $(m^3 \cdot m^{-3})$ are the soil water content of the evaporative and the transpirative layers at field capacity, $\theta_{E,t}$ $(m^3 \cdot m^{-3})$ and $\theta_{T,t}$ $(m^3 \cdot m^{-3})$ are the volumetric water contents of the evaporative and the transpirative layers, z_e (m) is the depth of the surface soil layer that is subject to drying by way of evaporation, $z_{T,t}$ (m) is the depth of the transpirative layer, and η_{irr} is the application efficiency of the irrigation method.

Further specifications of the method vary depending on its characteristics; for example, specifications for sprinkler irrigation include the activation time and the hourly distribution (e.g., uniform between 6 am-10 am) and the parameters appearing in the equation for the estimation of the amount of water, Q_{loss} (mm), evaporated from droplets sprayed through the air:

$$Q_{loss} = a_{loss} + b_{loss} \cdot u_2 + c_{loss} \cdot \mathrm{T}_{mean} \tag{4.8}$$

where T_{mean} ($°C$) and u_2 ($m \cdot s^{-1}$) are respectively the mean daily air temperature and the wind speed at $2\,m$ height, and a_{loss}, b_{loss} and c_{loss} are parameters set by the user for the specific method.

IdrAgra allows defining the irrigation practice for each cell of the study area.

4.1.4.1.1 Specifications for paddy fields

In paddy fields, irrigation is supplied only if effective rainfall is zero and from emergence to mid-season; the irrigation amount is at least equal to the unsaturated hydraulic conductivity of the transpirative layer:

$$\left\{P_{eff} = 0 \ \wedge K_{cb\ i-1} \leq K_{cb\ i}\right\} \Rightarrow Q_{i,min} \ = 10 \cdot 24 \cdot K_T \tag{4.9}$$

where P_{eff} ($mm \cdot d^{-1}$) is the effective rainfall, $K_{cb,t}$ ($-$) is the crop coefficient on day t, $Q_{i,min}$ ($mm \cdot d^{-1}$) is the minimum irrigation supply, K_T is the unsaturated hydraulic conductivity of the transpirative layer, equal for rice to $0.04\ cm \cdot h^{-1}$.

The irrigation $Q_{rri,t}$ (mm) of day t is therefore calculated as:

$$Q_{irr,t} = \max\left\{\frac{E_{i,t-1}+T_{i,t-1}}{\eta_i}, Q_{irr,min}\right\} \tag{4.10}$$

where $E_{i,t-1}$ ($mm \cdot d^{-1}$) is the evaporation rate of day $t-1$, $T_{i,t-1}$ ($mm \cdot d^{-1}$) is the potential crop transpiration rate of day $t-1$, η_i (-) is the field application efficiency and $Q_{irr,min}$ ($mm \cdot d^{-1}$) is the minimum irrigation supply.

4.2 NEED simulation

The NEED simulation follows the same rationale of the USE simulation, but in a reverse order. In fact, in this case, the irrigation applications for each cell are obtained first by solving the hydrological balance equation of the two layers with the user-defined irrigation practice, then the daily irrigation requirements of the individual cells are aggregated at the IU level and at the water source level, accounting for conveyance losses.

4.2.1 Crop irrigation needs

During the NEED simulation, irrigation application in cell *i* is triggered by the same criterion of the USE simulation, i.e. when:

$$\left(V_{T,i,t} - V_{Tr,i,t}\right) - \left(TAW_{i,t} - RAW_{i,t}\right) < \alpha_i RAW_{i,t} \tag{4.11}$$

where $V_{T,i,t}$ (mm) is the total water content of the transpirative layer of cell *i* in day *t*, $V_{Tr,i,t}$ (mm), $TAW_{i,t}$ (mm) and $RAW_{i,t}$ (mm) are, respectively, the residual water content, the total available water and the readily available water of the same cell layer; finally, α_i (-) is a user-defined threshold coefficient for the activation of irrigation. The irrigation methods are also defined ad in the case of the USE simulation (see par.4.1.4), therefore the irrigation depth can be either a fixed value or it can be computed by equation:

$$Q_{irr,t} = \frac{(\theta_{fc,E}-\theta_{E,t})Z_e+(\theta_{fc,T}-\theta_{T,t})z_{T,t}}{\eta_{irr}} \tag{4.12}$$

where $\theta_{fc,E}$ $(m^3 \cdot m^{-3})$ and $\theta_{fc,T}$ $(m^3 \cdot m^{-3})$ are the soil water content of the evaporative and the transpirative layers at field capacity, $\theta_{E,t}$ $(m^3 \cdot m^{-3})$ and $\theta_{T,t}$ $(m^3 \cdot m^{-3})$ are the volumetric water contents of the evaporative and the transpirative layers, z_e (m) is the depth of evaporative soil layer, $z_{T,t}$ (m) is the depth of the transpirative layer and η_{irr} is the irrigation method efficiency.

At the end of the simulation the model provides in output the timeseries of the daily values of the irrigation depth $Q_{irr,t}$ in each cell of the study area for the whole simulation horizon, plus all the variables of the cell hydrological balance.

4.2.2 **Source diversion needs**

The daily irrigation needs of the cells can be aggregated at the source level by applying the following equation:

$$Q_{j,t} = \sum_{i=1}^{N_{c,j}} \varepsilon_{ij} \eta_{ij} q_{i,t} A_c \tag{4.13}$$

where $Q_{j,t}$ is the water volume that needs to be diverted or withdrawn from source *j* to satisfy the irrigation water needs of its command area, $N_{c,j}$ is the total number of irrigable cells in the command area of source *j*, ε_{ij} (-) is the ratio of the total water volume diverted from the j^{th} source, $q_{i,t}$ $(mm \cdot d^{-1})$ is the irrigation water need of cell i, η_{ij} (-) is the conveyance efficiency from the j^{th} source to the i^{th} cell. and A_c. is the surface area of the cells.

Irrigation water needs can be also aggregated at smaller scale, i.e. at the IU level, if IUs are available.

5 Crop yield module

The crop yield is estimated through a procedure in five sequential steps, with an approach that aims to maintaining the simplicity of the classical FAO Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam, 1979), but also mutuates some of the principles that are applied in the more recent FAO model Aquacrop (Steduto *et al.* 2012).

5.1 Biomass

The biomass B produced cumulatively $(t \cdot ha^{-1})$ is calculated as:

$$B = WP^*_{adj} \sum(\frac{T}{ET_0}) \tag{5.1}$$

where T is the crop transpiration $(t \cdot ha^{-1})$, ET_0 is reference evapotranspiration (mm), and WP^*_{adj} is the water productivity parameter $(t \cdot ha^{-1})$.

WP^*_{adj}, that is normalized to consider crop type (i.e. it distinguishes between C3 and C4 crops and considers the crop sink strength coefficient) and atmospheric carbon dioxide concentration, is calculated by CropCoef program and is an input to the simulation.

5.2 Water stress yield reduction factor

Water stress response is modelized by the same approach used in IIASA/FAO 2012.

The total water requirement of a crop without any water stress is assumed to be the crop-specific potential transpiration T_m. T_m is calculated in proportion to reference potential transpiration ET_0, multiplied by crop and crop-stage specific parameters, as in § 3.2.

Yield reduction in response to water deficits is calculated as a function of the relationship between actual crop evapotranspiration $\sum T_a$ $(mm \cdot d^{-1})$ and maximum crop evapotranspiration $\sum T_m$ $(mm \cdot d^{-1})$, both accumulated within the four crop stages.

The sensitivity of each crop to water stress is expressed by the value of the water stress coefficient ky (fractional, $-$), a crop-specific parameter which changes with crop development stage. ky values for each of the four development stages $(ky_1, \ldots, ky_4)$ and an average ky value for the overall crop cycle (ky_0) are applied.

Water-stress yield reduction factor is than calculated as:

$$fc^T = 1 - ky_0 \left(1 - \frac{\sum_1^{TCL} T_a}{\sum_1^{TCL} T_m}\right) \tag{5.2}$$

$$TTa_j = \sum_{k \in D_j} T_{a_k} \tag{5.3}$$

$$TTm_j = \sum_{k \in D_j} T_{m_k} \quad j \in [1,4] \tag{5.4}$$

$$fc^{CS} = \prod_{j=1}^{4} \left[1 - ky_j \left(1 - \frac{TTa_j}{TTm_j}\right)\right]^{\lambda_j} \tag{5.5}$$

$$f_c = \min(fc^T, fc^{CS}) \tag{5.6}$$

Where TTa_j and TTm_j are respectively total actual transpiration and total potential transpiration for days during crop stage d_j.

The weighting coefficients λ_j add to one and are taken as the relative length of each crop development stage. Hence, f_c is taken as the minimum of factor fc^T, representing the effect of overall water deficit, and the factor fc^{CS}, representing the weighted effect of crop-stage specific water stress.

5.3 Heat stress yield reduction factor

Heat stress yield reduction factor f_{HS} is calculated considering only the thermal sensitive period (TSP), defined as the days between $0.45GPL$ and $0.75GPL$, where GPL stands for growing period length of the considered crop:

$$f_{HS_d} = \begin{cases} 1 & \mathrm{T}_{day} < \mathrm{T}_{crit} \\ 1 - \frac{\mathrm{T}_{day} - \mathrm{T}_{\mathrm{crit}}}{\mathrm{T}_{lim} - \mathrm{T}_{crit}} & \mathrm{T}_{crit} \leq \mathrm{T}_{day} \leq \mathrm{T}_{lim} \\ 0 & \mathrm{T}_{day} \geq \mathrm{T}_{lim} \end{cases} \tag{5.7}$$

$$f_{HS} = \frac{\sum_1^{TSP} f_{HS_d}}{TSP} \tag{5.8}$$

where T_{day} is the mean diurnal temperature (Chow & Levermore, 2007) ($°C$), and T_{crit} and T_{lim} are respectively a crop specific critical temperature threshold ($°C$) and limit temperature threshold ($°C$).

5.4 Potential and actual yield

For most crops, only part of the biomass produced is partitioned to the harvested organs to give yield Y_p ($t \cdot ha^{-1}$), and the ratio of yield to biomass is known as harvest index HI_0 (-), hence:

$$Y_p = HI_0 \cdot B \tag{5.9}$$

Separation of Y_p into B and HI_0 makes it possible to consider effects of environmental conditions and stresses on B and HI_0 separately.

The actual yield Y_a ($t \cdot ha^{-1}$) is then determined using the equation:

$$Y_a = Y_p \cdot \min(f_C, f_{HS}) \tag{5.10}$$

where Y_p is the potential crop yield calculated using equation 5.9, f_C ($t \cdot ha^{-1}$) is water stress yield reduction factor (-) and f_{HS} is heat stress yield reduction factor (-).

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