Technical manual

version 3.0

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Nomenclature

Study area: the spatial domain where the IdrAgra simulation is run; the domain may include one or more irrigation schemes where water is supplied by multiple water sources.

Simulation horizon: time period of at least one year where the IdrAgra simulation is run on a daily basis; a year in IdrAgra is considered as the time period January 1st-December 31st.

Discretization mesh: the regular mesh used to discretize the spatial domain of the study area; the size of the mesh elements (cells) is defined by the user; this is one of the two ways in which the study area can be subdivided for model implementation.

Discretization layer: the layer of polygons (cells) defined by the user that the model uses to discretize the spatial domain of the study area; this is the second way in which the study area can be subdivided for model implementation.

Cell: a volume of soil of the study area delimited at the surface by one of the cells of the discretization mesh/layer and extending to the depth where the roots of the cell vegetation can reach to extract water and nutrients. With the discretization mesh the cells are square-based prism, with discretization layer cells are prisms whose base is generically a polygon.

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source: any source of irrigation water, either from surface water or from groundwater, where water can be diverted or withdrawn and conveyed to specific zones (command area of the source) within the study area; the study area can include one or more command areas and each of them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

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 distribution 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 storage 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 withdrawal 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. Therefore they cover both sources that feed collective irrigation systems, where water conveyance and distribution is typically managed by an irrigation agency or consortium of users, and private sources that feed individual farms (or a small group of farms), managed farmers themselves, where conveyance and distribution are much simpler (pumping wells are a typic al case). The data that IdrAgra needs to simulate these sources include:

- the timeseries of observed daily withdrawal for the whole simulation horizon;
- the list of IUs supplied by the source;
- the share of the total withdrawal of each IU.

- UNMONITORED sources. The second type include all the sources where the timeseries of daily withdrawal are not available. For these sources, the daily withdrawal is computed runtime by the IdrAgra model, according to a set of parameters that the user needs to provide. UNMONITORED sources can belong to two different categories:
  - Collective: the source provides water supply to a command area including one or more IUs; this is typically the case of withdrawals from groundwater through a well field managed in a coordinated way to supply irrigation to the IU(s); the well field capacity needs to be specified and its operating rule must be defined considering the irrigation water demand of the whole command area;
  - Private: the source provides water supply to a single field; this is typically the case of a field receiving irrigation supply from a pumping well owned and managed by an individual farmer, whose characteristics and operation are unknown; the operating rule needs to be defined/guessed considering only the single field water demand.

In both cases, it is assumed that the daily water volume required according to the operating rule is always available and the model calculates and then provides the timeseries of withdrawals as a simulation output.

1 Introduction

IdrAgra is a distributed-parameter agrohydrological model that 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 system,
- crop yield.

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

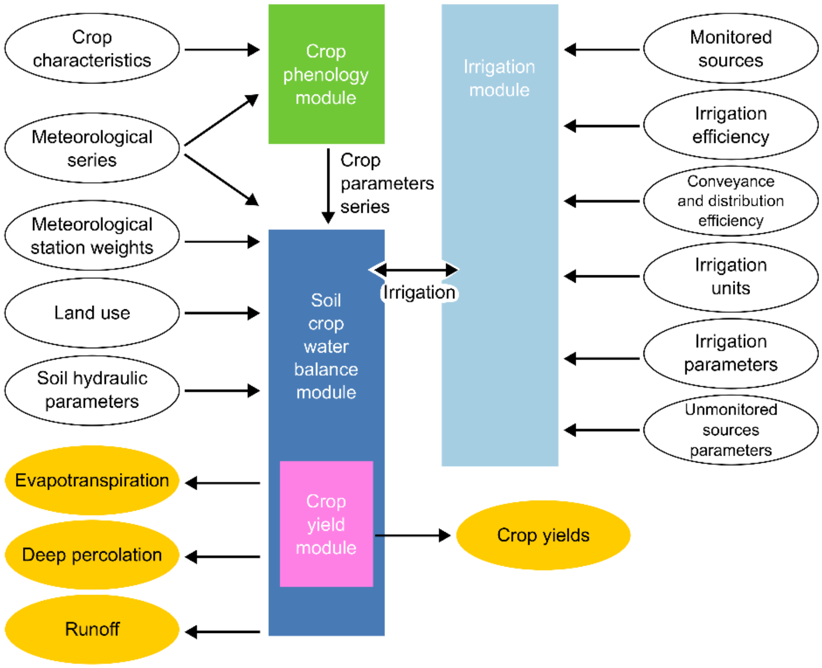

Figure 1: Flowchart of the IdrAgra simulation model: modules are represented as colored boxes, inputs in white background ellipses, outputs in light blue background ellipses.

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 daily irrigation water requirements of a study area over a user defined time horizon, accounting for the space variability soil and crop characteristics, and for the efficiency of irrigation method of each field. If conveyance and distribution network efficiencies are provided, the model can estimate the cumulative daily flow diversion requirement from each of the irrigation water sources. Figure 2 shows 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 either with a regular spatial mesh of square elements or with a vectorial layer of polygons,
- setting land use and soil hydraulic parameters of each cell in the study area,
- setting irrigation method and management criterion for each cell in the study area,
- running the simulation of the daily water balance for each cell of the study area over the simulation horizon.

Indicating the water sources feeding the study area and subdividing the area into Irrigation Units are optional in the NEED mode. If the sources are provided, along with the values of the conveyance efficiency from each source to each Irrigation Unit, the model computes also the daily values of the water volume that needs to be withdrawn from of each source to satisfy the crop water requirements of the study area.

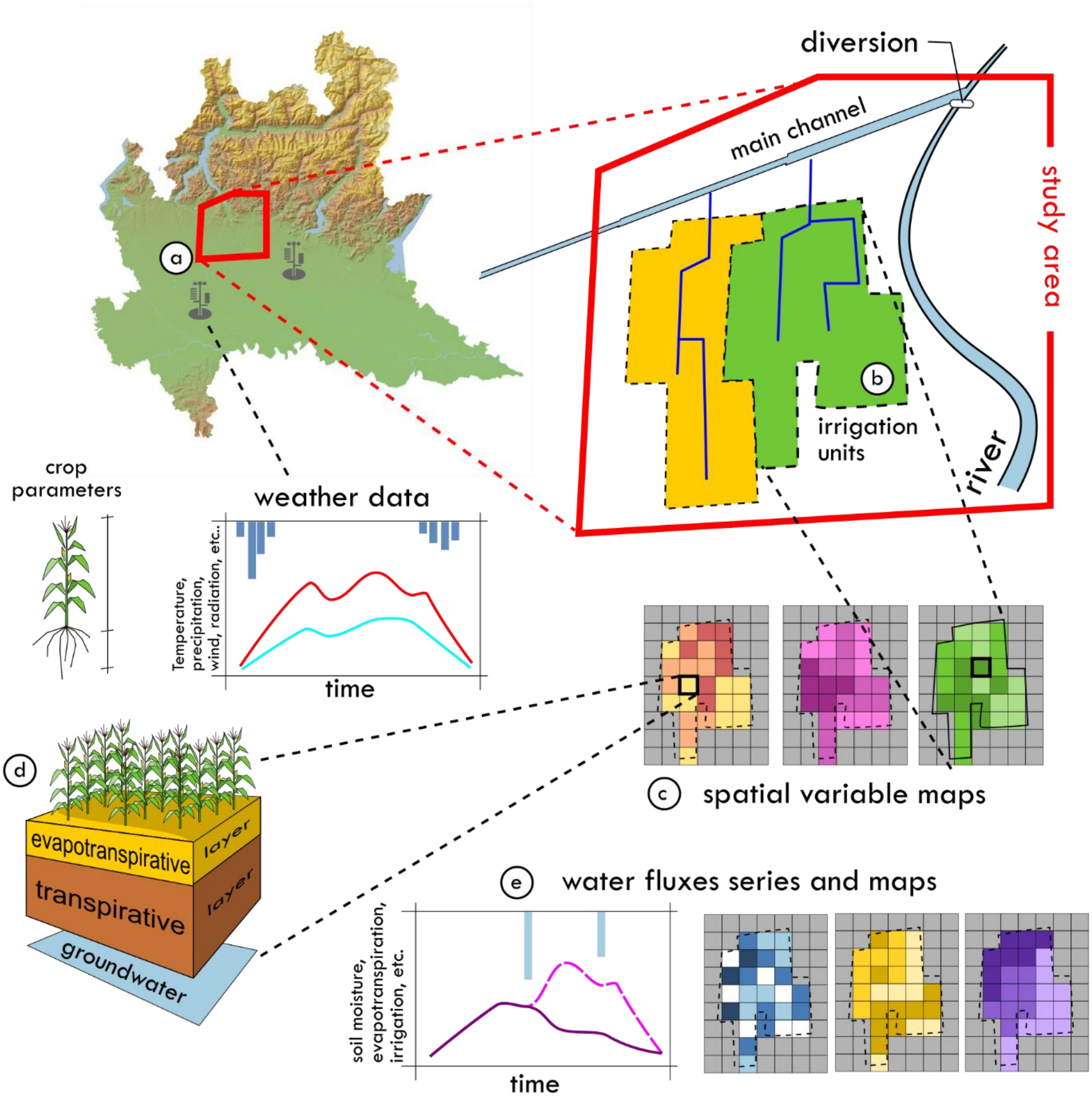

Figure 2: Schematic of the NEED mode operation: a) identification of the study area, selection of the meteorological stations and crop types; b) identification of the Irrigation Units (optional); c) space discretization with a regular mesh; d) computation of the daily hydrological balance for each cell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

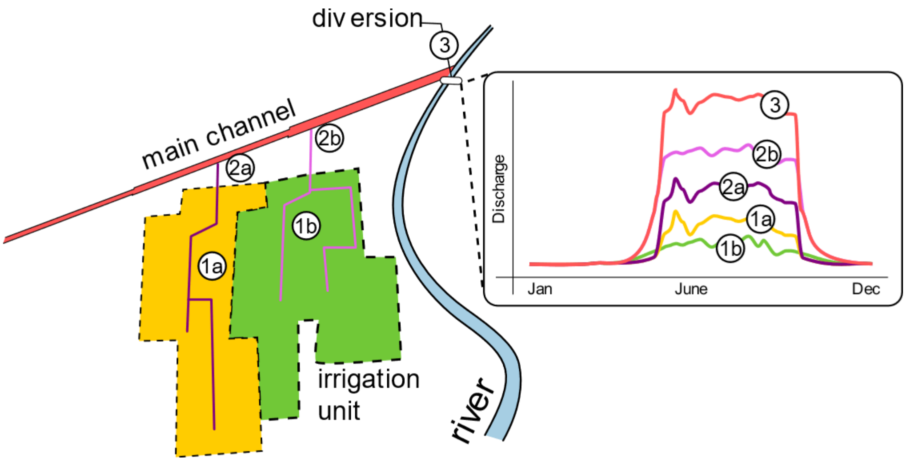

Figure 3: Graphical representation of the hydraulic connection between an Irrigation Unit (or a cell) and the water source where irrigation water supplied to the cell originates; the NEED model allows combining all the IU (or cells) linked to a source to compute the total daily flowrate that is needed 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 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 either with a regular spatial mesh of square elements or with a vectorial layer of polygons,
- 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 (required),
- defining conveyance efficiencies from each water source to each of the Irrigation Units receiving the water supply,
- running the simulation of the water conveyance, distribution, application and soil water balance for each cell of the mesh over the simulation horizon with daily time step.

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.

In both modes the discretization mesh or the discretization layer are user-defined. For the sake of simplicity the following texts and figures in this manual will refer to the case of regular discretization mesh.

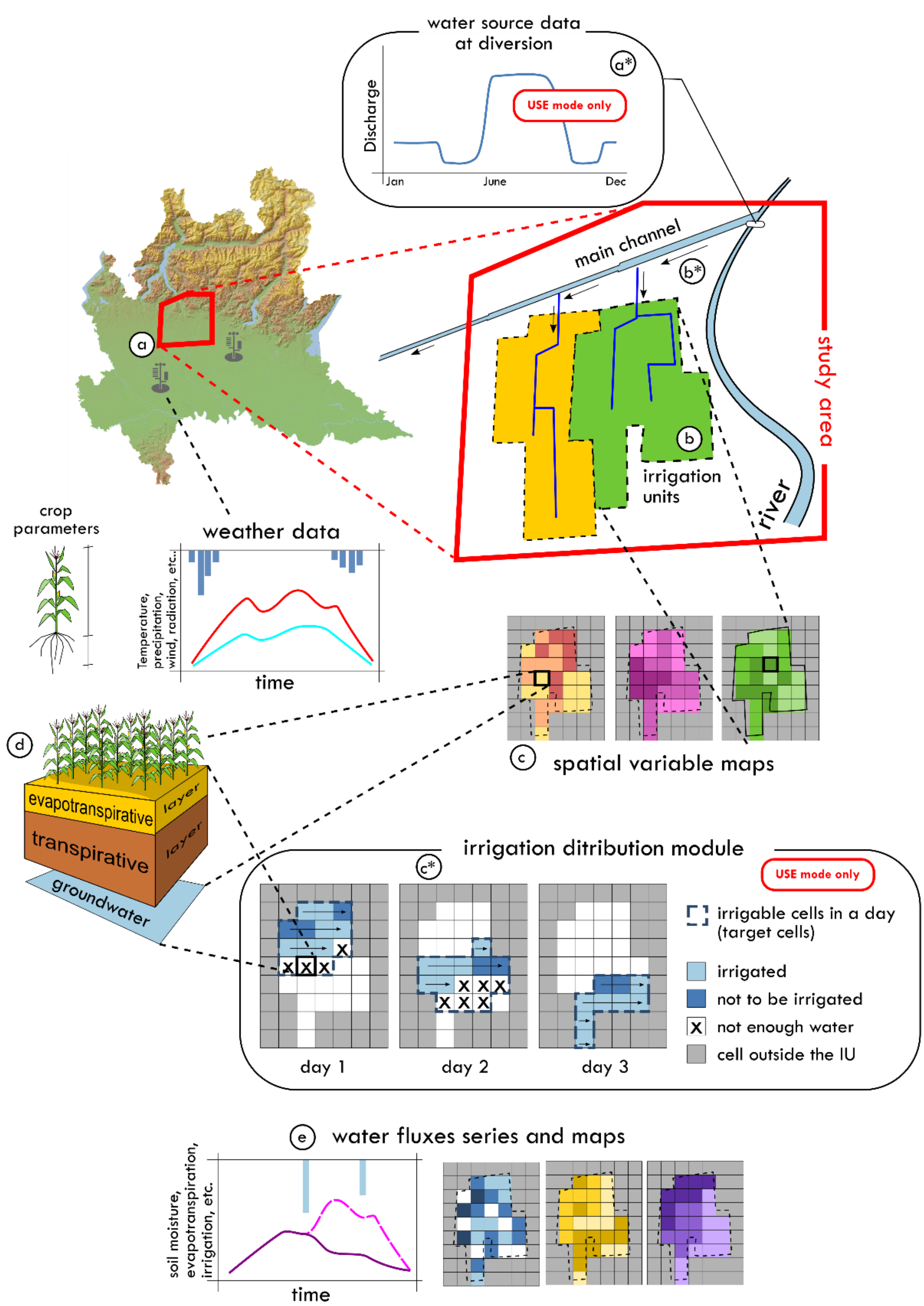

Figure 4: Schematic of the USE mode operation: in addition to the steps of the NEED mode (Figure 2) the USE mode requires a*) identification of the water sources, collection of the daily input series of withdrawals; b*) definition of the conveyance path from each source to each IU (or cell); c*) distribution 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 identifies a set of admissible sowing dates based on a threshold temperature value (Figure 5, panels a and b), according to the following 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.

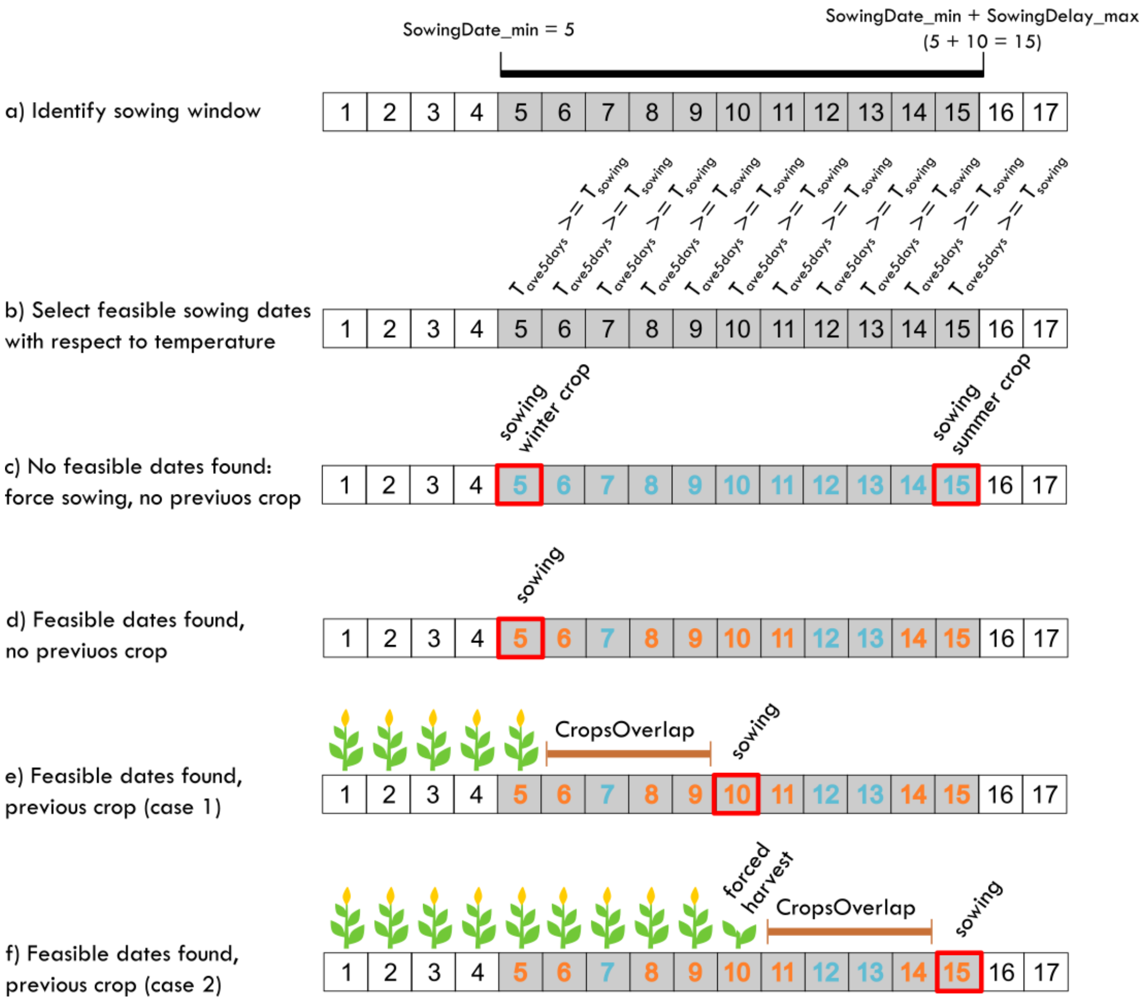

Figure 5: Scheme of the routine to select sowing dates (bold numbered cells represent dates when temperature requirements for sowing are satisfied, dark grey cells represent days of the sowing window).

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 the 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.

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):

$$GD_t = \begin{cases} 0 & \mathrm{T}_{max} < \mathrm{T}_{base} \\ \mathrm{T}_{ave} - \mathrm{T}_{base} & \mathrm{T}_{base} \le \mathrm{T}_{min} < \mathrm{T}_{max} \le \mathrm{T}_c \\ \frac{(\mathrm{T}_{ave}-\mathrm{T}_{base})\left(\frac{\pi}{2}-\theta\right)+W\cos(\theta)}{\pi} & \mathrm{T}_{min} < \mathrm{T}_{base} < \mathrm{T}_{max} \le \mathrm{T}_c \\ (\mathrm{T}_{ave} - \mathrm{T}_{base}) - \frac{(\mathrm{T}_{ave}-\mathrm{T}_c)\left(\frac{\pi}{2}-\varphi\right)+W\cos(\varphi)}{\pi} & \mathrm{T}_{base} \le \mathrm{T}_{min} < \mathrm{T}_c < \mathrm{T}_{max} \\ \frac{(\mathrm{T}_{ave}-\mathrm{T}_{base})\left(\frac{\pi}{2}-\theta\right)+W\cos(\theta)}{\pi} - \frac{(\mathrm{T}_{ave}-\mathrm{T}_c)\left(\frac{\pi}{2}-\varphi\right)+W\cos(\varphi)}{\pi} & \mathrm{T}_{min} < \mathrm{T}_{base} < \mathrm{T}_c < \mathrm{T}_{max} \\ \mathrm{T}_c - \mathrm{T}_{base} & \mathrm{T}_c \le \mathrm{T}_{min} \end{cases} \quad (2.2)$$

where t (d) is the daily time step, GD_t $(°C\ d)$ is the thermal time of the day t, $\mathrm{T}_{\min}$ $(°C)$ 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 $\mathrm{T}_{daybase}$ and T_{cutoff} described in Installation & Use manual) and the remaining terms are calculated as follows:

$$\mathrm{T}_{ave} = (\mathrm{T}_{max} + \mathrm{T}_{min})/2 \quad (2.2.1)$$

$$W = (\mathrm{T}_{max} - \mathrm{T}_{\min})/2 \quad (2.2.2)$$

$$\theta = \arcsin[(\mathrm{T}_{base} - \mathrm{T}_{ave})/W] \quad (2.2.3)$$

$$\varphi = \arcsin[(\mathrm{T}_c - \mathrm{T}_{ave})/W] \quad (2.2.4)$$

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 the daily vernalisation factor, VF, that is calculated on a daily basis from the current average air temperature according to Eq. 2.3:

$$VF = \begin{cases} 0 & T_{ave} < T_{V,min} - T_{slope} \\ 1 - \frac{T_{V,min} - T_{ave}}{T_{slope}} & T_{V,min} - T_{slope} \leq T_{ave} < T_{V,min} \\ 1 & T_{V,min} \leq T_{ave} < T_{V,max} \\ 1 - \frac{T_{ave} - T_{V,max}}{T_{slope}} & T_{V,max} \leq T_{ave} < T_{V,max} + T_{slope} \\ 0 & T_{ave} \geq T_{V,max} + T_{slope} \end{cases} \quad (2.3)$$

where VF is the daily vernalisation factor [0-1] (-), $T_{V,min}$ $(°C)$ and $T_{V,max}$ $(°C)$ are respectively the low end and high end temperature thresholds for optimum vernalisation, T_{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).

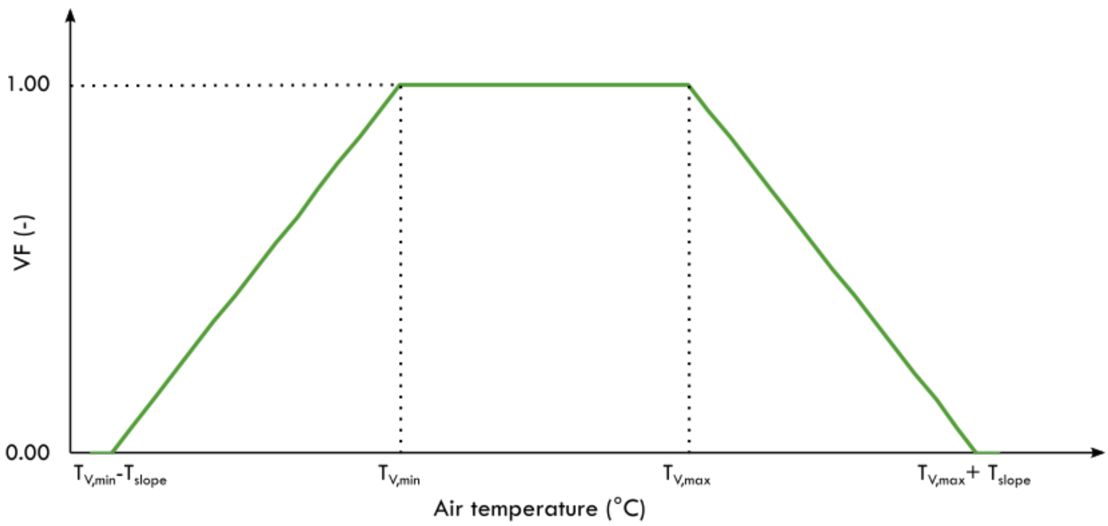

Figure 6: Pattern of the vernalisation contribution, VF_v, in response to temperature.

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 daily photoperiod factor, PF, which fluctuates between 0 and 1, computed according to a linear function (Figure 7).

For long-day crops, the relation is:

$$PF = \begin{cases} 0 & dlh < dlh_{if} \\ \frac{dlh - dlh_{if}}{dlh_{ins} - dlh_{if}} & dlh_{if} \leq dlh \leq dlh_{ins} \\ 1 & dlh > dlh_{ins} \end{cases} \quad (2.4)$$

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:

$$PF = \begin{cases} 1 & dlh < dlh_{ins} \\ \frac{dlh_{if}-dlh}{dlh_{if}-dlh_{ins}} & dlh_{ins} \leq dlh \leq dlh_{if} \\ 0 & dlh > dlh_{if} \end{cases} \quad (2.5)$$

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 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. 2.6:

$$dlh = \frac{24}{\pi}\omega_s \quad (2.6)$$

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

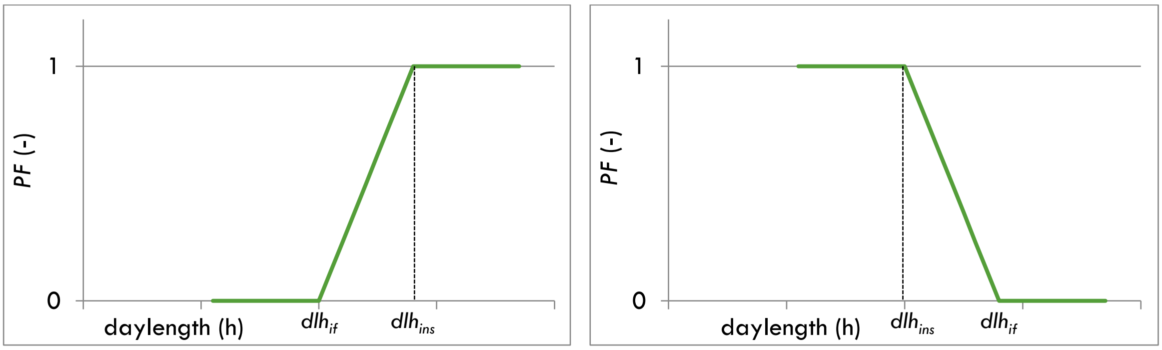

Figure 7: Pattern of the photoperiod factor, PF, in response to daylight hours in long-day plants (a) and short-day plants (b).

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. 2.7:

$$CGD_t = \sum_{j=i}^{t} GD_j \min(PF_j, VF_j) \quad (2.7)$$

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:

$$g_{l,CO_2} = g_l * \left[1.4 - 0.4 * \left(\frac{C_{a,i}}{330}\right)\right] \tag{2.8}$$

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:

$$r_{s,CO_2} = \frac{r_{l,CO_2}}{LAI_{active}} \tag{2.9}$$

where r_{s,CO_2} $(s\ m^{-1})$ is the (bulk) canopy (surface) resistance for a grass reference crop and, LAI_{active} $(m^2\ m^{-2})$ can be assumed equal to $0.5\ LAI$.

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 $2\ m\ s^{-1}$ as proposed in Allen et al., 1998:

$$K_{cb} = K_{cb(Tab)} + [0.04(\overline{u_2} - 2) - 0.004(RH_{min} - 45)]\left(\frac{\bar{h}}{3}\right)^{0.3} \tag{2.10}$$

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 $20\% < RH_{min} < 80\%$, $\bar{h}$ (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:

$$WP^*_{adj} = [1 + f_{type}(f_{CO_2} - 1)]WP^*] \tag{2.11}$$

where f_{type} (-) is a crop type coefficient, f_{CO_2} (-) is a correction coefficient for CO_2 and WP^* $(t\ ha^{-1})$ is the crop biomass water productivity (reference values are $30\text{–}\ 35\ g\ m^{-2}$ for C4 crops, $15 - 20\ g\ m^{-2}$ for C3 crops and values lower than $15\ g\ m^{-2}$ for some leguminous crops). The coefficients f_{type} (-) and f_{CO2} (-) are computed according to the following equations:

$$f_{type} = \max\left[0; min\left(1; \frac{40 - WP^*}{40 - 20}\right)\right] \tag{2.12}$$

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

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. 2.14 and f_{sink} (-) is the crop sink strength coefficient [0-1].

$$0 \leq w = 1 - \frac{(550 - C_{a,i})}{(550 - C_{a,o})} \leq 1 \quad (2.14)$$

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. 2.7 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 study area 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 (evapotranspirative layer) includes a few upper 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 generally 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 evapotranspirative and transpirative soil layers through the equations described in the following sections.

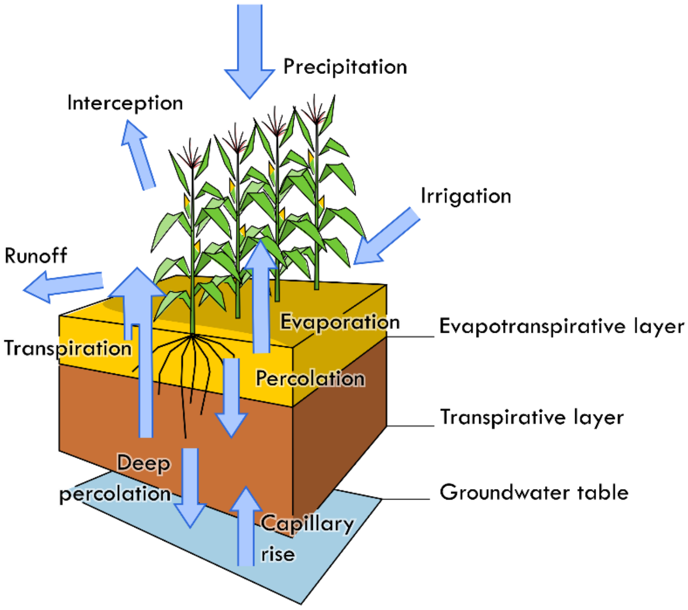

Figure 8: Scheme of the IdrAgra soil crop water balance module.

3.1 Evapotranspirative layer

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

$$U_{E,h}^{*}=\begin{cases}U_{E,h}^{**}=U_{E,h-1}+H_{inf,h}^{*}-E_h-T_{E,h}-H_{E,h}^{*} & U_{E,h}^{**}\le U_{s,E}\\ U_{s,E} & U_{E,h}^{**}>U_{s,E}\end{cases} \tag{3.1}$$

where $U_{E,h}^{*}$ (mm), $H_{inf,h}^{*}$ (mm) and $H_{E,h}^{*}$ (mm) are the preliminary estimates of the value of the soil water storage of the evapotranspirative layer at the end of time step h, the infiltration during time step h, the flux from the evapotranspirative layer into the transpirative one, respectively; E_h and $T_{E,h}$ (mm) are the actual evaporation and transpiration depths (provided by the FAO-Penman-Monteith equation, see § 3.4), $U_{s,E}$ (mm) is the soil water storage at saturation; finally $U_{E,h}^{**}$ is a service variable. The discretization time step adopted in eq. 3.1 is hourly, as indicated by the subscript h; if necessary for numerical accuracy reasons, the integration time step can be reduced automatically by the model. Therefore, those variables that are treated with a daily timestep (net rainfall, runoff, evaporation and transpiration) are uniformly distributed over the 24 hours of each day, while only the distribution within the day of irrigation application depth, $H_{irr,h}$, can be specified for each irrigation method (e.g., 4 hours duration starting from 8 am; see specifications of the input file of irrigation method in the Installation & Use Manual).

$U^*_{E,h}$, $H^*_{inf,h}$ and $H^*_{E,h}$ are all preliminary estimates since their final value can be determined only after completing the water balance calculation for the transpirative layer; in fact, $H^*_{E,h}$ might exceed the water holding and drainage capacity of the lower layer and therefore it might have to be reduced consequently. $U^*_{E,h}$ and $H^*_{inf,h}$shall then be updated accordingly (see eq. 3.15-3.18 in par. 3.2).

The preliminary value of the amount of infiltration during the time step h, $H^*_{inf,h}$, is set equal to:

$$H^*_{inf,h} = \begin{cases} H_{irr,h} + U_{pnd,h-1} + \frac{P_t - P_{e,t} - I_t}{24} & \text{if } U^{**}_{E,h} \leq U_{s,E} \\ H_{irr,h} + U_{pnd,h-1} + \frac{P_t - P_{e,t} - I_t}{24} - \left(U^{**}_{E,h} - U_{s,E}\right) & \text{if } U^{**}_{E,h} > U_{s,E} \end{cases} \quad (3.2)$$

where $H_{irr,h}$ (mm) is the net[1] irrigation depth in time step h, $U_{pnd,h-1}$ (mm) is the ponded volume at the beginning of the same time step, 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, and I_t (mm) is the canopy rainfall interception, computed following Braden (1985) as:

$$I_t = a_I \cdot LAI_t \left(1 - \frac{1}{1+\frac{f_{pc,t} \cdot P_t}{a_I \cdot LAI_t}}\right) \quad (3.3)$$

where, LAI_t $(m^2 \cdot m^{-2})$ is the Leaf Area Index, a_I (mm) is an empirical coefficient, $f_{pc,t}$ $(-)$ is a plant cover factor that can be derived from LAI_t by the simple relationship $\min\left(\frac{LAI_t}{3}, 1\right)$, and a_I (mm) is an empirical parameter, representative of the plant specific interception storage capacity per leaf area, that for an average canopy can be assumed equal to 2, 5 mm.

The flux $H^*_{E,h}$ is modelled assuming that it equals the saturated hydraulic conductivity of the evapotranspirative layer, $K_{s,E}$ $(mm \cdot h^{-1})$, when the current storage, $U^*_{E,h}$, exceeds the value at field capacity, $U_{fc,E}$ (mm), and equal to the unsaturated hydraulic conductivity, $K_{E,h}$ $(mm \cdot h^{-1})$ for lower storage values, i.e.:

$$H^*_{E,h} = \begin{cases} K_{E,h} \cdot 1\,(h) & \text{if } U^*_{E,h} \leq U_{fc,E} \\ K_{s,E} & \text{otherwise} \end{cases} \quad (3.4)$$

The unsaturated hydraulic conductivity is estimated using the Brooks-Corey (1964) equation:

$$K_{E,h} = K_{s,E} \left(\frac{U^*_{E,h} - U_{r,E}}{U_{s,E} - U_{r,E}}\right)^{n_E} \quad (3.5)$$

where $U_{r,E}$ (mm) and $U_{s,E}$ (mm) are the residual and saturated water storages of the evapotranspirative layer, respectively, and n_E (-) is a dimensionless parameter.

3.2 Transpirative layer

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

[1] Depending on the irrigation method the gross irrigation depth may be reduced due to application losses, like jet evapotranspiration and canpy interception in the case of sprinkler irrigation (see par. 4.4).

$$U_{T,h} = \begin{cases} U_{T,h}^{*} = U_{T,h-1} + H_{E,h} - T_{T,h} - H_{T,h} & U_{T,h}^{*} \le U_{T,max} \\ U_{T,max} & U_{T,h}^{*} > U_{T,max} \end{cases} \tag{3.6}$$

where $U_{T,h}$ (mm) is the water storage of the transpirative layer at the end of time step h, $U_{T,h}^{*}$ (mm) is a service variable, $T_{T,h}$ (mm) is the actual transpiration depth (provided by the FAO-Penman-Monteith equation, see § 3.4), $H_{T,h}$ (mm) is the depth of the cumulated flux through at the bottom of the layer during time step h. This flux can be either of percolation or capillary rise, depending on the soil water storage, the depth to the saturated surface and the soil characteristics. The downward flux is assumed to be predominantly gravity driven and, therefore, is assumed to take place at a rate equal to the unsaturated hydraulic conductivity $K_{T,h}$ $(mm \cdot h^{-1})$, while, when capillary flux prevails, it is computed using the model of Liu et al. (2006). Therefore $H_{T,h}$ is given by the following equation:

$$H_{T,h} = \begin{cases} -H_{cap,h} & \text{if } \ H_{cap,h} > 0 \\ \ K_{T,h} \cdot 1\ (h) & \text{if } \ H_{cap,h} = 0 \end{cases} \tag{3.7}$$

where $H_{cap,h}$ (mm) is the capillary flux.

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

$$K_{T,h} = K_{s,T} \left(\frac{U_{T,h} - U_{r,T,h}}{U_{s,T,h} - U_{r,T,h}} \right)^{n_T} \tag{3.8}$$

where $K_{s,T}$ $(mm \cdot h^{-1})$ is the saturated hydraulic conductivity of the transpirative layer, $U_{T,h}$ (mm) is the water storage in the transpirative layer, $U_{r,T,h}$ (mm) is the residual water storage of the transpirative layer, $U_{s,T,h}$ (mm) is the saturated water storage of the transpirative layer, and n_T (-) is the Brooks-Corey exponent of the transpirative layer.

When the groundwater table is sufficiently 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) assumes that capillary flux occurs only when the water storage in the transpirative layer falls below a threshold value $\widehat{U}_{T,h}$ (mm) and that it cannot exceed a maximum value that depends upon the groundwater depth and the evapotranspiration demand. Capillary flux in time step h will be indicated as $H_{cap,h}$ (mm), while its maximum as $\widehat{H}_{cap,h}$ $(mm \cdot h^{-1})$. Liu et al. (2006) consider a 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 $z_{r,h}$ (sum of the evaporative and transpirative layers depths in IdrAgra).

The critical soil water storage $\widehat{U}_{T,h}$ (mm), is estimated by:

$$\widehat{U}_{T,h} = \ U_{T_{fc},h} \ \cdot \left(d_{gw,h} - z_{r,h} + 1\right)^{b_{C,1}} \tag{3.9}$$

where $U_{T_{fc},h}$ (mm) is the storage of the transpirative layer at field capacity, $d_{gw,h}$ (m) is the groundwater depth at time step h, $b_{C,1}$ $(-)$ is an empirical parameter that depends on soil type. The critical groundwater depth, $\hat{d}_{gw,h}$ (m), i.e. the threshold value for groundwater depth above which the potential capillary flux does not increase anymore, is estimated by:

$$\hat{d}_{gw,h} = \begin{cases} z_r - 1 + 24\ a_{C,3}(E_h + T_{p,h}) + b_{rc,3} & (E_h + T_{p,h}) \le 4/24\ mm \cdot h^{-1} \\ z_r - 1 + a_{C,3}\ 4 + b_{rc,3} & (E_h + T_{p,h}) > 4/24\ mm \cdot h^{-1} \end{cases} \tag{3.10}$$

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

The potential capillary flux, $\widehat{H}_{cap,h}$ $(mm \cdot h^{-1})$, is estimated by:

$$\widehat{H}_{cap,h} \begin{cases} T_{p,h} & d_{gw,h} \leq \hat{d}_{gw,h} \\ \min(T_{p,h}, \frac{a_{rc,4} \cdot (d_{gw,h} - z_r + 1)^{b_{rc,4}}}{24}) & d_{gw,h} > \hat{d}_{gw,h} \end{cases} \quad (3.11)$$

where, $a_{C,4}$ $(-)$ and $b_{C,4}$ $(-)$ are empirical parameters that depend on soil type.

The actual capillary flux, $H_{cap,h}$ $(mm \cdot h^{-1})$, is then provided by the following equation:

$$H_{cap,h} = \begin{cases} \widehat{H}_{cap,h} & U_{T,h} < \breve{U}_{T,h} \\ \widehat{H}_{cap,h} \left(\frac{\widehat{U}_{T,h} - U_{T,h}}{\widehat{U}_{T,h} - \breve{U}_{T,h}} \right) & \breve{U}_{T,h} \leq U_{T,h} \leq \widehat{U}_{T,h} \\ 0 & U_{T,h} > U_{T,h} \end{cases} \quad (3.12)$$

where $\breve{U}_{T,h}(mm)$ is the so-called steady state soil water storage, i.e. the value of the soil water storage below which the flux remains constant at its maximum, given by:

$$\breve{U}_{T,h} = a_{C,2} \cdot \left(d_{gw,h} - z_r + 1 \right)^{b_{C,2}} \quad (3.13)$$

where $b_{C,2}$ $(-)$ is an empirical parameter that depends on soil type and $a_{C,2}$ $(-)$ is a reference soil water storage above the average between the storage at field capacity, $U_{T_{fc},h}$ (mm), and at wilting point, $U_{T_{wp},h}$ (mm):

$$a_{C,2} = 1.1 \frac{\left(U_{T_{fc},h} - U_{T_{wp},h} \right)}{2} \quad (3.14)$$

The values of the empirical parameters in 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
$b_{C,1}$	-0.17	-0.16	-0.32
$b_{C,2}$	-0.27	-0.54	-0.16
$a_{C,3}$	-1.3	-0.15	-1.4
$b_{C,3}$	6.6	2.1	6.8
$a_{C,4}$	4.6	7.55	1.11
$b_{C,4}$	-0.65	-2.03	-0.98

Once the water balance of the transpirative layer has been determined, the excess of water $\Delta U_{T,h} = U^*_{T,h} - U_{s,T,h}$ that occurs when $U^*_{T,h} > U_{s,T,h}$ in Eq. (3.6) 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 evapotranspirative layer, if there is any, and the preliminary values of storage, infiltration and downward flux of the layer are updated accordingly.

The final values of the three variables are given by:

$$U_{E,h} = \min(U^*_{E,h} + \Delta U_{T,h}; U_{s,E}) \quad (3.15)$$

$$H_{inf,h} = H^*_{inf,h} - \min\left(0; U_{E,h} - U^*_{E,h}\right) \quad (3.16)$$

$$H_{E,h} = \min\left(H^*_{E,h}; H^*_{E,h} - \Delta U_{T,h}\right) \quad (3.17)$$

Finally, the ponded water volume at the end of time step h becomes:

$$U_{pnd,h} = \max(0; U^{**}_{E,h} - U_{s,E} + \Delta U_{T,h}) \quad (3.18)]$$

3.3 Increased percolation after irrigation application

The estimation of percolation, obtained by the equations (3.4) and (3.7), can be been modified to account for higher gradients of soil water potential at the interface between the evapotranspirative and transpirative layers during and shortly after irrigation events and for non-uniformity of irrigation application over the field surface. Both these factors, in fact, might determine an increase of the percolation flux compared to the lumped representation using Darcy's gravitational flux described in the two previous sections. When combined with the spatial variability of soil characteristics and water storage within the cell, this effect can be magnified and cause a significant underestimation of the percolation flux due to irrigation, particularly when high and uneven amounts are applied onto the field like with border irrigation. To account for this, the following correction can be used in IdrAgra:

$$H_{E,irr} = (1 + a_E e^{-t \cdot b_E}) H_E \qquad (3.19)$$
$$H_{T,irr} = (1 + a_T e^{-t \cdot b_T}) H_T$$

where $H_{E,irr}$ (mm) and $H_{T,irr}$ (mm) are the outflows from the evaporative to the transpirative layer and from the root zone to the deeper subsoil accounting for irrigation management, H_E (mm) and H_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 empirical parameters that need to be calibrated for each irrigation method, considering also the influence of soil characteristics.

3.4 Crop transpiration and soil evaporation

3.4.1 Reference crop evapotranspiration

Daily reference crop evapotranspriation ET_0 $(mm \cdot d^{-1})$, i.e. the evapotranspiration calculated from a hypothetical extensive surface of *green*, well-watered grass with a 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:

$$ET_{0,t} = \frac{0.408\Delta(R_{n,t} - G_t) + \gamma \frac{900}{T_{mean,t} + 273} u_2 (e_{s,t} - e_{a,t})}{\Delta_t + \gamma(1 + 0.34 u_{2,t})} \qquad (3.20)$$

where $ET_{0,t}$ $(mm \cdot d^{-1})$ is the reference daily evapotranspiration, $R_{n,t}$ $(MJ \cdot m^{-2} \cdot d^{-1})$ is the net daily radiation at the crop surface, G_t $(MJ \cdot m^{-2} \cdot d^{-1})$ is the soil heat flux density, $T_{mean,t}$ $(°C)$ and $u_{2,t}$ $(m \cdot s^{-1})$ are respectively the mean daily air temperature and the wind speed at $2\ m$ height, $e_{s,t}$ (kPa) and $e_{a,t}$ (kPa) are respectively the saturation and the actual vapour pressure, Δ_t $(kPa \cdot °C^{-1})$ is the slope vapour pressure curve and γ $(kPa \cdot °C^{-1})$ is the psychrometric constant. Values of all variables in equation (3.20) refer to day t. The approach used to determine the values of the individual variables in the equation is described in Allen et al. (1998) and transcribed in the sequel for completeness.

Since the model adopts a hourly timestep in the water balance of the evapotranspirative and transpirative soil layers (cfr. Par. 3.1 and 3.2), hourly values of reference crop potential evapotranspiration are derived assuming a gaussian distribution of the cumulated daily value $ET_{0,t}$, as shown in Figure 9. The standard deviation of the distribution varies with Julian date to reflect the variable duration of daylight hours that is estimated with Eq. 2.6. Therefore the hourly value $ET_{0,h,t}$, is given by the following equation:

$$ET_{0,h,t} = \varphi_{h,t} ET_{0,t} \quad (3.21)$$

where $\varphi_{h,t}$ is the ratio of $ET_{0,t}$ occurring in hour h of day t. This is obviously a simplification that does not account for variable cloud conditions during the day but is considered sufficiently accurate for the sake of water balance implementation at the spatial and temporal scales typical of IdrAgra applications.

Note that, for the sake of simplifying notation, $ET_{0,h,t}$ is indicated as $ET_{0,h}$ in both Par. 3.1 and 3.2.

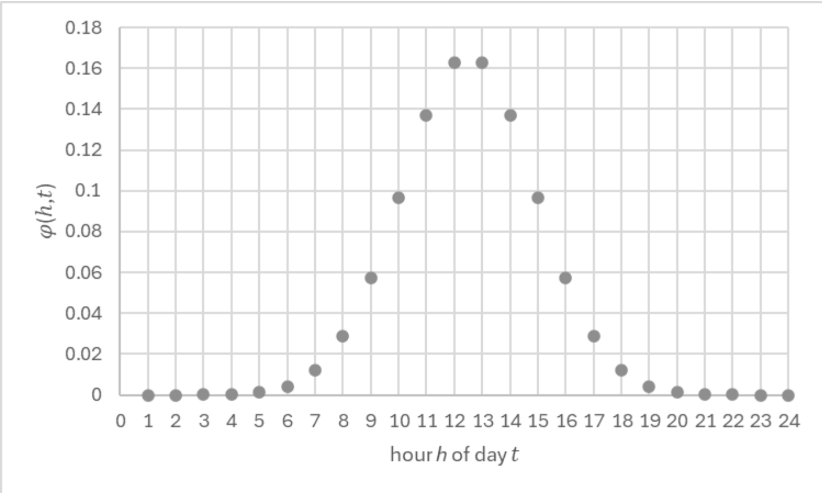

Figure 9: Example of hourly distribution daily reference crop evapotranspiration.

3.4.1.1 Atmospheric parameters

The atmospheric pressure at elevation z (m) above sea level, $\mathrm{P}_{atm,z}$ (kPa) is calculated employing a simplification of the ideal gas law and assuming $20°C$ for a standard atmosphere, as:

$$\mathrm{P}_{atm,z} = 101.3 \left(\frac{293 - 0.0065z}{293}\right)^{5.26} \quad (3.22)$$

The psychrometric constant, γ $(kPa \cdot °C^{-1})$, is calculated as:

$$\gamma = \frac{c_p \mathrm{P}_{atm}}{\varepsilon\lambda} = 0.665 \cdot 10^{-3} \mathrm{P}_{atm} \quad (3.23)$$

where, 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, T_{mean} $(°C)$, is defined as the mean of the daily maximum and minimum temperatures:

$$\mathrm{T}_{mean} = \frac{\mathrm{T}_{max} + \mathrm{T}_{min}}{2} \quad (3.24)$$

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

The saturation vapour pressure $\mathrm{e}^0(\mathrm{T}_{air})$ (kPa) at the air temperature T_{air} $(°C)$ is calculated as:

$$\mathrm{e}^0(\mathrm{T}_{air}) = 0.6108 e^{\frac{17.27 \mathrm{T}_{air}}{\mathrm{T}_{air} + 237.3}} \quad (3.25)$$

where T_{air} is measured at $2\ m$ height.

Due to the non-linearity of equation (3.25), 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:

$$e_s = \frac{e^0(T_{max}) + e^0(T_{min})}{2} \quad (3.26)$$

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:

$$\Delta = \frac{4098\left(0.6108 e^{\frac{17.27 T_{air}}{T_{air}+237.3}}\right)}{(T_{air}+237.3)^2} \quad (3.27)$$

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

$$e_a = \frac{e^0(T_{min})\frac{RH_{max}}{100} + e^0(T_{max})\frac{RH_{min}}{100}}{2} \quad (3.28)$$

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

3.4.1.2 Radiation

The extra-terrestrial radiation, R_a ($MJ \cdot m^{-2} \cdot d^{-1}$), is estimated by:

$$R_a = \frac{24 \cdot 60}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \quad (3.29)$$

where 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 (rad), are given by:

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365} day\right) \quad (3.30)$$

$$\delta = 0.409\sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (3.31)$$

where 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, ω_s (rad), is given by:

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \quad (3.32)$$

where φ (rad) is the latitude and δ (rad) is the solar declination.

The clear-sky radiation, R_{so} ($MJ \cdot m^{-2} \cdot d^{-1}$), is calculated with the Ångström formula:

$$R_{so} = (0.75 + 2 \cdot 10^{-5} z) R_a \quad (3.33)$$

where 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:

$$R_{ns} = (1 - \alpha)R_s \quad (3.34)$$

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:

$$R_{nl} = \sigma \left(\frac{T^4_{max,K} + T^4_{min,K}}{2} \right) \left(0.34 - 0.14\sqrt{e_a}\right) \left(1.35 \frac{R_s}{R_{so}} - 0.35\right) \quad (3.35)$$

where σ is the Stefan-Boltzmann constant, equal to $4.903 \cdot 10^{-9}\ MJ \cdot K^{-4} \cdot m^{-2} \cdot d^{-1}$, $T_{max,K}$ (K) and $T_{min,K}$ (K) are respectively the maximum ($T_{max,K} = T_{max} + 273.16$) and minimum ($T_{min,K} = T_{min} + 273.16$) daily absolute temperatures, e_a (kPa) is the actual vapour pressure. 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} ($MJ \cdot m^{-2} \cdot d^{-1}$):

$$R_n = R_{ns} - R_{nl} \quad (3.36)$$

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

3.4.2 **Soil evaporation**

The soil evaporation, E_t ($mm\ d^{-1}$), is the product of potential evapotranspiration $ET_{0,t}$ times the soil evaporation coefficient $K_{e,t}$ that, according to Allen *et al.* (1998), can be expressed as:

$$K_{e,t} = f_{ew,t} K_{r,t} \left(K_{c_{max},t} - K_{cb,t},\right) \quad (3.37)$$

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

$$K_{c\_max} = \max\left(\left\{ 1.2 + \left[0.04\left(u_{2,t} - 2\right) - 0.004\left(RH_{min,t} - 45\right)\right] \left(\frac{h_{crop,t}}{3}\right)^{0.3} \right\}, \left\{K_{cb,t} + 0.05\right\} \right) \quad (3.38)$$

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 3.38 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 storage of the evapotranspirative layer at the end of the previous day $U_{E,t-1}$ (mm), and can be computed as:

$$K_{r,t} = \begin{cases} 1 & U_{E,t-1} \geq U_{REW} \\ \frac{U_{E,t-1} - 0.5U_{wp,E}}{U_{REW} - 0.5U_{wp,E}} & U_{wp,E} \leq U_{E,t-1} < U_{REW} \\ 0 & U_{E,t-1} < 0.5\ U_{wp,E} \end{cases} \quad (3.39)$$

where U_{REW} (mm) is the water storage in the evapotranspirative layer when the readily evaporative water has been removed, and $U_{wp,E}$ (mm) is the soil water storage in the evapotranspirative layer at wilting point.

In equation (3.39), U_{REW} is calculated as:

$$U_{REW} = 0.4 \cdot \left(U_{fc,E} - 0.5U_{wp,E}\right) \tag{3.40}$$

where $U_{fc,E}$ (mm) and $U_{wp,E}$ (mm) are respectively the soil water storage in the evapotranspirative layer at field capacity and at wilting point.

When the water supply affects the entire surface of the field, as with precipitation or sprinkler irrigation, then the fraction of soil surface from which most evaporation occurs, $f_{ew,t}$, is equal to $(1 - f_{c,t})$, where $f_{c,t}$ is the average fraction of soil surface covered by vegetation at time step t. However, for irrigation systems where only a fraction of the ground surface is wetted, like with drip irrigation, $f_{ew,t}$ is limited to the fraction of the soil surface that is wetted:

$$f_{ew,t} = \min(1 - f_{c,t}, f_{w,t}) \tag{3.41}$$

where f_{ew} $(-)$ is the fraction soil surface that is both exposed and wetted, f_c $(-)$ is the fraction of soil surface covered by vegetation $[0 - 1]$ and $f_{w,t}$ $(-)$ is the fraction of wetted soil surface $[0.01 - 1]$. $f_{c,t}$ should be provided as an input to the model; when f_c it is not available the model computes an estimation using the relationship (Allen et al., 1998):

$$f_c = \left(\frac{\mathrm{K}_{cb} - \mathrm{K}_{c\,min}}{\mathrm{K}_{c\,max} - \mathrm{K}_{c\,min}}\right)^{(1+0.5h)} \tag{3.42}$$

where $\mathrm{K}_{c\,min}$ $(-)$ is the minimum value of K_c for dry bare soil with no ground cover $[\approx 0.15 - 0.20]$, $\mathrm{K}_{c\,max}$ $(-)$ is the maximum value of K_{cb} immediately following wetting (equation 3.38) and h (m) is the mean plant height.

Where water is supplied to the field only by irrigation $f_{w,t}$ is constant and is equal to f_{irr}, i.e. to the value of the fraction of the soil surface that is wetted by the method that is used to irrigate the specific field. When both precipitation and irrigation occur the value of $f_{w,t}$ evolves in time, varying between 1 after a rainfall event and f_{irr} after an irrigation following a prolonged period with no precipitations. The algorithm applied in the IdrAgra model is the following:

$$f_{w,t} = \begin{cases} f_{w,NEW} & \text{if } f_{w,NEW} > f_{w,t-1} \\ \dfrac{f_{w,t-1}(U_{E,t-1} - U_{wp,E}) + f_{w,NEW} \cdot \min(U_{E,t-1} - U_{wp,E} + H_{irr,t};\, U_{s,E} - U_{wp,E})}{U_{E,t-1} - U_{wp,E} + \min(U_{E,t-1} - U_{wp,E} + H_{irr,t}; U_{s,E} - U_{wp,E})} & \text{if } f_{w,NEW} \leq f_{w,t-1} \end{cases} \tag{3.43}$$

where

$$f_{w,NEW} = \begin{cases} 1 & \text{if } P_t \geq P_{min} \text{ and } H_{irr,t} = 0 \\ f_{irr} & \text{if } H_{irr,t} > 0 \text{ and } P_t < P_{min} \\ f_{w,t-1} & \text{if } P_t < P_{min} \text{ and } H_{irr,t} = 0 \\ \dfrac{P_t + f_{irr}\,H_{irr,t}}{P_t + H_{irr,t}} & \text{if } P_t > P_{min} \text{ and } H_{irr,t} > 0 \end{cases} \tag{3.44}$$

P_{min} (mm) is the threshold depth value below which rainfall can be considered not significant, whose default value is set to $5\ mm$.

3.4.3 Crop transpiration

The potential crop transpiration is given by:

$$T_h = \mathrm{K}_{cb,h} ET_{0,h} \tag{3.45}$$

where $\mathrm{K}_{cb,h}$ is the basal crop coefficient i.e. 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). The basal crop coefficient is calculated on a daily basis by interpolating its values at the initial stage $(\mathrm{K}_{cb\,ini})$, the mid-season stage $(\mathrm{K}_{cb\,mid})$ and at the end of the late season stage $(K_{cb\,end})$ that need to be provided in input to the model. The duration of the crop growth stages is computed by IdrAgra based on the accumulation of growing degree day (GDD), with threshold values of GDD for the transition from one stage to the next that also need to be provided in input for each crop type. An example of the crop coefficient curve of an annual crop is shown in Figure 10. 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 model assumes that the value of the crop coefficient is constant during the day.

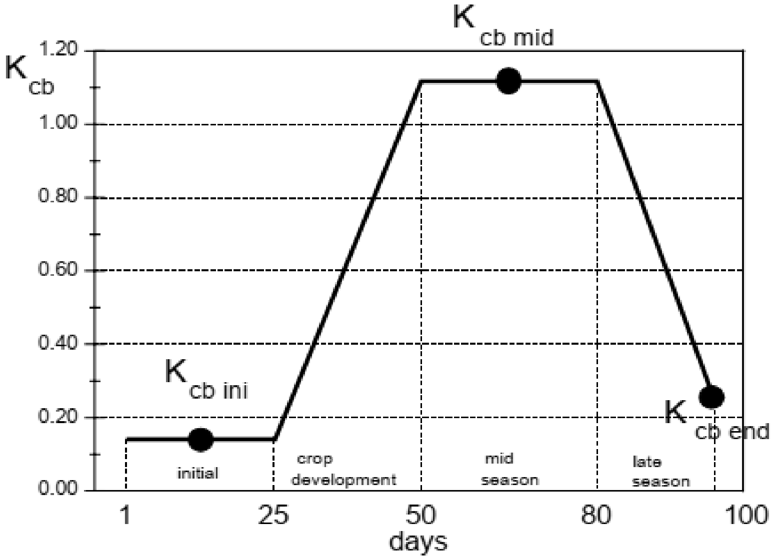

Figure 10: Crop coefficient curve for annual crops. Source: Allen *et al.*, 1998.

T_h is subdivided between the first and second layer according to corresponding root fractions:

$$T_{E,h} = T_{c,h} RF_{E,h} = T_{c,h}(1 - RF_{T,h}) \tag{3.46}$$

$$T_{T,h} = T_{c,h} RF_{T,h} \tag{3.47}$$

where $T_{E,h}$ and $T_{T,h}$ are the potential crop transpirations from the first and second layer, and $RF_{E,h}$ (-) and $RF_{T,h}$ (-) are the fractions of active roots in the same layers at the beginning of time interval h. The value of $RF_{T,h}$ increases during the agricultural season; the model assumes that the root density remains constant and therefore the growth of $RF_{T,h}$ can be described by the relationship:

$$RF_{T,h} = RF_{T,max} \left(\frac{z_{T,h}}{z_{T,max}} \right) \tag{3.48}$$

where $RF_{T,max}$ (-) is the fraction of the total active roots that uptake water from this layer when the roots reach their full growth, $z_{T,h}$ (L) is the depth of the second layer at the beginning of time interval h and $z_{T,max}$ (L) is the maximum depth of the same layer. Note that the depth z_T is updated on a daily basis, therefore values $z_{T,h}$ and hence of $RF_{E,h}$ and $RF_{T,h}$ are constant in all the 24 steps of the same day t.

Actual transpiration is computed as the product of potential evapotranspiration times the reduction factor K_s due to water availability limitation (Allen *et al.*, 1998) that in IdrAgra is calculated separately for the first and second soil layer, by considering the respective water storages, as:

$$\mathrm{K}_{s,E,h} = \begin{cases} 1 & U_{E,h} \geq U_{RAW,E} \\ \frac{U_{E,h} - U_{wp,E}}{U_{RAW,E} - U_{wp,E}} & U_{wp,E} \leq U_{E,h} < U_{RAW,E} \\ 0 & U_{E,h} < U_{wp,E} \end{cases} \tag{3.49}$$

$$\mathrm{K}_{s,T,h} = \begin{cases} 1 & U_{T,h} \geq U_{RAW,T,h} \\ \frac{U_{T,h} - U_{wp,T,h}}{U_{RAW,T,h} - U_{wp,T,h}} & U_{wp,T,h} \leq U_{T,h} < U_{RAW,T,h} \\ 0 & U_{T,h} < U_{wp,T,h} \end{cases} \tag{3.50}$$

where $U_{E,h}$ and $U_{T,h}$ (mm) are the water storages in the evapotranspirative and transpirative layers at the beginning of time interval h, respectively, $U_{RAW,E}$ and $U_{RAW,T,h}$ (mm) are the water storages of the same layers when the readily available water has been depleted, and $U_{wp,E}$ and $U_{wp,T,h}$ (mm) are the soil water storages in the two layers at wilting point.

$U_{RAW,T,h}$ in equation (3.50) is calculated as:

$$U_{RAW,T} = U_{fc,T,h} - \left(U_{fc,T,h} - U_{wp,T,h}\right) \cdot p_h \tag{3.51}$$

where $U_{fc,T,h}$ (mm) is the soil water volume of the transpirative layer at field capacity and p_h (-) is the adjusted mean fraction of total available water (TAW) that can be depleted from the root zone before moisture stress occurs. $U_{RAW,E}$ in equation 3.49 is computed in a completely analogous way.

The fraction p_h in equation 3.51 is calculated from the reference value p_{tab}, that must be included among the crop input parameters, as:

$$p_h = p_{tab} + 0.04 \cdot (5 - ET_{c,h}) \tag{3.52}$$

where $ET_{c,h}$ (mm) is the potential crop evapotranspiration. p_h is limited between $[0.1 - 0.8]$ as in Allen *et al.* (1998).

Figure 11 shows a graphical representation of the relationship between K_s and soil water storage of equations 3.49 and 3.50; at increasing soil water depletion stress will be induced when water storage drops under $(TAW - RAW)$.

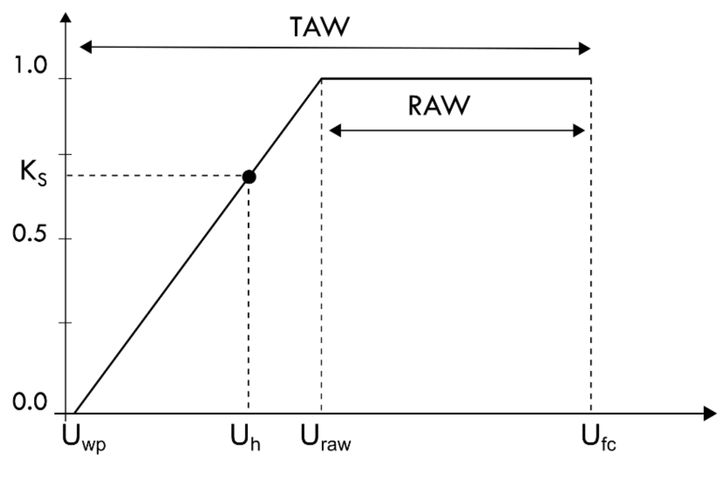

Figure 11: Water stress coefficient, K_s. Source: Allen *et al.* (1998).

3.5 Surface runoff

IdrAgra computes daily surface runoff volume using the Soil Conservation Service Curve Number method (SCS, 1972). The method 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 used in many hydrological models (see, e.g., the SWAT model, Neitsch et al., 2011).

The SCS curve number method computes the effective rainfall $P_{e,t}$ $(mm \cdot d^{-1})$, i.e. is the superficial rainfall excess in day t, by the following equation:

$$P_{e,t} = \frac{(P_t - I_a)^2}{P_t - I_a + S} \quad (3.53)$$

where 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 storage. It is defined as:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \quad (3.54)$$

where CN (-) is the Curve Number. In equation 3.54, 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 3.53 becomes:

$$P_e = \frac{(P - \lambda_{CN} \cdot S)^2}{P + 0.8S} \quad (3.55)$$

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 when not frozen: depth to water table, saturated hydraulic conductivity, and depth to a very slowly permeable layer. Soils can be grouped into four classes of runoff potential:

A. Low - 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 - 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 - 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 - 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.

CN class	Cover	Hydrologic Soil Group					
	Land use	Treatment or practice	Hydrologic condition	A	B	C	D
1	Fallow	Bare soil	---	77	86	91	94
		Crop residue cover[1]	Poor	76	85	90	93
			Good	74	83	88	90
2	Row crops	Straight row	Poor	72	81	88	91
			Good	67	78	85	89
3	Small grains	Straight row	Poor	65	76	84	88
			Good	63	75	83	87
4	Close-seeded or broadcast legumes or rotation	Straight row	Poor	66	77	85	89
			Good	58	72	81	85
5	Meadow – continuous grass, protected from grazing and generally mowed for hay	---	---	30	58	71	78
6	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):

$$CN_1 = CN_2 - \frac{20\cdot(100-CN_2)}{100-CN_2+e^{2.533-0.0636\cdot(100-CN_2)}} \quad (3.56)$$

$$CN_3 = CN_2 \cdot e^{0.0673\cdot(100-CN_2)} \quad (3.57)$$

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

The curve number varies with total soil water storage U_t (mm) as follows:

$$CN_x = \begin{cases} CN_1 & U_t \geq U_{wp,t} \\ \frac{CN_2 - CN_1}{U_{fc\_wp,t} - U_{wp,t}}\left(U_t - U_{wp,t}\right) + CN_1 & U_{wp,t} < U_t < U_{fc\_wp,t} \\ CN_2 & U_t = U_{fc\_wp,t} \\ \frac{CN_3 - CN_2}{U_{fc\_wp,t} - U_{wp,t}}\left(U_t - U_{fc\_wp,t}\right) + CN_2 & U_{fc\_wp,t} < U_t < U_{fc,t} \\ CN_3 & U_t = U_{fc,t} \\ \frac{CN_4 - CN_3}{U_{s,t} - U_{fc,t}}\left(U_t - \theta_{fc,t}\right) + CN_3 & U_{fc,t} < U_t < U_{s,t} \\ CN_4 & U_t \geq \theta_s \end{cases} \quad (3.58)$$

where CN_1 $(-)$, CN_2 $(-)$ and CN_3 $(-)$ are the CN values for moisture condition I, II and III curve numbers respectively, CN_4 $(-)$ is the value for moisture condition at saturation, equal to 95, $U_t = U_{E,t} + U_{T,t}$ (mm) is the soil water storage of the entire profile, $U_{wp,t}$, U_{fc} and U_s (all mm) are the soil water storages of the whole soil profile (first and second layer) at wilting point, at field capacity and at saturation, respectively, and $U_{fc\_wp,t}$ (mm) is the soil water storage at Antecedent Moisture Condition II:

$$U_{fc\_wp,t} = U_{wp,t} + \frac{2}{3}\left(U_{fc,t} - U_{wp,t}\right) \quad (3.59).$$

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:

$$CN_{2s} = \frac{CN_3 - CN_2}{3} \cdot \left(1 - 2 \cdot e^{-13.86 \cdot slp}\right) + CN_2 \quad (3.60)$$

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:

$$CN_x = \begin{cases} (CN)_{fallow} & \text{before plowing} \\ (CN)_{crop} & \text{between plowing and normal peak height} \\ 2(CN)_{crop} - (CN)_{fallow} & \text{between normal peak height and harvest time} \\ (CN)_{fallow} & \text{after harvesting} \end{cases} \quad (3.61)$$

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 previous paragraphs.

3.6 Spatial interpolation of meteorological and crop datasets

IdrAgra needs 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 algorithm allows the spatial interpolation of the variables from the point values that are available at the location of the meteorological stations. The 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 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:

$$z_{x,y} = \sum_{i=1}^{n} \frac{d_{x,y,i}^{-2}}{\sum_{i=1}^{n} d_{x,y,i}^{-2}} z_i = \sum_{i=1}^{n} w_{x,y,i} z_i \quad (4.62)$$

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). The values of the weights $w_{x,y,i}$ need to be provided as inputs to IdrAgra.

3.6.2 Spatial interpolation of crop parameters

For each cell in the domain, crop emergence, crop harvest and growing period duration are calculated from the *n* nearest meteorological stations. The value of each of the three parameters is computed as the weighted average of the corresponding values calculated by CropCoef at the *n* weather stations where the weights are proportional to the inverse of the squared distances of the cell from the stations.

Then, if the day of the simulation is between the emergence day and harvest day as defined above, the reference day $t_{x,y}$ to be used to extract the phenological parameters from the closest weather station is calculated as:

$$t_{x,y} = g_{x,y}^{e} + \left(t - g_{x,y}^{e}\right) d_{x,y} - iran_{x,y} \quad (4.63)$$

where $g_{x,y}^{e}$ $(-)$ is the emergence date in the (x, y) cell, t 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 a value randomly extracted between $\pm d_s$ days, with d_s defined in the simulation parameters (e.g., 10 days).

The weighting length factor is calculated as the ratio between the growing period duration at the closest weather station and the weighted averaged growing period duration considering again the n closest stations as in par. 3.6.1. Thus, if tab is the series of a phenological parameter of a crop respect to the closest weather station, on a specific cell of coordinate x,y, its value is:

$$tab_{x,y} = tab[t_{x,y}] \quad (4.64)$$

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 where irrigation is applied according to the user-defined irrigation practice (see § 4.1.4). The daily irrigation requirements of the individual cells can then 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 and withdrawn for irrigation use, possibly from multiple sources, and information about conveyance and distribution are fed into the model, that simulates the irrigation system functioning from the sources to the IUs and till the 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 water availability, therefore crop water stress may occur.

The module can also deal with unmonitored water sources (e.g. unmonitored pumping wells), 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 area, on the conveyance and distribution efficiencies from the sources to the IUs and to the individual cells, and on the irrigation methods and practices.

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

- MONITORED sources.
- UNMONITORED sources.

4.1.1 **MONITORED sources**

MONITORED sources include any irrigation water source for which the daily value of the water supply is directly monitored by a gaging station. For each source i, the timeseries of withdrawals $W_{i,t}$ (m^3) during each day t of the simulation period must be provided as input files (see Installation & Use manual for the input file format specifications).

4.1.2 **UNMONITORED sources**

UNMONITORED sources are irrigation water sources allow treating situations whose existence is known (or presumed) but for which data on the volumes daily withdrawn are not available. This is sometimes the case of private wells for which flow monitoring is often not compulsory or obligations are quite weak (e.g., annual withdrawals only are available).

IdrAgra provides an option to treat these sources which is based on the assumption that the daily water volume withdrawn by an unmonitored source depends on the conditions of the area that is supplied by the source itself, computed runtime by IdrAgra. The daily water volume is computed according to a set of parameters that define the operating rule according to which the withdrawal is determined. 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 unmonitored sources:

- **Collective**: the source provides water supply to one or more Irrigation Units; 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 typically managed collectively by an irrigation agency or consortium;
- **Private**: the source provides water supply to an individual cell or to a group of cells; this is typically the case of irrigation wells or small diversions from surface water that are owned and managed by an individual farmer, that can be present in large numbers in irrigated areas and for which it is often difficult to obtain precise information on the source characteristics (e.g. pump capacity) and operation.

In the case of **Collective UNMONITORED sources,** it is assumed that the decision on the daily amount of water withdrawal is taken based on the soil moisture conditions of the N_{CU} irrigable cells in the command area supplied by the source. Specifically, the weighted mean value $\overline{DU_t}$ of the soil storage deficit 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:

$$\overline{DU_t} = \sum_{i=1}^{N_{CU}} DU_{t,i} \frac{T_{c,t,i}}{\sum_{i=1}^{N_{CU}} T_{c,t,i}} = \sum_{i=1}^{N_{CU}} \left(U_{fc,t,i} - U_{t,i}\right) \frac{T_{c,t,i}}{\sum_{i=1}^{N_{CU}} T_{c,t,i}} \quad (4.1)$$

where $U_{t,i}$ (mm) is the sum of the soil water storages in the first and second layer of cell i weighted with the corresponding root fraction, $U_{fc,t,i}$ (mm) is the soil water storage of whole soil profile (first plus second layer) at field capacity weighted in the same way, $T_{c,t,i}$ (mm) is the potential crop transpiration of cell i during time step t.

The withdrawal from the source is activated only if the $\overline{DU_t}$ drops below a fraction the of the weighted average value of the readily available water $\overline{RAW_t}$

$$\overline{RAW_t} = \sum_{i=1}^{N} p_{t,i}\left[RF_{E,t,i}\left(U_{E,fc,t,i} - U_{E,wp,t,i}\right) + RF_{T,t,i}\left(U_{T,fc,t,i} - U_{T,wp,t,i}\right)\right] \frac{T_{c,t,i}}{\sum_{i=1}^{N} T_{c,t,i}} \quad (4.2)$$

where $U_{E,wp,t,i}$ and $U_{T,wp,t,i}$ (mm) are the soil water storage of the first and second layer at wilting point at time t in cell i, $U_{E,fc,t,i}$ and $U_{T,fc,t,i}$ (mm) are the analogous values at field capacity, and $p_{t,i}$ $[0-1]$ $(-)$ is the fraction of TAW that can be depleted from the root zone of cell i before moisture stress occurs.

The activation can be partial or complete, depending on the value of $\overline{DU_t}$. IdrAgra considers four stages of withdrawal activation through the coefficient ϕ_{CU}:

$$\phi_{CU} = \begin{cases} 0 & \text{if } \overline{DU_t} \geq \alpha_{CU,0}\overline{RAW_t} \\ \phi_{CU,1} & \text{if } \alpha_{CU,2}\overline{RAW_t} < \overline{DU_t} \leq \alpha_{CU,1}\overline{RAW_t} \\ \phi_{CU,2} & \text{if } \alpha_{CU,3}\overline{RAW_t} < \overline{DU_t} \leq \alpha_{CU,2}\overline{RAW_t} \\ 1 & \text{if } \overline{DU_t} \leq \alpha_{CU,3}\overline{RAW_t} \end{cases} \quad (4.3)$$

Where $\alpha_{CU,0}$, $\alpha_{CU,0}$, $\alpha_{CU,0}$, $\alpha_{CU,0}$ (with $0 \leq \alpha_{CU,0} < \alpha_{CU,1} < \alpha_{CU,2} < \alpha_{CU,3} \leq 1$) and $\phi_{CU,1}$, $\phi_{CU,2}$ (with $0<\phi_{CU,1}<\phi_{CU,2}<1$) are user defined parameters. The actual withdrawal $Q_{CU,t}$ $(m^3 s^{-1})$ is then calculated as:

$$Q_{CU,t} = \phi_{CU} Q_{CU}^{MAX} \quad (4.4)$$

where Q_{CU}^{MAX} $(m^3 s^{-1})$ is the maximum admissible (according to the license) or feasible (depending on pump characteristics) daily withdrawal volume.

Water withdrawals from a **Private UNMONITORED source** are determined assuming that in each cell i where this type of source is active, irrigation application is triggered based on two conditions: (1) the cell will not receive a supply from any collective source in the next days, i.e. it does not fall within the cells potentially irrigable within a number of days in the future specified for each IU, and (2) the water storage deficit of the cell exceeds a fraction $\alpha_{PU,i}$ $(-)$ of the readily available water:

$$U_{fc,t,i} - U_{t,i} > \alpha_{PU,i}\left(U_{fc,t,i} - U_{wp,t,i}\right)p_{i,t} \quad (4.5)$$

If both conditions are met, the water withdrawal is equal to irrigation water depth set for the cell, according to the irrigation method and application triggering criterion as illustrated in section 4.1.4. Conveyance and distribution losses are not considered in the IdrAgra simulation of Private UNMONITORED sources; these losses can be easily accounted by post-processing the IdrAgra simulation results if the values of conveyance and distribution efficiencies are available; it can be observed, however, that often these sources are close to the destination cells and therefore they are small and can be neglected. Moreover, IdrAgra provides in output the withdrawal for each cell where a Private UNMONITORED source is active; if one source supplies more than one cell aggregation of daily volume at the source needs to be carried out by the user, again post-processing the simulation results.

4.1.3 **Irrigation water conveyance and distribution**

The command area of each water source w is subdivided into **Irrigation Units (IU)**, each entitled of a share $\varepsilon_{w,j}$ $(-)$ of the withdrawn discharge $Q_{w,t}$ at time step t. The actual water supply $Q_{act,j,t}$ $(m^3 s^{-1})$ of source w to IU j in time step t is calculated as:

$$Q_{act,j,t} = \eta_{conv,w,j}\varepsilon_{w,j}Q_{w,j,t} \quad (4.6)$$

where $\eta_{conv,w,j}$ is the conveyance and distribution efficiency of the hydraulic path from source w to the fields in IU j, assumed constant for all the fields in the IU. If the j^{th} IU receives water from multiple sources, the total volume supplied to the IU is given by:

$$Q_{act,j,t} = \sum_{w=1}^{N_{s,j}} \eta_{conv,w,j}\varepsilon_{w,j}Q_{w,t} \quad (4.7)$$

where $N_{s,j}$ is the total number of sources supplying the j^{th} IU.

The distribution of the irrigation volume delivered from MONITORED and collective UNMONITORED sources. to an IU among the individual cells is then simulated by IdrAgra through a method that replicates the mechanism of **distribution on rotation** (Figure 12). In each day the method:

- computes the total water volume available in the irrigation unit as the sum of volumes supplied by MONITORED and collective UNMONITORED water sources;
- scans the irrigable cells of the IU starting from the last one reached in the previous day, checking if irrigation is needed according to the specific triggering criterion of each cell (see next section) and applying irrigation or not accordingly;
- updates the cumulated actual use (water actually applied on the fields) and the cumulated potential use (water potentially applicable on the fields, even if not actually applied;

- stops the daily routine when the cumulated potential use exceeds the available water volume in the case of rigid rotation of the irrigation distribution among the fields; if a degree of flexibility is allowed, stops the routine when either the cumulated actual use or the cumulated potential use times a flexibility factor ($\alpha_{flex} > 1$) exceed the available water volume.

Note that if the available water volume is not completely used, the surplus left at the end of the day is summed to irrigation supply delivered in the following day. The surplus is saved in the simulation output files.

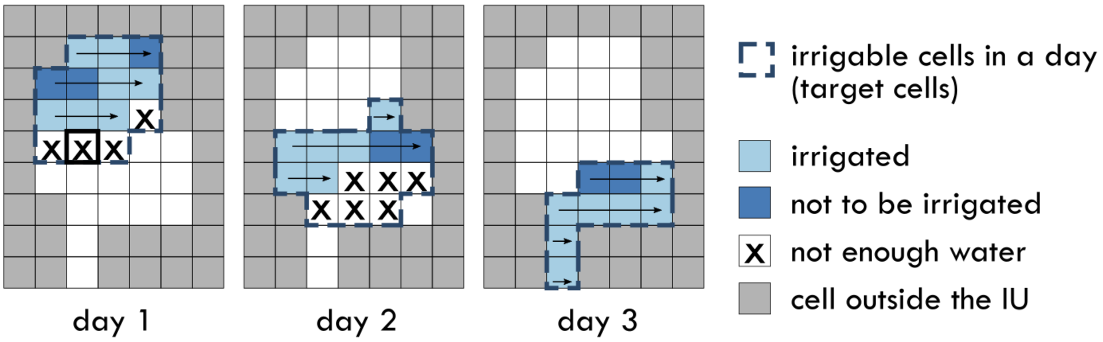

Figure 12: IdrAgra simulation of irrigation water distribution on-rotation in a IU in two consecutive days.

4.1.4 Irrigation application

The final decision if a cell i is irrigated or not in day t and the way in which water is applied onto the cell are defined by the irrigation activation criterion and by the application method, respectively.

The activation criterion is the rule according to which irrigation is required or not by a cell. In IdrAgra a cell requires irrigation 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. if the water storage deficit of the cell exceeds a fraction $\alpha_{M,i}$ $(-)$ of the readily available water:

$$U_{fc,t,i} - U_{t,i} > \alpha_{M,i}\left(U_{fc,t,i} - U_{wp,t,i}\right)p_{i,t} \tag{4.8}$$

where $U_{t,i} = RF_{E,t}U_{E,t,i} + RF_{T,t}U_{T,t,i}$ (mm) is the total soil water storage in cell i weighted with root fractions, $U_{fc,t,i}$ (mm) is the weighted soil water storage of the whole soil profile (first plus second layer) at field capacity.

When irrigation application is triggered, the application depth in cell i is set to a fixed value $H_{irr\_f,i}$ (mm) and provided directly as a number (e.g., 30 mm). A different approach is followed only in the case of paddy fields, as described in par. 4.3.

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 crop irrigation needs for each cell are obtained first, by solving the hydrological balance equation of the two layers with the user-defined irrigation method and activation criterion, and then they can be eventually cumulated at the irrigation unit scale and at the individual water sources considering the distribution and conveyance efficiencies.

During the NEED simulation, irrigation application in cell i is triggered by the criterion of equation (4.8). Irrigation application characteristics are also defined as in the case of the USE simulation (see sec. 4.1.4), therefore the irrigation depth $H_{irr,t,i}$ (mm) in cell i can either assume a fixed value $H_{irr\_f,i}$ or it can be computed by equation:

$$H_{irr,t,i} = \frac{U_{fc,t,i} - U_{t,i}}{\eta_{irr,i}} \qquad (4.9).$$

where $\eta_{irr,i}$. is the irrigation method efficiency. Further specifications of the irrigation application practice must be defined as already illustrated in sec.4.1.4. Only in the case of paddy fields a different approach is followed, as described in the next paragraph.

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

4.3 Specifications for paddy fields

In paddy fields the daily amount of irrigation is derived under the assumption that at the onset of the irrigation season the fields are flooded and then the flooding depth is maintained constant, i.e. that irrigation compensates the evapotranspration and percolation losses. Moreover, irrigation is considered active only from emergence till the end of mid-season. Therefore, irrigation is articulated in three stages: flooding; maintenance; depletion. The change of stage is determined by checking the value of the basal crop coefficient $K_{cb,t}$:

- field is flooded in the day t_f when $K_{cb,t_f-1} = 0$ and $K_{cb,t_f} > 0$;
- maintenance goes from day t_f to day t_m when $K_{cb,t_m} > K_{cb,t_{m+1}}$;
- depletion goes from day t_m to day t_d when $K_{cb,t_d-1} > 0$ and $K_{cb,t_d} = 0$.

Therefore, the irrigation depth $H_{irr,h}$in each of the twenty-four hourly time steps h of the generic day t is computed as:

$$H_{irr,h} = \begin{cases} 0 & \text{if } t_m < t < t_f \\ H_{flood}/24 + \left(U_{s,E} - U_{E,h}\right) + \left(U_{s,T} - U_{T,h}\right) + \left(10K_{s,T} + E_{i,h-1} + T_{i,h-1} + T_{T,h-1}\right) - P_{eff,h} & \text{if } t = t_f \\ \max\left[0; \left(10K_{s,T} + E_{h-1} + T_{E,h-1} + T_{T,h-1}\right) - P_{eff,h}\right] & \text{if } t_f < t < t_m \end{cases} \qquad (4.10)$$

where H_{flood} (mm) is the water depth in the field at the end of day t_f, $P_{eff,h}$ (mm) is the effective rainfall in time step h day t, $K_{s,T}$ $(cm\ h^{-1})$ is the saturated hydraulic conductivity of the transpirative layer, E_h, $T_{E,h}$ and $T_{T,h}$ (mm) are the evaporation and transpirations from the first and second layer, respectively.

4.4 Irrigation application duration and water losses

The irrigation event commonly has a duration of few hours. IdrAgra permits to define the event duration and timing within the day (e.g., starting at 6 am for 4 hours).

When a fixed volume of water is applied (i.e. USE mode and NEED mode fixed volume) a loss rate coefficient $\alpha_{loss,t}$ $(-)$ can be applied to account for possible losses prior or post application of irrigation to the field. The coefficient is defined through the following equation:

$$\alpha_{loss,t} = a_{loss} + b_{loss} \cdot u_{2,t} + c_{loss} \cdot \mathrm{T}_{mean,t} \qquad (4.11)$$

where $\mathrm{T}_{mean,t}$ ($°C$) and $u_{2,t}$ ($m \cdot s^{-1}$) are respectively the mean air temperature and wind speed at $2\ m$ height in day t, and a_{loss}, b_{loss} and c_{loss} are parameters set by the user according to the irrigation method characteristics. The equation accounts for the factors affecting evaporation and drift losses typical of sprinkler irrigation, but it can account also for tailwater losses typical of surface irrigation methods by assuming that they are proportional to the irrigation volume supplied (i.e., by assigning a positive value to a_{loss} - $0 \leq a_{loss} < 1$ - and setting $b_{loss} = 0,\ c_{loss} = 0$).

IdrAgra allows defining different irrigation application specifications for each cell of the study area.

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 includes some additional elements derived from the AEZ methodology (IIASA/FAO, 2012).

5.1 Biomass

The biomass B produced cumulatively ($t \cdot ha^{-1}$) is calculated as (Steduto et al., 2012):

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

where WP^*_{adj} is the water productivity parameter ($t \cdot ha^{-1}$), T and ET_0 are the actual daily crop transpiration (mm) and the reference crop potential evapotranspiration, respectively (both mm), and the summation extends over a whole agricultural season. WP^*_{adj} 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 the CropCoef module and is an input to the IdrAgra simulation.

5.2 Water stress yield reduction factor

Water stress response is modelled by the same approach used in IIASA/FAO (2012). Yield reduction in response to water deficits is calculated as a function of the actual and potential crop transpiration T_a and T_m (both $mm \cdot d^{-1}$), both accumulated over each of the four crop stages and over the whole crop cycle.

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, …, ky_4) and an average ky value for the overall crop cycle (ky_0) are applied.

Water-stress yield reduction factor, f_C , is than calculated as:

$$f_C = \min(fc^{WC}, fc^{CS}) \tag{5.2}$$

where:

$$fc^{WC} = 1 - ky_0 \left(1 - \frac{\sum_{t=d_0}^{d_5} T_{a,t}}{\sum_{t=d_0}^{d_5} T_{m,t}}\right) \tag{5.3}$$

$$fc^{CS} = \prod_{j=1}^{4} \left[1 - ky_j \left(1 - \frac{\sum_{t=d_{j-1}}^{d_j} T_{a,t}}{\sum_{t=d_{j-1}}^{d_j} T_{m,t}}\right)\right]^{\lambda_j} \tag{5.4}$$

d_o indicates the starting day of the crop cycle, while d_1, d_2, d_3, d_4 are the final days of each of the four development stages; λ_j coefficients add to one and are taken as the length of each crop development stage relative to the duration of the whole crop cycle. Hence, f_c is taken as the minimum of factor fc^{WC}, representing the effect of the overall water deficit during the Whole Cycle of the crop, 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, defined as the days between $0.45GPL$ and $0.75GPL$, where GPL stands for growing period length of the considered crop:

$$f_{HS_t} = \begin{cases} 1 & \mathrm{T}_t < \mathrm{T}_{crit} \\ 1 - \frac{\mathrm{T}_t - \mathrm{T}_{\mathrm{crit}}}{\mathrm{T}_{lim} - \mathrm{T}_{crit}} & \mathrm{T}_{crit} \leq \mathrm{T}_t \leq \mathrm{T}_{lim} \\ 0 & \mathrm{T}_t \geq \mathrm{T}_{lim} \end{cases} \tag{5.5}$$

$$f_{HS} = \frac{\sum_{t=1}^{TSP} f_{HS_t}}{TSP} \tag{5.6}$$

where T_t is the mean diurnal temperature (Chow & Levermore, 2007) in day t of the thermal sensitive period ($°C$), T_{crit} and T_{lim} are, respectively, a crop specific critical temperature threshold ($°C$) and limit temperature threshold ($°C$), and TSP (day) is the duration of the thermal sensitive period.

5.4 Potential and actual yield

For most crops, only part of the biomass produced is partitioned to the harvested organs. Indicating with Y_p $(t \cdot ha^{-1})$ the potential yield and with B $(t \cdot ha^{-1})$ the total crop biomass one can write:

$$Y_p = HI_0 \cdot B \tag{5.7}$$

where HI_0 (-), known as harvest index, is the ratio of yield to biomass.

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

$$Y_a = Y_p \cdot \min(f_C, f_{HS}) \tag{5.8}$$

where Y_p is the potential crop yield calculated using equation 5.7, 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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