Release Note AquaCrop

Version 7.3
July 2026

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Abstract

Updates

1. Adjustment for ageing of the maximum crop transpiration coefficient ($Kc_{Tr,x}$)

The linear daily decrease of $Kc_{Tr,x}$ is replaced by an exponential decrease which decline is specified by an itemized cumulative decrease at maturity.

2. Updated root zone expansion

In AquaCrop, the root zone expansion can be restricted by crop water stress, a too dry subsoil or by the restricted permeability of a soil horizon. In previous versions of AquaCrop the expansion rate, after a period of restriction, was too much reduced so that the maximum rooting depth could no longer be reached during the season. In Version 7.3 the expansion rate after a period of restriction is higher, and remains so as long as the maximum rooting depth is not yet reached.

3. Updated water extraction in root zone

The amount of water that can be extracted out of the various compartments of the root zone is determined by the specified extraction period.

4. Premature end of the growing period of annual crops

Since annual crops are unlikely to survive a cold winter period, the crop may be killed before maturity is reached when planted too late in the season. In AquaCrop version 7.3, the user can specify a date at which the growing period will end when it gets too cold to reach maturity before winter sets in.

5. Time aggregation of the daily output

In AquaCrop version 7.3 it is possible to aggregate daily results into periods of 10 days or months. Until now, this option was only available in the stand-alone (plugin) versions of AquaCrop.

6. Frequency analysis

When running a simulation, the simulation results which are updated at the end of each daily time step are available in the Simulation Run menu. In Version 7.3, an extra button in the control panel of the Simulation Run menu, gives access to a series of new menus in which a frequency analysis of the simulation results can be performed. The results of the frequency analysis can provide information for the design of irrigation charts, to improve irrigation and/or field management, to study the effect of climate change, etc.

7. Specifying the end of the irrigation period

Since irrigation is typically stopped a few days before maturity, version 7.3 now includes an option to explicitly specify the end of the irrigation period. This option is available when generating an irrigation schedule

8. Determination of soil hydraulic properties from soil texture

9. Updated annual CO_2 concentrations at Mauna Loa

The observed CO_2 concentrations up to 2025 have been updated with the latest published results on the NOAA website.

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1. Adjustment for ageing of the maximum crop transpiration coefficient ($Kc_{Tr,x}$)

$Kc_{Tr,x}$ is the coefficient for maximum crop transpiration in a well-watered soil and complete canopy (CC = 1).

1.1 Several adjustments of KcTr,x when running a simulation

When running a simulation, AquaCrop will adjust $Kc_{Tr,x}$;

- **for ageing:** the canopy ages slowly and undergoes a progressive though small reduction in transpiration and photosynthetic capacity;
- **during senescence**: when senescence is triggered, the transpiration and photosynthetic capacity of the green portion of the canopy drops markedly with time;
- **for elevated [CO_2]:** the overall transpiration response to elevated [CO_2] is relatively small but significant.

1.2 Simulation of ageing in Version 7.2 and previous

After the time t_{CCx} required to reach CC_x under optimal conditions and before senescence, the canopy ages slowly and undergoes a progressive though small reduction in transpiration and photosynthetic capacity (Fig. 1.1). This is simulated by applying an adjustment factor (f_{age}) that decreases $Kc_{Tr,x}$ by a constant and slight fraction per day, resulting in an adjusted crop coefficient. The ageing comes in effect at t_{CCx} which is the time when CC_x (maximum canopy cover) would have been reached without water stress (i.e. at the beginning of the mid-season). A short lag phase of 5 days is assumed. After the lag phase of 5 days, $Kc_{Tr,x,adj}$ is given by:

$$Kc_{Trx,adj} = Kc_{Tr,x} - (t-5)\, f_{age}\, CC_x \qquad \text{(Eq. 1.1)}$$

where t is the time in days after t_{CCx} (t is zero before and at t_{CCx}), and f_{age} is the reduction expressed as a fraction of CC_x. The f_{age} coefficient is a crop parameter, since it will require some adjustment for annual crops such as sugarcane.

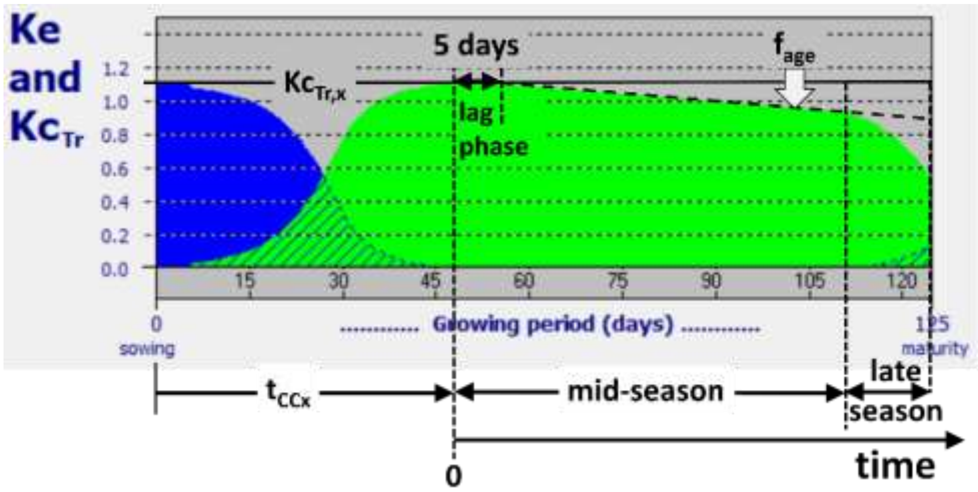


Figure 1.1 – Crop transpiration coefficient Kc_{Tr} (green shape) throughout the crop cycle for $Kc_{Tr,x}$ = 1.1, CC_x = 100%, and f_{age} 0.30%/day

The same applies for forage and pasture crop. However, since the canopy is harvested at each cut, a new canopy has to develop which cancels the ageing. Once CC_x is reached after a cutting, the ageing kicks in again and is described by Eq. 1.1.

Table 1.1 shows, for the calibrated crops available in the database of AquaCrop (Vers. 7.2),:

- the specified f_{age} coefficient;
- the specified total length of the mid and late season in calendar days (L_{season}: starting at t_{CCx} until maturity);
- the specified maximum canopy cover (CCx);
- the calculated cumulative decrease at crop maturity of $Kc_{Tr,x}$ (Eq. 1) due to ageing (= f_{age} (L_{season}-5days) CCx) .

Table 1.1 – The specified f_{age}, the specified total length of the mid and late season (L_{season}), the specified maximum canopy cover (CCx), and the calculated cumulative decrease at crop maturity of $Kc_{Tr,x}$ due to ageing, for the calibrated crops in the crop data base of AquaCrop (Version 7.2)

Crop	**f_{age}**	**L_{season}**	**CCx**	**Calculated cumulative decrease at crop maturity f_{age} (L_{season} – 5 days) CCx**
	[%/day]	**[days]**	**[%]**	**[%]**
Group 1: [f_{age} (L_{season}-5days) CCx] ≈ 18 %				
Cotton	0.30	62	98	17
Maize	0.30	78	96	21
Soybean	0.30	58	98	16
Sunflower	0.30	71	98	19
Dry beans	0.30	51	99	14
Group 2: [f_{age} (L_{season}-5days) CCx] ≈ 9 %				
Quinoa	0.15	107	75	11
Potato	0.15	65	92	8
Rice	0.15	58	95	8
Sugar beet	0.15	69	98	9

Tomato	0.15	47	75	5
Wheat	0.15	78	96	11
Barley	0.15	28	80	3
Sorghum	0.30	42	90	10
Tef	0.30	44	81	9
Alfalfa	0.05	217	95	10
Casava	0.05	260	95	12
Average (Group 1 and 2)	**0.20**	**83**		**11**
Sugar cane	0.15	301	95	42

Comments:

- For the calibrated perennial crops (alfalfa and cassava), which have a long season, a small value for f_{age} was considered: 0.05 %/day;
- For the calibrated annual crops, the specified f_{age} is either 0.30 or 0.15 %/day;
- The value of f_{age} for sugar cane is out of range;
- When calculating the cumulative decrease at crop maturity [= f_{age} (L_{season} – 5days) CCx], two main groups can be distinguished: Group 1 with a cumulative decrease at crop maturity of approximately 18%, and Group 2 with a cumulative decrease of approximately 9%.

1.3 Update in Version 7.3

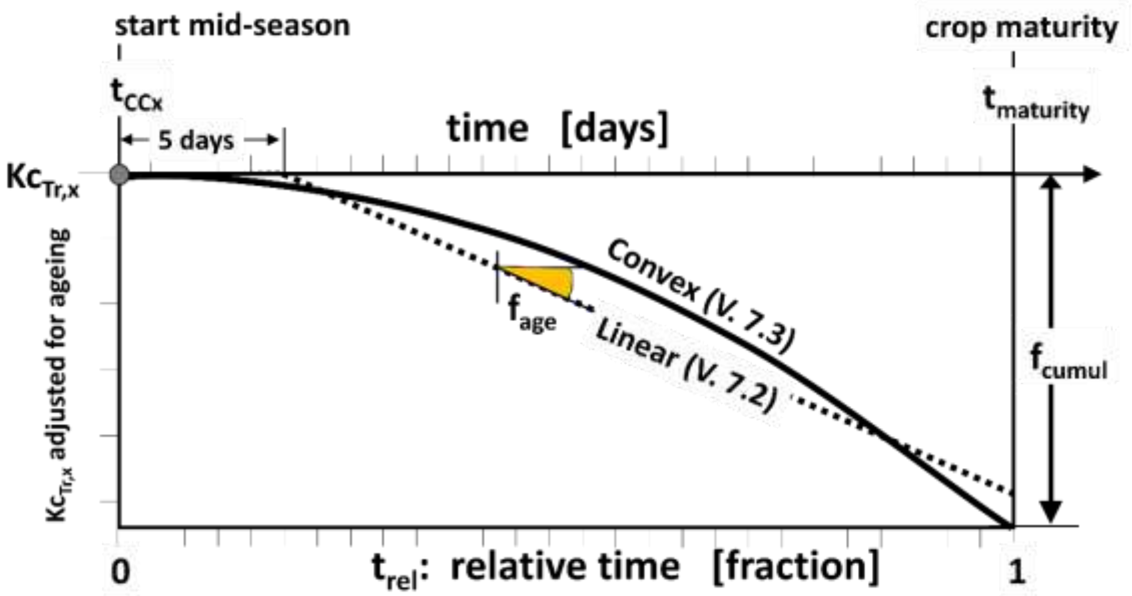


Figure 1.2 – Convex (bold line) decrease of the coefficient for maximum crop transpiration ($Kc_{Tr,x}$) as a result of ageing between the start of mid-season until crop maturity, and the linear decrease (dashed line) considered in previous versions of AquaCrop (Version 7.2 and previous).

- The linear decrease of $Kc_{Tr,x}$ (f_{age}) is replaced by an exponential decrease (Fig. 1.2).
- The decrease starts immediately at t_{CCx} which is the time when CC_x (maximum canopy cover) would have been reached without water stress (i.e. at the start of the mid-season). The 5-day lag phase no longer applies, since the convex shape of the curve captures that lag phase.
- The f_{age} (the decrease of $Kc_{Tr,x}$ per day) is replaced by f_{cumul} which is the cumulative decrease at crop maturity of $Kc_{Tr,x}$ due to ageing (Fig. 1.2).

$$Kc_{Trx,adj} = Kc_{Tr,x} - \left[\frac{\left(e^{f_{shape}\ t_{rel}} - 1\right)}{\left(e^{f_{shape}} - 1\right)}\right]\ f_{cumul}\ CC_x \qquad \text{(Eq. 1.2)}$$

where
$Kc_{Trx,adj}$	adjusted coefficient for maximum crop transpiration [-]
$Kc_{Tr,x}$	coefficient for maximum crop transpiration [-]
t_{rel}	relative time [-] between start of mid-season (t_{CCx}) and crop maturity
f_{shape}	shape factor (fixed at 1) [-]
f_{cumul}	cumulative decrease at crop maturity of $Kc_{Tr,x}$ due to ageing [-]
CCx	maximum green canopy cover [-]

For the calibrated crops available in the data base of AquaCrop (Table 1), the update in Version 7.3 is compared with the linear decrease (Version 7.2 and previous) in Figures 1.3 for a cumulative decrease (f_{cumul}) of 11% at maturity

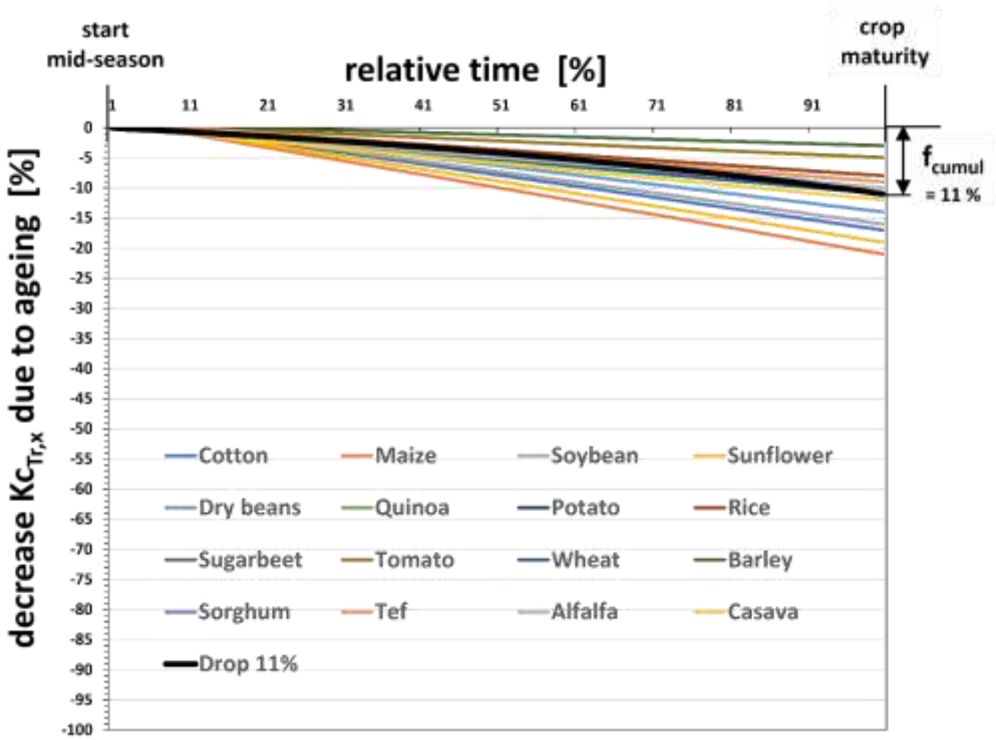


Figure 1.3 – Linear decrease (colored lines) and Convex decrease (black bold line) for a cumulative decrease of 11% at maturity, of the coefficient for maximum crop transpiration ($Kc_{Tr,x}$) as a result of ageing between the start of mid-season and crop maturity for all crops in the database of AquaCrop (Table 1.1).

1.4 Default value for f_{cumul}

The effect on crop transpiration, biomass production and crop yield between Version 7.2 and previous (with a linear decrease of $Kc_{Tr,x}$) and Version 7.3 (with the exponential decrease of $Kc_{Tr,x}$) are insignificant when a f_{cumul} of 11% at crop maturity is considered for all calibrated crops.

In Figures 1.4 and 1.5, simulation results obtained with Version 7.2 and 7.3 are compared:

- Figure 1.4: the calculated seasonal crop transpiration normalized for ETo (i.e. Σ(Tr/ETo)) in the absence of temperature, water, salt or soil fertility stress for the 16 calibrated crops in the database of AquaCrop (Table 1.1). A constant ETo and a Tmax of 28°C and Tmin of 12°C, where considered in the calculation.
- Figure 1.5: the simulated crop yield of rainfed winter wheat for 22 successive years (1979 – 2001) in Tunis on a sandy loam. The sowing was generated by considering the first occurrence of 20 mm in 4 days starting from 1 October (rainfall criterion) and a moderate soil fertility was assumed. The simulation started on 1 August with the soil profile at permanent wilting point.

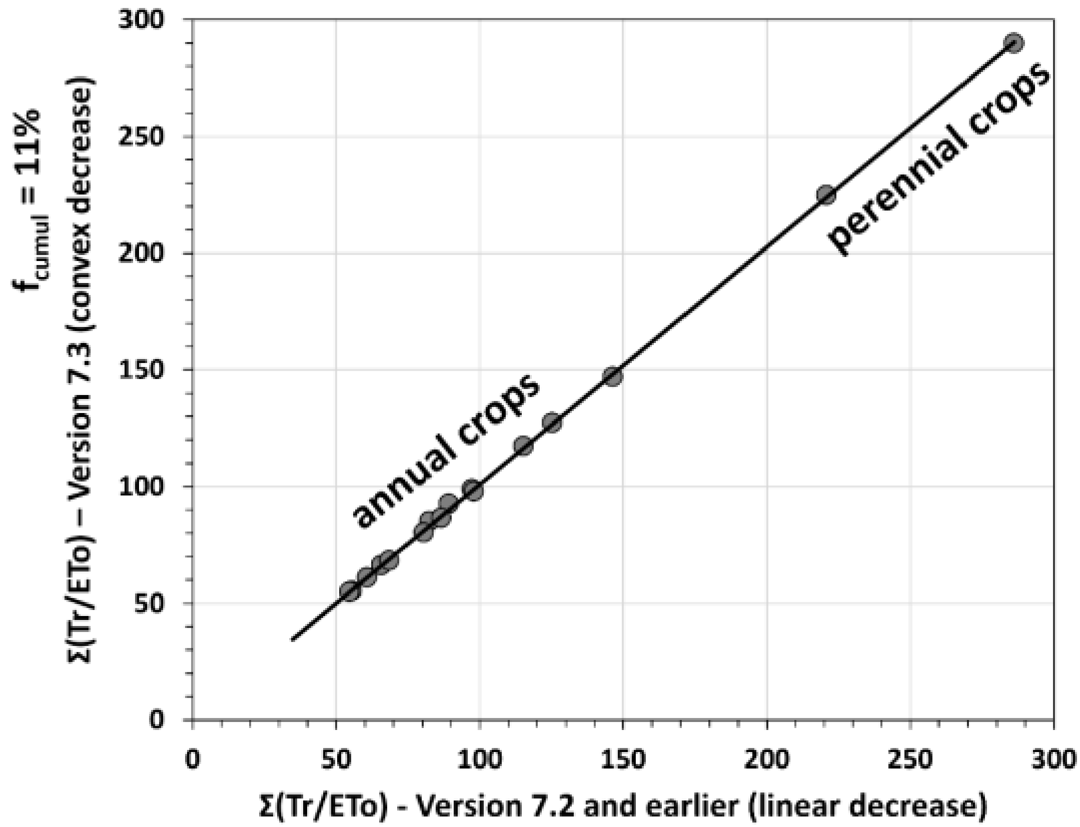


Figure 1.4 – Seasonal crop transpiration normalized for ETo (i.e. Σ(Tr/ETo)) for the 16 calibrated crops in the database of AquaCrop (Table 1.1) in the absence of temperature, water, salinity and soil fertility stress.

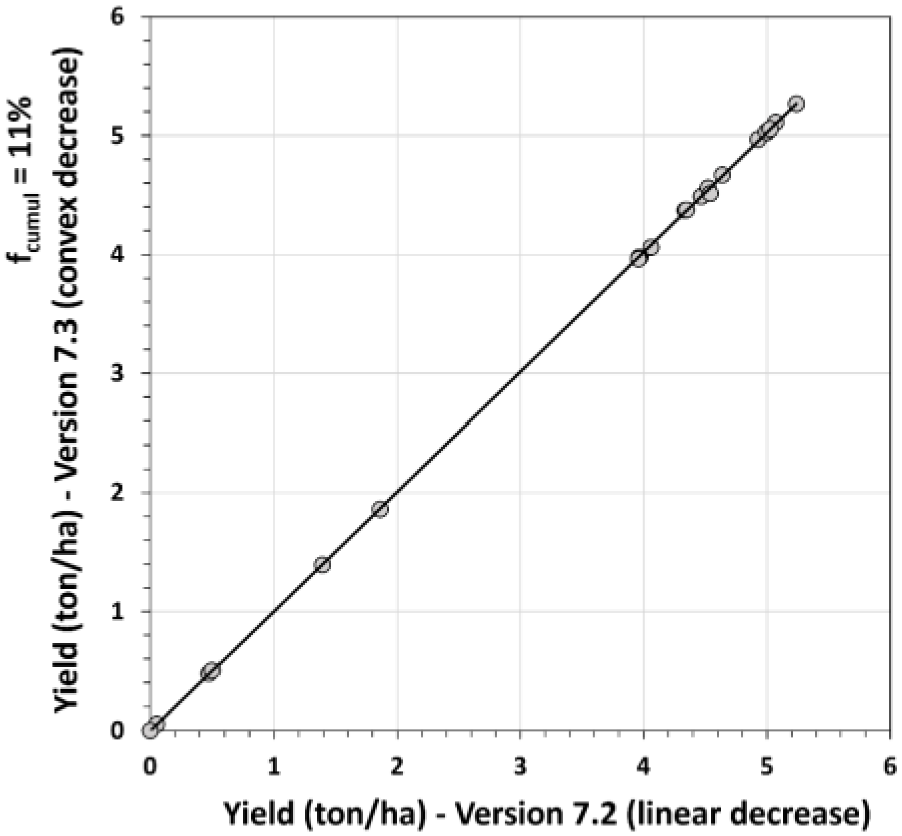


Figure 1.5 – Simulated crop yield of rainfed winter wheat in Tunis for 22 successive years with moderate soil fertility.

1.5 Conclusions

- The exponential decline for ageing better mimics the fact that more leaves will age over time than the linear decline;
- By running simulations with a fixed value of 11% for f_{cumul} for all calibrated crops, differences in the simulation results between Version 7.2 and 7.3 are insignificant;
- By specifying the cumulative decrease at maturity due to ageing, the ageing coefficient (f_{cumul}) may be easier to estimate. In the previous versions (V7.2), the user had to take into account the length of the season in calendar days when determining f_{age} (expressed in fraction per day);
- A value of 11% for f_{cumul} is used as default for all crops, but the user is still be able to fine-tune the value if required for calibration (Fig. 1.6);
- Because the decrease is expressed as a function of relative time (t_{rel} in Eq. 1.2), the ageing procedure can directly be used when simulating in growing degree days (no longer need to temporarily switch for the calculation of ageing to the calendar day mode).

1.6 Specification in AquaCrop

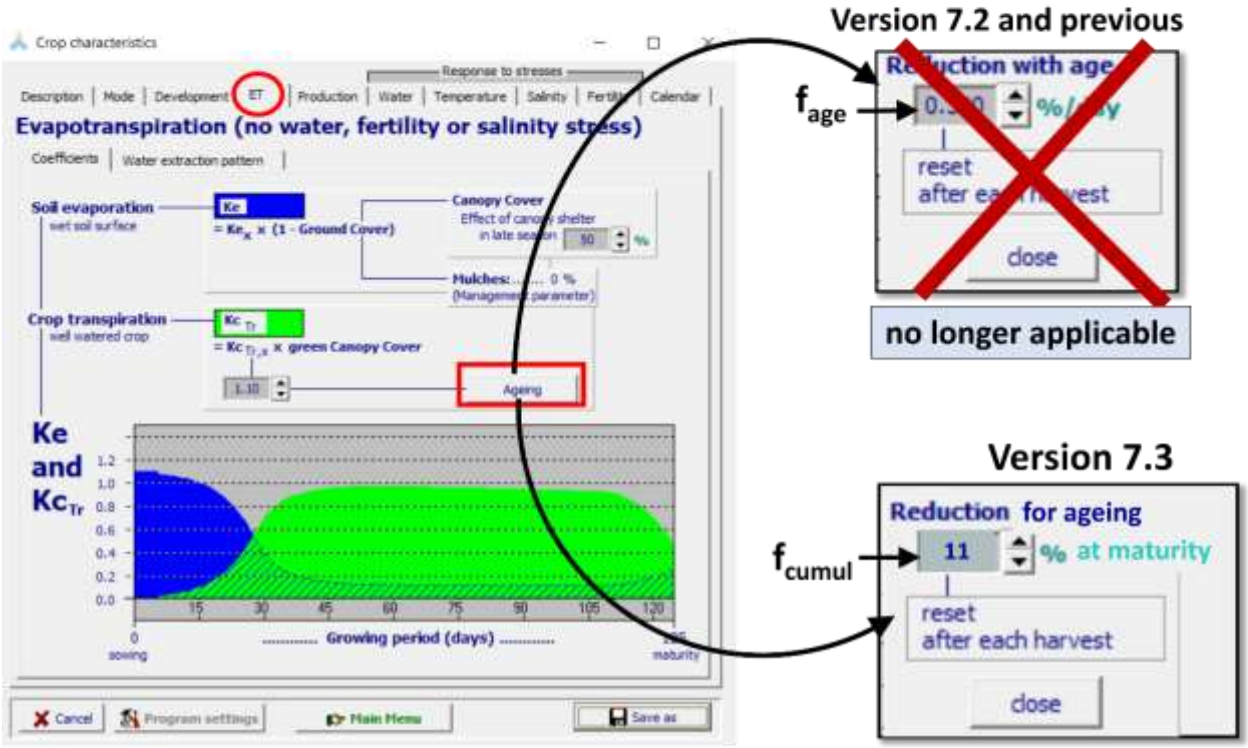


Figure 1.6 – Pop-up window in the *Crop characteristics menu* for the specification of the ageing coefficient: f_{age} in Version 7.2 (no longer applicable) and f_{cumul} in Version 7.3

2. Updated root zone expansion

2.1 Expansion of the root zone when not restricted

The expansion of the effective rooting depth (Z) in a well water soil is simulated by considering an exponential root deepening function till the maximum rooting depth (Z_x) is reached. In AquaCrop the development of the rooting depth is simulated by considering the n[th] root of time. Once half of the time required for crop emergence (or plant recovery in case of transplanting) is passed by ($t_0/2$), the rooting depth starts to increase from an initial depth Z_o till the maximum effective rooting depth Z_x is reached:

$$Z = Z_o + (Z_x - Z_o)\sqrt[n]{\frac{\left(t - \frac{t_0}{2}\right)}{\left(t_x - \frac{t_0}{2}\right)}} \qquad \text{(Eq. 2.1)}$$

where Z effective rooting depth at time t [m];
Z_o starting depth of the root zone expansion curve [m];
Z_x maximum effective rooting depth [m];
t_o time to reach 90 % crop emergence [days or growing degree days];
t_x time after planting when Zr_x is reached [days or growing degree days];
t time after planting [days or growing degree days];
n shape factor.

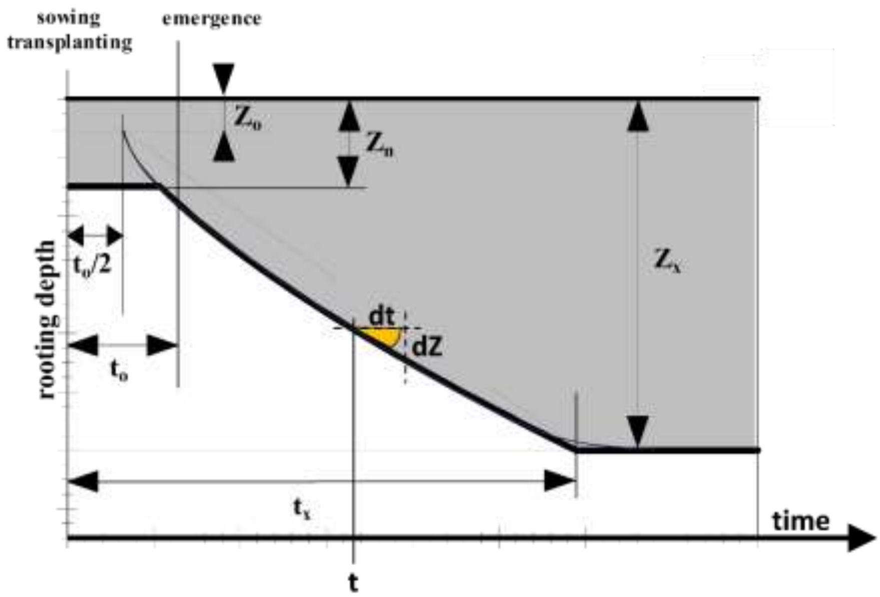


Figure 2.1 – Development of the effective rooting depth (shaded area) from sowing till the maximum effective rooting depth (Z_x) is reached with an indication of the root zone expansion rate (dZ/dt) at time t.

The development of the effective root zone starts when Z exceeds the minimum effective rooting depth (Z_n) and advances till the maximum effective rooting depth (Z_x) is reached (Fig. 2.1). At any time the effective rooting depth Z is given by

$$Z_n \leq Z \leq Z_x \quad \text{(Eq. 2.2)}$$

The shape factor n, which is crop specific, determines the decreasing speed of the root zone expansion in time. For values larger than 1, the expansion of the root zone is more important just after planting than later in the season. The larger the value of n, the stronger the discrepancy between the expansion rates at the beginning and end of the period for root zone expansion. The expansion of the effective root zone is constant (linear) when n is 1.

The starting depth of the root zone expansion curve Z_o is a program parameter and expressed as a fraction of Z_n. The average expansion rate of the effective root zone can never exceed a maximum value (fixed at 5 cm/day).

2.2 Simulation of the root zone expansion when restricted

In AquaCrop the root zone expansion is restricted:
- when soil water stress in the root zone starts to affect crop transpiration;
- when the soil water content in the sub soil (below the expanding root zone) is too dry;
- in soil horizons which permeability restricts root zone expansion.

This is simulated by reducing the non-restrictive root zone expansion (dZ) with a reduction factor (f_{red})

$$dZ_{adj} = f_{red}\ dZ \quad \text{(Eq. 2.3)}$$

Where dZ_{adj}: the adjusted expansion;
f_{red} : reduction factor varying between 0 (when root zone expansion is completely halted) and 1 (when root zone expansion is not affected).

As described in the reference manual, the reduction factor (f_{red}) is expressed as a function of
- the stomatal stress coefficient Ks_{sto} (in case of water stress);
- the soil water content in the sub soil (in case of a dry subsoil)
- the penetrability of the soil layer (in case of restrictive soil horizons)

2.2.1 Previous versions of AquaCrop (Version 7.2 and earlier)

In previous versions of AquaCrop, the non-restrictive expanding rate (dZ/dt) at any time, is given by the slope of the root zone expansion line at time t (see Fig. 2.1), where t is the time since planting. At the time (t_x) where Z_x can be reached in absence of restrictions, dZ/dt is zero. This makes that the maximum rooting depth (Z_x) cannot be reached at the end of the growing period if the root zone expansion was restricted during a certain time (Fig. 2.2).

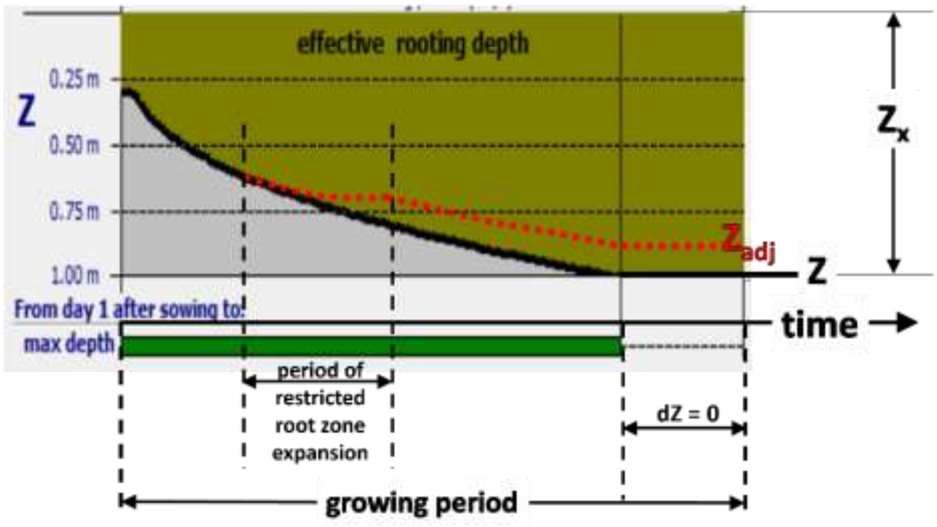


Figure 2.2 – Simulation of the effective rooting depth (Z_{adj}) in previous AquaCrop versions (7.2 and earlier)

2.2.2 AquaCrop Version 7.3

In AquaCrop Version 7.3, the expansion rate (dZ/dt) is no longer determined by the time (t) after planting, but by the time ($t_{V7.3}$) needed to reach the current Z according to Eq. 2.1 (Fig. 2.3).

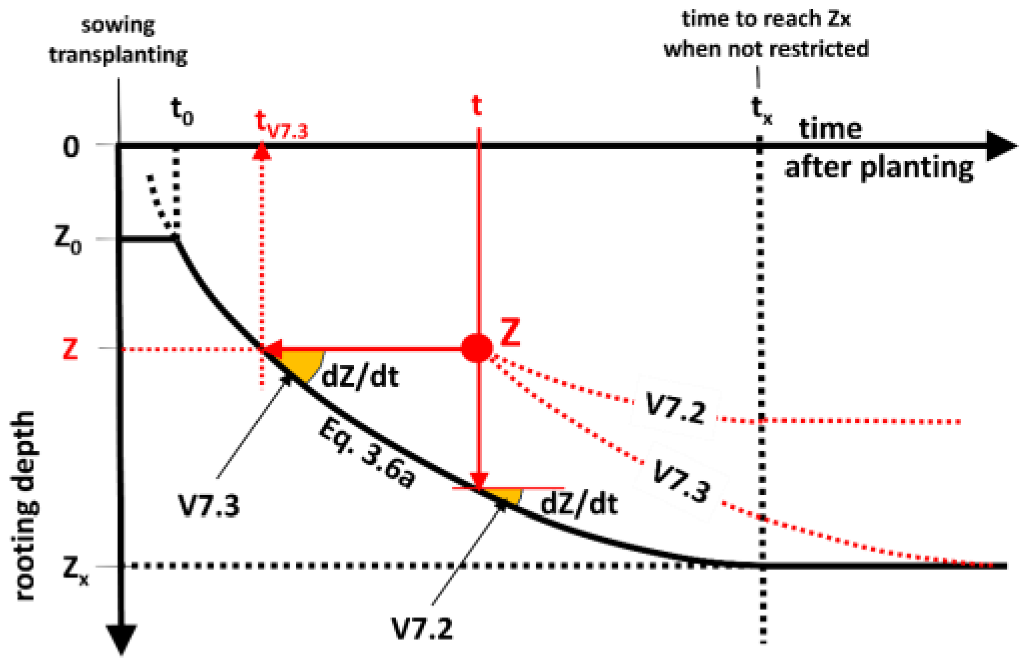


Figure 2.3 – The simulated expansion of the root zone (red dotted line) in the previous (V7.2) and updated Version (V7.3) of AquaCrop at time t after planting when a rooting depth of only Z was reached (due to previous restrictions).

By rewriting Eq. 2.1, the time ($t_{V7.3}$) is given by

$$t_{V7.3} = \left[\frac{(Z - Z_0)}{(Z_x - Z_0)}\right]^n \left(t_x - \frac{t_0}{2}\right) + \frac{t_0}{2} \quad \text{(Eq. 2.4)}$$

This means that after a period of restriction, the expansion rate (dZ/dt) is higher than in Version 7.2, especially when the actual rooting depth (Z) is still small (Fig. 2.3). Further on, the root zone expansion rate remains positive as long as Z_x is not yet reached (Fig. 2.4).

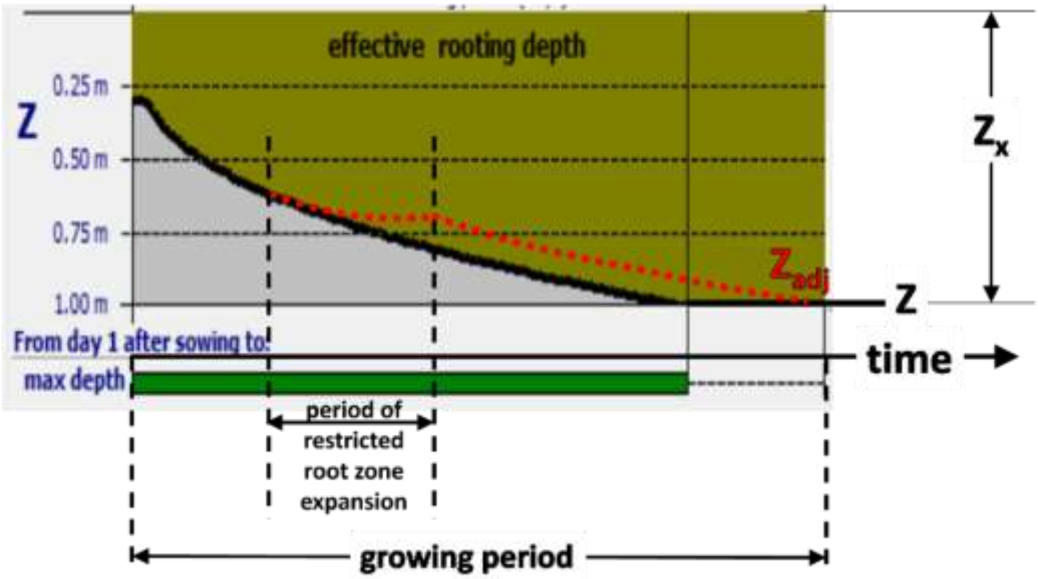
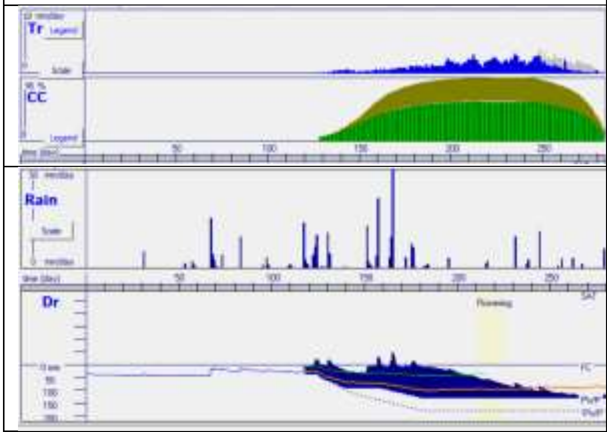
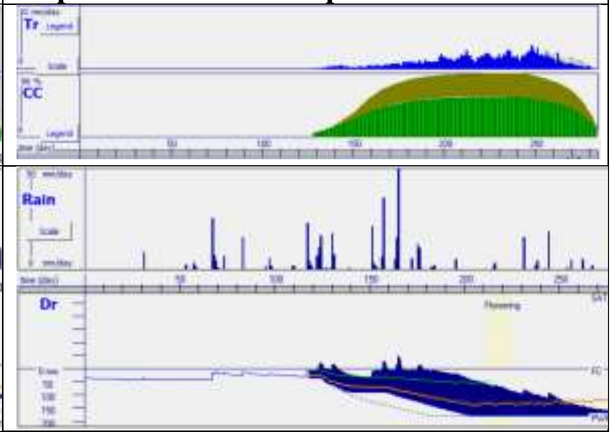
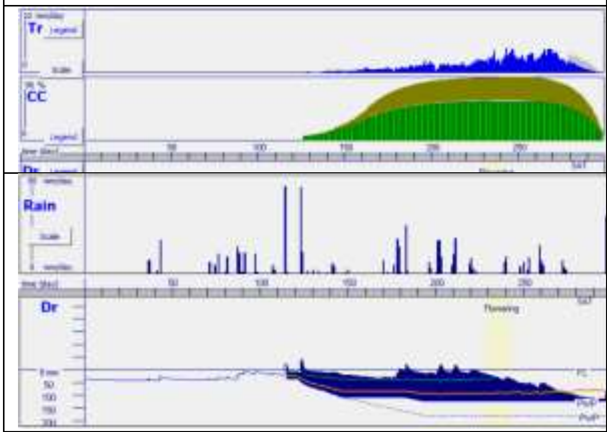
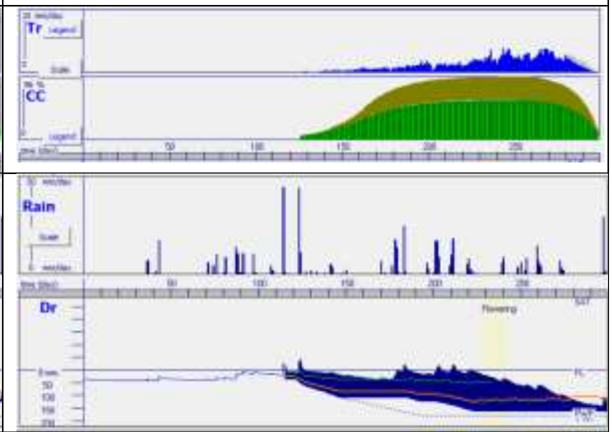
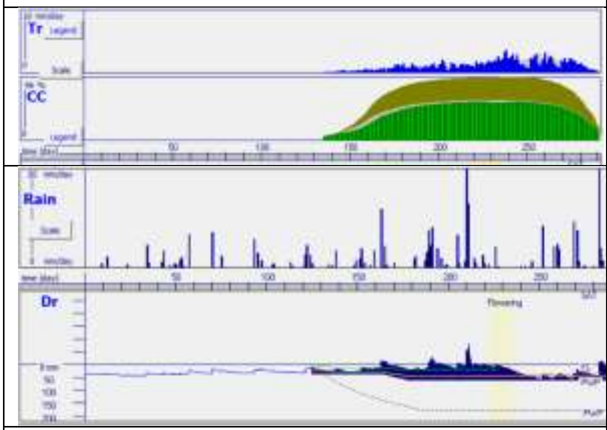
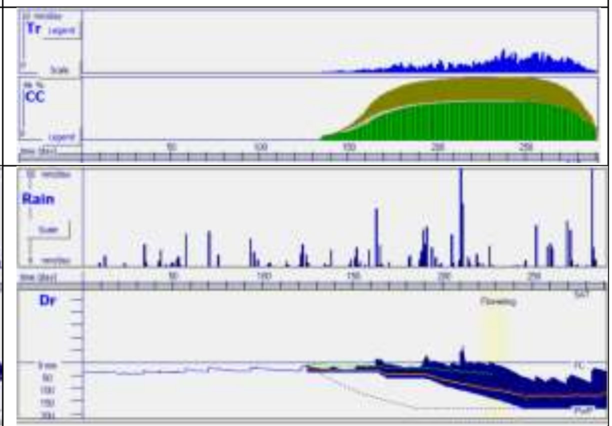


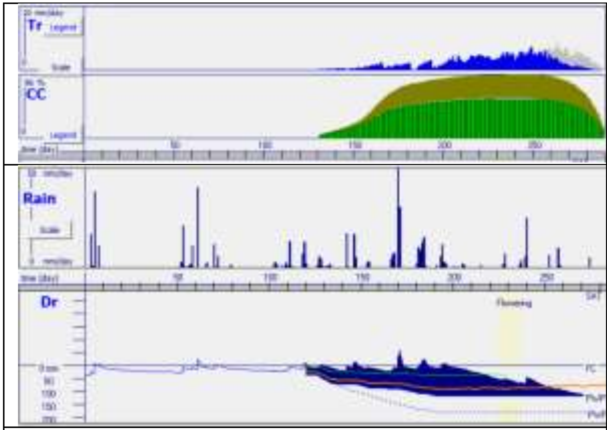
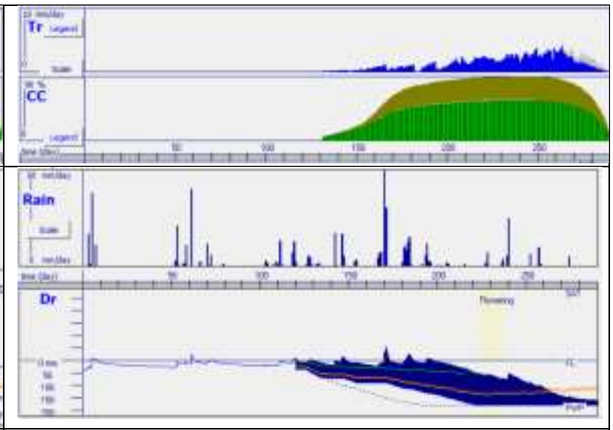
Figure 2.4 – Simulation of the effective rooting depth (Z_{adj}) in AquaCrop Version 7.3

2.3 Simulation of root zone expansion of rain-fed winter wheat in Tunis by AquaCrop version 7.2 and 7.3

Simulation:

Sowing took place at the 2nd occurrence of 20 mm of rain in 4 days since 1 October
Winter wheat required 2,400 GDD to reach maturity
Maximum possible rooting depth (Zx): 1.5 m
Soil fertility: moderate
Soil type: Sandy loam
The soil water content at the start of the simulation (1 Augustus) is at Permanent Wilting Point
Root zone expansion is often restricted in the growing period by a dry subsoil

Version 7.2	**Version 7.3** **Improved root zone expansion**
	
Season 1989 – 1990: Maximum Rooting depth reached: 1.08m	Season 1989 – 1990: Maximum Rooting depth reached: 1.50 m
	
Season 1991 – 1992 Maximum Rooting depth reached: 1.03 m	Season 1991 – 1992 Maximum Rooting depth reached: 1.35 m
	
Season 1995 – 1996 Maximum Rooting depth reached: 0.50 m	Season 1995 – 1996 Maximum Rooting depth reached: 1.50 m

	
Season 1998 – 1999 Maximum Rooting depth reached: 0.98 m	Season 1998 – 1999 Maximum Rooting depth reached: 1.50 m

3. Updated water extraction in root zone

3.1 Maximum root extraction rate (S_x) and the total extraction rate (Σ 1000$S_x$dz)

The maximum sink term (Sx) specifies the maximum amount of water that can be extracted by the crop roots in the time step of 1 day. It is expressed in m^3(water) per m^3(soil) per day. In AquaCrop distinction is made between the:

- maximum root extraction in top quarter of the root zone, Sx (top ¼);
- maximum root extraction in bottom quarter of the root zone, Sx (bottom ¼)

which are both non-conservative crop parameters, and can be altered by the user ((Fig. 1).

In the AquaCrop model the maximum root extraction rate at the top of the soil profile ($S_{x,top}$) might be different from the maximum extraction rate at the bottom of the root zone ($S_{x,bottom}$). The assigned S_x values at different soil depths are proportional to the specified water extraction pattern (Fig. 3.1). Apart from the root distribution, S_x is also determined by the total root volume. The total root volume determines the total amount of water that can be extracted out of the root zone, i.e. the total extraction rate (Σ 1000 S_x dz).

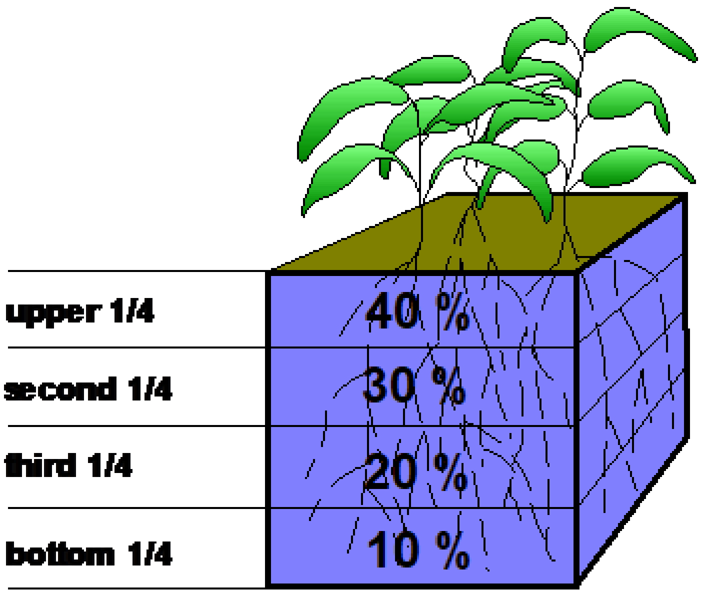


Figure 3.1 – Default extraction pattern in the root zone

The total extraction rate and the root distribution in the root zone are crop parameters which can be adjusted. The default values (which are assigned when the crop is created) are:

- for root distribution: 40, 30, 20, 10% (where the values refer to the upper, second, third and bottom quarter of the root zone as in Fig. 3.1), and

- for total extraction rate Σ 1000 S_x dz: A default 3 mm/day for each 0.10 m of rooting depth is considered. By making Σ $S_x$dz very small, extremely low root volume resulting in severely water stress even in a well-watered soil for normal climatic conditions can be simulated.

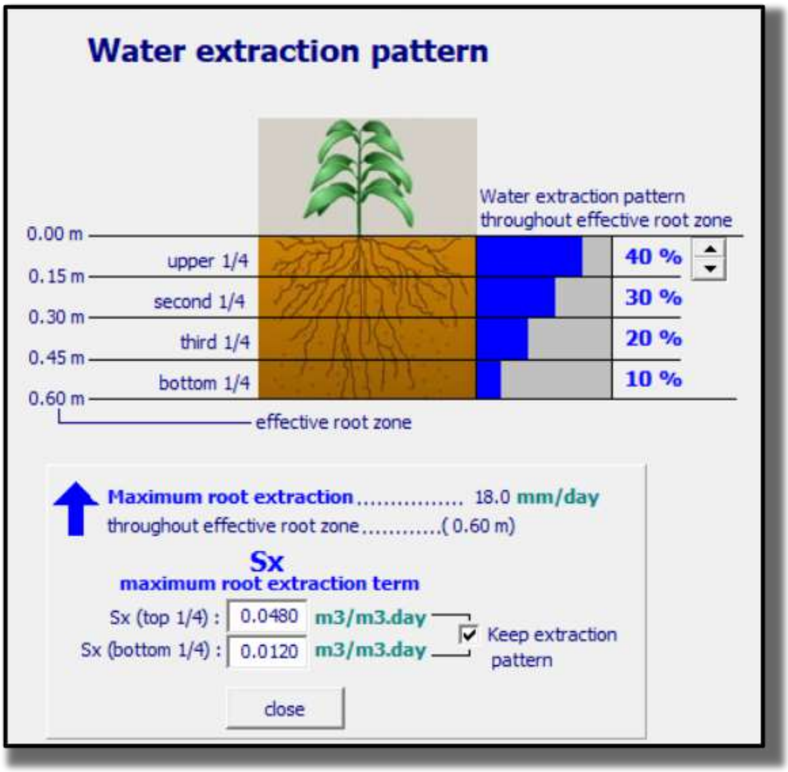


Figure 3.2 – An example of the specified water extraction pattern throughout the effective root zone of 0.60m (40, 30, 20, 10 %), and values for the maximum sink term (Sx) at the top and bottom quarter of the root zone (0.60 m).

3.2 Soil water extraction in Version 7.2 and earlier

The calculation procedure consists of the following steps:

1. Determination of the transpiration demand by considering the average soil water content in the considered soil volume (top soil or root zone) and as such the average total water stress in the soil volume:

$$Tr = \overline{Ks_{soil\ volume}}\ Ks_{Tr}\ Kc_{Tr}\ ET_o \qquad \text{(Eq. 3.1)}$$

where $\overline{Ks_{soil\ volume}}$ is the average soil water stress in the considered soil volume induced by a shortage or an excess of water and/or aeration stress. A linear relationship between the water stress coefficient ($\overline{Ks_{soil\ volume}}$) and the soil water content in the considered soil volume is assumed.

2. Determination of the amount of water that can be extracted out of the root zone at various depths, by considering the maximum root extraction rate and the water stress coefficient at the various depths (soil compartments):

$$S_i = Ks_i \; S_{x,i} \qquad \text{(Eq. 3.2)}$$

where S_i sink term ($m^3.m^{-3}.day^{-1}$) at soil depth i;
Ks_i water stress factor (dimensionless) for soil water content θ_i at soil depth i;
$S_{x,i}$ maximum root extraction rate ($m^3.m^{-3}.day^{-1}$) at soil depth i.

The root extraction rate or sink term, S, (Feddes et al., 1978; Hoogland et al., 1981, Belmans et al., 1983) expresses the amount of water that can be extracted by the roots at a specific depth per unit of bulk volume of soil, per unit of time ($m^3.m^{-3}.day^{-1}$). Depending on the type of water stress, Ks_i is either Ks_{sto} or Ks_{aer} in Eq. 3.2. To determine the value of Ks_i for the given θ_i, the assigned shape of the Ks curve (linear or convex) is considered.

3. By integrating Eq. 3.2 over the different compartments of the root zone, the exact amount of water that can be extracted by transpiration is obtained:

$$Tr = \sum_{top}^{bottom} 1000 \left(Ks_i \; S_{x,i} \right) dz_i \quad \leq \quad \overline{Ks}_{soil\ volume} \; Ks_{Tr} \; Kc_{Tr} \; ET_o \qquad \text{(Eq. 3.3)}$$

where dz_i is the thickness of the soil compartment (m). The integration starts at the top of the soil profile and is stopped when the sum is equal to the transpiration demand given by Eq. 3.1 or the bottom of the root zone is reached.

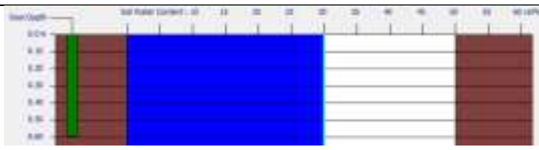
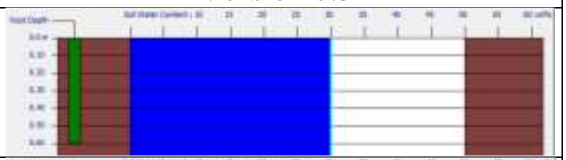
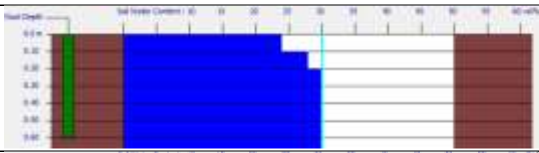
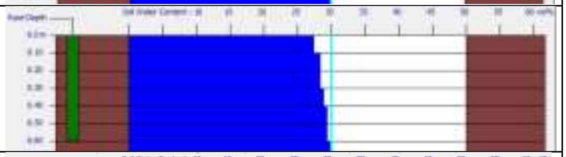
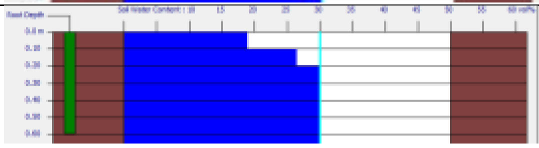
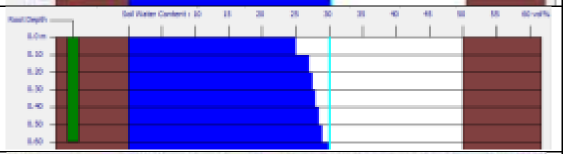
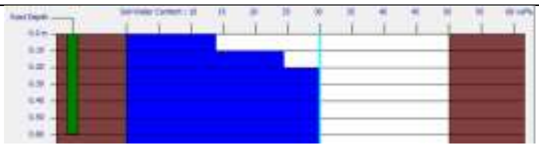
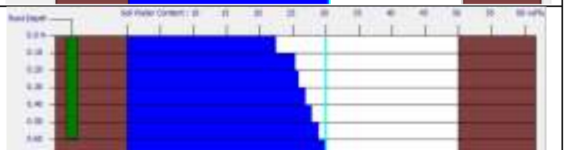
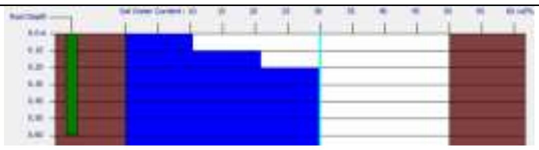
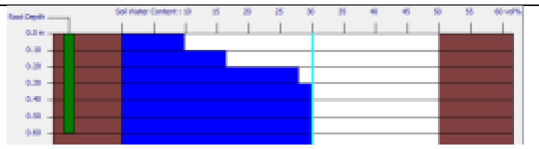
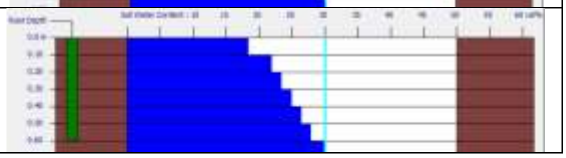
When the maximum root extraction rate over the entire root zone (Σ $1000 S_x dz$) is too small (as a result of a limited root volume), the amount of water that can be extracted by transpiration will be smaller than the demand (Eq. 3.1). The transpiration demand can easily be extracted out of the root zone if S_x at the various depths is sufficiently large. **When S_x is large, the root zone well-watered (Ks = 1) and the transpiration demand small, water will only be extracted from the top of the root zone.** When the top becomes increasingly drier (Ks_i < 1), more and more water will need to be extracted at the lower part of the root zone.

3.3 Updated soil water extraction in AquaCrop Version 7.3

3.3.1 Inadequacy of Version 7.2 for data assimilation

The calculation procedure in Version 7.2 and earlier makes that when S_x is large, the root zone well-watered (Ks = 1) and the transpiration demand small, water will only be extracted from the top of the root zone (see Fig. 3.3 in the early days if the presented simulation). As such the specified extraction pattern (e.g. 40/30/20/10 % as in Fig. 3.1) is neglected. Only when the top soil becomes sufficient dry (Ks_i < 1), more and more water is extracted at the lower part of the root zone (see Fig. 3.3 in the later days if the presented simulation).

Since only the soil water content of the top soil can be observed by satellites, the neglection of the extraction pattern makes that the observed water content in the top soil may be different (it will be most of the time wetter) from the simulated water content in the top soil. Since for data assimilation it is important to respect the extraction pattern, the calculation procedure was updated.

Day	Version 7.2 and earlier	Version 7.3
start		
1		
2		
3		
4		
5		

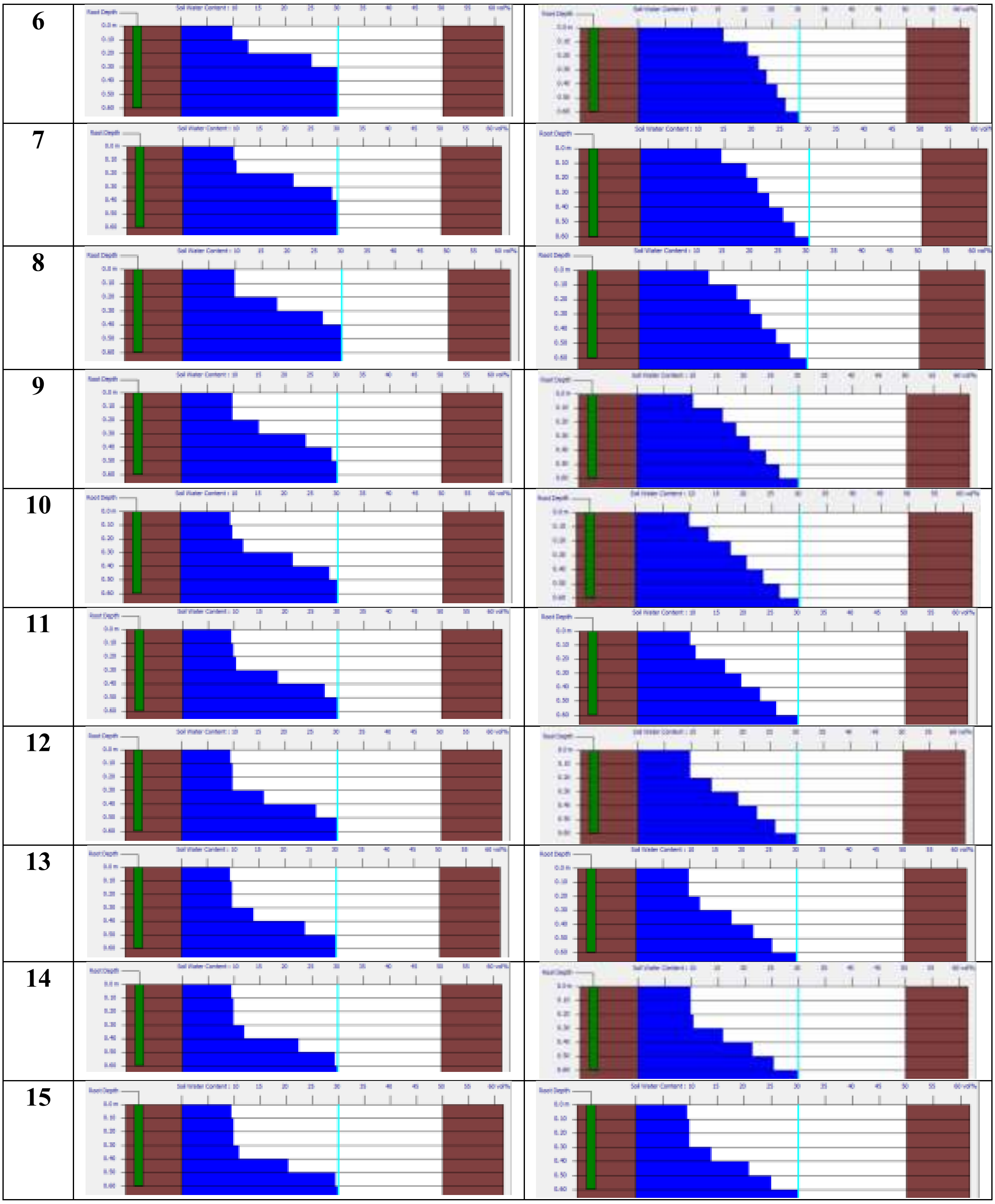


Figure 3.3 – The variation in 15 successive days of the soil water profile in the root zone of 0.60 m as a result of a daily potential crop transpiration of 6.8 mm/day as simulated in previous (7.2 and earlier) and the updated (7.3) AquaCrop version.

Figure 3.3 presents the soil water profile in the root zone of 0.60 m in a loamy soil as simulated by the previous (7.2 and earlier) and the updated (7.3) AquaCrop version. The water extraction pattern throughout the effective root zone (40, 30, 20, 10 %), and values for the maximum sink term (Sx) at the top and bottom quarter of the root zone (0.60 m) as specified in Figure 3.2 were considered.

At the start of the simulation period, the soil water content in the root zone was at Field capacity. The reference evapotranspiration (ETo = 7 mm/day), and the Canopy Cover (CC = 80%) were constant over the entire simulation period of 15 successive days. By considering ETo, CC and the crop transpiration coefficient ($Kc_{Tr,x}$ = 1.1), the potential transpiration rate remained 6.8 mm/day over the entire simulation period.

3.3.2 Updated calculation procedure

The calculation procedure consists of the following steps:

1. (as in previous AquaCrop Versions): Determination of the transpiration demand by considering the average soil water content in the considered soil volume (top soil or root zone) and as such the average total water stress in the soil volume:

$$Tr = \overline{Ks_{soil\ volume}}\ Ks_{Tr}\ Kc_{Tr}\ ET_o \qquad \text{(Eq. 3.4)}$$

   where $\overline{Ks_{soil\ volume}}$ is the average soil water stress in the considered soil volume induced by a shortage or an excess of water and/or aeration stress. A linear relationship between the water stress coefficient ($\overline{Ks_{soil\ volume}}$) and the soil water content in the considered soil volume is assumed.

2. (as in previous AquaCrop versions): Determination of the amount of water that can be extracted out of the root zone at various depths, by considering the maximum root extraction rate and the water stress coefficient at the various depths (soil compartments):

$$S_i = Ks_i\ S_{x,i} \qquad \text{(Eq. 3.5)}$$

   where
   - S_i sink term ($m^3.m^{-3}.day^{-1}$) at soil depth i;
   - Ks_i water stress factor (dimensionless) for soil water content θ_i at soil depth i;
   - $S_{x,i}$ maximum root extraction rate ($m^3.m^{-3}.day^{-1}$) at soil depth i.

   The root extraction rate or sink term, S, (Feddes et al., 1978; Hoogland et al., 1981, Belmans et al., 1983) expresses the amount of water that can be extracted by the roots at a specific depth per unit of bulk volume of soil, per unit of time ($m^3.m^{-3}.day^{-1}$). Depending on the type of water stress, Ks_i is either Ks_{sto} or Ks_{aer} in Eq. 3.10n. To determine the value of Ks_i for the given θ_i, the assigned shape of the Ks curve (linear or convex) is considered.

3. **Updated:** By integrating Eq. 3.5 over the different compartments of the **entire** root zone, the **maximum** amount of water that can be extracted by transpiration is obtained:

$$Tr_{max} = \sum_{top}^{bottom} 1000\ \left(Ks_i\ S_{x,\,i}\right)\ dz_i \qquad \text{(Eq. 3.6)}$$

   where dz_i is the thickness of the soil compartment (m). The integration starts at the top of the soil profile and is stopped when the bottom of the root zone is reached.

4. **Updated:** The amount of water that will be extracted out of each compartment of the root zone, is determined by the specified extraction pattern (e.g. 40/30/20/10 % as in Fig. 3.1) and the ratio Tr/Tr_{max}.

3.3.3 Conclusion

Although the update calculation procedure hardly affects the simulation results, the simulated water distribution in the root zone may be more realistic in the updated version. This is important for data assimilation (adjustment of simulated results by remote sensing).

In Figure 3.4 and 3.5, difference in simulation results between previous (V7.2 and earlier) and the updated (V7.3) AquaCrop version for two different study cases are presented.

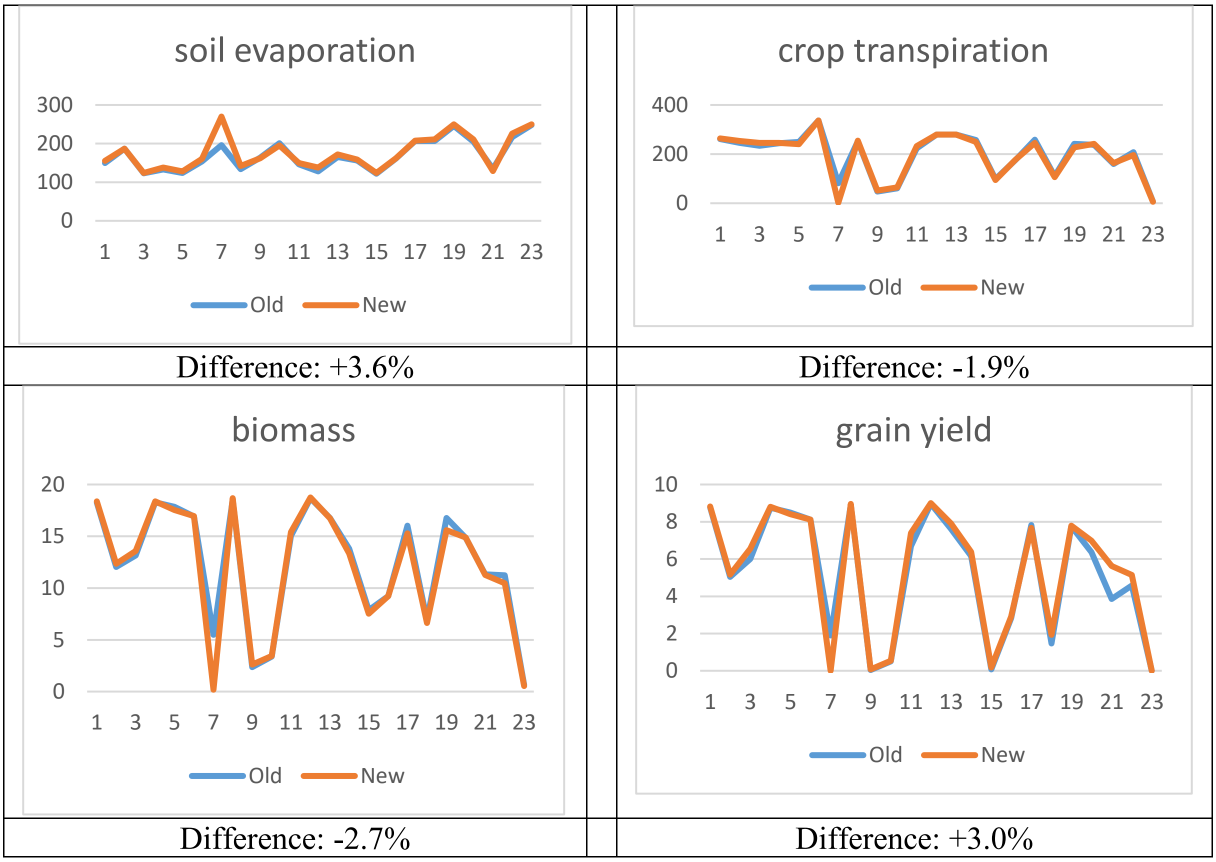
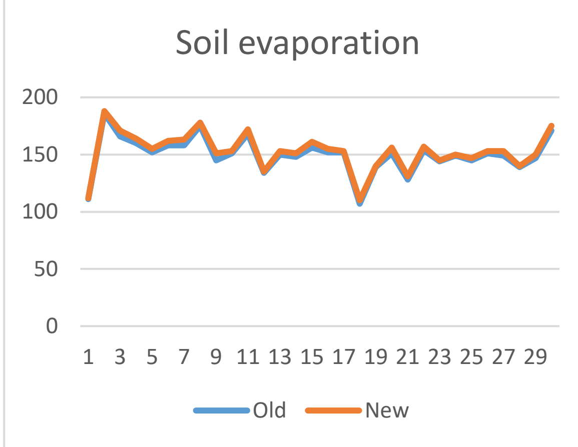
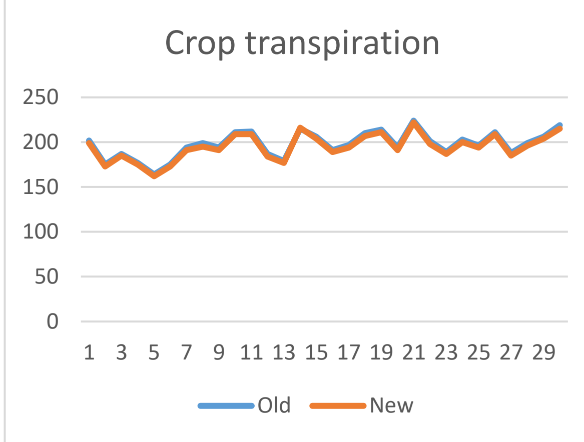


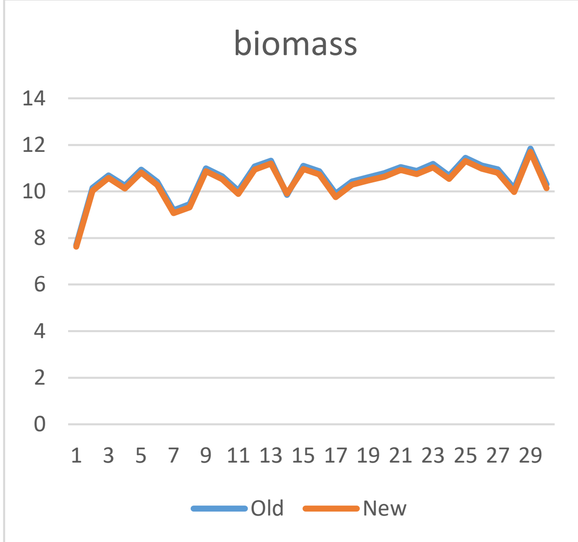
Figure 3.4 – Soil evaporation, crop transpiration, biomass production and grain yield of winter wheat in Tunis over 23 successive years as simulated by previous AquaCrop Versions (Old: blue line) and the updated AquaCrop Version 7.3 (New: yellow line). The simulation started on 1 August on a bare sandy loam soil which soil water content was at Permanent Wilting Point. Planting was considered at the 2nd occurrence of 20 mm of rain in 4 successive days, in the time window: 1 October – 31 December. Severe water stress resulting in crop failure was observed in several years.



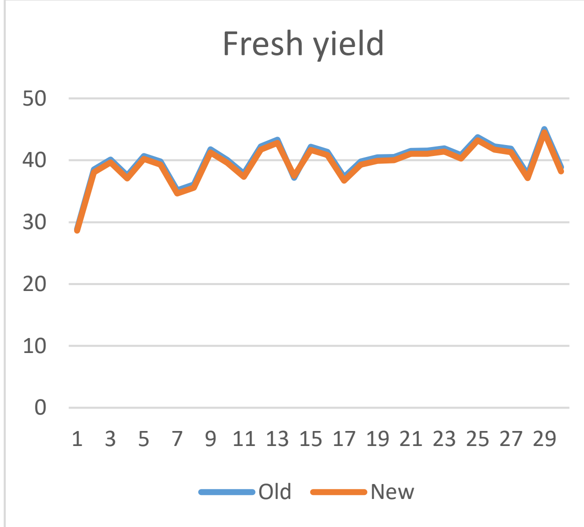
Difference: +2.0%



Difference: -1.3%



Difference: -1.2%



Difference: -1.2%

Figure 3.5 – Soil evaporation, crop transpiration, biomass production and fresh potato yield in Brussels (Belgium) over 29 successive years as simulated by previous AquaCrop Versions (Old: blue line) and the updated AquaCrop Version 7.3 (New: yellow line). The simulation started on 1 January on a bare loamy soil which soil water content was at Field Capacity. Planting was considered at 1 April. Water stress was absent in all years.

4. Premature end of the growing period of annual crops

4.1 Shortcoming in previous AquaCrop versions (V7.2 and earlier)

The length of the growing period (from sowing till crop maturity) can be expressed in AquaCrop in calendar days or Growing Degree Days (GDD). Expressed in GDD, the length of the growing period will change with the temperature regime of the year. In a warm year the growing period of annual crops is shorter than in a cold year (Fig. 4.1a). However, if there are insufficient growing degrees for an annual crop to reach maturity before winter sets in, AquaCrop extends the growing season into the following year, and only ends the growing period until sufficient growing degrees have been accumulated to reach maturity (Fig. 4.1b).

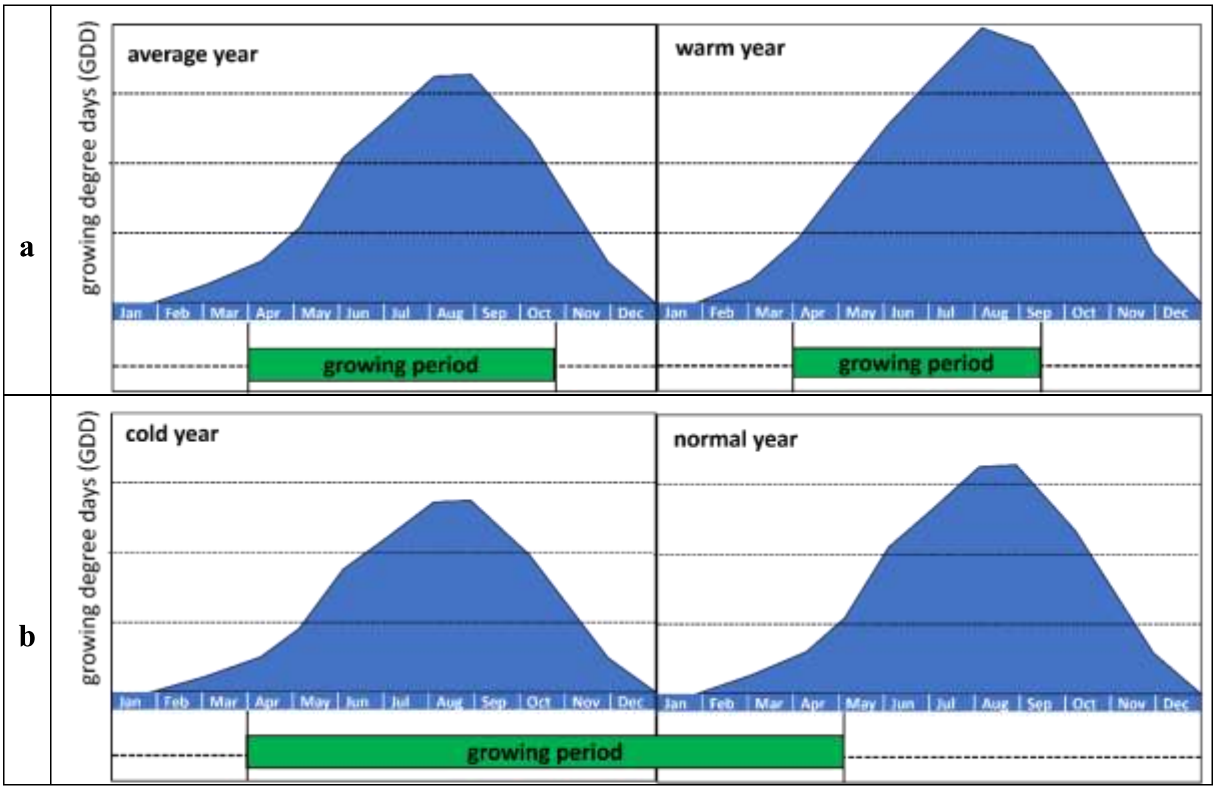
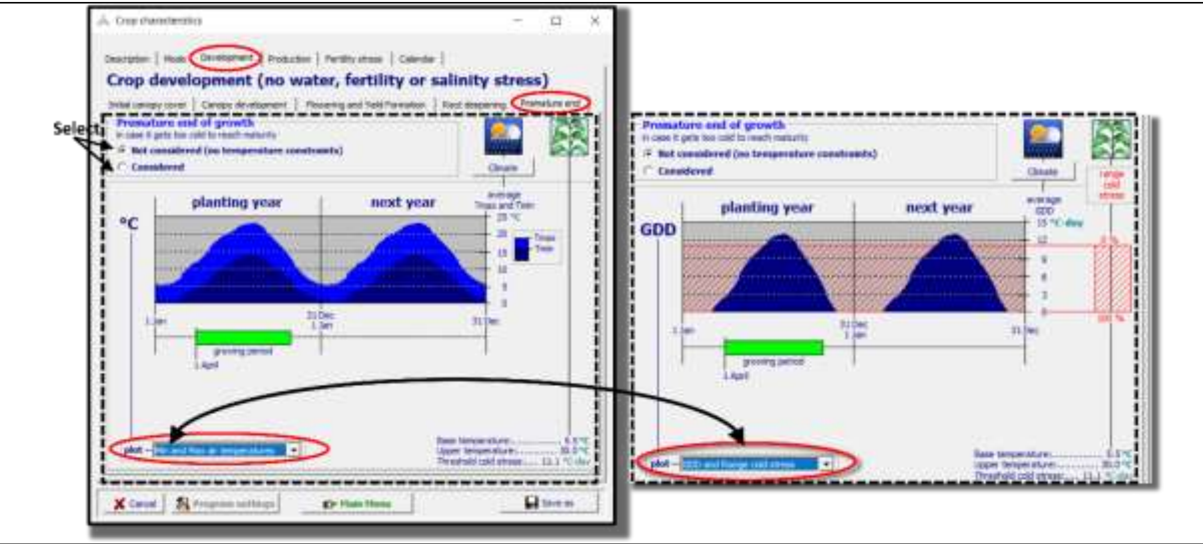


Figure 4.1 – The available growing degrees (blue area) and the simulated growing period (green bar) of an annual crop (a) in an average and warm year, and (b) in a cold year when there are insufficient growing degrees for the annual crop to reach maturity before winter sets in.

Since annual crops are unlikely to survive a cold winter period, the extension of the growing period in a following year is not realistic. In AquaCrop version 7.3 this shortcoming has been addressed by taking into account an end of the growing period that cannot be exceeded.

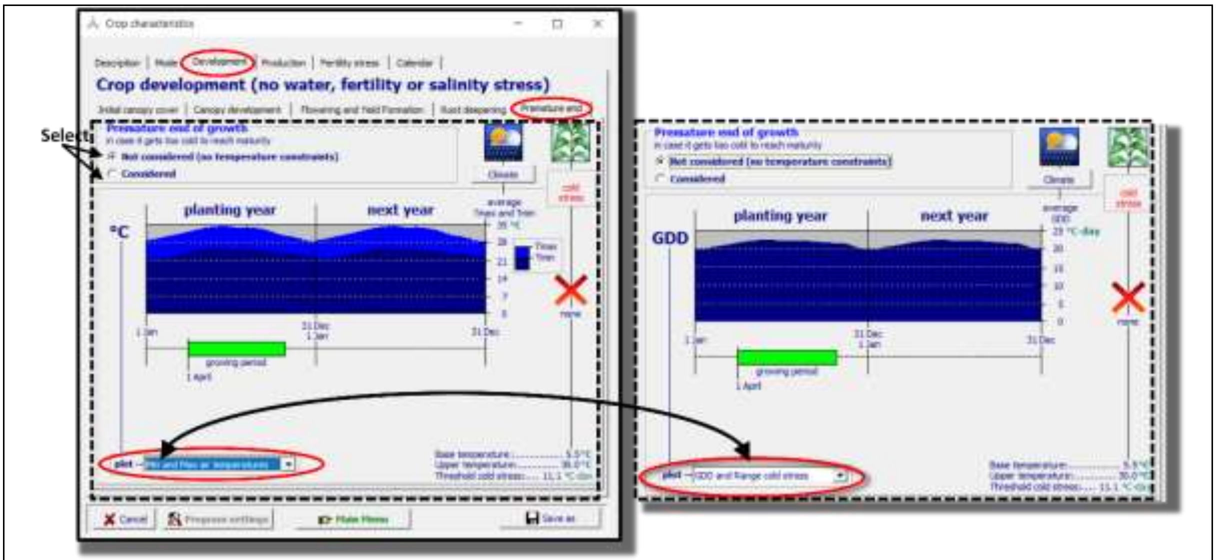
4.2 Specification of the premature end of the growing period in Version 7.3

A premature end of the growing period is specified in the “Premature end” tab-sheet of the “Development” tab-sheet of the ***Crop characteristics*** menu (Fig. 4.2 and 4.3). The display for the selected climate of (a) the mean daily minimum and maximum air temperature or (b) the mean daily Growing Degree Days (GDD) and the corresponding range of cold stress, can provide valuable information to consider whether or not an early termination of growth.



a (display of the mean daily minimum and maximum air temperature)	b (display of the mean daily GDD and the correspoding range of cold stress)

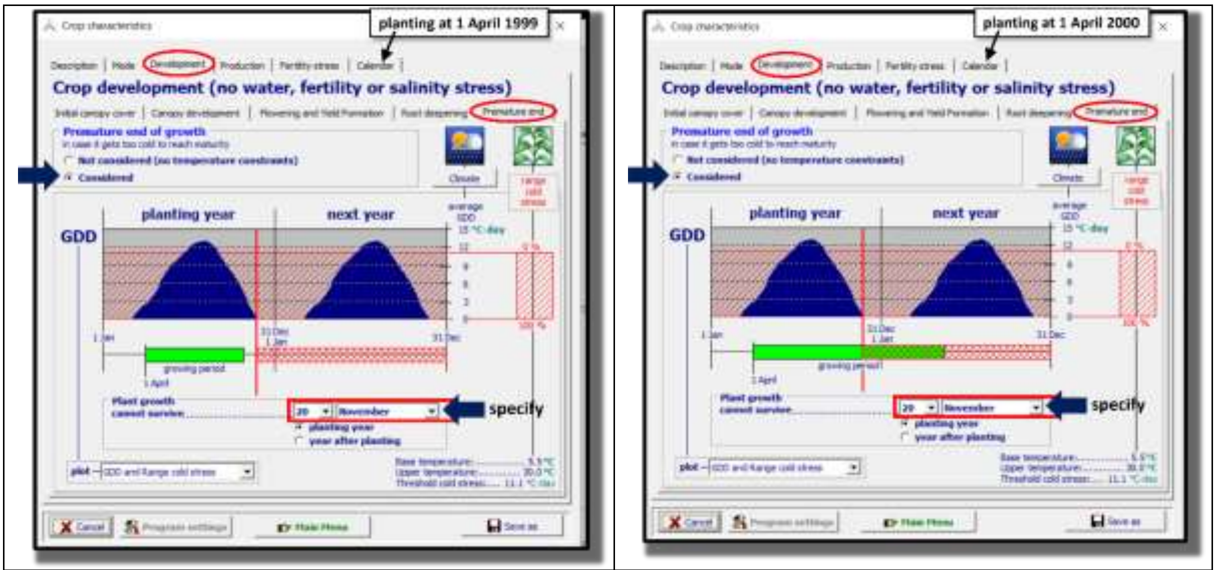
Figure 4.2 – The “Premature end” tab-sheet (a cold Northern climate is selected).



a (display of the mean daily minimum and maximum air temperature)	b (display of the mean daily GDD and the correspoding range of cold stress)

Figure 4.3 – The “Premature end” tab-sheet (a tropical climate is selected).

If the annual crop is unlikely to survive a cold winter period, the option of a premature end of the growing period needs to be considered (Fig. 4.4). The user specifies the date at which the crop cannot survive in the ***Crop characteristics*** menu (Fig. 4.4a, 20 November of the planting year). As a result, AquaCrop will terminate the growing period prematurely if not enough growing degrees can be collected to reach maturity before the specified end date (Fig. 2.4b).



a (selected planting year 1999)	b (selected planting year 2000)

Figure 4.4 – The selection of the date (20 November of the planting year) at which plant growth cannot survive if a premature end of growth is considered in the *Crop characteristics* menu. Depending on the temperature regime of the selected planting year (1999 or 2000), AquaCrop specifies whether the length of the growing period will be terminated prematurely (b) or not (a).

To avoid over calibration, the premature end is specified by a specific date and not by a temperature criterion. For such a criterion, for example, account will have to be taken of (i) the minimum number of growing degrees, (ii) that can still be collected during a series of consecutive days, and (iii) which is valid after a certain date. Since this information might not be readily available the user needs to specify only a date. Because cold stress is likely to be already very severe around that date, the accuracy of the chosen date is not so important. The simulation results will not differ much for different chosen dates, because crop growth and production are already very low during that period.

Because in the Southern Hemisphere annual crops are typically planted at the end of the calendar year, the option exists to select the premature end date in the “year after planting”.

4.3 Application in Projects

When creating a multiple run project in which the simulation is repeated in successive years, AquaCrop indicates in the Calendar tab-sheet for each of the successive years, whether or not an early end is taken into account (Fig. 4.5).

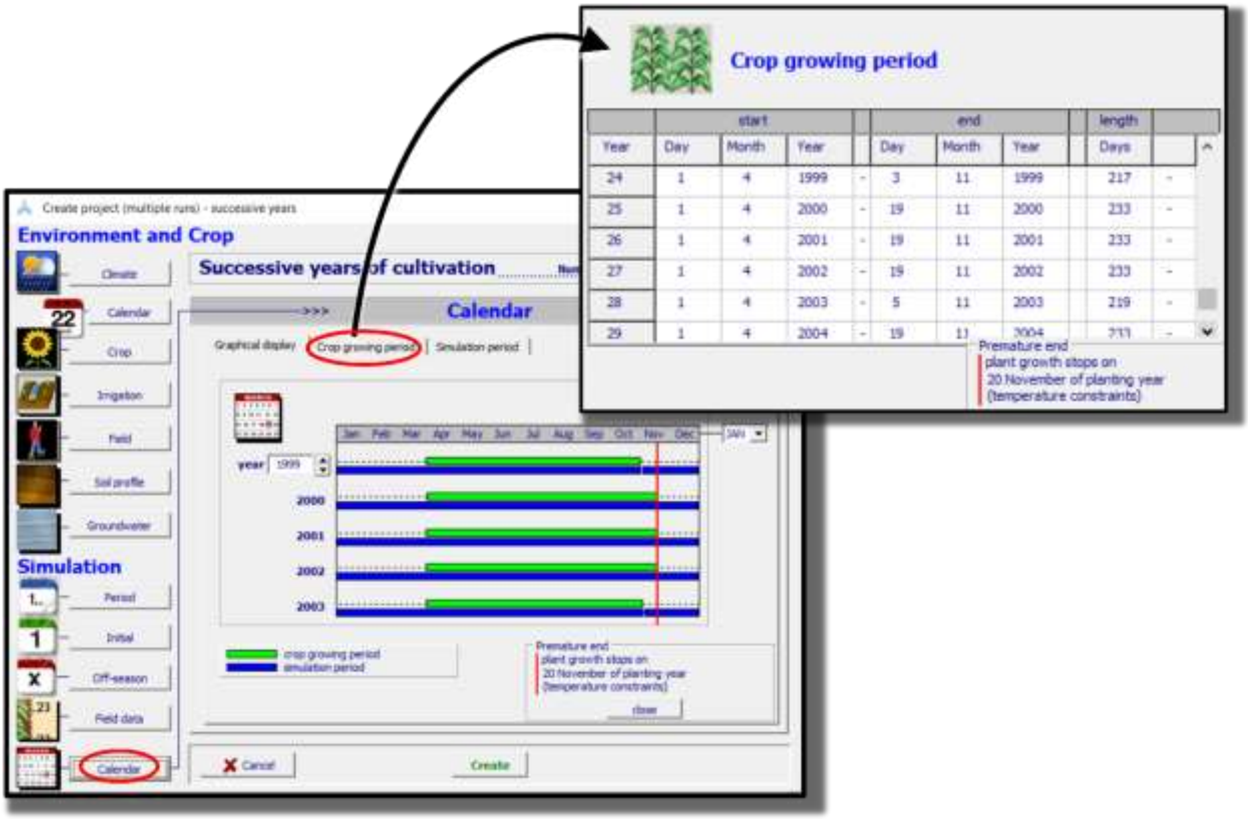


Figure 4.5 – The display for the successive years in the *Create project* menu of the simulation (blue) and crop growing period (green) of an annual crop for which a premature end was considered (as specified in Fig. 4).

5. Time aggregation of the daily output

On exit of the ***Simulation run*** menu, it is possible to save the output. Distinction is made between files containing daily simulation results, seasonal results and evaluation of simulation results (Fig. 5). The files are stored by default in the OUTP directory of AquaCrop. By selecting the **<Output files>** command, the user can specify the files to be recorded in the ***Output files*** menu. To prevent that the simulation results are overwritten at each run, a different file name (and even a different directory) can be specified. The data in the files can be retrieved in spread sheet programs for further processing and analysis.

In AquaCrop version 7.3 it is possible to aggregate daily results into periods of 10 days or months (Fig. 5). Until now, this option was only available in the stand-alone (plugin) versions of AquaCrop.

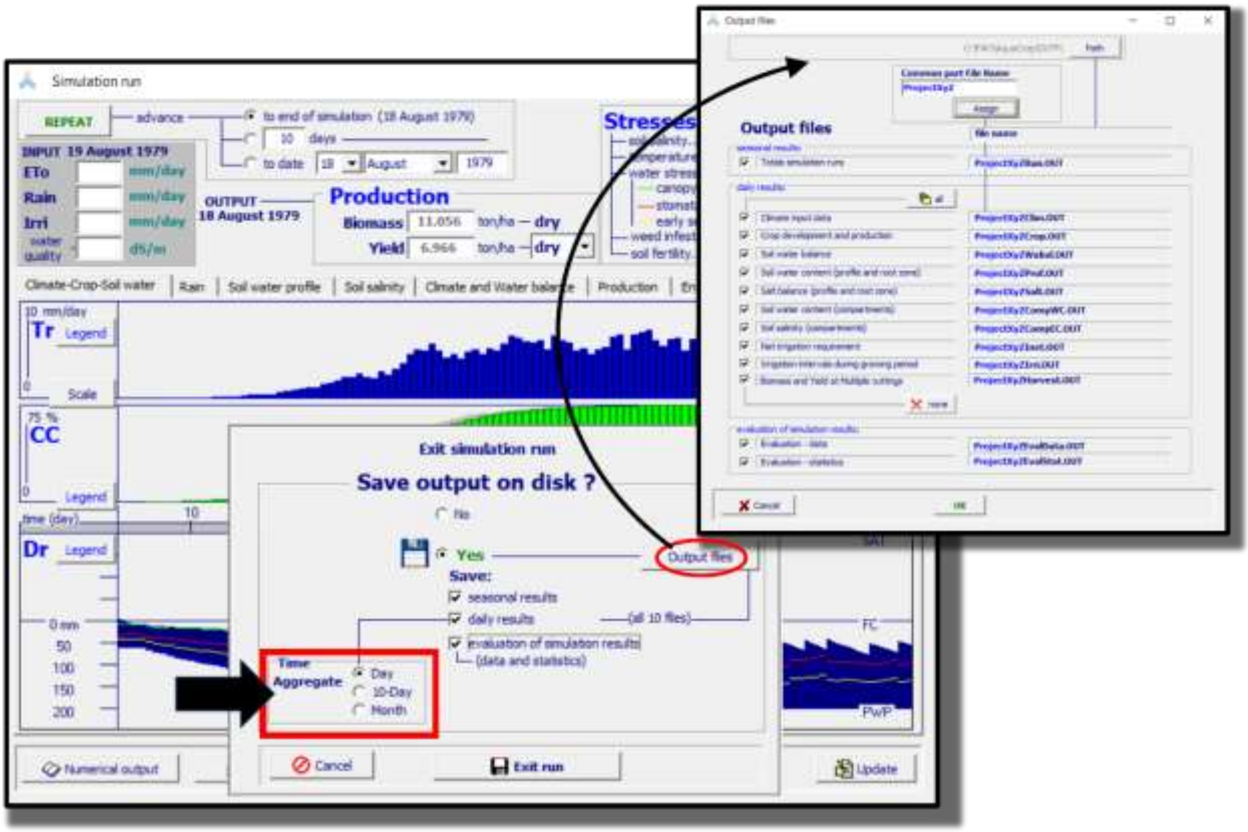


Figure 5. – The option of time aggregation of the daily results, on exit of the *Simulation run* menu in AquaCrop Version 7.3.

6. Frequency analysis

When running a simulation, the simulation results which are updated at the end of each daily time step are available in the ***Simulation Run*** menu (Fig. 6.1). A lot of data and graphs are available in a series of tab sheets of the menu. With the buttons in the control panel (at the bottom of the menu), the user has access (i) to the daily results and (ii) to an evaluation of simulation results with field data, (iii) can update state variables when running a simulation and (iv) can specify the results that need to be saved in a series of output files.

In Version 7.3, the extra button <**Frequency analysis**> in the control panel of the ***Simulation Run*** menu (Fig. 6.1), gives access to a series of new menus in which a frequency analysis of the simulation results can be performed. The results of the frequency analysis can provide information for the design of irrigation charts, to improve irrigation and/or field management, to study the effect of climate change, etc.

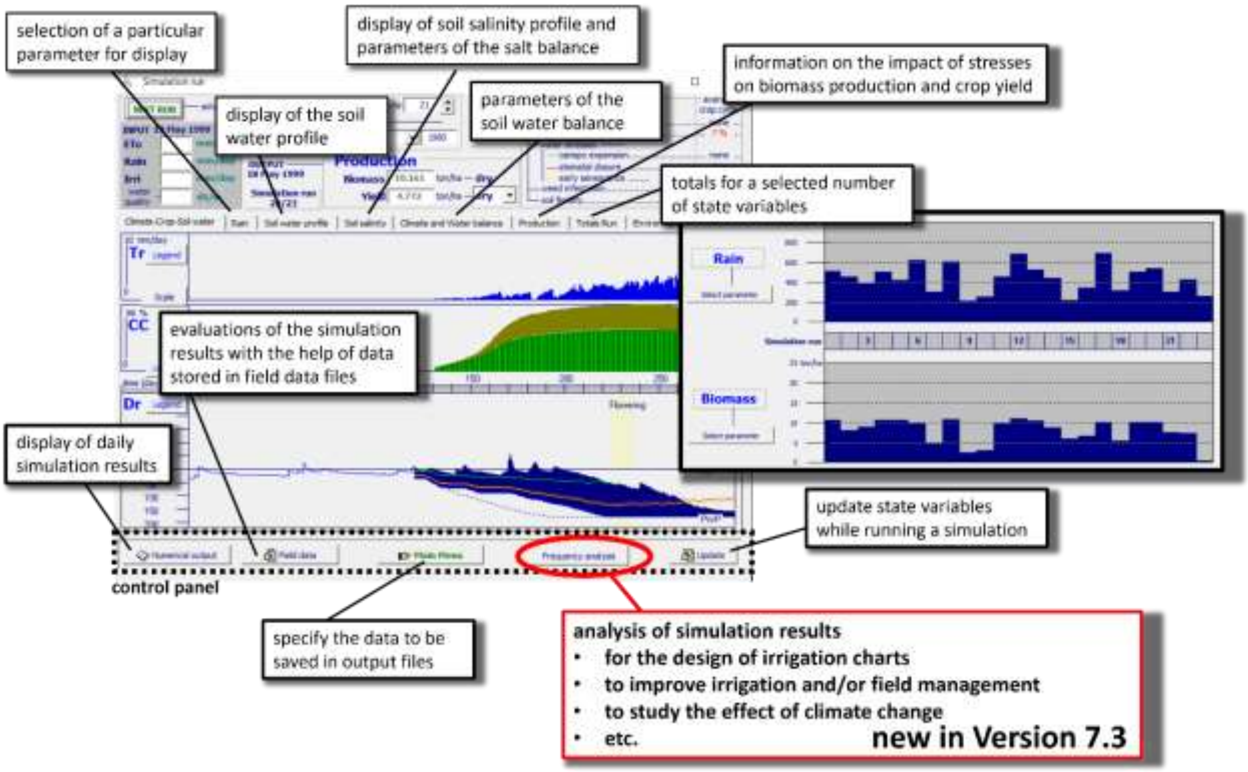


Figure 6.1 – The Simulation run menu with information on the data and graphs displayed in the several tab-sheets, and the options available in the control panel for displaying, saving, evaluating and analysing simulation results.

6.1 Selection of time aggregation

The <**Frequency analysis**> button is only available in the control panel of the ***Simulation Run*** menu, when multiple run projects (of successive years) are run. To have access to a frequency analysis, simulation results of at least 4 years are required.

Before performing a frequency analysis, the appropriate option for the time aggregation of the simulation results must be selected in the ***Goal of frequency analysis*** menu. The selection varies depending on the purpose of the frequency analysis:

- to design irrigation schedules, the time aggregation of daily data in 10-daily or monthly time steps is most suitable,
- to improve irrigation and/or field management, the aggregation of the simulation results over the entire growing period can give valuable information,
- to analyse climate data (rainfall, ETo, air temperature), a time aggregation over a month, season or year can be very useful.

By hitting the <**Perform frequency analysis**> button in the ***Goal of frequency analysis*** menu, the frequency analysis menu with the intended purpose and corresponding time aggregation of the simulation results is displayed (Fig. 6.2).

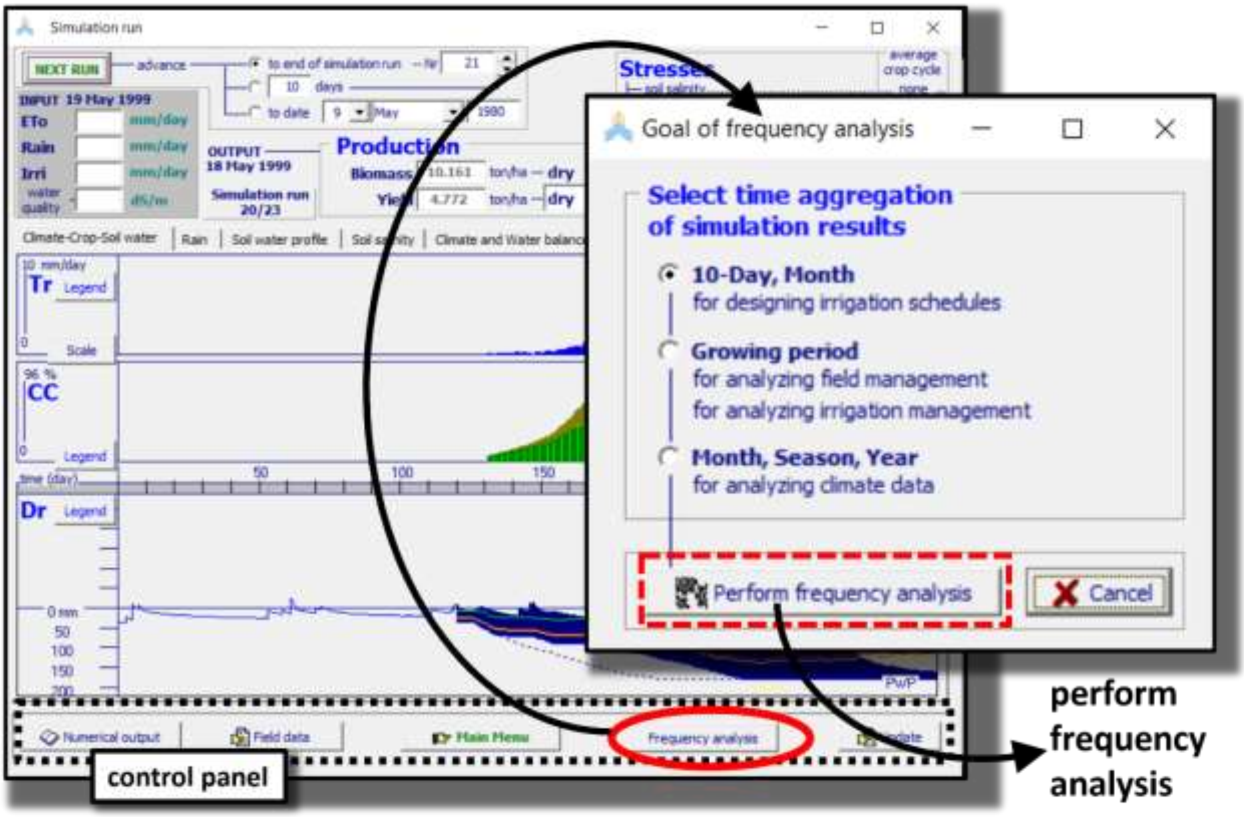


Figure 6.2 – Selection of the purpose and corresponding time aggregation of the simulation results in the Goal of frequency analysis menu.

6.2 Frequency analysis (10 daily or monthly data)

A frequency analysis is performed on the data of each of the decades (10-day) or months of the growing period for the number of successive years (e.g. 20, 30, …) considered in the multiple run project.

6.2.1 Available options

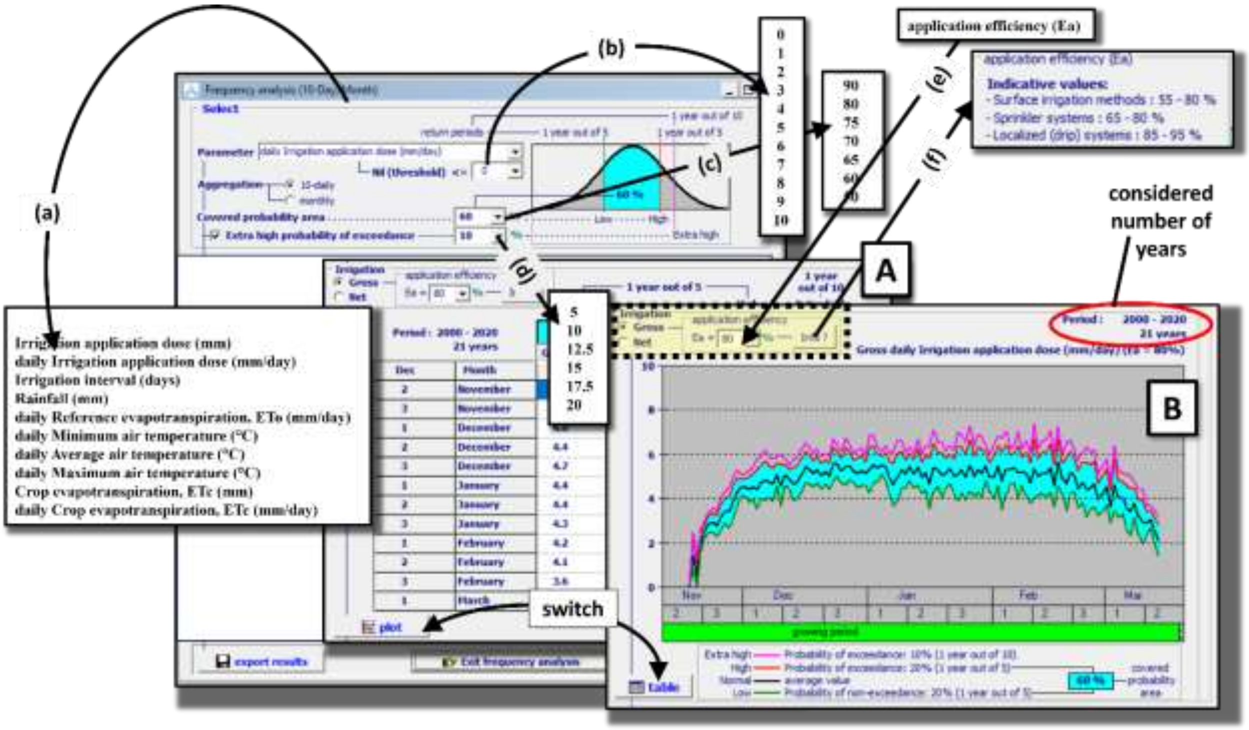


Figure 6.3 –The Frequency analysis (10-Daily or Monthly time aggregation) menu.

- **Selection of (a) the parameter to be analysed**

In the ***Frequency analysis (10-Daily or Monthly time aggregation)*** the parameter to be analysed can be selected (Fig. 6.3a). It consists of the data for each decade (10-day) or month of the growing period of the successive years of the multiple project (21 years in the example in Fig. 6.3).

Distinction is made between the total 10-day or monthly amounts of the:
- Irrigation application dose (mm)
- Crop evapotranspiration, ETc (mm)

and their 10-day or monthly average:
- Daily Irrigation application dose (mm/day)
- Daily Crop evapotranspiration, ETc (mm/day)

Also, the Irrigation interval (days), the total of 10-day and monthly Rainfall (mm), and the 10-day or monthly average of the
- daily Reference evapotranspiration, ETo (mm/day)
- daily Minimum air temperature (°C)

- daily Average air temperature (°C)
- daily Maximum air temperature (°C)

are available for a frequency analysis.

▪ Selection of (b) the Nil (threshold) value

When running the frequency analysis a normal distribution is assumed. For daily, 10-daily and monthly data of a sufficient large number of years, this is most of the time valid. However, the data for the small considered periods (day, 10-day, month) in a year might be zero or near zero in some of the years. If the occurrence of low 10-day or months values in the years is high, the frequency distribution of the data of the successive years becomes severely skewed to the right.

The method to analyse time-series with zero or near zero data (the so-called nil values) is to separate temporarily the nil values from the non-nil values. In the ***Frequency analysis (10-Daily or Monthly time aggregation)*** the nil threshold can be specified (Fig. 6.3b). By excluding the nil's from the frequency analysis, the frequency distribution becomes less skewed to the left, and the data can be analysed (Fig. 6.4).

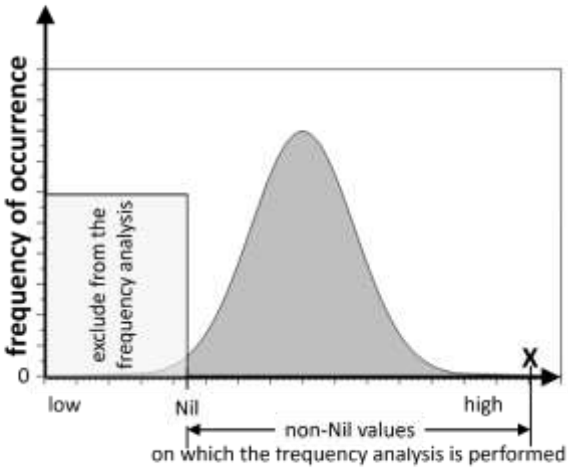


Figure 6.4. – The separation of the nil values from the non-nil values for performing a frequency analysis

▪ Selection of (c) the covered probability area and (d) an extra high probability of exceedance

Different covered probability areas (Fig. 6.3c) can be selected in the ***Frequency analysis (10-Daily or Monthly time aggregation).*** By selecting a covered probability area, also the corresponding probabilities of exceedance and non-exceedance and the return period are defined (Fig. 6.5).

Since a normal distribution is completely characterized by its average and standard deviation, they can be used to make estimates for selected probabilities or return period:

$$X_p = \bar{X} \pm k\ s \qquad \text{(Eq. 6.1)}$$

where X_p is the value having a specific probability of (non)-exceedance, $\overline{X}$ is the sample mean, s the standard deviation and k a frequency factor.

The selection of covered probability area and as such the probability of (non)-exceedance is related to the risk one wants to accept (e.g. risk of under-irrigation) or the damage a shortage may cause (e.g. shortage of applied irrigation water). An extra high probability of exceedance (Fig. 6.3d) can also be selected in the ***Frequency analysis (10-Daily or Monthly time aggregation).*** With the calculated corresponding value for the selected parameter (X_p in Eq. 6.1) the risk or damage may be reduced.

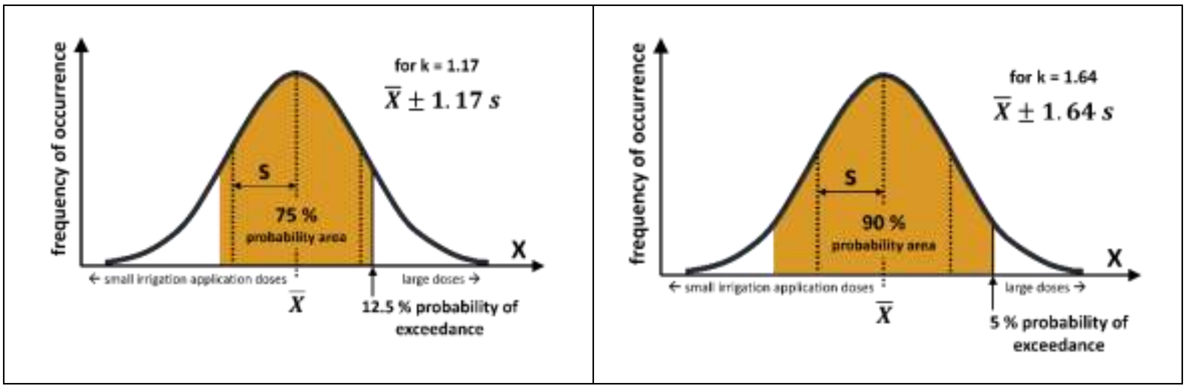


Figure 6.5 – Example of the probability of non-exceedance and the corresponding covered probability area for various k (X is the irrigation application dose in this example)

Table 6.1 – Probabilities of (non)-exceedance, and the corresponding covered probability areas and return periods

Probability of (non)-exceedance	Probability area covered	Return period
5 %	90 %	1 year out of 20
10 %	80 %	1 year out of 10
12.5 %	75 %	1 year out of 8
15 %	70 %	1 year out of 7
17.5 %	65 %	1 year out of 6
20 %	60 %	1 year out of 5
25 %	50 %	1 year out of 4

▪ Switch between the probability table (A) and probability plot (B)

By clicking on the **<plot>** or **<table>** button in the ***Frequency analysis (10-Daily or Monthly time aggregation)*** menu (Fig. 6.3), the user can switch between the probability table (Fig. 6.3A) for the selected parameter and the corresponding plot (Fig. 6.3B).

▪ Selection of (e) the application efficiency (Ea) and (f) the display of indicative values

Since distribution and application losses are not considered in the simulations of AquaCrop, the specified or generated irrigation amounts are net irrigation application doses. By specifying a field application efficiency (Ea) (Fig. 6.3e), the net application dose can be converted in the gross application dose that needs to be applied on the field. The field efficiency (Ea) considers the amount of irrigation water that is lost during the application of the water on the field.

6.2.2 Export results

By clicking on the **<export results>** button in the ***Frequency analysis (10-Daily or Monthly time aggregation)*** menu the ***Export results of Frequency analysis*** menu is displayed (Fig. 6.6).

The default file name (Fig 6.6.b) is composed by (i) the number of the Frequency analysis executed (Fig. 6.6a) and (ii) the name of the project file. The default description (Fig. 6.6c) provides an overview of the selected options. Both the default file name and description can be edited by the user. The folder where the output file needs to be stored can be altered as well (Fig. 6.6d).

By clicking on the **<export>** button in the ***Export results of Frequency analysis*** menu, the results are exported to the specified folder, and the control returns back to the ***Frequency analysis (10-Daily or Monthly time aggregation)*** menu for another frequency analysis.

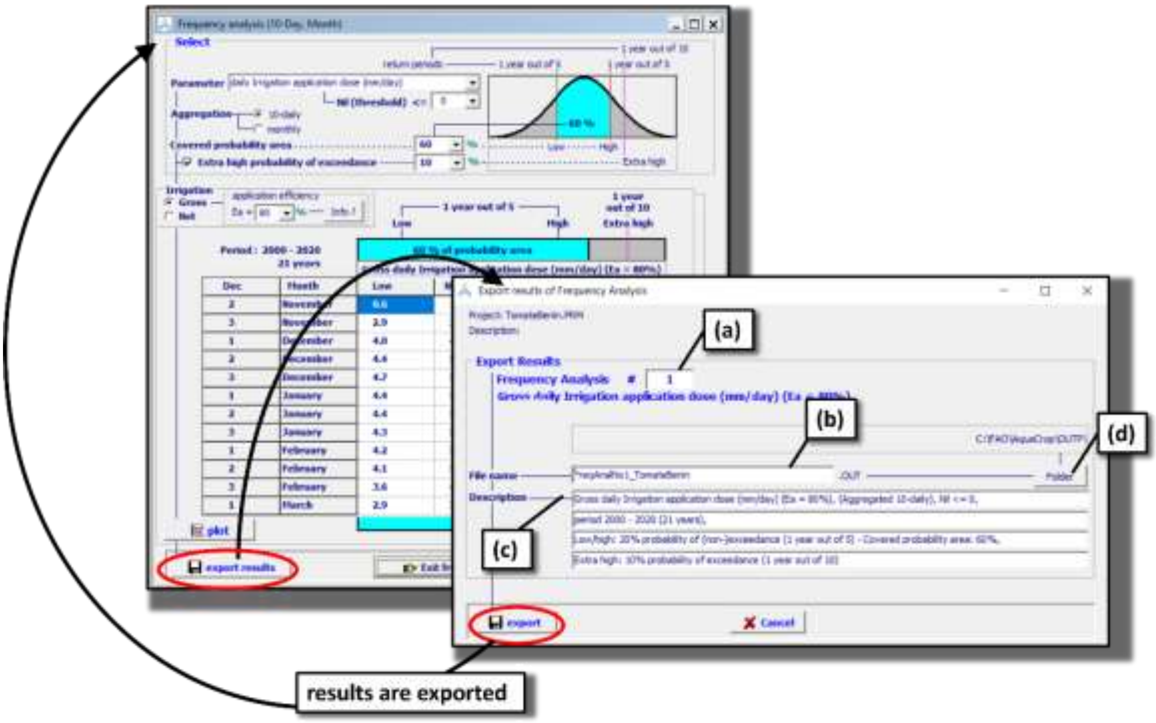


Figure 6.6 – The Export results of Frequency analysis menu

6.2.3 Output file

In the ***Frequency analysis*** menu and the output file, the results of the frequency analysis for the selected options are reported as global probabilities. By calculating the global probability, the nil and no-nil values are combined. The global probability is calculated by

$$G_X(x) = (1 - p)F_X(x) \qquad \text{(Eq. 6.2)}$$

where $G_X(x)$ is the cumulative probability distribution of all X (i.e. for the probability of exceedance the prob(X ≥ x) for X ≥ nil), p is the probability that X is nil, and $F_X(x)$ is the cumulative probability distribution of the non-nil values of X (i.e. for the probability of exceedance the Prob(X ≥ nil) for X > nil).

The global distribution is a mixed distribution with a finite probability that X = nil and a continuous distribution of probability for X > nil (for probability of exceedance) or for X ≤ nil (for probability of non-exceedance).

6.2.4 Some possible applications

In Chapter 6, "Analysis of output data" (still under development) of the AquaCrop Reference Manual, the steps of the development of several applications are preesented. Some possible applications are:

- **An irrigation chart**

The simulated guidelines for irrigation scheduling for different weather conditions (Fig. 6.7) can be presented in a table on an irrigation chart. The Low, Normal and High values are considered to be representative for the cool (87.5 % probability of exceedance), normal (average values) and warm (12.5% probability of exceedance) weather conditions;

- **Gross irrigation requirement during the peak period**

Perform a frequency analysis on the irrigation requirement during the peak month for a number of successive years. Present the irrigation requirement for various probabilities of exceedance.

Probability of exceedance	Return period	Gross irrigation requirement in peak month
20 %	1 year out of 5	150 mm
10 %	1 year out of 10	210 mm
5 %	1 year out of 20	240 mm

- **Required information for the design of the irrigation infrastructure**

- **Study of the effect of climate change**

(by performing the analysis for the current and future climate conditions)

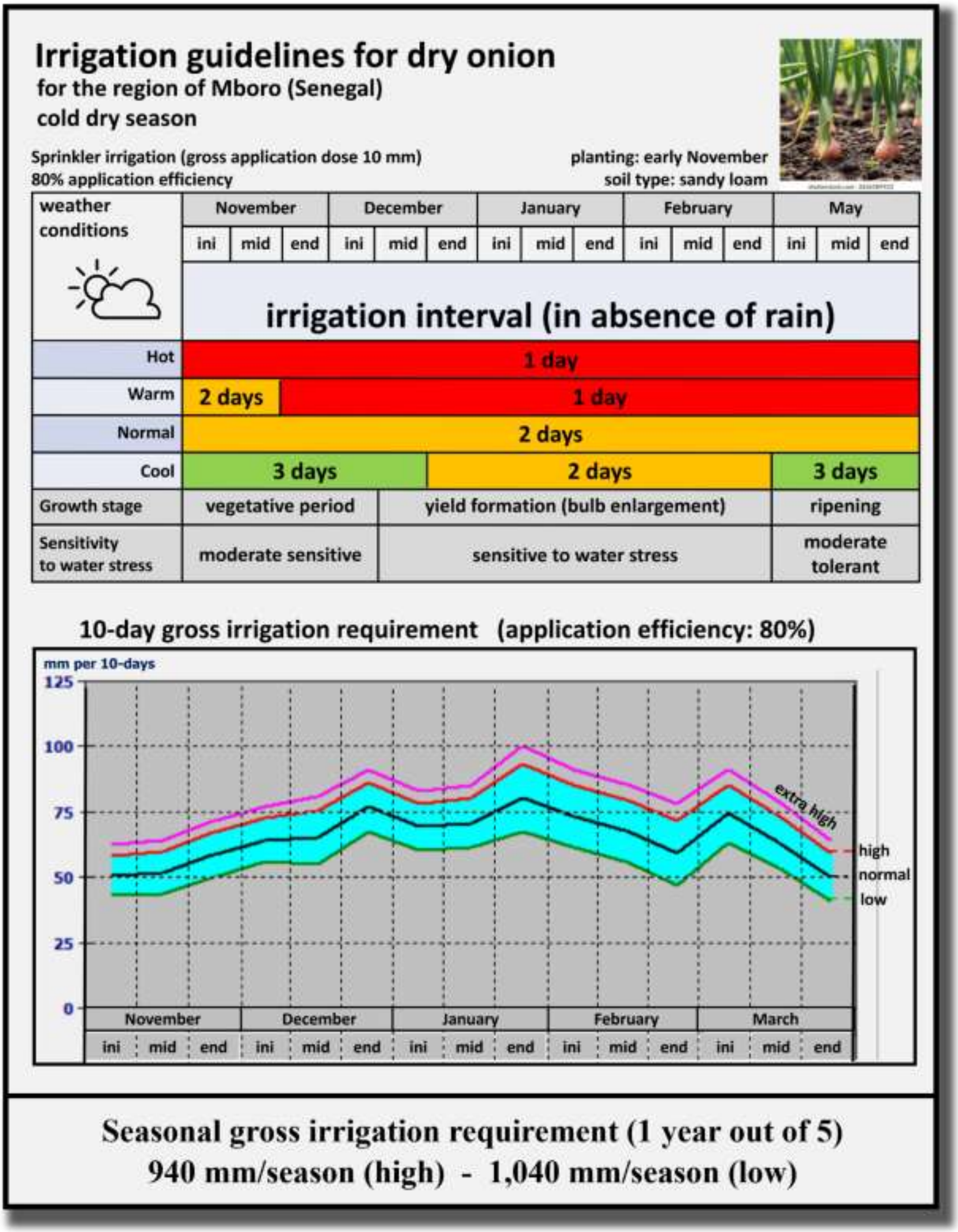


Figure 6.7 – Example of an irrigation chart

6.3 Frequency analysis (growing period)

A frequency analysis is performed on totals of the entire growing period for the number of successive years (e.g. 20, 30, …) considered in the multiple run project.

To improve irrigation and/or field management, the totals of a particular parameter over the entire growing period can give valuable information.

After selecting the purpose of the frequency analysis in the ***Goal of frequency analysis*** menu and hitting the <**Perform frequency analysis**> button, the frequency analysis can be performed (Fig. 6.8).

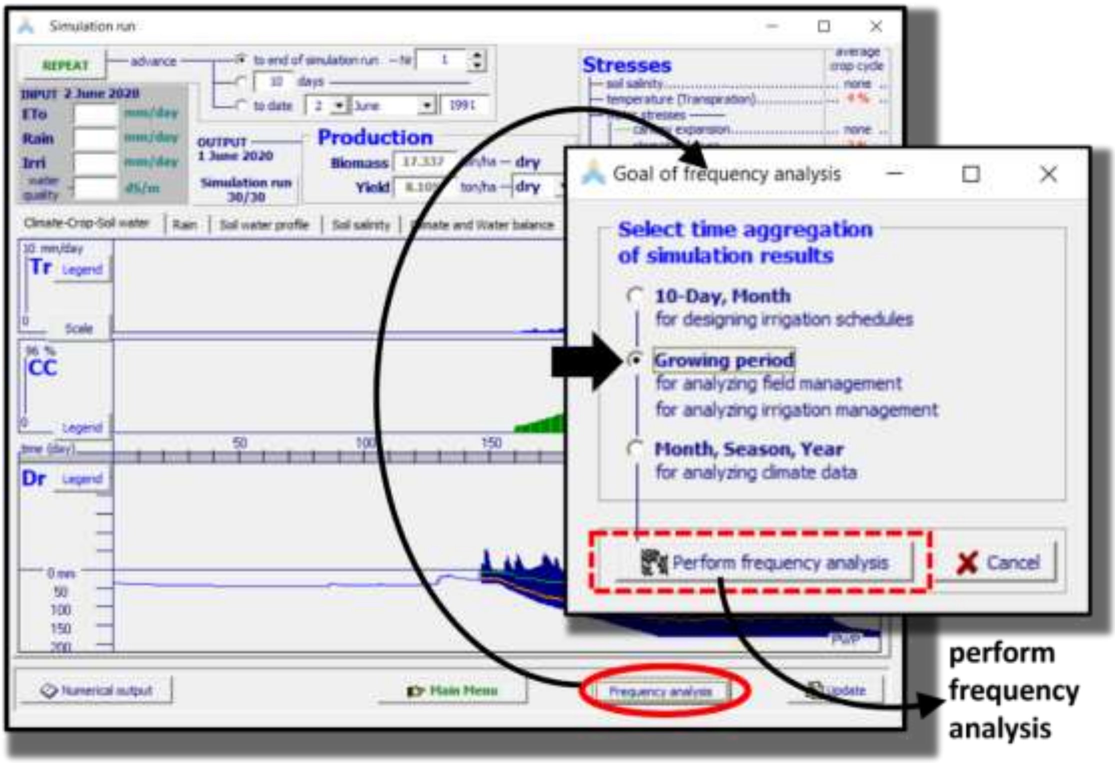


Figure 6.8 – Selection of the purpose and corresponding time aggregation of the simulation results in the Goal of frequency analysis menu.

6.3.1 *Available options*

- **Selection of the parameter to be analysed**

In the ***Frequency analysis (growing period)*** menu (Fig. 6.9) the parameter to be analysed can be selected:

- Biomass (ton/ha)
- Yield fresh/dry (ton/ha)
- Irrigation (mm)
- Planting date (Day Number)
- Length of growing period (days)
- WPet (kg/m3), which is the Yield-ET water productivity
- Relative biomass (%)

A frequency analysis is performed on the totals of the selected parameter for the growing period for each of the successive years (22 years in the example, Fig. 6.9) covering the multiple simulation run (1979 - 2000 in the example, Fig. 6.9). The expected value for different global probabilities of (non)-exceedance and exceedance are calculated, and subsequently plotted and displayed in the 'Global probability' tab-sheet (Fig. 6.9).

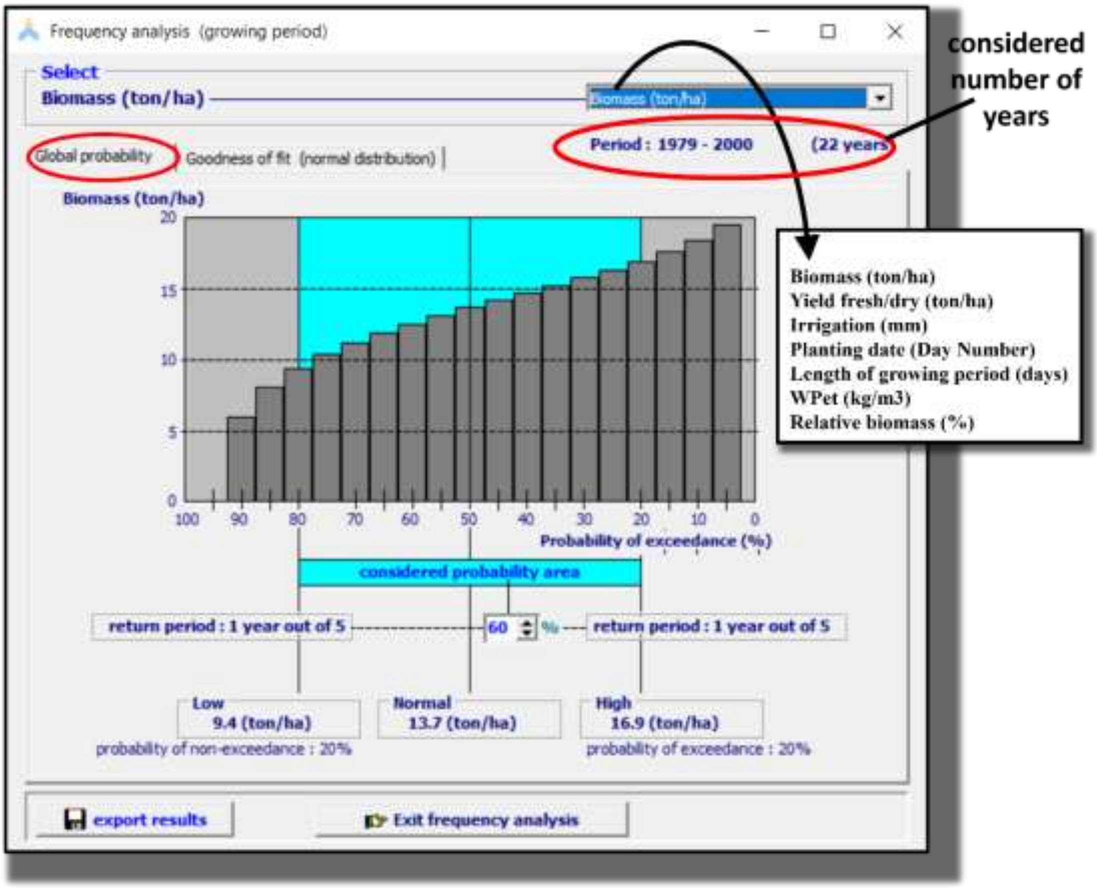


Figure 6.9 –The 'Global probability' tab-sheet of the Frequency analysis (growing period) menu.

- ## Improving the goodness of fit of the normal distribution

The plot of the cumulative density function (CDF) in the 'Goodness of fit (normal distribution)' tab-sheet of the ***Frequency analysis (growing period)*** menu (Fig. 6.11) is the plot of the yearly values versus their cumulative probability of exceedance. By rescaling the vertical axis of the CDF (stretched at both ends and compressed in the centre), the data will fall on a straight line if it is normal distributed (Fig. 6.10)

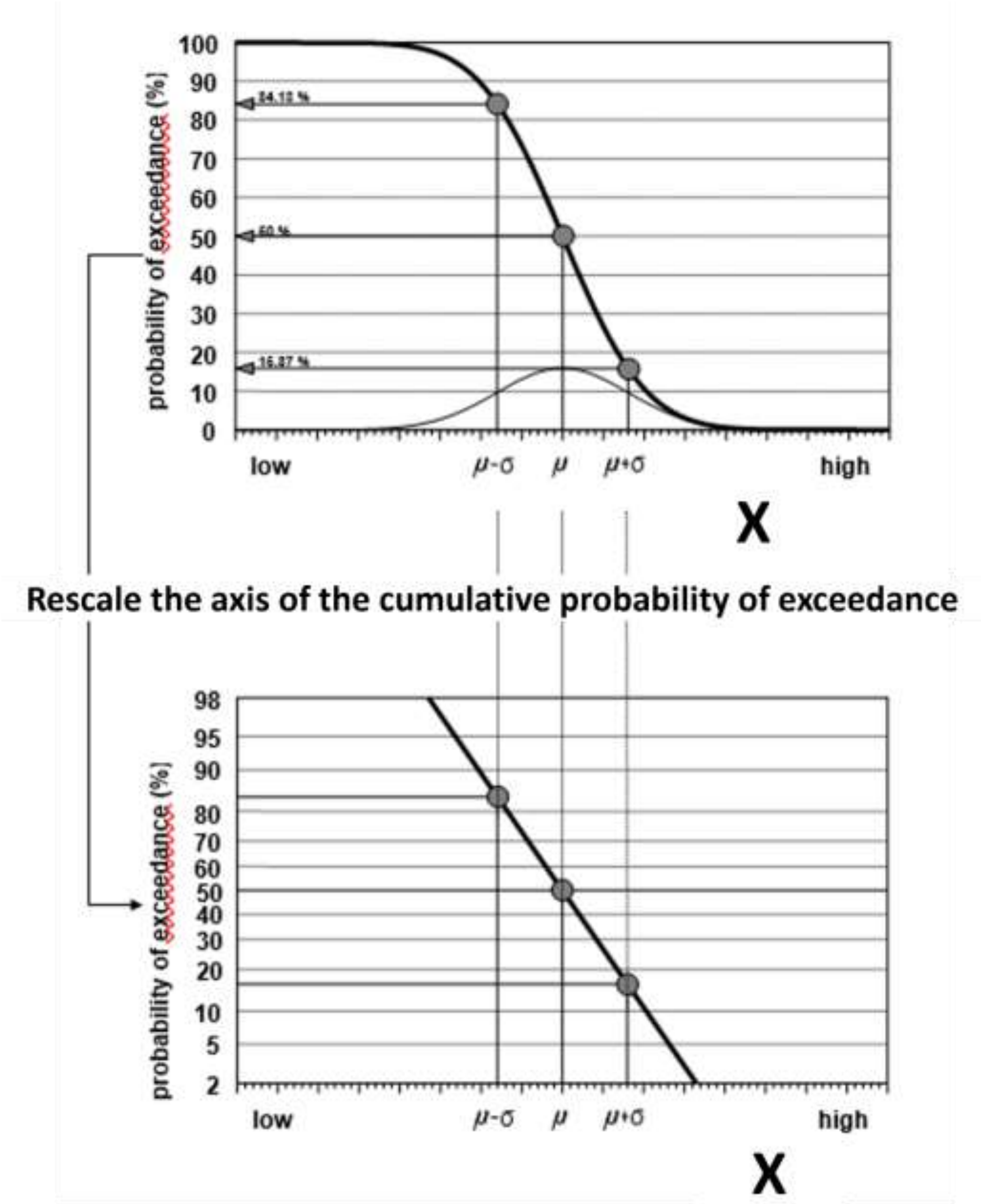


Figure 6.10 – Rescaling of cumulative probability axis of the CDF function

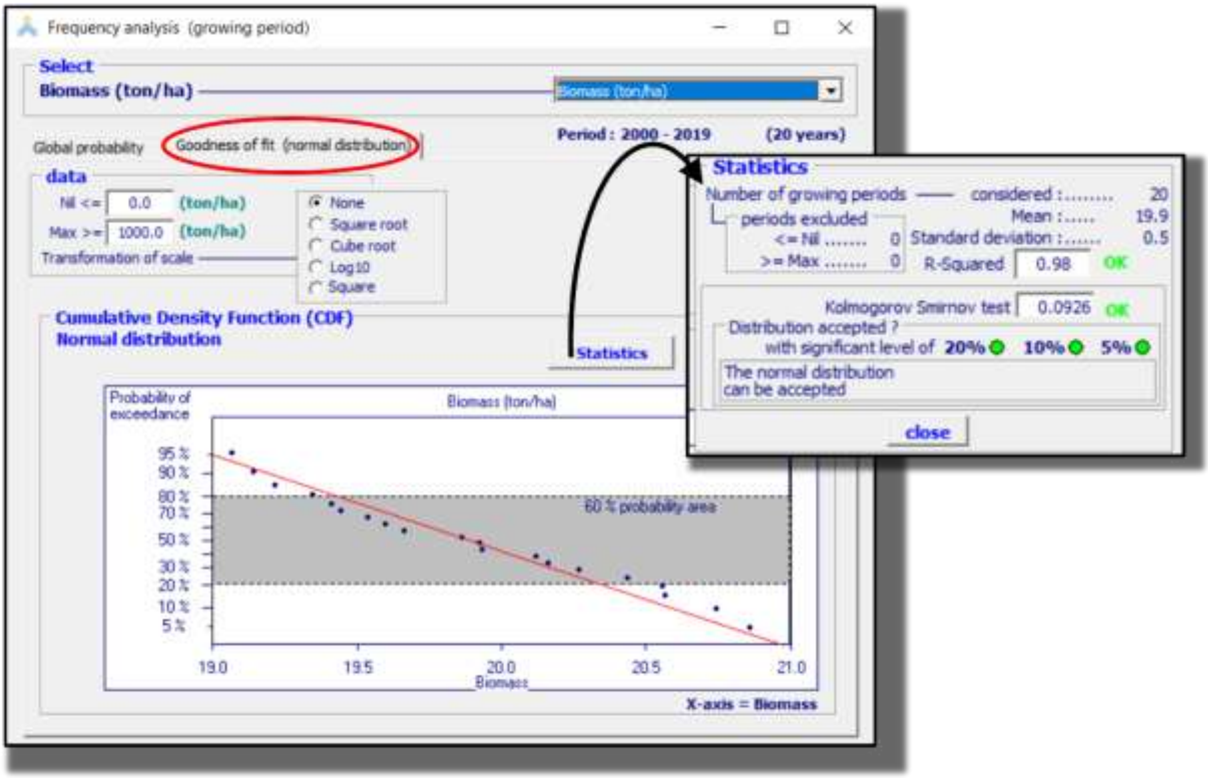


Figure 6.11 –The 'Goodness of fit (normal distribution)' tab-sheet of the Frequency analysis (growing period) menu.

If the data in the probability plot (Fig. 6.11) fall in a reasonable alignment, it may be assumed that the data can be approximated by the assumed normal distribution. Since the data is only a sample of the total population it would be rare for a set of data to plot exactly on a line and a decision must be made as to whether or not the deviations from the line are random variations or represent true deviations indicating that the data does not follow the given normal probability distribution. By fitting a line through the points an indication of the goodness of fit is given by the coefficient of determination (R^2) of the fitted line. Owing to sampling variations, the points will depart somewhat from the line even with data that follow perfectly the assumed distribution (Fig. 6.11).

Apart from the graphical method (check if the points fall in a reasonable alignment in the plot of the CDF) and the R-square for evaluating the goodness of fit, AquaCrop displays also the results from the Kolmogorov-Smirnov test. The statistic used in this test is the greatest absolute difference between the cumulative density function for the data and the fitted normal distribution. The difference is compared with critical values selected according to the significance levels of $\alpha = 0.20$, 0.10 and 0.05. If the difference is smaller than the critical value the assumed probability distribution is accepted with that level of significance (Fig. 6.11).

When the points in the probability plot do not fall in a reasonable alignment, the data is most likely not distributed as the normally distribution especially if the points deviate from the straight line in some systematic matter (Fig. 6.12).

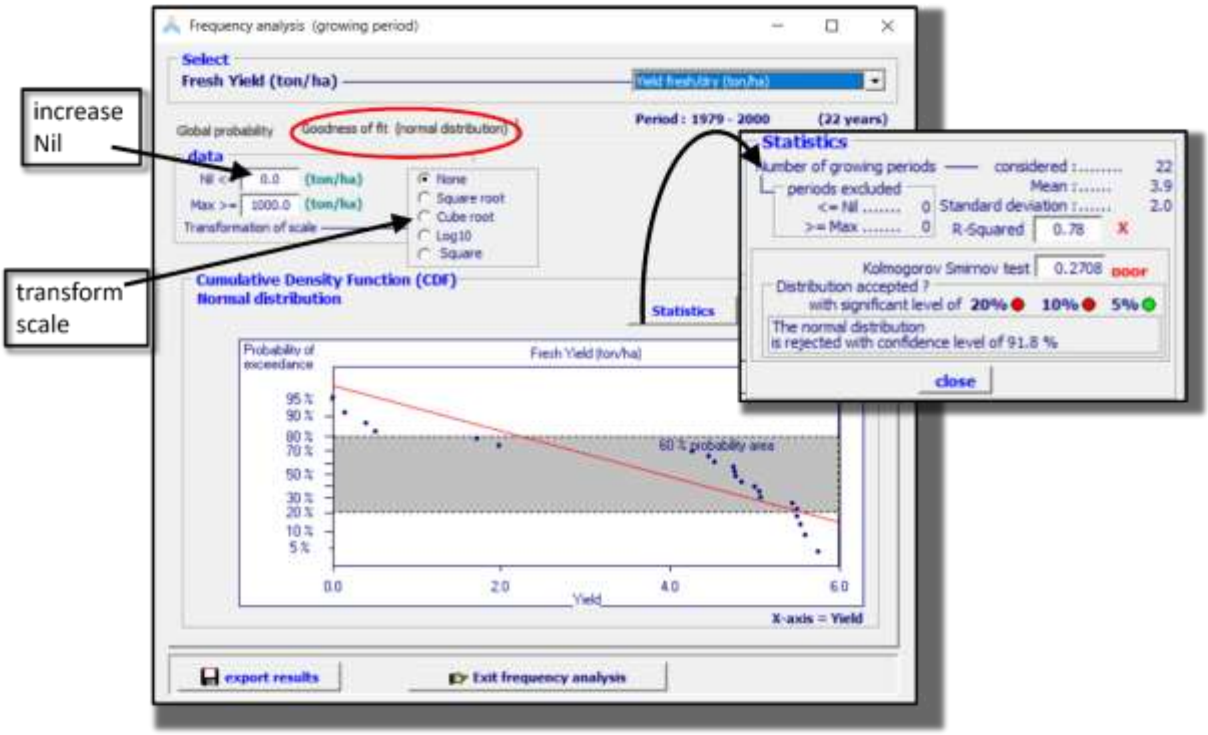


Figure 6.12 – Options in the 'Goodness of fit (normal distribution)' tab-sheet of the Frequency analysis (growing period) menu to improve the goodness of fit.

AquaCrop offers several options to improve the goodness of fit:

- **Increase Nil:** The yearly values might be zero or near zero in some of the years, which makes that the frequency distribution becomes skewed to the left. The method to analyse time-series with zero or near zero data (the so-called nil values) is to separate temporarily the nil values from the non-nil values. In the menu the nil threshold can be specified (Fig. 6.12). By excluding the nil's from the frequency analysis, the frequency distribution becomes less skewed to the left, and the data can be analysed (Fig. 6.13).
- **Transform scale:** When the goodness-of-fit is inadequate, an attempt can be made to normalize the data by selecting a mathematical operator. Since dealing with a normal distribution has several practical advantages, it is common practice to transform data that are not normally distributed so that the resulting normalized data can be presented by the normal curve. The transformation of the data will change the scale of the records (i.e. the abscissa of the probability plot). Operators available to rescale the data are the square root (resulting in a fairly moderate transformation), the cube root, the logarithm and the square (resulting in a substantive transformation).

By selection a Nil of 2.0 ton/ha (6 years will be excluded out of the analysis) and considering the square of the simulated yearly biomass for the 16 remaining years (Fig. 6.13), the data departs less from the straight line (as in Fig. 6.12) and the statistics improve.

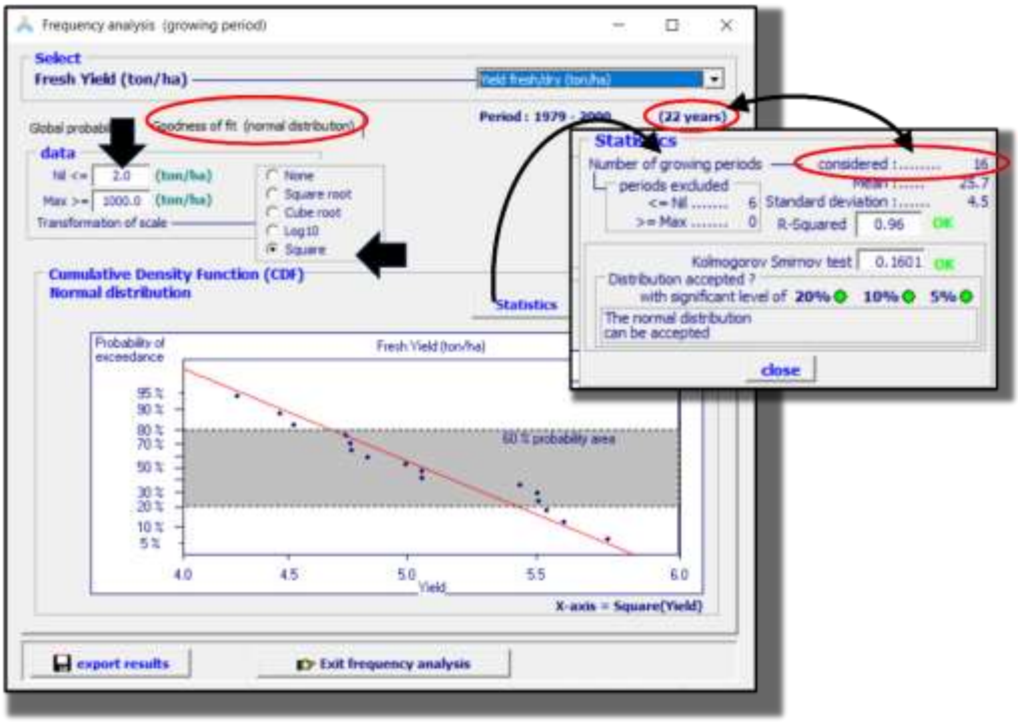


Figure 6.13 – Improving the Goodness of fit (normal distribution) of Fig. 6.12, by selecting a Nil of 2.0 ton/ha and considering the square of the yearly values.

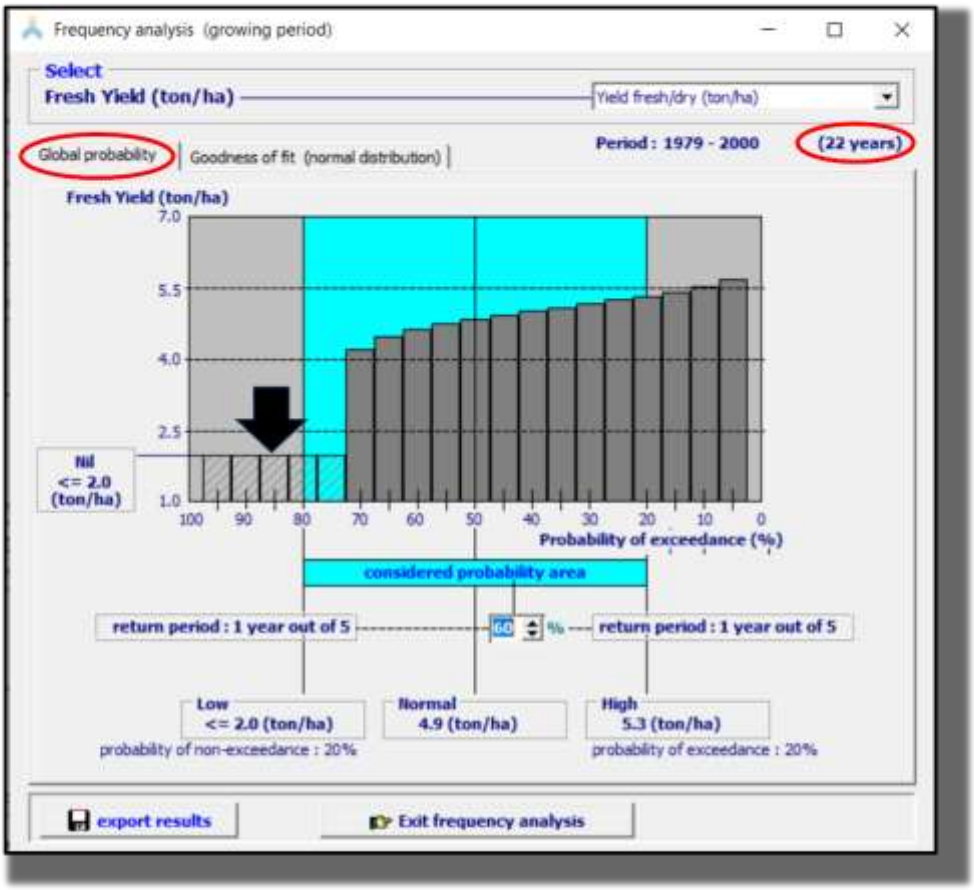


Figure 6.14 – Plot and display of the global probability values in the 'Global probability' tab-sheet of the Frequency analysis (growing period) menu. The fresh yield in the 22 years is smaller than or equal to nil (2.0 ton/ha) for the 20% probability of non-exceedance.

By calculating the global probability, the nil (in 6 years) and no-nil (in 16 years) values are combined (Fig. 6.14). The global probability for the 22 years is calculated by

$$G_X(x) = (1 - p)F_X(x) \qquad \text{(Eq. 6.3)}$$

where $G_X(x)$ is the cumulative probability distribution of all X (i.e. for the probability of exceedance the prob(X ≥ x) for X ≥ nil), p is the probability that X is nil, and $F_X(x)$ is the cumulative probability distribution of the non-nil values of X (i.e. for the probability of exceedance the Prob(X ≥ nil) for X > nil).

The global distribution is a mixed distribution with a finite probability that X = nil and a continuous distribution of probability for X > nil (for probability of exceedance) or for X ≤ nil (for probability of non-exceedance).

6.3.2 Export results

By clicking on the **<export results>** button in the ***Frequency analysis (Growing period)*** menu the ***Export results of Frequency analysis*** menu is displayed (Fig. 6.15).

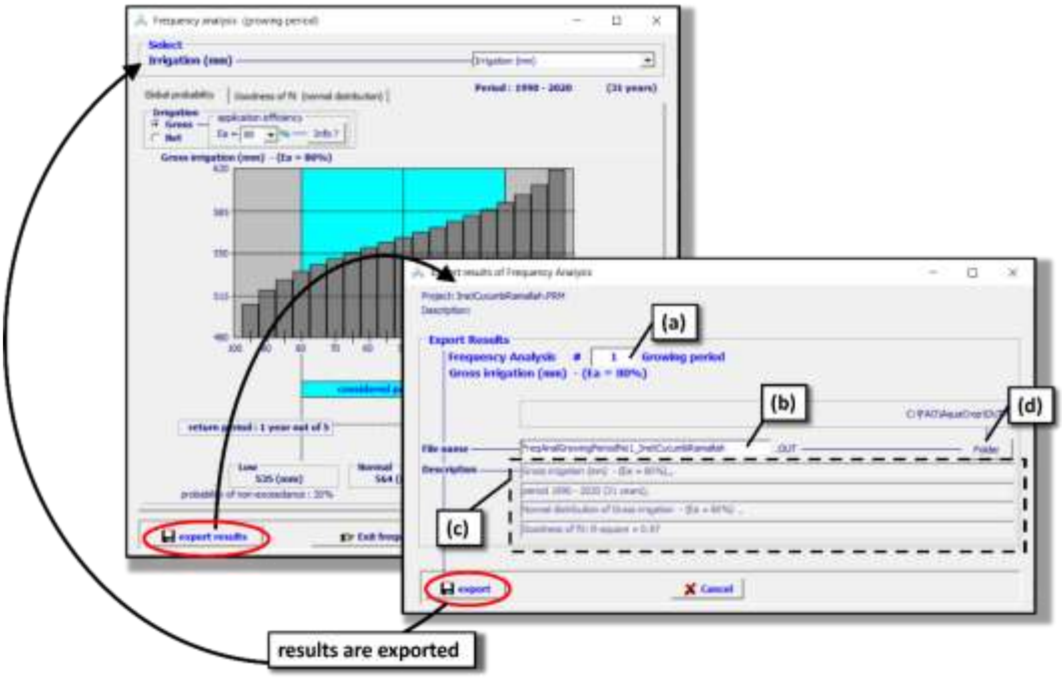


Figure 6.15 – The Export results of Frequency analysis menu

The default file name (Fig 6.15.b) is composed by (i) the number of the Frequency analysis performed (Fig. 6.15a) and (ii) the name of the project file. The default description (Fig. 6.15c) provides an overview of the selected options and statistics of the goodness of fit. Both the default file name and description can be edited by the user. The folder where the output file needs to be stored can be altered as well (Fig. 6.15d).

By clicking on the **<export>** button in the ***Export results of Frequency analysis*** menu, the results are exported to the specified folder, and the control returns back to the ***Frequency analysis (Growing period)*** menu for another frequency analysis.

6.3.3 *Output file*

In the analysis (e.g. Fig. 6.14) and the output file (Tab. 6.2), the results of the frequency analysis for the selected options are reported as global probabilities, which is a mixed distribution with a finite probability that X = nil and a continuous distribution of probability for X > nil (for probability of exceedance) or for X ≤ nil (for probability of non-exceedance).

Table 6.2 – Example of the output file of a frequency analysis of the gross irrigation requirement for 31 successive years

```
AquaCrop 7.3 (July 2026) - Output created on (date) : 03/07/2026   at (time) : 10:57:57

Gross irrigation (mm)  - (Ea = 80%),,
period 1990 - 2020 (31 years),
Normal distribution of Gross irrigation  - (Ea = 80%)  ,
Goodness of fit: R-square = 0.97


 Number of growing periods considered     : (31 years)
 Number of periods <= Threshold(Nil): 0
 Number of periods >= Threshold(Max): 0


                   Global Probability        Return Period     Gross irrigation (mm)  - (Ea
= 80%)
---------------------------------------------------------------------------------------------
 Probability of non-exceedance:    5%        20 years              508
 Probability of non-exceedance:   10%        10 years              520
 Probability of non-exceedance:   15%         7 years              529
 Probability of non-exceedance:   20%         5 years              535
 Probability of non-exceedance:   25%         4 years              541
 Probability of non-exceedance:   30%                              546
 Probability of non-exceedance:   35%                              551
 Probability of non-exceedance:   40%                              555
 Probability of non-exceedance:   45%                              559
 Probability of exceedance....:   50%                              564
 Probability of exceedance....:   45%                              568
 Probability of exceedance....:   40%                              572
 Probability of exceedance....:   35%                              577
 Probability of exceedance....:   30%                              581
 Probability of exceedance....:   25%         4 years              586
 Probability of exceedance....:   20%         5 years              592
 Probability of exceedance....:   15%         7 years              599
 Probability of exceedance....:   10%        10 years              607
 Probability of exceedance....:    5%        20 years              619

 Global probability: Probability of nil, max, non-nil and non-max values     (31 years)
```

6.3.4 *Some possible applications*

In Chapter 6, "Analysis of output data" (still under development) of the AquaCrop Reference Manual, the steps of the development of several applications are preesented. Some possible applications are:

- **Field management**

For 30 (Ramallah, West bank) and 23 (Tunis, Tunisia) successive years, the yield of rainfed winter wheat was simulated in the two locations by assuming an unlimited soil fertility. The results of the frequency analysis of the relative biomass for various probabilities are presented in the Table below.

Probability of exceedance	**Return period**	**Relative biomass (B_{rel})**	
		Ramallah	**Tunis**
5 %	1 year out of 20	**≥ 96 %**	**= 100 %**
10 %	1 year out of 10	**≥ 88 %**	**= 100 %**
20 %	1 year out of 5	**≥ 78 %**	**≥ 95 %**
25 %	1 year out of 4	**≥ 74 %**	**≥ 92 %**
50 %	1 year out of 2	**≥ 59 %**	**≥ 78 %**
Probability of non-exceedance			
50 %	1 year out of 2	**≤ 59 %**	**≤ 78 %**
25 %	1 year out of 4	**≤ 44 %**	**≤ 60 %**
20 %	1 year out of 5	**≤ 40 %**	**≤ 55 %**
10 %	1 year out of 10	**≤ 30 %**	**≤ 38 %**
5 %	1 year out of 20	**≤ 22 %**	**≤ 14 %**

In the absence of irrigation, the average biomass production is 59 % of the potential production in Ramallah and 78% in Tunis. Since unlimited soil fertility was assumed, the simulated yield is entirely the result of water stress. The analysis can give indication on the required level of soil fertility level if the objective is to reach the simulated yield in a specific return period (e.g. 78% of the potential yield in 1 year out of 5 in Ramallah). By comparing the cost of improving soil fertility and the gain in yield, it is clear that for Ramallah, unlimited soil fertility is not a valuable option, while for Tunis (where 95% of the yield can be reached in 1 year out of 5) it may be considered if the costs to improve soil fertility are reasonable.

- **Irrigation management**

For 30 (Ramallah, West bank) and 23 (Tunis, Tunisia) successive years, the irrigation requirement for winter wheat was simulated in the two locations by assuming an unlimited soil fertility. The results of the frequency analysis of the relative biomass for various probabilities are presented in the Table below.

Probability of exceedance	**Return period**	**Net irrigation requirement (mm)**	
		Ramallah	**Tunis**
5 %	1 year out of 20	**≥ 366**	**≥ 362**
10 %	1 year out of 10	**≥ 346**	**≥ 303**
20 %	1 year out of 5	**≥ 321**	**≥ 238**
25 %	1 year out of 4	**≥ 311**	**≥ 215**

50 %	1 year out of 2	**≥ 266**	**≥ 134**
Probability of non-exceedance			
50 %	1 year out of 2	**≤ 266**	**≤ 134**
25 %	1 year out of 4	**≤ 212**	**≤ 70**
20 %	1 year out of 5	**≤ 196**	**≤ 56**
10 %	1 year out of 10	**≤ 147**	**≤ 24**
5 %	1 year out of 20	**≤ 88**	**= 0**

By comparing the cost of the irrigation infrastructure (construction), the availability of irrigation water, and the yields that can be reached, valuable information becomes available to decide whether or not irrigation is necessary, and if so, how much water needs to be available.

- **Leaching requirement when the quality of the irrigation water is low**

By running simulations with various levels of over-irrigation (to leach salts out of the root zone), a frequency analysis can give information on the required minimum amount of leaching to reach a certain yield level for a particular return period (e.g. 70 % of the potential yield need to be reached in 1 year out of 5).

- **The effect of crop, irrigation and/or field management on the ET water productivity (WP_{et})**

By running simulations with various planting dates (crop management), or different levels of soil fertility, weed management, field surface practices, mulches (field management), or different levels of irrigation, leaching (irrigation management), the effect on the ET water productivity (kg(yield)/ m^3(ET)) for various probability levels or return period can be studied.

- **The effect of climate change**

By running simulations for the current and future climate the effect of climate change on crop yield, length of the growing period, generated planting date (+by a temperature or rainfall criterion), irrigation water requirement, etc. can be studied.

6.4 Frequency analysis (climate data)

A frequency analysis can be performed on the climate data of a number of successive years. There are two ways to get to the ***Frequency analysis (climate data)*** menu (Fig. 6.16):

A. - select the **<Frequency analysis>** button in the ***Simulation Run*** menu, and subsequently the time aggregation ‘Month, Season, Period’ (with the goal for analyzing climate data) in the ***Goal of Frequency analysis*** menu; or

B. – select directly the **<Frequency analysis>** button in the ***Climatic data*** menu.

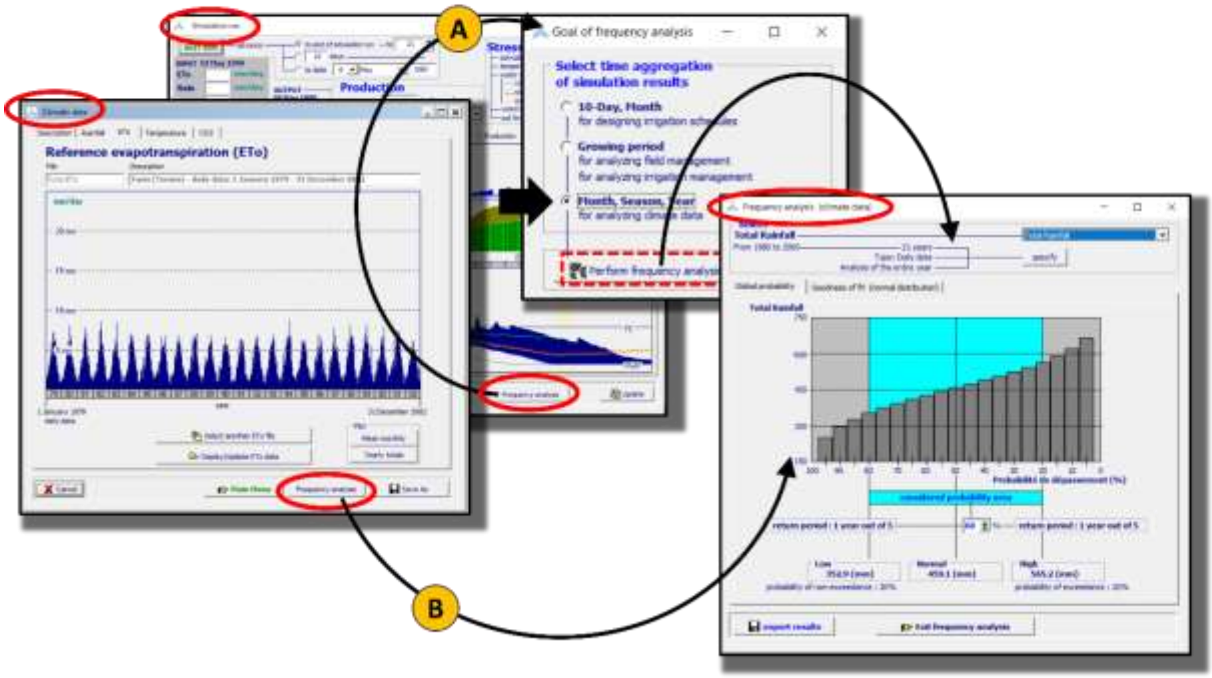


Figure 6.16 – Options to get to the *Frequency analysis (climate data)* menu.

6.4.1 Available options

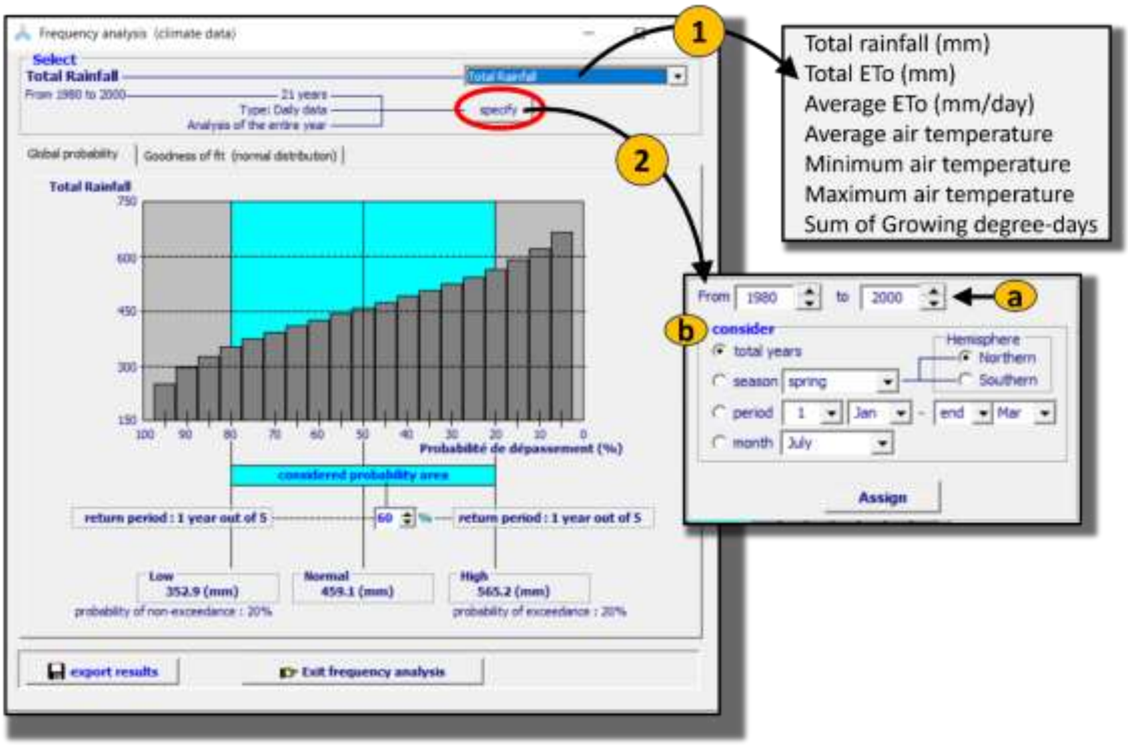


Figure 6.17 – Selection of the parameter to be analysed and the time period to be considered in the Frequency analysis (climate data) menu.

▪ Selection of the parameter to be analysed

In the ***Frequency analysis (climate data)*** menu (Fig. 6.17 – 1) the parameter to be analysed can be selected:

- Total rainfall (mm)
- Total ETo (mm)
- Average ETo (mm/day)
- Average air temperature
- Minimum air temperature
- Maximum air temperature
- Sum of Growing degree-days

▪ Selection of the time period to be analysed

The user can select the starting year and end year to be analyzed (Fig. 6.17 – 2.a).

For the selected number of years, a frequency analysis is performed on the sum (total rainfall, total ETo, or Sum of the growing days) or average (average ETo, or average mean, minimum and maximum air temperature) for a selected time period (Fig. 6.17 – 2.b). The time period to be considered can be:

- the total year,
- a specific season (spring, summer, fall or winter),
- a specific period (from a specific day – to a specific day),
- a specific month.

▪ **Improving the goodness of fit of the normal distribution**

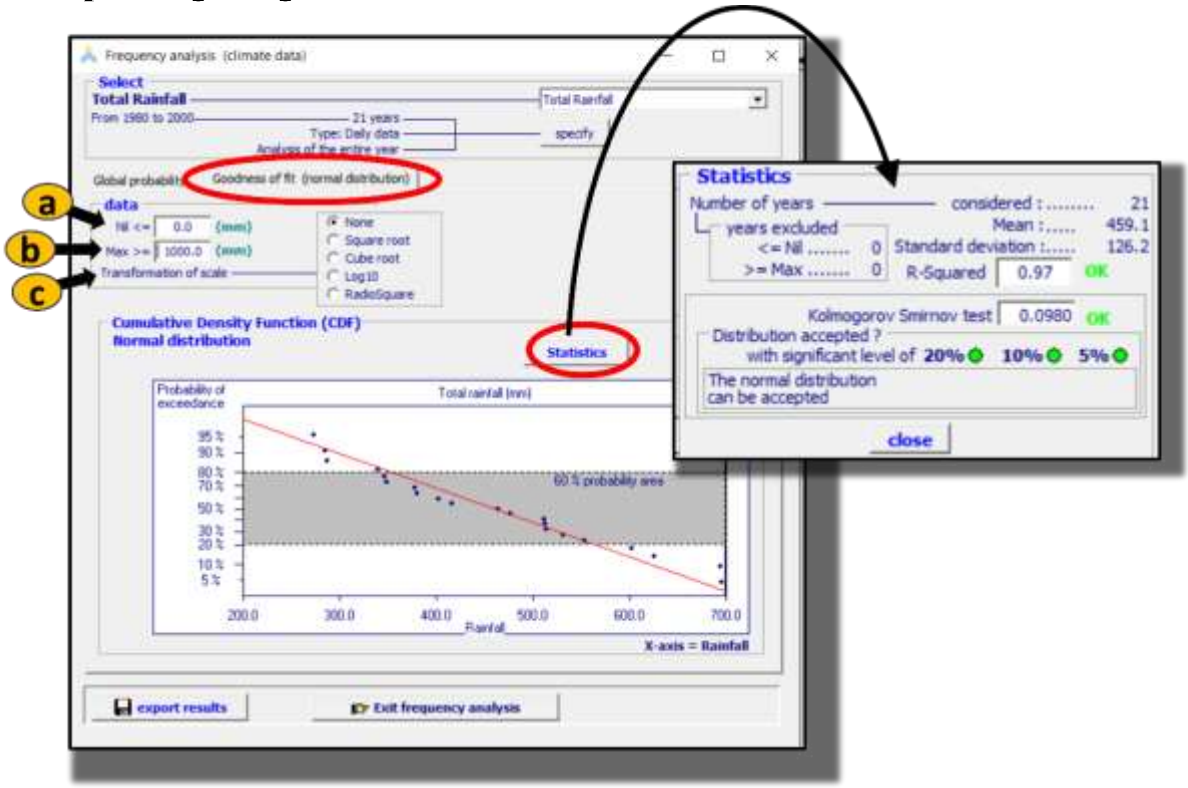


Figure 6.18 – Options in the 'Goodness of fit (normal distribution)' tab-sheet of the Frequency analysis (climate data) menu to improve the goodness of fit.

If the data in the probability plot (Fig. 6.18) fall in a reasonable alignment, it may be assumed that the data can be approximated by the assumed normal distribution. Since the data is only a sample of the total population it would be rare for a set of data to plot exactly on a line and a decision must be made as to whether or not the deviations from the line are random variations or represent true deviations indicating that the data does not follow the given normal probability distribution. By fitting a line through the points an indication of the goodness of fit is given by the coefficient of determination (R^2) of the fitted line. Owing to sampling variations, the points will depart somewhat from the line even with data that follow perfectly the assumed distribution.

Apart from the graphical method (check if the points fall in a reasonable alignment in the plot of the CDF) and the R-square for evaluating the goodness of fit, AquaCrop displays also the results from the Kolmogorov-Smirnov test. The statistic used in this test is the greatest absolute difference between the cumulative density function for the data and the fitted normal distribution. The difference is compared with critical values selected according to the significance levels of $\alpha = 0.20$, 0.10 and 0.05. If the difference is smaller than the critical value the assumed probability distribution is accepted with that level of significance (Fig. 6.18).

AquaCrop offers several options to improve the goodness of fit if the point in the probability plot do not fall in a reasonable alignment:

- **Increase Nil:** The values of the selected parameter may be zero or near zero in some of the years, which makes that the frequency distribution becomes skewed to the left. The method to analyse time-series with zero or near zero data (the so-called nil values) is to separate temporarily the nil values from the non-nil values. In the menu the nil threshold can be specified (Fig. 6.18 – a). By excluding the nil's from the frequency analysis, the frequency distribution becomes less skewed to the left, and the data can be analysed.

- **Reduce Max:** A maximum value above which the value of the selected parameter may not exceed can be specified as well (Fig. 6.18 – b). As such the user separates temporarily the maximum value(s) from the other data. By excluding the maximums from the frequency analysis, the frequency distribution becomes less skewed to the right, and the data can be analysed.
- **Transform scale:** When the goodness-of-fit is inadequate, an attempt can be made to normalize the data by selecting a mathematical operator. Since dealing with a normal distribution has several practical advantages, it is common practice to transform data that are not normally distributed so that the resulting normalized data can be presented by the normal curve. The transformation of the data will change the scale of the records (i.e. the abscissa of the probability plot). Operators available to rescale the data are the square root (resulting in a fairly moderate transformation), the cube root, the logarithm and the square (resulting in a substantive transformation).

6.4.2 Export results

By clicking on the **<export results>** button in the ***Frequency analysis (climate data)*** menu the ***Export results of Frequency analysis*** menu is displayed (Fig. 6.19).

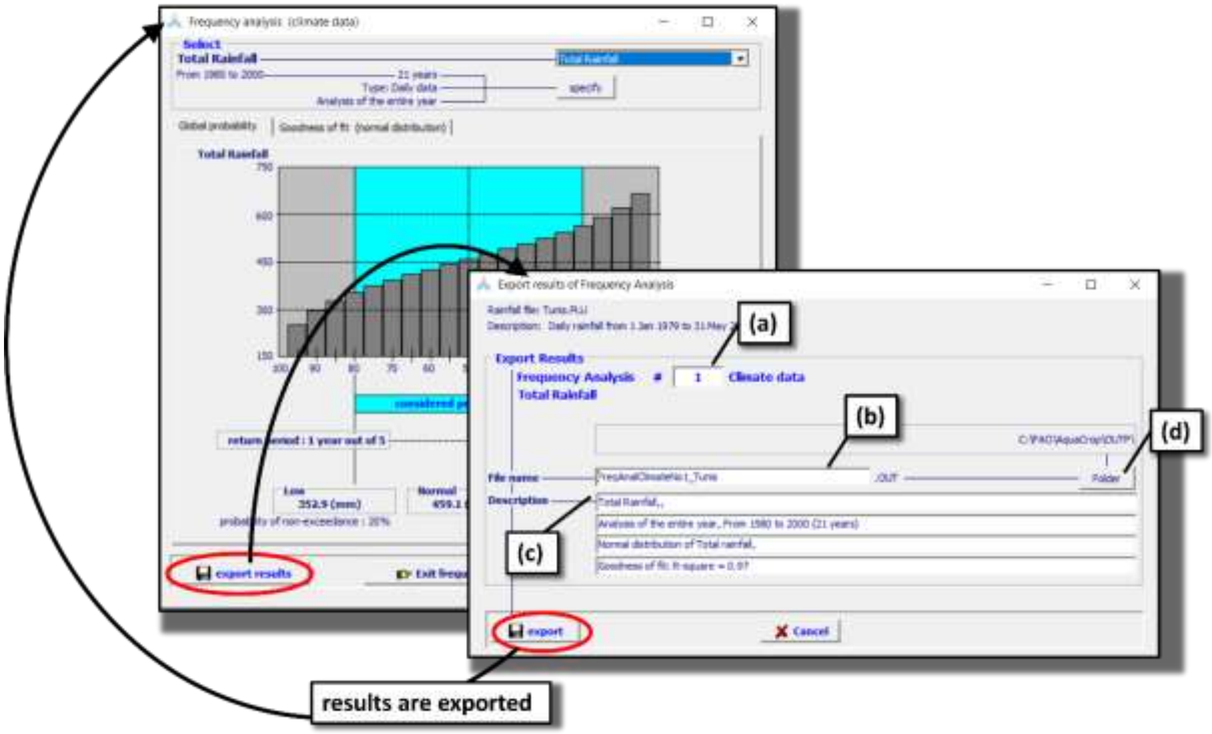


Figure 6.19 – The Export results of Frequency analysis menu

The default file name (Fig 6.19-b) is composed by (i) the number of the Frequency analysis performed (Fig. 6.19-a) and (ii) the name of the project file. The default description (Fig. 6.19-c) provides an overview of the selected options and statistics of the goodness of fit. Both the default file name and description can be edited by the user. The folder where the output file needs to be stored can be altered as well (Fig. 6.19-d).

By clicking on the **<export>** button in the ***Export results of Frequency analysis*** menu, the results are exported to the specified folder, and the control returns back to the ***Frequency analysis (climate data)*** menu for another frequency analysis.

6.4.3 Output file

In the analysis and the output file (Tab. 6.3), the results of the frequency analysis for the selected options are reported as global probabilities, which is a mixed distribution with a finite probability that X <= nil and X >= Max, and a continuous distribution of probability for Max>X > nil.

Table 6.3 – Example of the output file of a frequency analysis of the tot total rainfall in Tunis in 21 successive years for the period 1980 – 2000.

```
AquaCrop 7.3 (January 2026)

Total Rainfall,,
Analysis of the entire year, From 1980 to 2000 (21 years)
Normal distribution of Total rainfall,
Goodness of fit: R-square = 0.97


 Analysis of the entire year, From 1980 to 2000 (21 years)
 Years excluded <= Threshold(Nil): 0
 Years excluded >= Threshold(Max): 0


                   Global Probability        Return Period     Total Rainfall
------------------------------------------------------------------------------------------
 Probability of non-exceedance:    5%         20 years            251.5
 Probability of non-exceedance:   10%         10 years            297.4
 Probability of non-exceedance:   15%          7 years            328.3
 Probability of non-exceedance:   20%          5 years            352.9
 Probability of non-exceedance:   25%          4 years            374.0
 Probability of non-exceedance:   30%                             393.0
 Probability of non-exceedance:   35%                             410.5
 Probability of non-exceedance:   40%                             427.2
 Probability of non-exceedance:   45%                             443.3
 Probability of exceedance....:   50%                             459.1
 Probability of exceedance....:   45%                             474.9
 Probability of exceedance....:   40%                             491.0
 Probability of exceedance....:   35%                             507.6
 Probability of exceedance....:   30%                             525.2
 Probability of exceedance....:   25%          4 years            544.1
 Probability of exceedance....:   20%          5 years            565.2
 Probability of exceedance....:   15%          7 years            589.8
 Probability of exceedance....:   10%         10 years            620.8
 Probability of exceedance....:    5%         20 years            666.6

 Global probability: Probability of nil, max, non-nil and non-max values     21 years
```

6.4.4 Some possible applications

In Chapter 6, "Analysis of output data" (still under development) of the AquaCrop Reference Manual, the steps of the development of several applications are preesented. Some possible applications are:

By performing a frequency analysis on the current and future climate data, and by comparing (i) the annual totals or (ii) the climate data in a particular month, (iii) the climate data for a particular season (spring, summer, fall, winter), or (iv) for a specific period, the effect of climate change for the selected period can be studied. For example, one can investigate:

- How important is the effect of climate change on the total annual rainfall
- Does climate change alters the rainfall distribution in a particular season (e.g. wetter winters but drier summers)?
- How strongly is the increase of the maximum air temperature in the summer period in the future climate?
- Is the effect of climate change similar for all return periods, or more or less important in extreme years (years with a low return period)?
- Etc.

7. Specifying the end of the irrigation period

Various irrigation modes can be considered in AquaCrop:
- rainfed cropping (no irrigation in season) – which is the default,
- the determination of Net irrigation water requirement,
- an irrigation schedule by specifying the events to asses an existing irrigation schedule,
- the generation of an irrigation schedule by specifying a time and depth criterion for planning or evaluating a potential irrigation strategy.

Since irrigation is typically stopped a few days before maturity, version 7.3 now includes an option to explicitly specify the end of the irrigation period. This option is available when generating an irrigation schedule.

7.1 Generation of irrigation schedules

The option to generate an irrigation schedule is available for evaluating or planning purposes of a particular irrigation strategy. At run time irrigations are generated according to the specified time and a depth criterion. The time criterion specifies 'When' an irrigation has to be applied while the depth criterion determines 'How much' water has to be applied. The time and depth criteria with their corresponding parameters that need to be specified are listed in Tables 7.1 and 7.2.

Table 7.1 – Time criteria with corresponding parameter

Criterion	Parameter
Fixed interval (days)	Interval between irrigations (for example 10 days).
Allowable depletion (mm water)	Amount of water that can be depleted from the root zone (the reference is soil water content at field capacity) before an irrigation has to be applied (for example 30 mm)
Allowable depletion (% of RAW)	Percentage of RAW that can be depleted before irrigation water has to be applied (for example 100 %)
Water layer between bunds (mm water)	Threshold for the depth of the surface water layer that should be maintained between the soil bunds (for example 5 mm). An irrigation is generated when the level of the water layer reaches the threshold. This time criterion is only applicable when 'Fixed net application' is the depth criterion

Table 7.2 – Depth criteria with corresponding parameter

Criterion	Parameter
Back to Field Capacity (+/- extra mm water)	Extra water on top of the amount of irrigation water required to bring the root zone back to Field Capacity. The specified value can be zero, positive or negative: ▪ zero : the applied irrigation will bring the soil water content in the root zone at Field Capacity (reached at the end of the day);

	▪ positive: an over irrigation is planned for example for leaching purposes (for example + 20 mm); ▪ negative: an under irrigation is planned for example to profit from expected rainfall (for example – 10 mm)
Fixed application depth (mm water)	Net irrigation application depth.

After the selection of the criteria, the values linked with the time and depth criteria and water quality are specified in the ***Irrigation management*** menu (Fig. 7.1). The values specified at a specific day of the cropping period will be valid till the date where another value is specified or to the end of the cropping period when no values at later dates are specified. As such one can adjust the values to crop development or the time in the season. In Figure 7.2 the generated irrigation schedule as defined in Figure 7.1 is presented.

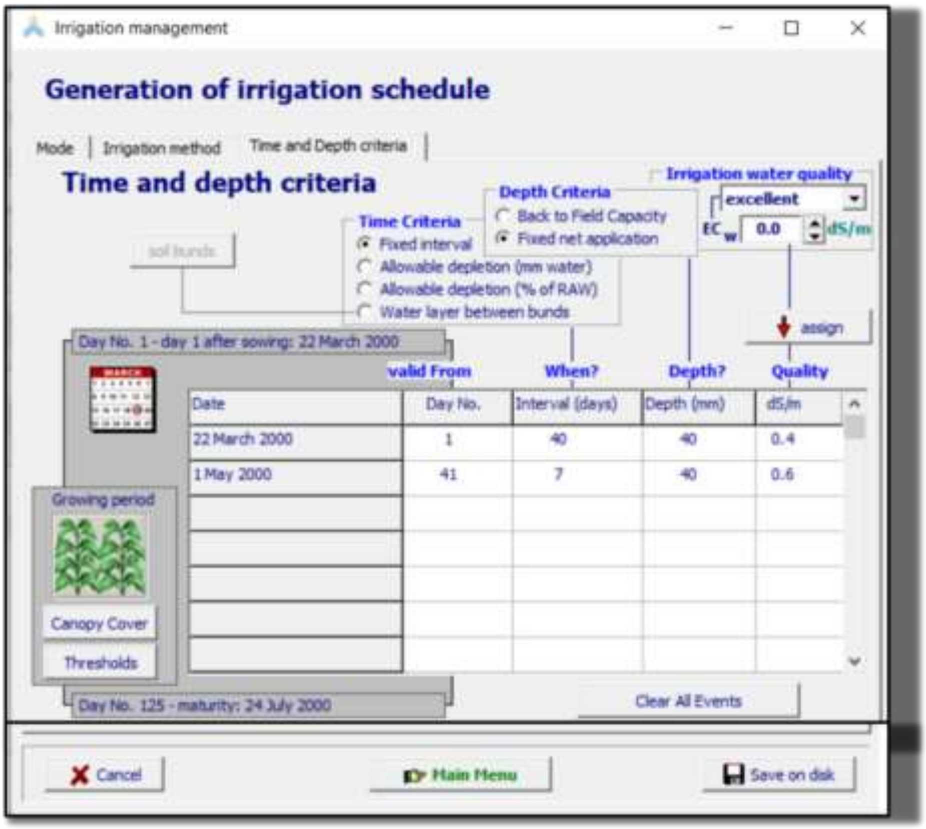


Figure 7.1 – Specifying an irrigation schedule in the Irrigation Management menu, where the fixed irrigation interval (time criterion) varies over the season, while the fixed irrigation application depth (depth criterion) remains constant, and the irrigation water quality deteriorates.

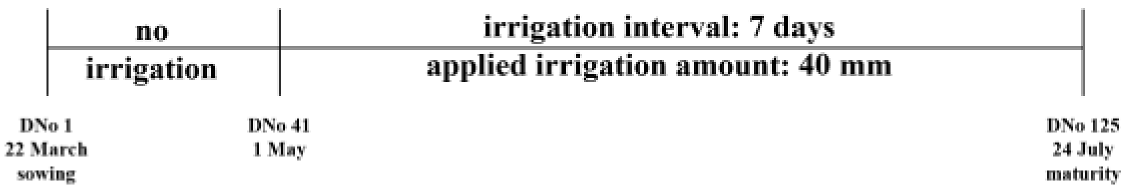


Figure 7.2 – Generated irrigation schedules as defined in Figure 7.1

7.2 Specifying the end of the irrigation period in previous versions

In previous versions of AquaCrop, the user had to specify an unrealistically long irrigation interval (such as 100 days in Figure 7.3), or an unrealistic high depletion (e.g. 500% of RAW) for the day number at which irrigation should stop (day 116 in Figure 7.3). This ensured that AquaCrop would not generate any further irrigation applications from that day on, as the specified interval or depletion could not be reached before the end of the growing season. To obtain the same result, it would also have been possible to assign 0 mm as the fixed net application (from that day on, all irrigation generated will be 0mm until the end of the growing season).

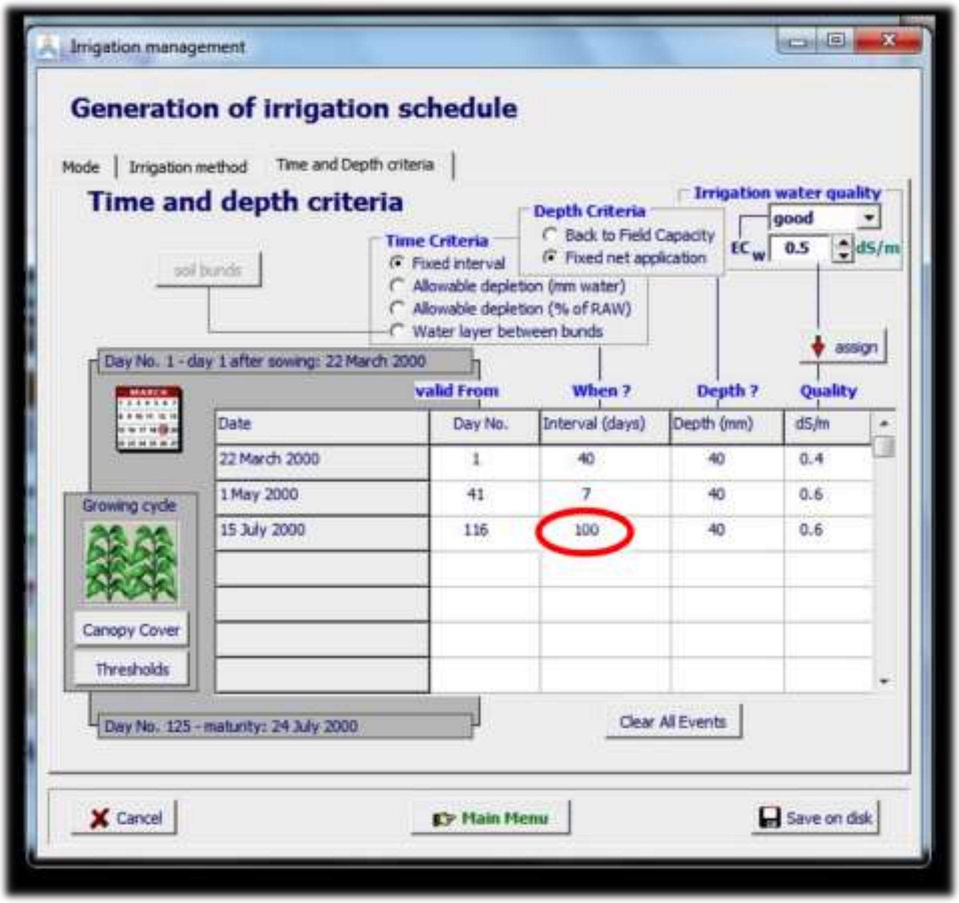


Figure 7.3 – The end of the irrigation at Day No. 116 is specified, by an unrealistically long irrigation interval (100 days).

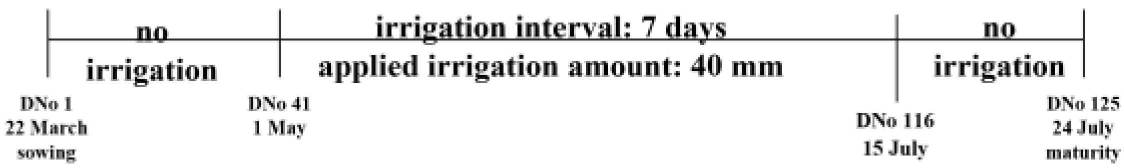


Figure 7.4 – Generated irrigation schedules as defined in Figure 7.3.

7.3 Specifying the end of the irrigation period in Version 7.3

All options available in previous version remains valid. Hence the user can still use the previous method to stop irrigating at a particular day.

However, the user can now also explicitly indicate how many days before the end of the growing period, irrigation should be stopped (Fig. 7.5). This makes the specification more straightforward. It also has the advantage that the end of the irrigation is well defined when the length of the growing period is not specified in calendar days but by a number of growing degree days. When the year is relative colder than usual, the growing period is stretched and maturity will be reached rather late, while in a year with relative warm temperatures, maturity will be reached early. Hence when running a simulation in growing degree days, the day number of the end of the growing period varies with the temperature regime of the year, and as such also the date at which irrigation ends.

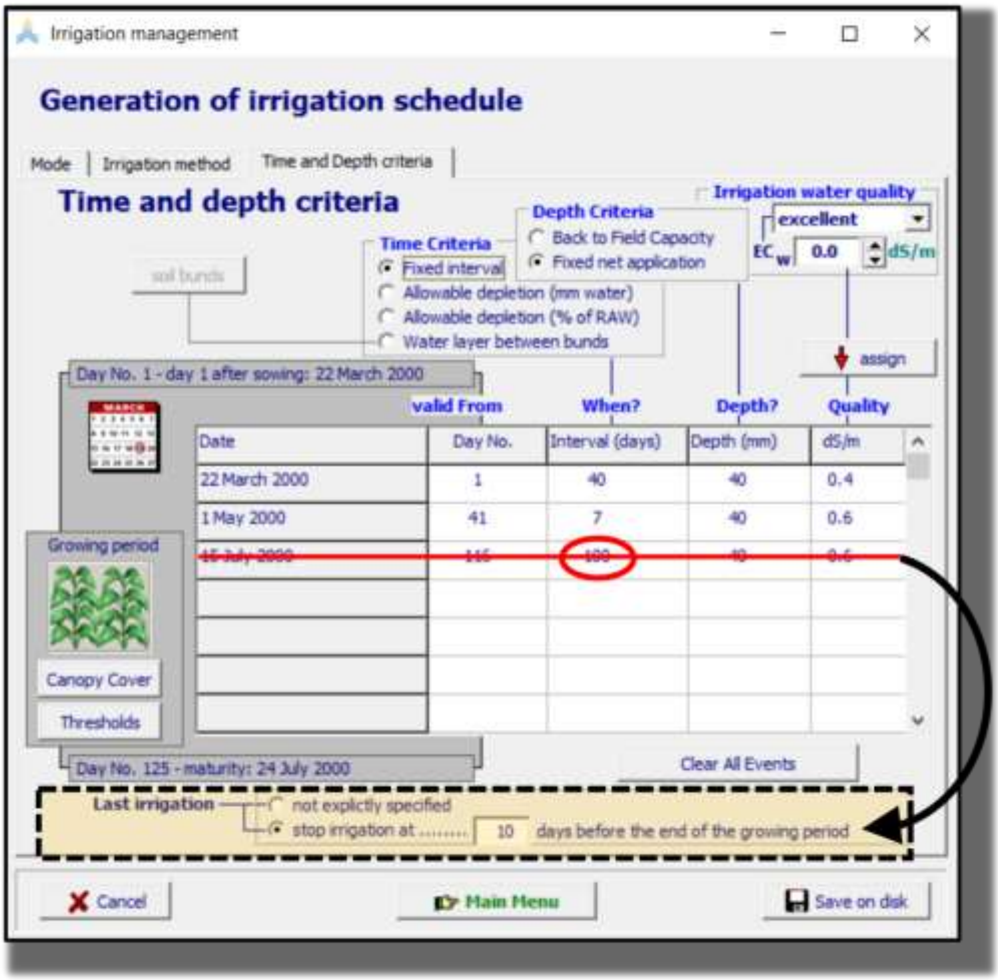


Figure 7.5 – Specification of the end of the irrigation period in AquaCrop Version 7.3. Irrigation stops at the specified number of days before the end of the growing period. This replaces the line required in previous version with an unrealistic long irrigation interval (crossed out in red).

7.4 Irrigation input file

The irrigation method, the percentage of the soil surface wetted by the irrigation, and (i) the timing, net application depth and water quality of the irrigation events or (ii) rules to generate irrigation events, or (iii) rules to determine net irrigation requirement, are specified in an irrigation file (files with extension IRR). In the absence of an irrigation file, rainfed cropping is assumed when running a simulation.

The irrigation input files for the specification of irrigation events, or for the determination of net irrigation water requirement do not change in Version 7.3.

One extra line is added to the input file for generating irrigations. In that line the days before the end of the growing period at which irrigation is stopped, is specified. Its structure is presented in table 7.3 and an example (for Fig. 7.5) is given in Table 7.4.

Table 7.3 – Structure of the irrigation file, generating irrigations (files with extension IRR)

Description	Format
First line is a description of the file content	String of characters
Version number of AquaCrop	Real (1 digit)
A number (1 to 5) used as a code to specify the irrigation method: 1 : Sprinkler irrigation 2 : Surface irrigation: Basin 3 : Surface irrigation: Border 4 : Surface irrigation: Furrow 5 : Drip irrigation	Integer
Percentage of soil surface wetted by irrigation. This percentage is generally closely linked with the irrigation method.	Integer
The number 2 used to specify the 'Generation of an irrigation schedule' irrigation mode:	Integer
A number (1 to 3) used as a code to specify the time criterion: 1 : Fixed interval; 2 : Allowable depletion (mm water); 3 : Allowable depletion (% of RAW); 4: Keep a minimum level of surface water layer between soil bunds	Integer
A number (1 to 2) used as a code to specify the depth criterion: 1 : Back to Field Capacity; 2 : Fixed net application depth.	Integer
The number (≥ 1) indicating the day on which irrigation ends (expressed as the number of calendar days before the end of growing period). The number is -9 (meaning not defined in AquaCrop) when the last irrigation is not explicitly specified	Integer

Empty line	-
Title ('…')	String of characters
Dotted line ('=====================================')	String of characters
If applicable specifies values for 2nd , 3rd , 4th , .. rule	

Table 7.4 – The updated irrigation file for generating irrigations (the example is for the selected options in Figure 7.5.

```
Description ….
   7.3   : AquaCrop Version (January 2026)
   1     : Sprinkler irrigation
 100     : Percentage of soil surface wetted by irrigation
   2     : Generate irrigation schedule
   1     : Time criterion = fixed intervals
   2     : Fixed application depth
  10     : days before end of growing period, the irrigation will be stopped

  From day     Interval (days)     Application depth (mm)     ECw (dS/m)
==========================================================================
       1              40                   40                     0.4
      41               7                   40                     0.6
```

8. Determination of soil hydraulic properties from soil texture

8.1 Soil horizons and their physical characteristics

The soil profile characteristics consist of soil physical parameters required to simulate the retention of water in the root zone and soil water movement. The soil profile can be composed of up to five different horizons, each with their own physical characteristics.

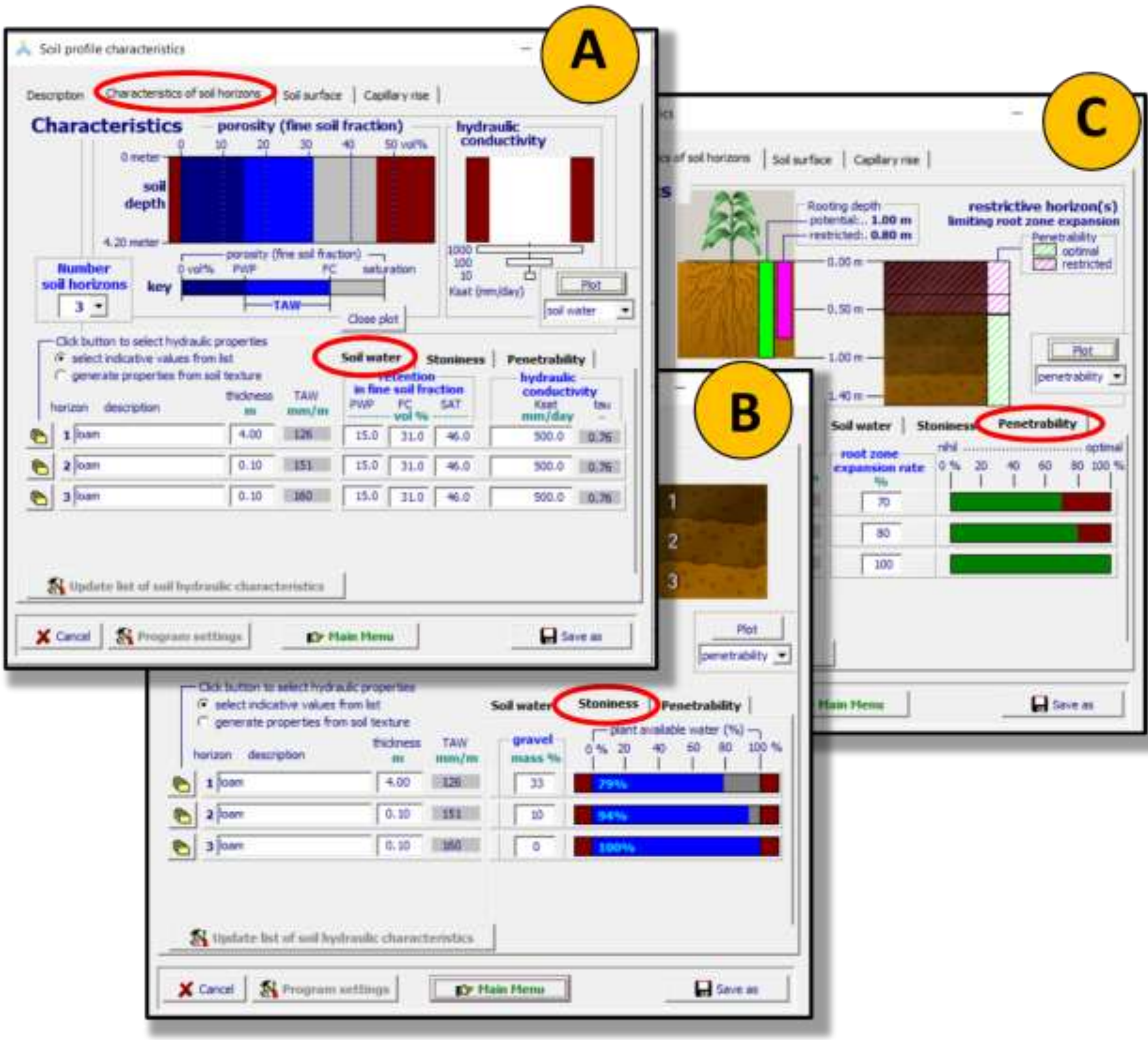


Figure 8.1 – Specification of physical characteristics of the various soil horizons in the (A) 'Soil water', (B) 'Stoniness' and (C) 'Penetrability' tab-sheet in the *Soil profile characteristics* menu.

In the ‘Characteristics of soil horizons’ tab-sheet of the ***Soil profile characteristics*** menu the number and thickness of the horizons are specified. The physical characteristics of the horizons and of their fine soil and mass fractions are specified in (Fig. 8.1):

- the ‘**Soil water**’ tab-sheet (Fig. 8.1 A);
- the ‘**Stoniness’** tab-sheet (Fig. 8.2 B)**;**
- the ‘**Penetrability’** tab-sheet (Fig. 8.3 C).

8.2 Indicative values for soil hydraulic properties and estimates based on soil texture

The amount of water remaining in the soil at saturation and field capacity varies with the soil texture, organic matter content and structure. The clay and organic matter content of a soil horizon predominantly define its soil water content at permanent wilting point. The saturated hydraulic conductivity (K_{sat}) does not only vary between soil types, but even for one specific soil type, a typical K_{sat} value does not exist. Even in a single field, it is not uncommon to measure rather important variations for K_{sat} in space and time as a result of variations in soil structure, bulk density, biological activity and soil management.

The user (i) can directly import locally determined values in the ***Soil profile characteristics*** menu, (ii) can make use of indicative values provided by AquaCrop for various soil textural classes (Fig. 8.2a), or (iii) can generate hydraulic properties from soil texture with the help of pedo-transfer functions (Fig. 8.2b).

8.2.1 Select indicative hydraulic properties

The values presented in Table 8.2 are derived with the help of pedo-transfer functions, and are only indicative values. The default values for the hydraulic conductivity at saturation (Ksat) were obtained by sampling 260 times the textural triangle of the Hydraulic Properties Calculator (developed by the USDA Agricultural Research Service in cooperation with the Washington State University), and by averaging the values for each textural class The indicative values in Table 8.2 are not intended to replace measurements.

Table 8.2 – Indicative values for the soil water content at saturation (SAT), field capacity (FC) and permanent wilting point (PWP), and for the updated saturated hydraulic conductivity (Ksat) for the 12 ‘soil profile’ files (corresponding with the twelve soil textural classes) in the DATA subdirectory of AquaCrop.

Soil textural class	soil water content			Saturated hydraulic conductivity
	Saturation	Field Capacity	Permanent Wilting Point	
	vol %	vol %	vol %	mm/day
Sand	36	13	6	3,000
Loamy sand	38	16	8	2,200
Sandy loam	41	22	10	1,200
Loam	46	31	15	500

Silt loam	46	33	13	575
Silt	43	33	9	500
Sandy clay loam	47	32	20	225
Clay loam	50	39	23	125
Silty clay loam	52	44	23	150
Sandy clay	50	39	27	35
Silty clay	54	50	32	100
Clay	55	54	39	35

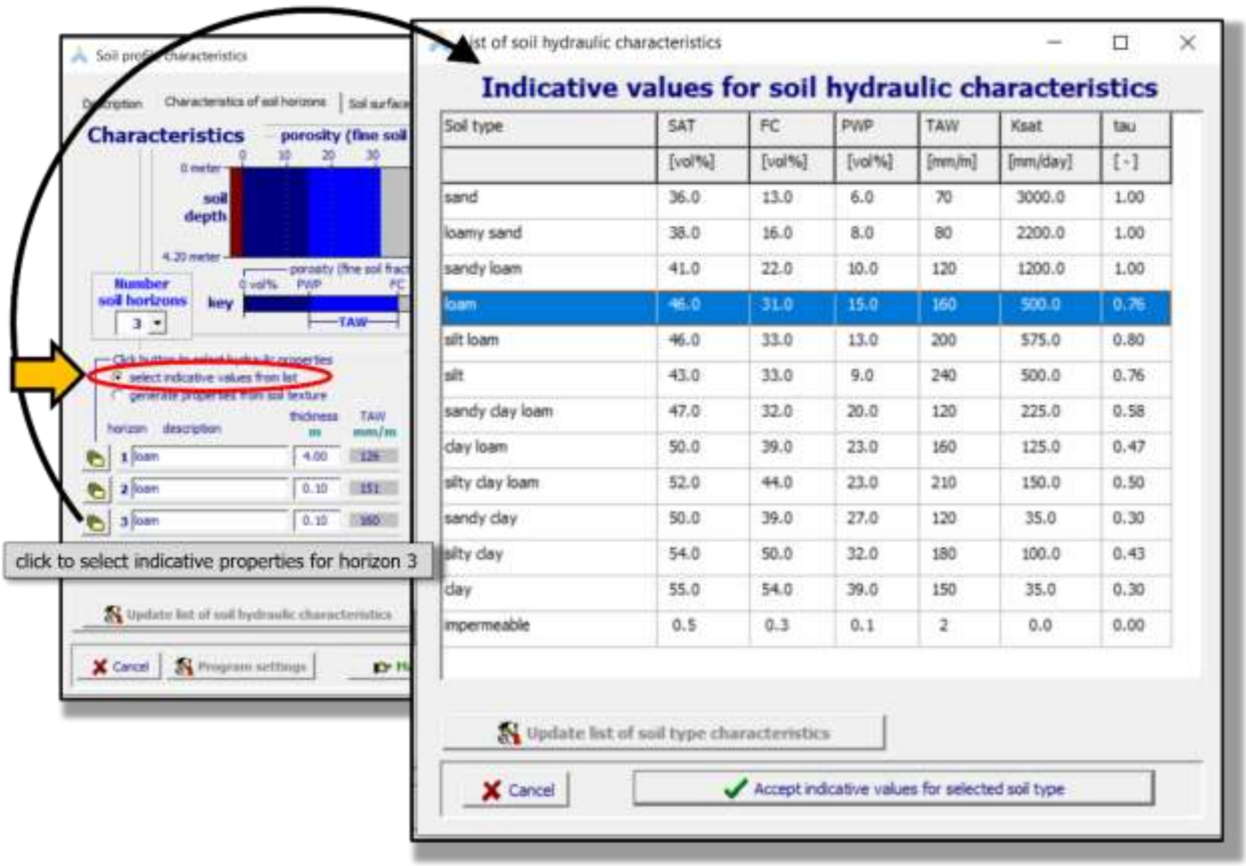


Figure 8.2a – Clicking one of the <Library> buttons in the *Soil profile characteristics* menu, displays the *List of soil hydraulic characteristics* menu where indicative values for soil hydraulic characteristics for various soil types can be selected.

8.2.2 Generate hydraulic properties from soil texture:

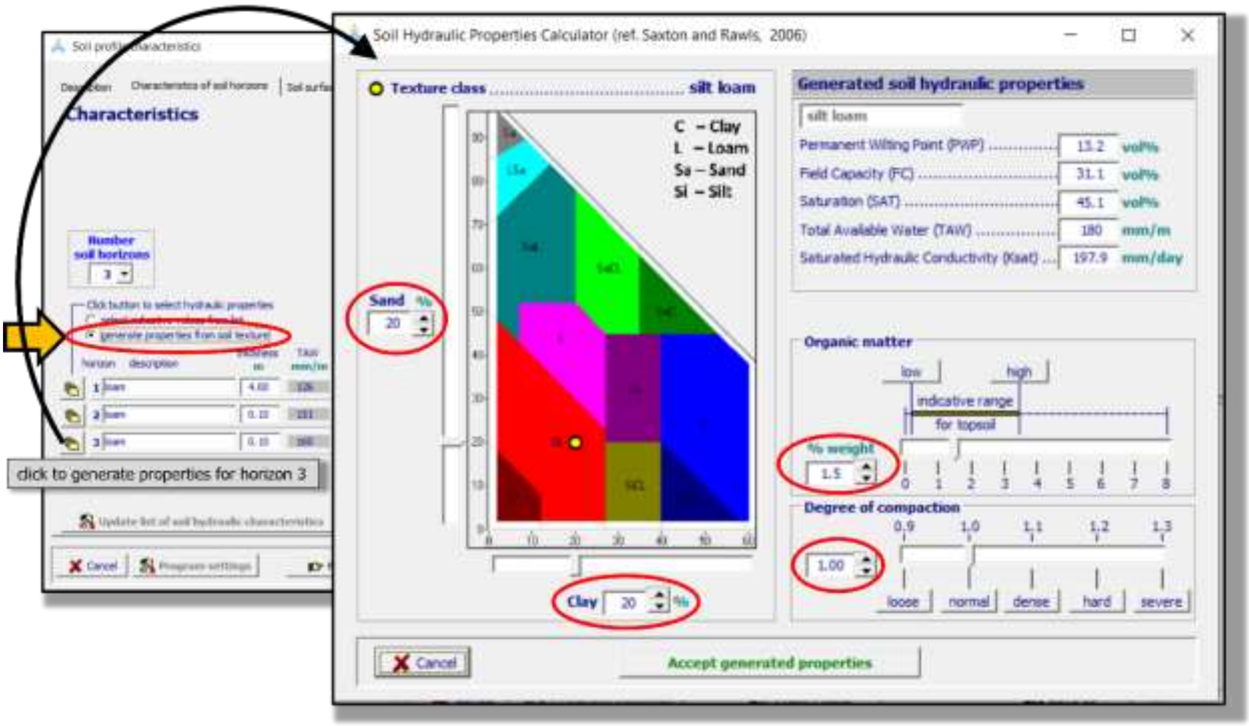


Figure 8.2b – Clicking one of the <Library> buttons in the *Soil profile characteristics* menu, opens the *Soil Hydraulic Properties Calculator* menu where soil hydraulic properties can be generated using the pedo-transfer functions of the Saxton and Rawls (2006).

The layout of the ***Soil Hydraulic Properties Calculator*** menu (Fig. 8.2b) is based on the layout of the Calculator developed by the USDA Agricultural Research Service in cooperation with the Washington State University (Keith E. Saxton: ksaxton@wsu.edu), and available on the Internet.

The generated soil hydraulic properties are obtained using the pedo-transfer functions of Saxton and Rawls (2006). As input, AquaCrop considers the selected (i) percentage of sand, (ii) percentage of clay, (iii) the percentage weight of organic matter and (iv) the degree of compaction (Fig. 8.2b)

8.3 Pedotransfer functions

Reference: *Saxton, K.E. and Rawls, W.J. (2006). Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Sci. Soc. Am. J. 70:1569–1578.*

Symbols

%OM : Organic matter [%weight]
C : clay fraction [-]
S : sand fraction [-]
DF : density factor [-]
Ksat : hydraulic conductivity at saturation [mm/hour]
θ_{33} : soil water content at Field Capacity (33 kP) at normal density [m³/m³]
θ_{1500} : soil water content at Permanent Wilting Point (1500 kP) [m³/m³]
θ_{SAT} : soil water content at Saturation (0 kP) at normal density [m³/m³]
ρ_N : normal density (g/cc)
ρ_{DF} : adjusted density (g/cc)
$\theta_{33,DF}$: soil water content at Field Capacity (33 kP) at adjusted density [m³/m³]
$\theta_{SAT,DF}$: soil water content at Saturation (0 kP) at adjusted density [m³/m³]

Permanent Wilting Point (θ_{1500})

$$\theta_{1500,t} = -0.024\,S + 0.487\,C + 0.006\,(\%OM) + 0.005\,S\,(\%OM) - 0.013\,C\,(\%OM) + 0.068\,S\,C + 0.031 \quad \text{(Eq. 1)}$$

$$\boldsymbol{\theta_{1500} = \theta_{1500,t} + 0.14\,\theta_{1500,t} - 0.02} \quad \textbf{(Eq. 2)}$$

Field Capacity (θ_{33}) and Saturation (θ_{SAT}) at normal density

$$\theta_{33,t} = -0.251\,S + 0.195\,C + 0.011\,(\%OM) + 0.006\,S\,(\%OM) - 0.027\,C\,(\%OM) + 0.452\,S\,C + 0.299 \quad \text{(Eq. 3)}$$

$$\boldsymbol{\theta_{33} = \theta_{33,t} + 1.283\,\theta_{33,t}^2 - 0.374\,\theta_{33,t} - 0.015} \quad \textbf{(Eq. 4)}$$

$$\theta_{(S-33),t} = 0.278\,S + 0.034\,C + 0.022\,(\%OM) - 0.018\,S\,(\%OM) - 0.027\,C\,(\%OM) - 0.584\,S\,C + 0.078 \quad \text{(Eq. 5)}$$

$$\theta_{(S-33)} = \theta_{(S-33),t} + 0.636\,\theta_{(S-33),t} - 0.107 \quad \text{(Eq. 6)}$$

$$\boldsymbol{\theta_{SAT} = \theta_{33} + \theta_{(S-33)} - 0.097\,S + 0.043} \quad \textbf{(Eq. 7)}$$

$$\rho_N = 2.65\,(1 - \theta_{SAT}) \quad \text{(Eq. 8)}$$

Field Capacity ($\theta_{33,DF}$) and Saturation ($\theta_{SAT,DF}$) at adjusted density

$$\rho_{DF} = \rho_N\,DF \quad \text{(Eq. 9)}$$

$$\boldsymbol{\theta_{SAT,DF} = 1 - \left(\frac{\rho_{DF}}{2.65}\right)} \quad \textbf{(Eq.10)}$$

$$\boldsymbol{\theta_{33,DF} = \theta_{33} - 0.2\,(\theta_{SAT} - \theta_{SAT,DF})} \qquad \textbf{(Eq.11)}$$

with the restriction that $(\theta_{SAT,DF} - \theta_{33,DF}) > 0.005$

<u>Saturated hydraulic conductivity (Ksat)</u>

$$B = \frac{[\ln(1500) - \ln(33)]}{[\ln(\theta_{33,DF}) - \ln(\theta_{1500})]} \qquad \text{(Eq. 12)}$$

$$\lambda = \frac{1}{B} \qquad \text{(Eq. 13)}$$

$$\mathbf{Ksat = 1930}\ \boldsymbol{(\theta_{SAT} - \theta_{33})^{(3-\lambda)}} \qquad \textbf{(Eq. 14)}$$

9. Update of the MaunaLoa CO2 file

The annual mean concentrations of CO_2 levels measured at the Mauna Loa Observatory are available in the 'MaunaLoa.CO2' file in the SIMUL subdirectory of AquaCrop. The concentrations for the various years are used to adjust the normalized biomass water productivity (WP*) for atmospheric [CO_2] of the year in which the crop was or will be cultivated. For the future years an increase of 2.5 ppm is assumed. The observed CO_2 concentrations up to 2025 have been updated (Table 9) with the latest published results on the NOAA website:
http://co2now.org/Current-CO2/CO2-Now/noaa-mauna-loa-co2-data.html

Table 9. – The default CO_2 concentrations in the MaunaLoa.CO2 file

Year	Annual Mean [CO_2] ppm	Year	Annual Mean [CO_2] ppm	Year	Annual Mean [CO_2] ppm
1902	297.4	1970	325.68	1999	368.54
1905	298.2	1971	326.32	2000	369.71
1912	300.7	1972	327.46	2001	371.32
1915	301.3	1973	329.68	2002	373.45
1924	304.5	1974	330.19	2003	375.98
1926	305	1975	331.12	2004	377.7
1929	305.2	1976	332.03	2005	379.98
1932	307.8	1977	333.84	2006	382.09
1934	309.2	1978	335.41	2007	384.02
1936	307.9	1979	336.84	2008	385.83
1938	310.5	1980	338.76	2009	387.64
1939	310.1	1981	340.12	2010	390.1
1940	310.5	1982	341.48	2011	391.85
1944	309.7	1983	343.15	2012	394.06
1948	310.7	1984	344.85	2013	396.74
1953	311.9	1985	346.35	2014	398.82
1954	314.1	1986	347.61	2015	401.02
1958	315.29	1987	349.31	2016	404.41
1959	315.98	1988	351.69	2017	406.76
1960	316.91	1989	353.2	2018	408.72
1961	317.64	1990	354.45	2019	411.65
1962	318.45	1991	355.7	2020	414.21
1963	318.99	1992	356.54	2021	416.41
1964	319.62	1993	357.21	2022	418.53
1965	320.04	1994	358.96	2023	421.08
1966	321.37	1995	360.97	2024	424.61
1967	322.18	1996	362.74	2025	427.35
1968	323.05	1997	363.88	2030	439.85
1969	324.62	1998	366.84	2099	609.85