Food and Agriculture Organization of the United Nations

Chapter 6

Analysis of output data

AquaCrop

Version 7.3

Reference manual

July 2026

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July 2026

By the AquaCrop users' community

Food and Agriculture Organization of the United Nations

Rome, 2026

Chapter 1. AquaCrop – FAO crop-water productivity model to simulate yield response to water

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Annexes

Chapter 6
Analysis of output data

6.1 Irrigation water requirement for various return periods

Dirk RAES and Lee HENG, 2026

For the design and management of irrigation systems, knowledge of the variation of the irrigation water requirement during the growing period, and the requirement during the peak period and total growing period are required. AquaCrop can simulate the irrigation water requirement over a series of successive years, and subsequently perform a frequency analysis, to determine the requirement for various return periods.

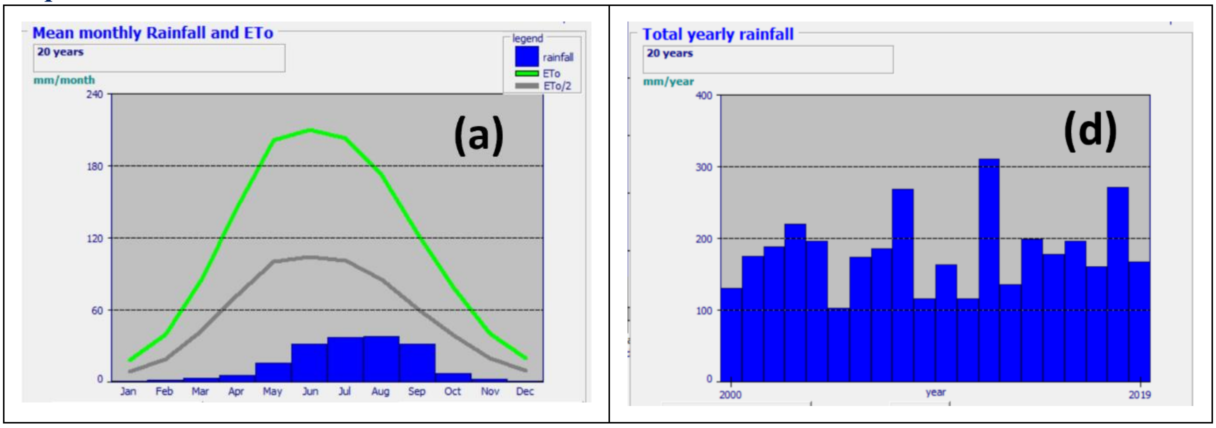
An example is worked out for the irrigation requirement of sunflower for the region of Bayannur (41.1 N; 108.0 E; 1073 m) in Inner-Mongolia (China).

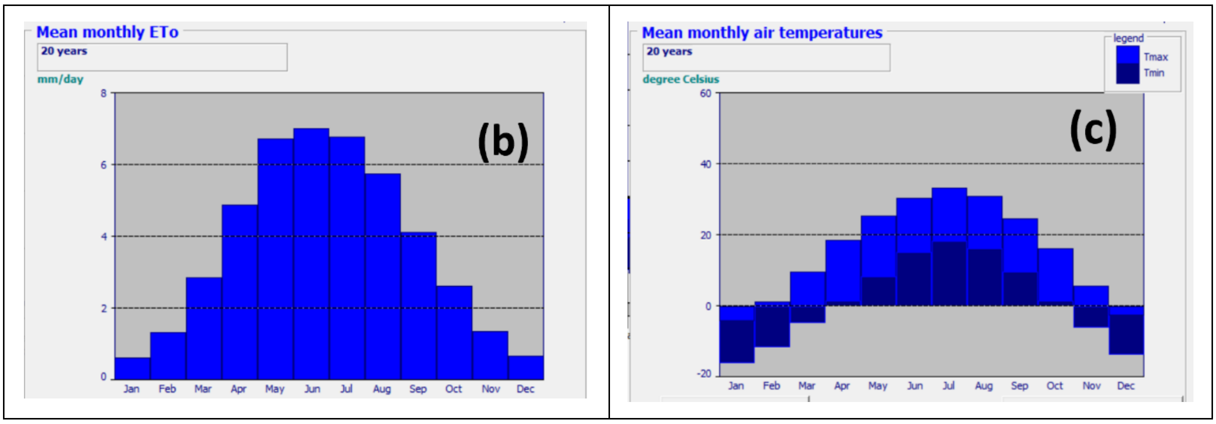
6.1.1 Input

□ **Climate data**

To gain an understanding of the variation of the irrigation requirement over the years, daily climate data for 20 successive years (from 1/1/2000 to 31/12/2019) was downloaded from NASA Power. It consisted of the maximum and minimum air temperature, mean relative humidity, wind speed, rainfall and incoming solar radiation. The daily data was imported in AquaCrop to compute ETo and to create a daily temperature, rainfall and ETo file (Box 6.11a).

Box 6.1.1a – Mean monthly climate data (a, b and c) and total yearly rainfall (d) for Bayannur for the period 1/1/2000 to 31/12/2019.

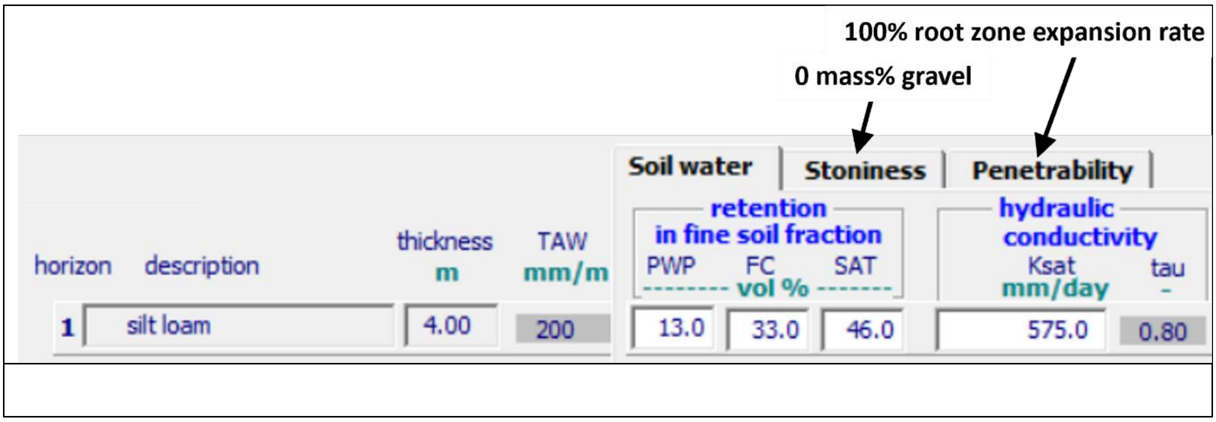




□ **Soil profile characteristics and groundwater**

The default characteristics for a silt loam (Box 6.1.1b) were considered (no stoniness and 100% permeability for roots). Capillary rise of a shallow groundwater table was not considered.

Box 6.1.1b – Total Available soil Water (TAW), soil water content at Permanent Wilting Point (PWP), Field Capacity (FC) and Saturation (SAT), hydraulic conductivity at soil saturation (Ksat) of the Silt Loam soil



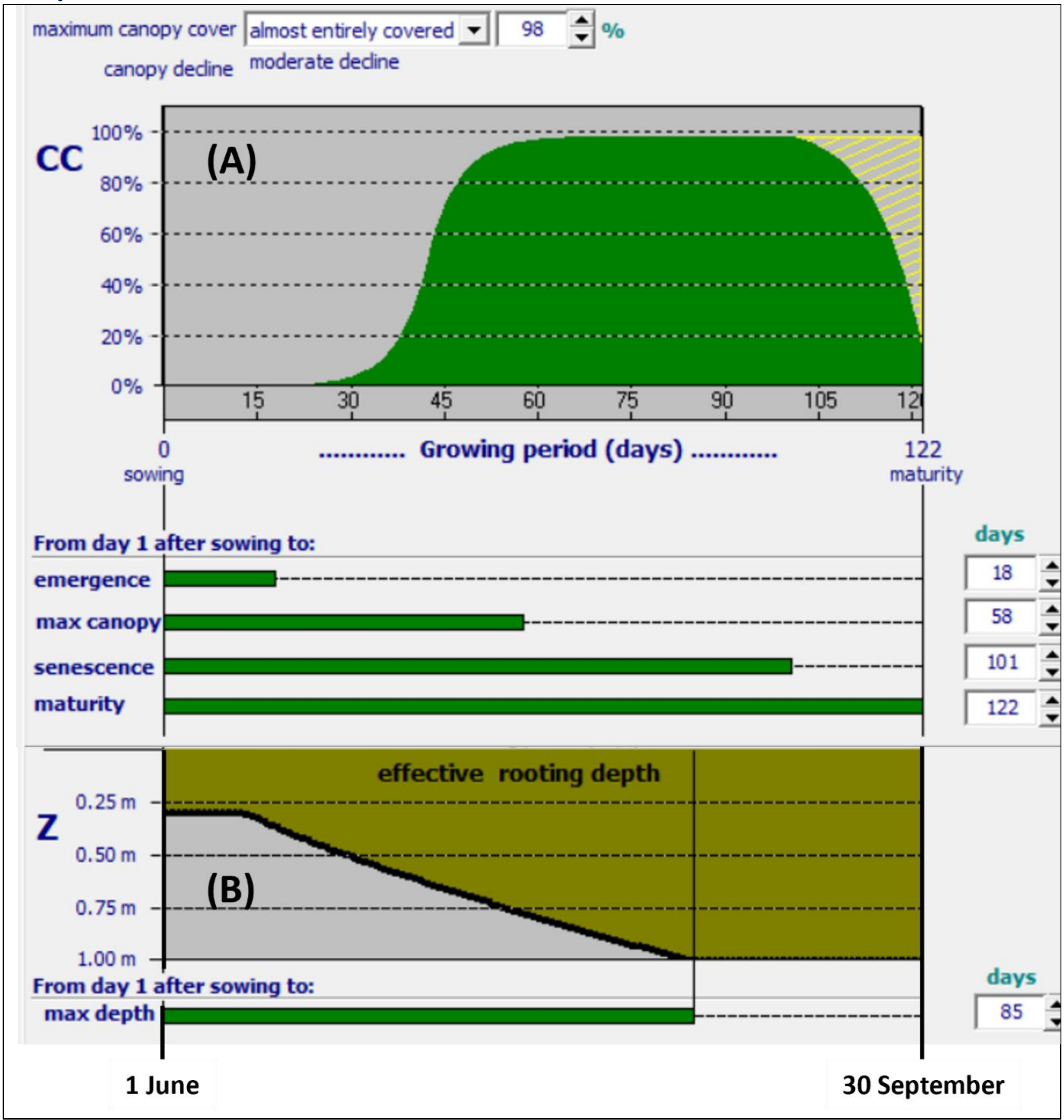
□ **Growing period and crop characteristics**

Since seedlings require warm soil to germinate, a planting date at 1 June was considered. The characteristics of the default (calendar) sunflower crop (available in the database of AquaCrop) were used. A harvest on 30 September was assumed (growing period of 122 days). By considering an average root zone expansion of 1 cm/day, the maximum effective rooting depth of 1 meter was reached after 85 days after sowing (Box 6.1.1c)

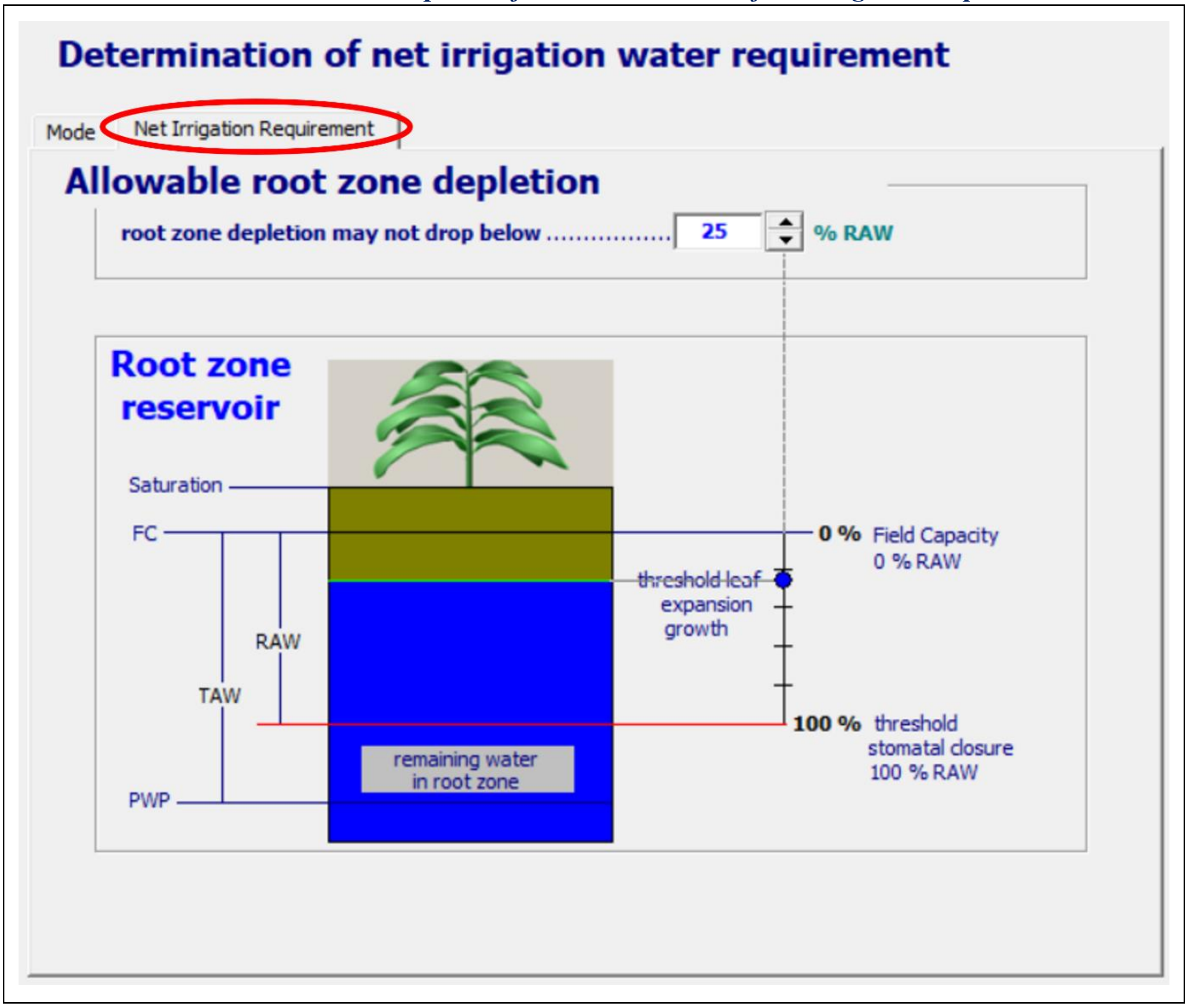
□ **Irrigation and field management**

- **Field management:** Optimal soil fertility and field conditions were assumed.
- **Irrigation water requirement**: To determine the irrigation requirement, the soil water content was not allowed to drop below 25% RAW. The threshold corresponds with the threshold for leaf-expansion water stress for sunflower (Box 6.1.1d).

Box 6.1.1c – Development of (A) the green Canopy Cover (CC), and (B) rooting depth (Z) of sunflower in Bayannur.



Box 6.1.1d – Allowable root zone depletion for the calculation of net irrigation requirement.

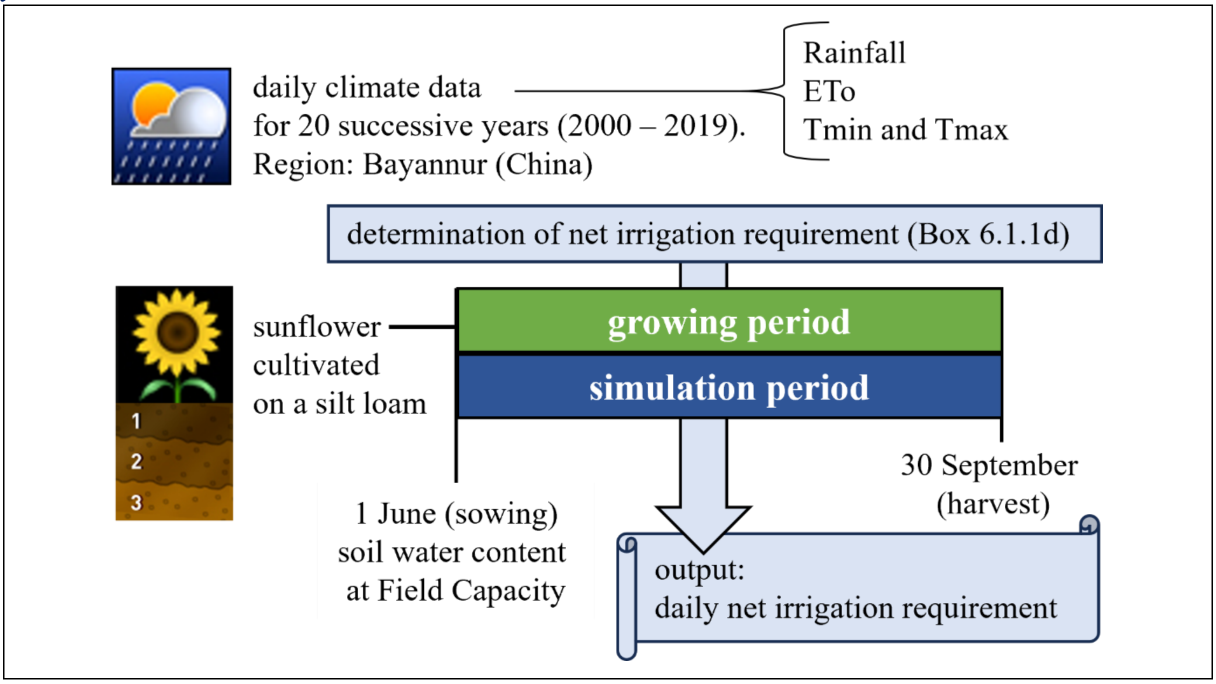


6.1.2 *Simulation of the irrigation requirement*

A project was created to determine the daily net irrigation requirement for sunflower for the region of Bayannur in Inner-Mongolia (China), for 20 successive years (2000 – 2019). The simulation period coincided with the growing period of the sunflowers. As a result of rainfall or a pre-irrigation, an initial soil water content at Field Capacity was assumed (Box 6.1.2a)

The seasonal output in the ***Simulation run*** menu showed that the seasonal net irrigation requirement and rainfall varied over the 20 successive years (Fig. 6.1.2a).

Box 6.1.2a – Project determining the daily net irrigation requirement for sunflowers in 20 successive years



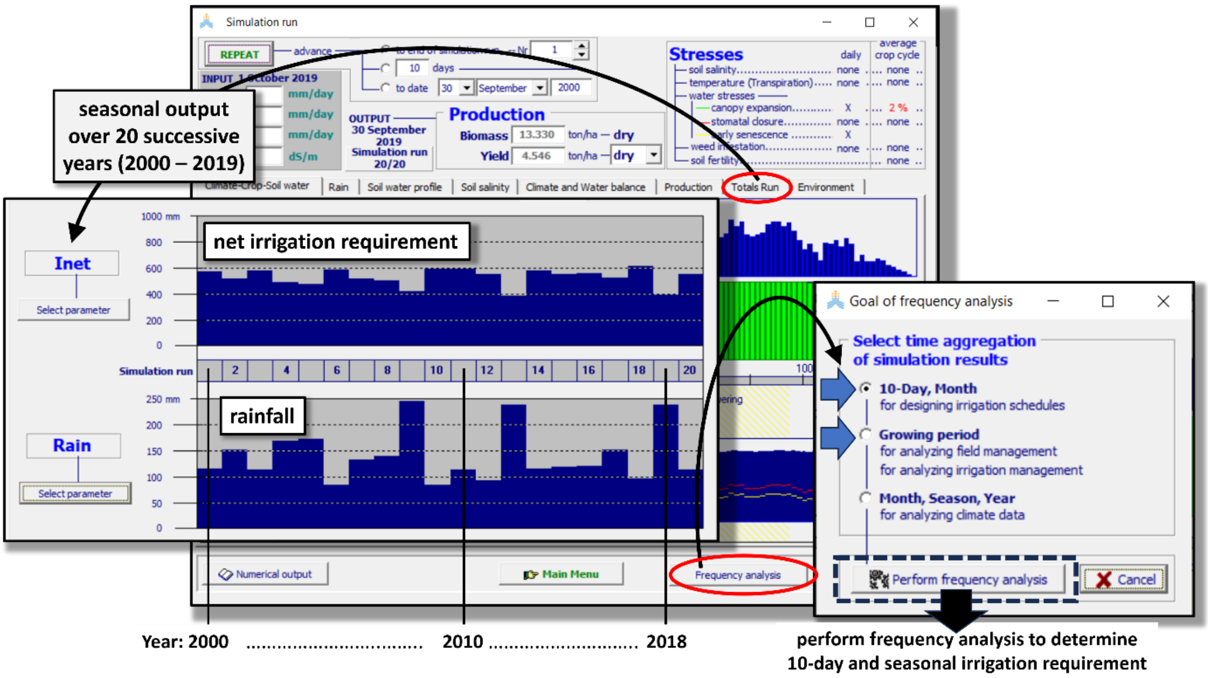


Figure 6.1.2a – Seasonal output over the 20 successive years and the <Frequency analysis> button in the "Simulation run" menu, which provides access to a series of menus for performing a frequency analysis, following the selection of the target in the "Goal of frequency analysis" menu.

- **Determination of the 10-day and peak irrigation water requirement**

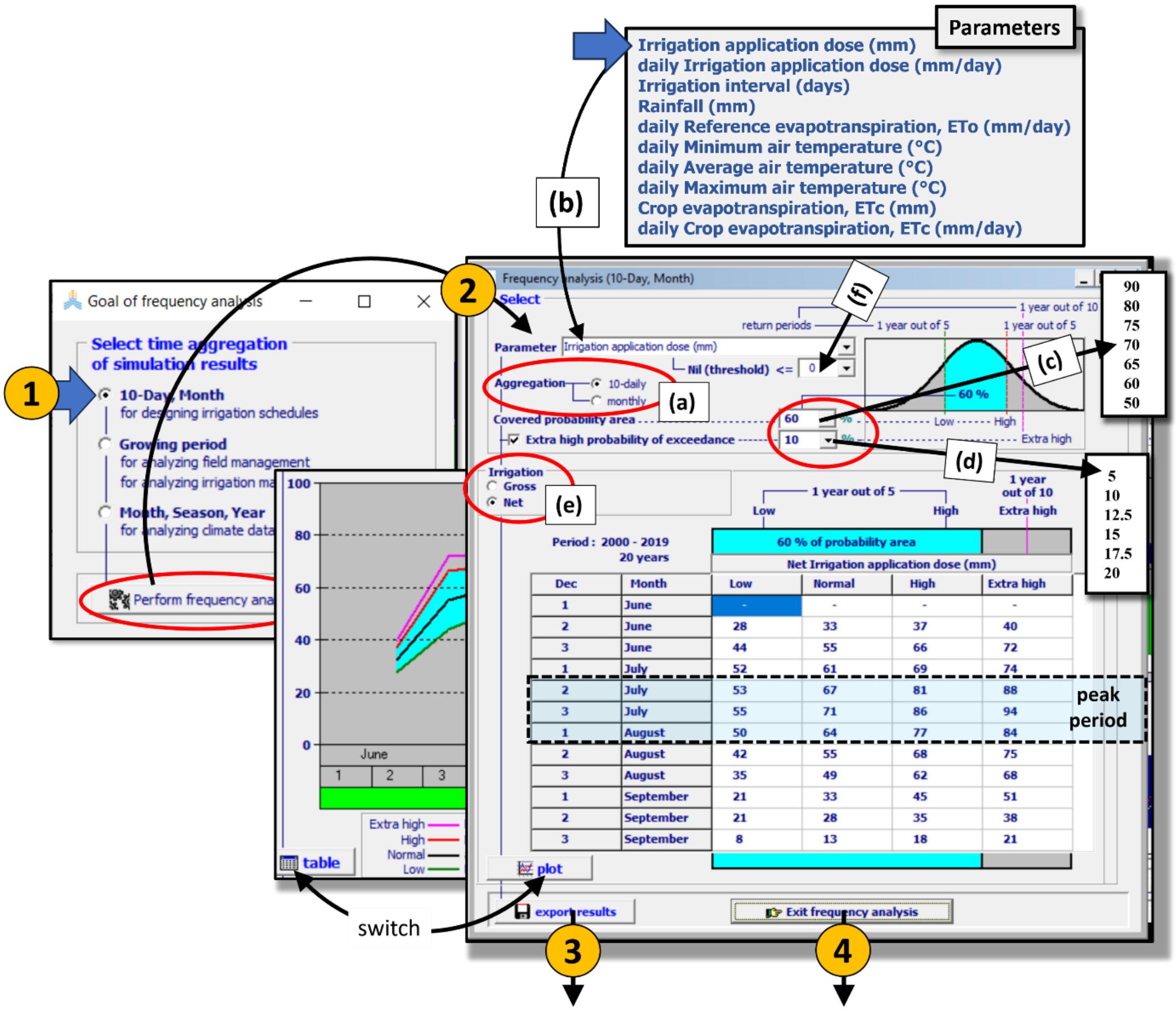


Figure 6.1.2b – Determination of the 10-day net irrigation water requirement with various probabilities of occurrence.

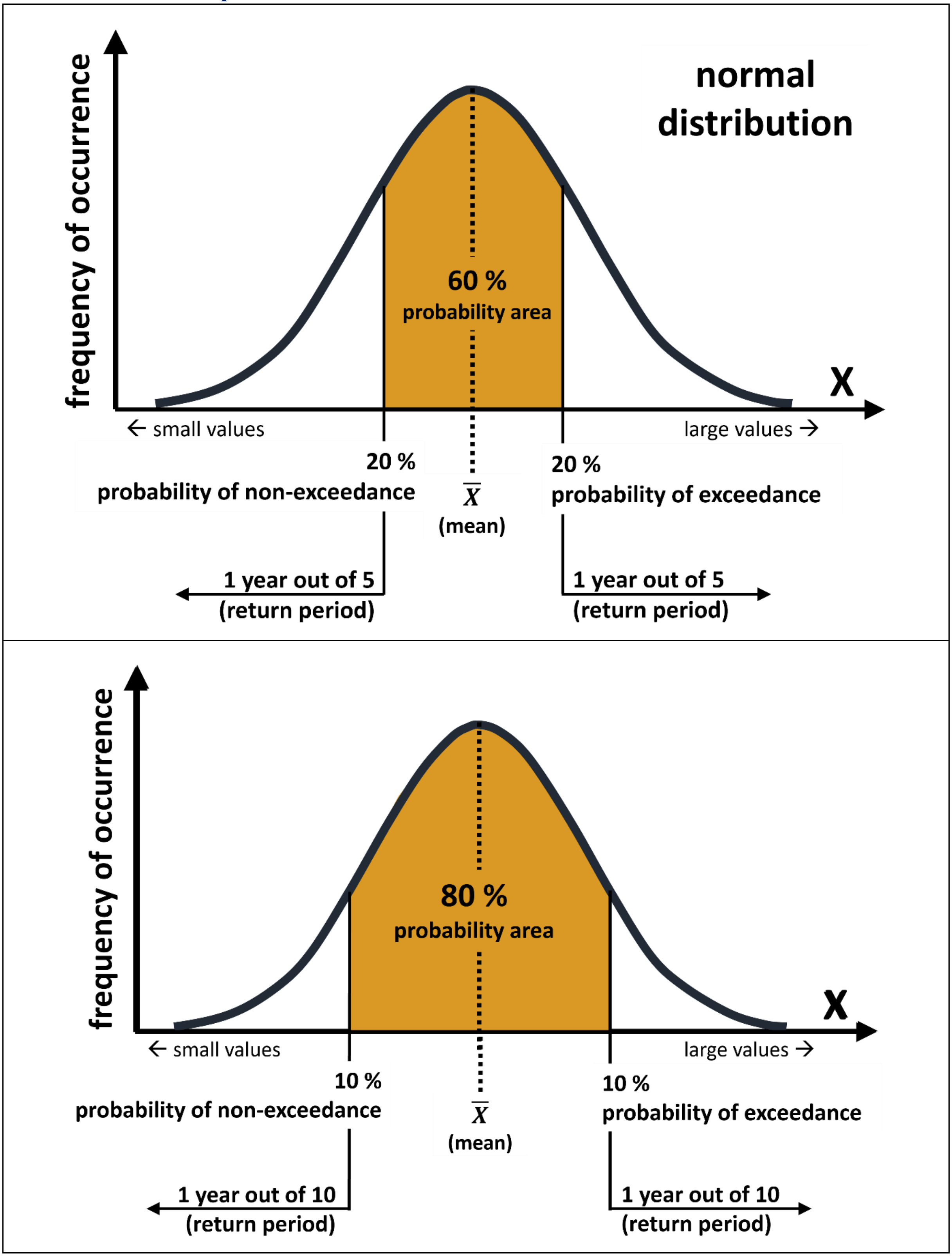
After ① selecting *'10-Day, Month'* in the ***Goal of frequency analysis*** menu, and clicking on the **<Perform frequency analysis>** button, ② the ***Frequency analysis (10-Day, Month)*** menu is displayed. From this menu, one can ③ export the results, and ④ return to the ***Simulation run*** menu (Fig. 6.1.2b).

In the ***Frequency analysis (10-Day, Month)*** menu, the user selects (Fig. 6.1.2b):

a) the time aggregation (*10-daily*);
b) the "*Irrigation application dose (mm)*" parameter, which corresponds with the total 10-day irrigation requirement;
c) the covered probability area (ranging from 50 to 90 %), which determines the return periods for the low and high irrigation requirement in the 10-day period (Box. 6.1.2b);
d) an extra high probability of exceedance (ranging from 5 to 20 % probability of exceedance);
e) if the net or gross irrigation application dose should be analyzed.

By clicking on the **<plot>** or **<table>** button at the bottom left corner of the ***Frequency analysis (10-Day, Month)*** menu (Fig. 6.1.2b), the user can switch between the probability table and the corresponding plot.

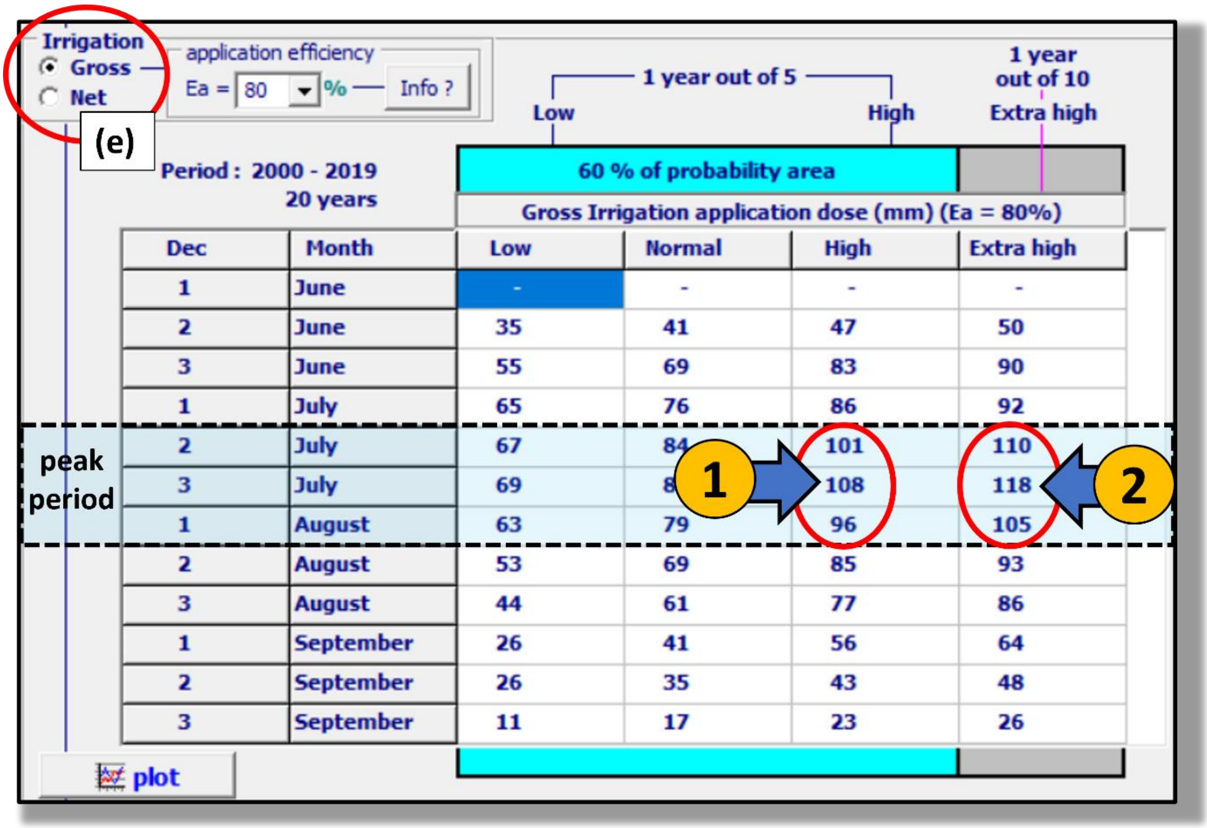
Box 6.1.2b – A 60 and 80% covered probability area, and the corresponding probabilities of (non)-exceedance and return periods.



When performing 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 irrigation requirement for small considered periods (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 monthly requirements in the years are 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-Day, Month)*** the nil threshold can be specified (option (f) in Fig. 6.1.2b). By excluding the nil's from the frequency analysis, the frequency distribution becomes less skewed to the left, and the data can be analysed. In the example of the sunflowers nil was set to zero.

Different covered probability areas (option (c) in Fig. 6.1.2b) can be selected in the ***Frequency analysis (10-Day, Month)*** menu. By selecting a covered probability area, also the corresponding probabilities of exceedance and non-exceedance and the return period are defined (Box 6.1.2b). In this example the covered probability area was 60%. Consequently:

- the 10-day low irrigation requirements have a probability of non-exceedance of 20 %; this means that in 1 year of 5, the irrigation requirements will be less;
- the 10-day high irrigation requirements have a probability of exceedance of 20 %; this means that the values cover the 10-day irrigation requirements in 4 years out of 5.



Dec	Month	Low	Normal	High	Extra high
1	June	-	-	-	-
2	June	35	41	47	50
3	June	55	69	83	90
1	July	65	76	86	92
2	July	67	84	101	110
3	July	69	8[illegible]	108	118
1	August	63	79	96	105
2	August	53	69	85	93
3	August	44	61	77	86
1	September	26	41	56	64
2	September	26	35	43	48
3	September	11	17	23	26

Figure 6.1.2c – 10-day Gross irrigation water requirements for sunflowers (mm per 10-day) for 4 years out of 5 ①, and 9 years out of 10 ②, during the peak period for a gross application efficiency (Ea) of 80%.

By selecting the gross irrigation requirement (option (e) in Fig. 6.1.2c), the user can covert the net requirement to gross, after specifying the field application efficiency.

In the example, about 100 mm (the range is 96 .. 108 mm) will cover the 10-day irrigation requirement in the peak period (mid-July to beginning of August) in 4 years out of 5 (Fig. 6.1.2c). To secure the net irrigation requirement in 9 years out of 10, up to 118 mm is required.

The content of the corresponding output file of the Frequency analysis is presented in Box. 6.1.2c.

Box. 6.1.2c – The output file of the 10-day frequency analysis of the gross irrigation requirement of sunflowers at Bayannur at various probabilities of exceedance and corresponding return periods.

AquaCrop 7.3 (July 2026) - Output created on (date) : … at (time) : …

10-daily Gross Irrigation application dose (mm) (Ea = 80%), Nil <= 0,
period 2000 - 2019 (20 years),
Low/high: 20% probability of (non-)exceedance (1 year out of 5) - Covered probability area: 60%,
Extra high: 10% probability of exceedance (1 year out of 10)

						----- global probability	-----		
Decade	Month	Years	%Nil	Average	StDev	Low	Normal	High	ExtraHigh
				mm	mm	mm	mm	mm	mm
1	6	20	100	-999	-999	-999	-999	-999	-999
2	6	20	5	43.0	7.288	35.1	40.9	46.7	49.7
3	6	20	0	69.2	16.518	55.3	69.2	83.1	90.4
1	7	20	0	75.9	12.464	65.5	75.9	86.4	91.9
2	7	20	0	83.8	20.257	66.8	83.8	100.8	109.7
3	7	20	0	88.3	23.263	68.7	88.3	107.8	118.0
1	8	20	0	79.5	19.733	62.9	79.5	96.1	104.7
2	8	20	0	69.0	19.000	53.0	69.0	84.9	93.3
3	8	20	0	60.6	19.485	44.3	60.6	77.0	85.6
1	9	20	0	41.0	18.043	25.8	41.0	56.1	64.0
2	9	20	5	36.6	10.504	26.4	34.8	43.2	47.6
3	9	20	10	18.4	7.978	10.5	16.5	22.6	25.7

Years : number of years considered
%Nil : percent of nils years
Average: average of the non-nil values
StDev : standard deviation of the non-nil values

Global probability: probability of nil and non-nil values
-999 : no data or insufficient data

□ **Determination of the seasonal irrigation water requirement**

After ① selecting *'Growing period'* in the ***Goal of frequency analysis*** menu and clicking on the **<Perform frequency analysis>** button, ② the ***Frequency analysis (growing period)*** menu is displayed. From this menu, one can ③ export the results, and (4) return to the ***Simulation run*** menu ④ (Fig. 6.1.2d).

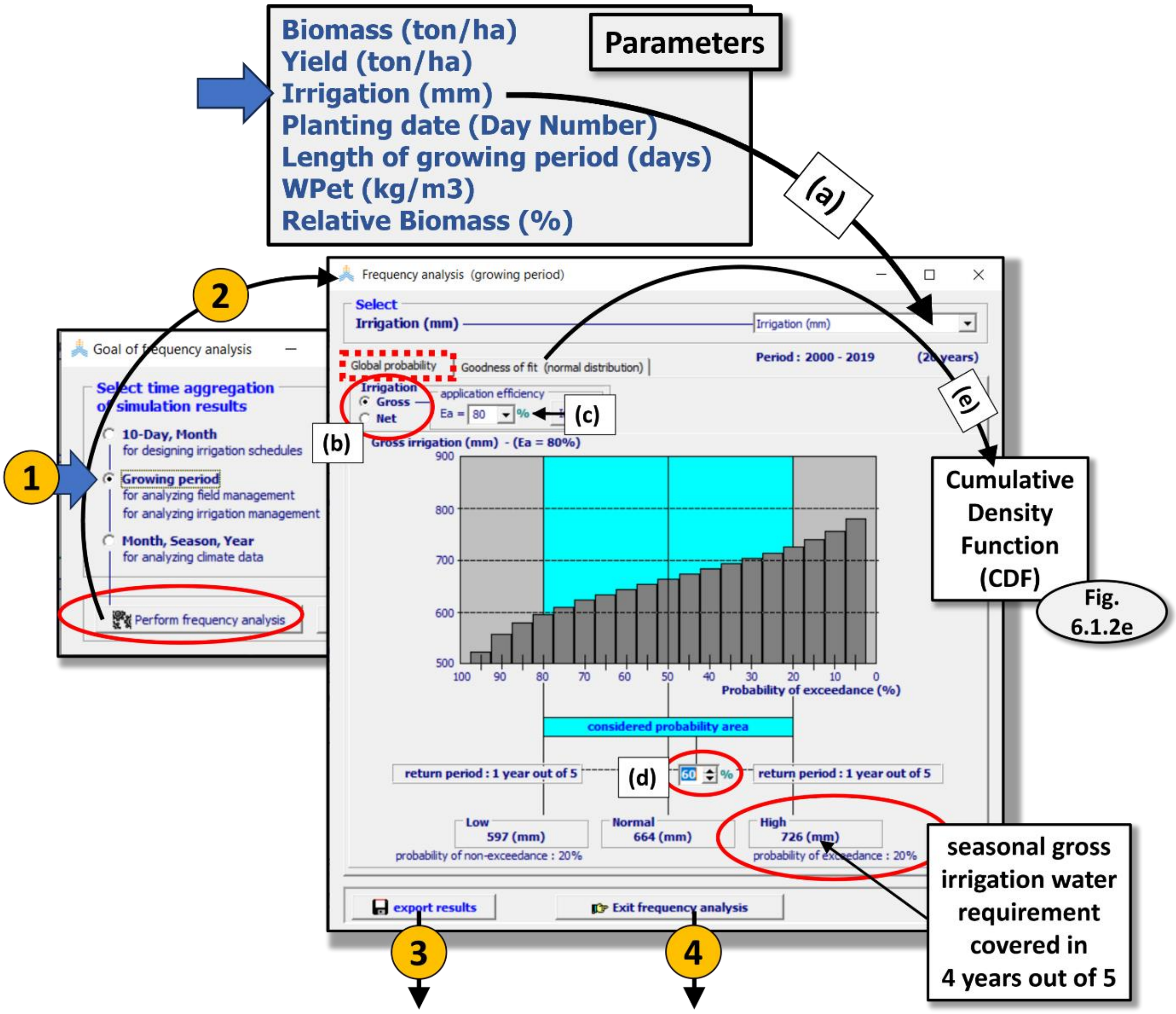


Figure 6.1.2d – Determination of the seasonal irrigation water requirement.

In the ***Frequency analysis (growing period)*** menu, the user selects (Fig. 6.1.2d):

a) the "*Irrigation (mm)*" parameter, which corresponds with the total seasonal irrigation requirement;
b) if the net or gross irrigation requirement should be analyzed;
c) the field application efficiency (Ea) when the gross irrigation requirement is considered;
d) the covered probability area (ranging from 50 to 90 %), which determines the return periods for the low and high irrigation requirement in the growing period (Box. 6.1.2b);
e) the ''*Goodness of fit*" tab-sheet in which the Cumulative Density Function (CDF) is displayed (see Fig. 6.1.2e).

Different covered probability areas (option (d) in Fig. 6.1.2d) can be selected in the ***Frequency analysis (growing period)*** menu. By selecting a covered probability area, also the corresponding probabilities of exceedance and non-exceedance and the return period are defined (Box 6.1.2b). In this example the covered probability area was 60%. Consequently:

- the seasonal low irrigation requirement has a probability of non-exceedance of 20 %, this means that in 1 year of 5, the seasonal irrigation requirement will be smaller than the displayed value (597 mm);
- the seasonal high irrigation requirement has a probability of exceedance of 20 %, this means that in 4 years out of 5, the irrigation requirement will be covered by the displayed value 726 mm).

In the example, 726 mm will cover the seasonal gross irrigation requirement in 4 years out of 5. A field application efficiency (Ea) of 80% was assumed (option (c) in Fig. 6.1.2d) to convert the net into the seasonal gross irrigation requirement.

When performing the frequency analysis a normal distribution is assumed. By displaying the Cumulative Density Function (CDF) the goodness of fit can be checked and improved if required (Fig. 6.1.2e).

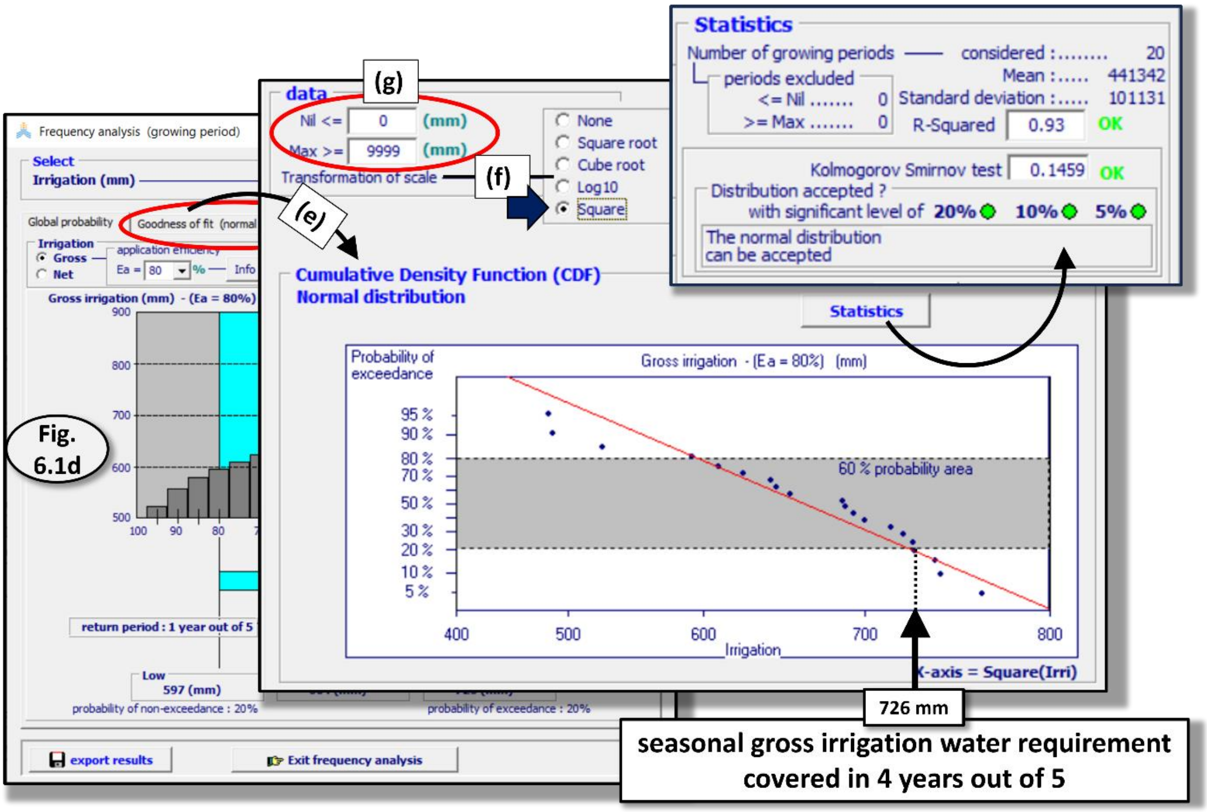


Figure 6.1.2e – Display of the Cumulative Density Function (CDF) with options (f and g) to improve the goodness of fit of the assumed normal distribution.

In Figure 6.1.2e, the probability scale (i.e. the vertical axis) of the Cumulative Density Function (CDF) is stretched at both ends and compressed in the centre. The distortion is such that in the CDF plot the data plots perfectly on the (red) straight line if the data is normal distributed. Hence, if the data in the CDF plot fall in a reasonable alignment, it may be assumed that the data is a normal distribution.

Since dealing with a normal distribution has several practical advantages, it is a common practice to transform data that are not normally distributed so that the resulting normalized data can be presented by the normal curve (straight line in the CDF plot). The transformation of the data will change the scale of the records (i.e. the abscissa of the Cumulative Density Function). Several transformations of scale can be considered (option (f) in Fig. 6.1.2e): the Square root, Cube root, Log10 and the Square of the data. Regarding the example of the gross irrigation requirement, the best fit was obtained by performing a frequency analysis on the square of the irrigation requirement (Fig. 6.1.2e). Although the results did not differ much when no transformation was applied, the Squaring of the data resulted in the highest R-square.

Another way to improve the 'goodness of fit' (option (g) in Fig. 6.1.2e) is to restrict the frequency analysis to only a portion of the data. Values below Nil (too small values) and/or above outliers (too high values) can be temporarily excluded from the frequency analysis. The frequency distribution then becomes less skewed to the left by excluding the nil's, and less skewed to the right by excluding the outliers. However, after performing the frequency analysis on the non-excluded values, the global probability is always displayed in the '*Global probability*' tab-sheet (Fig. 6.1.2d). The global probability is calculated by combining the probability of the non-excluded values with the probabilities of the Nil's and Outliers. In this example regarding irrigation requirements, the option of performing the analysis on a subset of the data was not considered, nor was it necessary.

The content of the output file of the Frequency analysis is presented in Box. 6.1.2d.

Box. 6.1.2d – The output file of the frequency analysis of the seasonal gross irrigation requirement of sunflowers at Bayannur at various probabilities of exceedance and corresponding return periods

```
AquaCrop 7.3 (July 2026) - Output created on (date) : … at (time) : …

Gross irrigation (mm)  - (Ea = 80%),,
period 2000 - 2019 (20 years),
Normal distribution of Squared (Gross irrigation  - (Ea = 80%)),
Goodness of fit: R-square = 0.93


 Number of growing periods considered     : (20 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                 524
 Probability of non-exceedance:   10%         10 years                 558
 Probability of non-exceedance:   15%          7 years                 580
 Probability of non-exceedance:   20%          5 years                 597
 Probability of non-exceedance:   25%          4 years                 611
 Probability of non-exceedance:   30%                                  623
 Probability of non-exceedance:   35%                                  634
 Probability of non-exceedance:   40%                                  645
 Probability of non-exceedance:   45%                                  655
 Probability of exceedance....:   50%                                  664
 Probability of exceedance....:   45%                                  674
 Probability of exceedance....:   40%                                  683
 Probability of exceedance....:   35%                                  693
 Probability of exceedance....:   30%                                  703
 Probability of exceedance....:   25%          4 years                 714
 Probability of exceedance....:   20%          5 years                 726
 Probability of exceedance....:   15%          7 years                 739
 Probability of exceedance....:   10%         10 years                 756
 Probability of exceedance....:    5%         20 years                 780

 Global probability: Probability of nil, max, non-nil and non-max values     (20 years)
```

Note that a function other than the normal distribution function must be used to estimate irrigation requirements for long return periods.

□ **Gross irrigation requirement for sunflowers for Bayannur (China)**

The results of the frequency analysis of the 10-day (Box 6.1.2c) and seasonal gross irrigation requirement (Box 6.1.2d) are summarized in Fig. 6.1.2f.

Gross irrigation requirement for sunflower for the region of Bayannur

planting: end May- early June
harvest: end September
soil type: silt loam

80% field application efficiency

	June		July			August			September			Total season
	mid	end	ini	mid	end	ini	mid	end	ini	mid	end	
	gross irrigation requirement in mm/10-day											mm/season
Very high	50	90	92	110	118	105	93	86	64	48	26	756
High	47	83	86	101	108	96	85	77	56	43	23	726
Normal	41	69	76	84	88	79	69	61	41	35	17	664
Low	35	55	65	67	69	63	53	44	26	26	11	597

Figure 6.1.2f – 10-daily and seasonal gross irrigation requirement (field application efficiency of 80%) covering 9 years out of 10 (very high),4 years out of 5 (high), 1 year out of 2 (normal) and 1 year out of 5 (low) for sunflowers in the region of Bayannur.

6.2 Charts for guiding irrigation in real time

Dirk RAES and Lee HENG, 2026

6.2.1 Concept

A chart for guiding irrigation at real time in the absence of rainfall, provides information for irrigation scheduling for hot, normal and cool weather conditions (Fig. 6.2.1a). The chart is designed for a specific (i) crop, (ii) growing period, (iii) climate region, (iv) soil type, and (v) irrigation method.

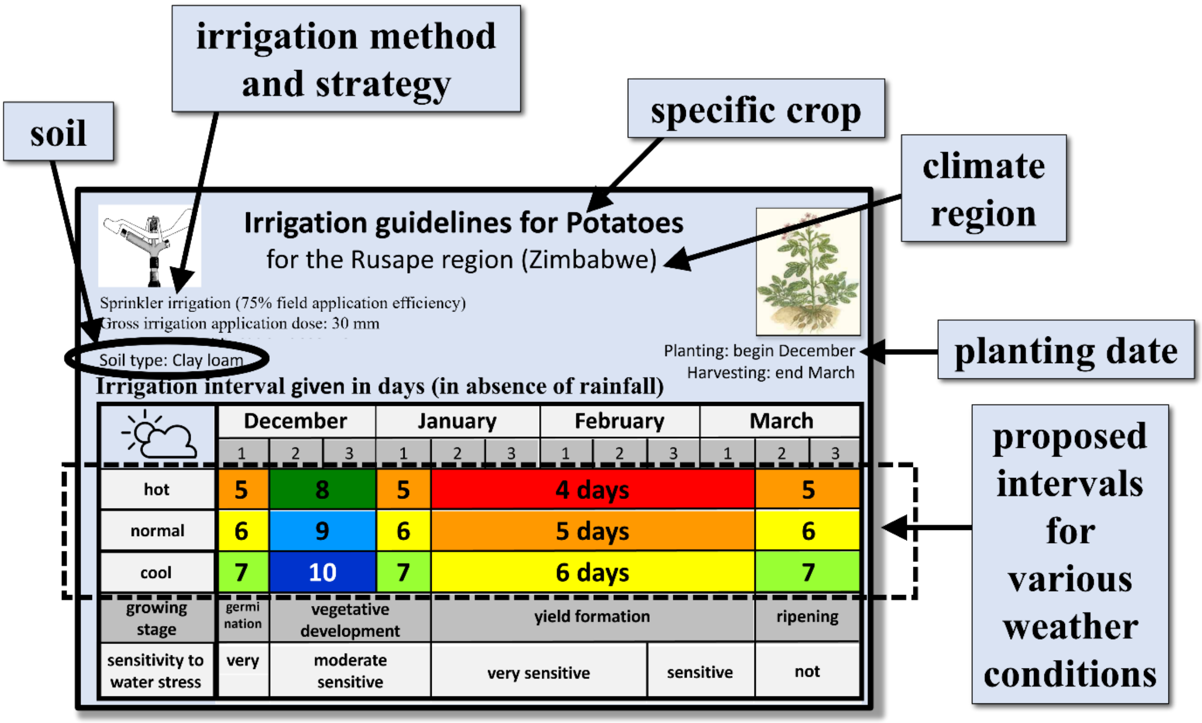


Figure 6.2.1a – Chart for guiding irrigation in real time

At the bottom of the Chart, information concerning the sensitivity of the crop to water stress is presented. In case of water shortage, this information is useful to further adjust the irrigation calendar while still maximising production:

- When the crop is not or moderately sensitive to water stress:
  By postponing irrigation applications during periods when the crop is not or moderately sensitive to water stress, irrigation water can be saved. A slight to moderate increase of the irrigation interval will not strongly affect crop yield.
- When the crop is sensitive to very sensitive to water deficits:
  Delaying irrigation applications during these periods should be avoided.

As an example, Irrigation charts are development in this Section for two different irrigation strategies. A strategy with:

- a fixed irrigation application dose, but variable irrigation interval (6.2.2)
- a fixed irrigation interval but variable irrigation application dose (6.2.3).

6.2.2 *Chart with a fixed application dose*

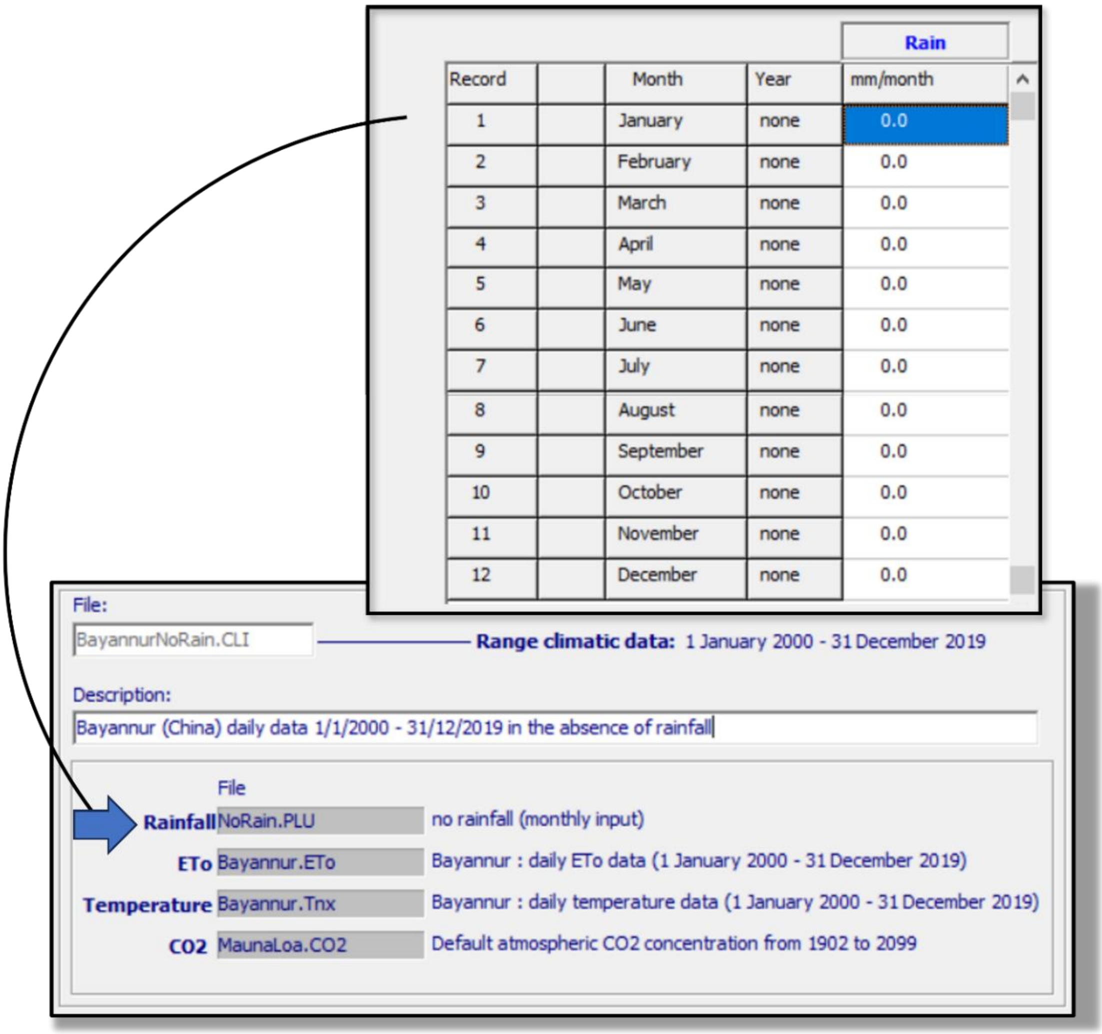
An example is worked out for sunflower for the region of Bayannur (41.1 N; 108.0 E; 1073 m) in Inner-Mongolia (China). For this example it is assumed that the crop is irrigated by a centre pivot (or linear move) with a fixed gross application dose of 25 mm. A field application efficiency (Ea) of 80% is assumed.

□ **Input**

The climate data, growing period and crop characteristics (Box 6.1.1c), soil profile characteristics and groundwater (Box 6.1.1b), and field management practices used, are identical to those employed for the calculation of the irrigation requirement as specified in Section 6.1.

However, since the charts guide irrigation in the absence of rainfall, the rainfall file in the climate file should be the "NoRain.PLU" file. This file is available in the data base of AquaCrop, and considers zero rainfall for each of the 12 months of an unidentified year (Box 6.2.2a).

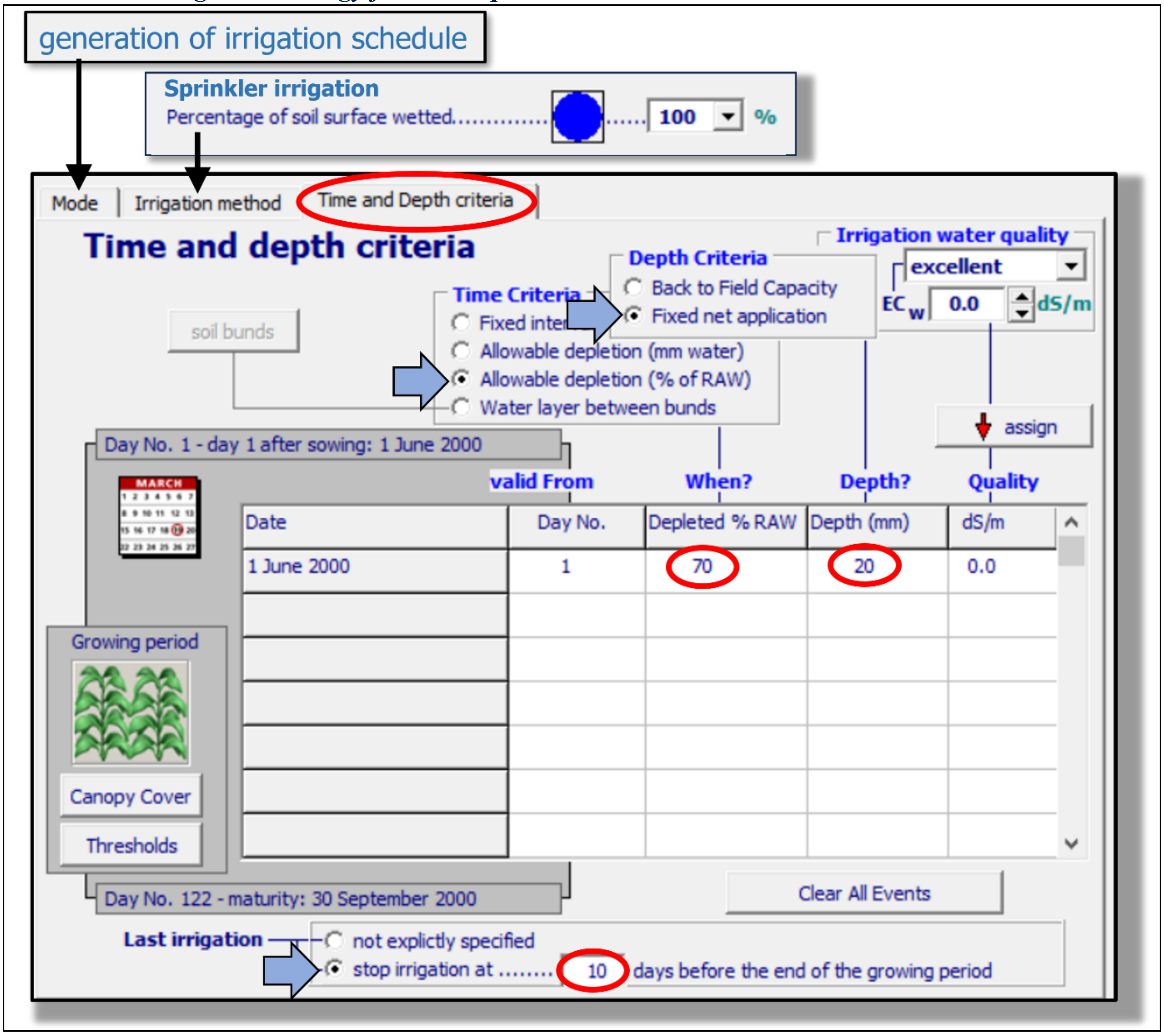
Box 6.2.2a – Climate file for determining irrigation schedules in the absence of rainfall



The Irrigation strategy for center pivot (linear move) consists of applying a fixed net application of 20 mm each time when the allowable soil water depletion of 70% RAW was reached. Whenever the root zone depletion reaches the specified threshold, AquaCrop will generate an irrigation event. Due to the crop development and changing weather conditions (ETo), the crop evapotranspiration and the irrigation interval will change during the growing season. The irrigation net application of 20 mm is 80% (Ea) of the considered gross depth of 25 mm,

The irrigation is stopped at 10 days before the end of the growing period (Box 6.2.2b).

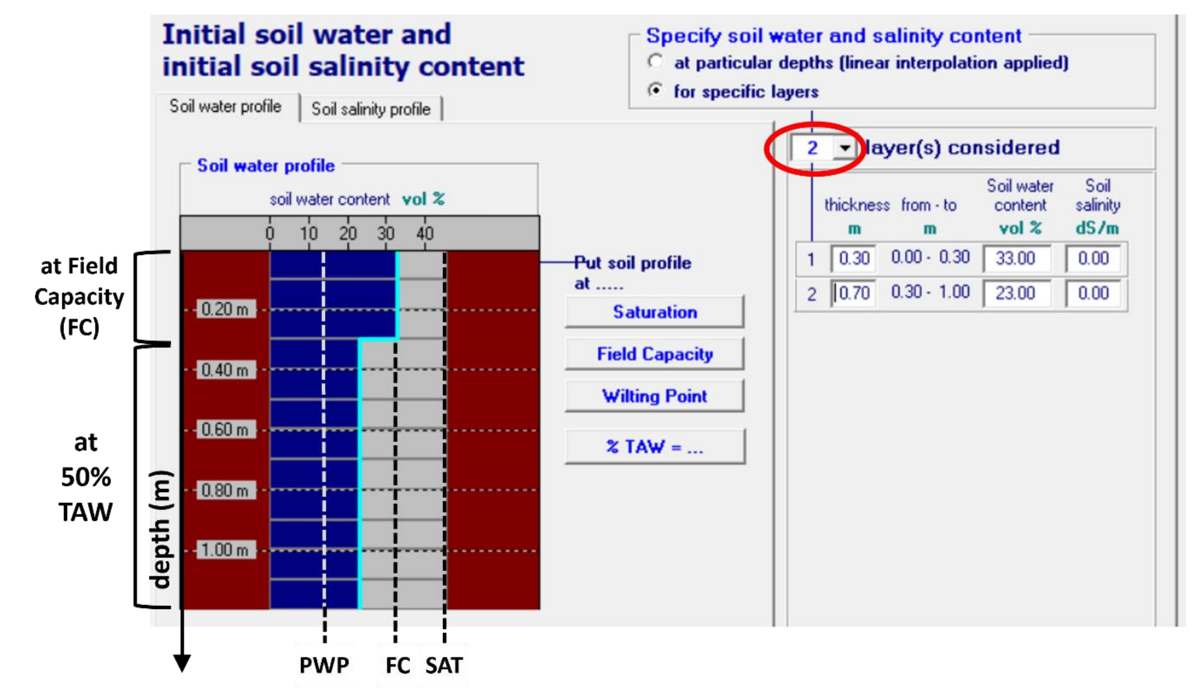
Box 6.2.2b – Irrigation strategy for center pivot/linear move



□ **Simulation with a fixed application dose**

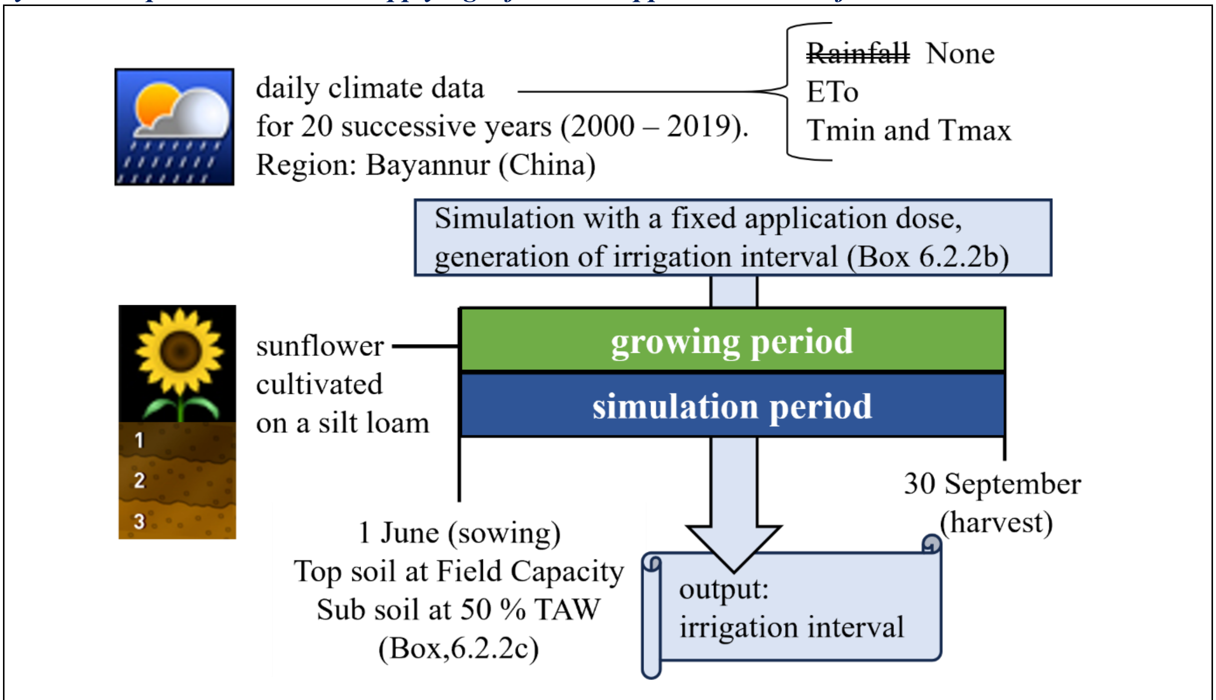
When running simulations in AquaCrop it can be assumed that the initial soil water content in the topsoil (0.30 m) is close to field capacity because of rain or pre-irrigation. The soil water content in the subsoil depends on the weather conditions before the irrigation season and will be less than 50% TAW if the weather conditions were mainly dry, and will be greater than 50% if they were wet. For this example (Box 6.2.2c), Field Capacity (33 vol%) was assumed for the top soil (0.30 m) at the start of the irrigation season, while the subsoil was at 50% TAW (23 vol%).

Box 6.2.2c – Initial soil water content at sowing (1 June)



A project was created to determine the irrigation interval for sunflower irrigated by a centre pivot/linear move for the region of Bayannur in Inner-Mongolia (China), for 20 successive years (2000 – 2019). The simulation period coincided with the growing period of the sunflowers (Box 6.2.2d).

Box 6.2.2d – Project determining the irrigation interval in 20 successive years for sunflowers irrigated by a Center pivot/Linear move applying a fixed net application dose of 20 mm



The seasonal output in the ***Simulation run*** menu showed that the total irrigation amount varied over the 20 successive years (Fig. 6.2.2a). Since precipitation has not been taken into account, the seasonal output is entirely due to the variation in the evapotranspiration demand (ETo) over the years.

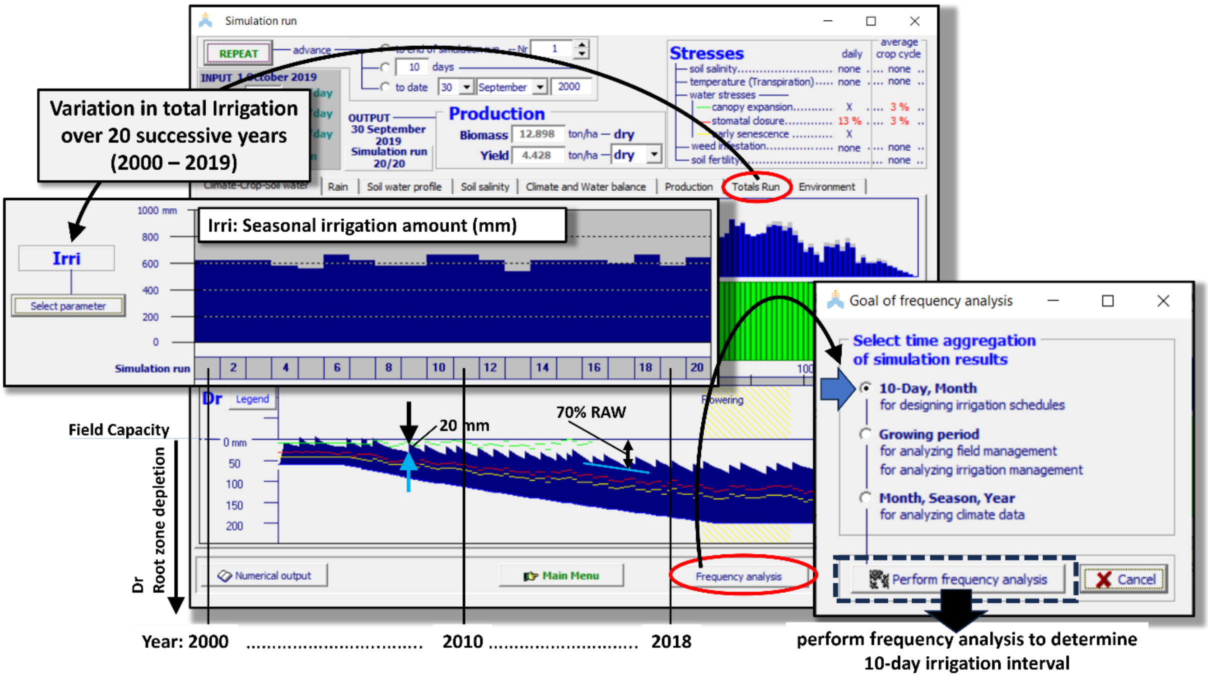


Figure 6.2.2a – Variation of the total applied irrigation amount over the 20 successive years and the <Frequency analysis> button in the "Simulation run" menu, which provides access to a series of menus for performing a frequency analysis on the irrigation interval.

□ Determination of the irrigation interval

After (1) selecting *'10-Day, Month'* in the ***Goal of frequency analysis*** menu, and clicking on the **<Perform frequency analysis>** button, (2) the ***Frequency analysis (10-Day, Month)*** menu is displayed. From this menu, the user can (3) export the results and (4) return to the ***Simulation run*** menu (Fig. 6.2.2b).

In the ***Frequency analysis (10-Day, Month)*** menu, the user selects (Fig. 6.2.2b):

a) the time aggregation (*10-daily*);
b) the "*Irrigation interval (days)*" as parameter;
c) the covered probability area (ranging from 50 to 90 %), which determines the return periods for the low and high irrigation interval in the 10-day period (Box 6.1.2b);
d) an extra low probability of exceedance (ranging from 5 to 20 % probability of non-exceedance);

By clicking on the **<plot>** or **<table>** button in the ***Frequency analysis (10-Day, Month)*** menu (Fig. 6.2.2b), the user can switch between the probability table for the selected parameters and the corresponding plot.

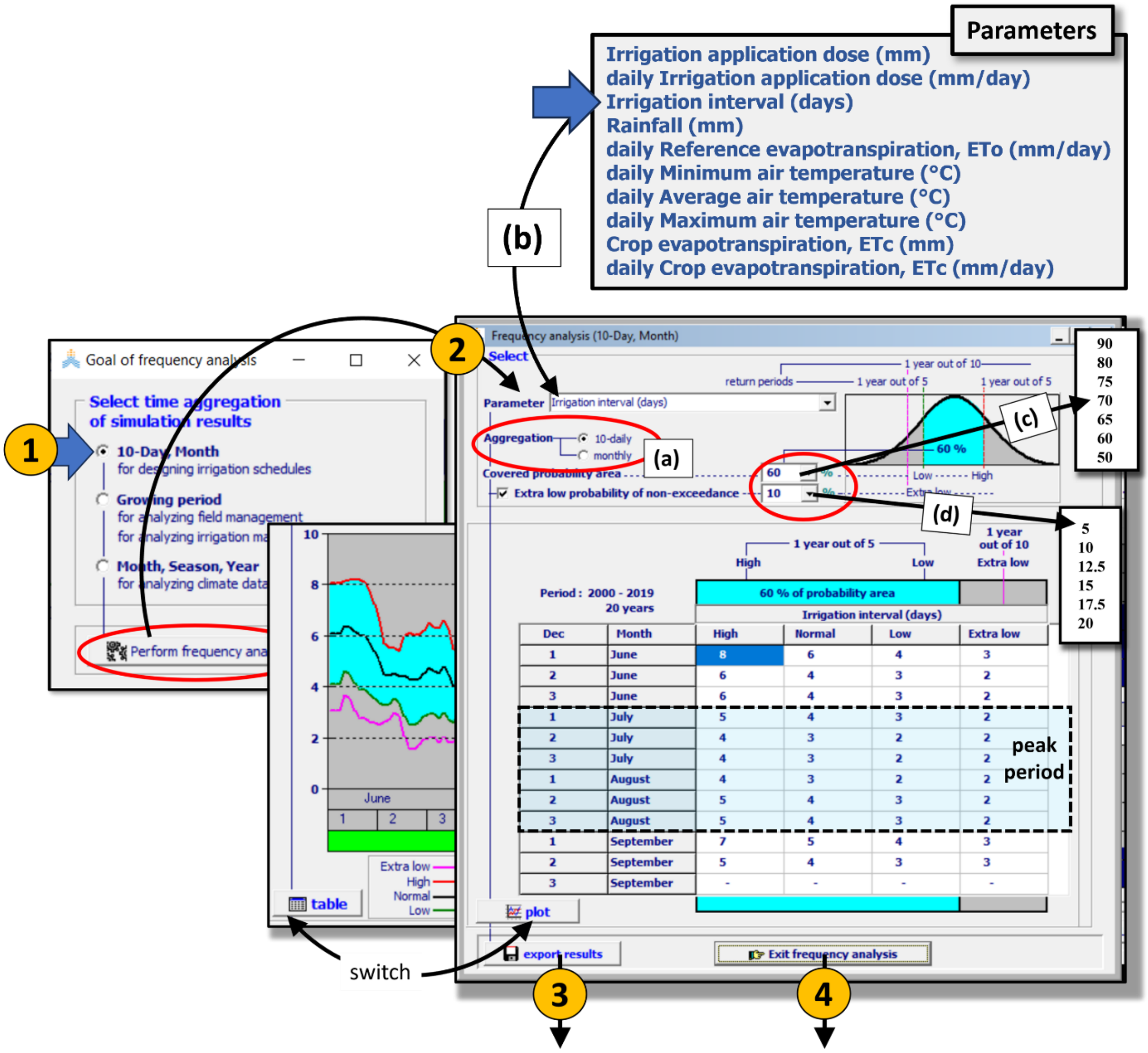


Figure 6.2.2b – Determination of the 10-day irrigation interval for center pivot/linear move for various probabilities of occurrence.

Different covered probability areas (option (c) in Fig. 6.2.2b) can be selected in the ***Frequency analysis (10-Day, Month)*** menu. By selecting a covered probability area, also the corresponding probabilities of exceedance and non-exceedance and the return periods are defined (Box 6.1.2b). In this example the covered probability area was 60%. Consequently:

- the 10-day large irrigation intervals have a probability of non-exceedance of 20 %, this means that in 4 years of 5, the irrigation interval will be smaller;
- the 10-day small irrigation interval has a probability of exceedance of 20 %, this means that the intervals are valid in 4 years out of 5.

In the example, a 2 to 3 days irrigation interval in the peak period (July – August) and in the absence of rainfall, will cover the crop water need in 4 years out of 5 (Fig. 6.2.2b). A 2-day irrigation interval in this period secures the crop water needs in 9 years out of 10.

The content of the corresponding output file of the Frequency analysis is presented in Box. 6.2.2e. The results can be summarized in an irrigation chart (Fig. 6.2.2c).

Box. 6.2.2e – The output file of the 10-day frequency analysis of the irrigation interval of sunflowers at Bayannur at various probabilities of exceedance and corresponding return periods.

```
AquaCrop 7.3 (July 2026) - Output created on (date) : …   at (time) : …

Irrigation interval (days), (Aggregated 10-daily), Nil: N/A,
period 2000 - 2019 (20 years),
Low/high: 20% probability of (non-)exceedance (1 year out of 5) - Covered probability area: 60%,
Extra low: 10% probability of non-exceedance (1 year out of 10)

Aggregated 10-daily
                                                            ----- global probability -----
    Decade      Month      Years       %Nil   Average      StDev      High    Normal      Low   ExtraLow
                                                 days       days      days      days     days       days
         1          6          -          -         -          -       8.0       6.0      4.0        3.0
         2          6          -          -         -          -       6.0       4.0      3.0        2.0
         3          6          -          -         -          -       6.0       4.0      3.0        2.0
         1          7          -          -         -          -       5.0       4.0      3.0        2.0
         2          7          -          -         -          -       4.0       3.0      2.0        2.0
         3          7          -          -         -          -       4.0       3.0      2.0        2.0
         1          8          -          -         -          -       4.0       3.0      2.0        2.0
         2          8          -          -         -          -       5.0       4.0      3.0        2.0
         3          8          -          -         -          -       5.0       4.0      3.0        2.0
         1          9          -          -         -          -       7.0       5.0      4.0        3.0
         2          9          -          -         -          -       5.0       4.0      3.0        3.0
         3          9          -          -         -          -      -999      -999     -999       -999
```

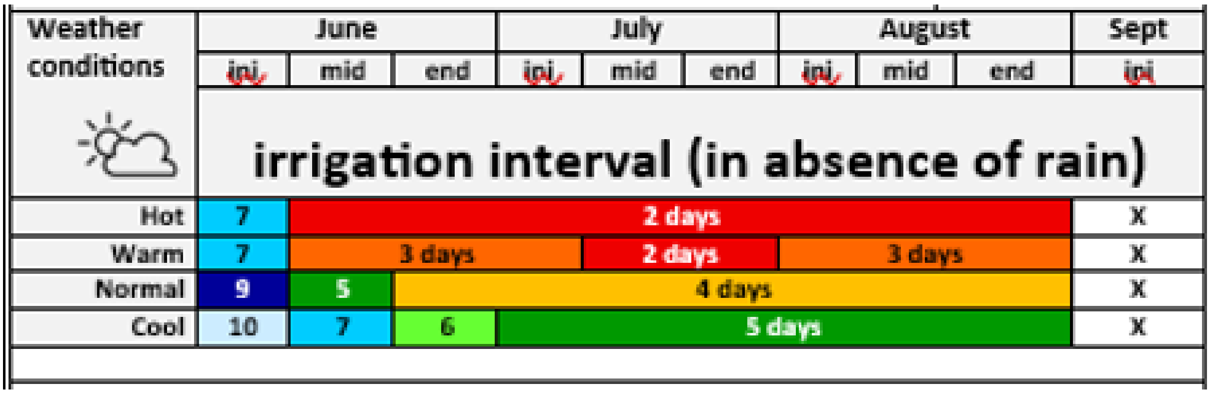


Figure 6.2.2c – Generated irrigation intervals in the absence of rain during the growing period of the sunflowers.

□ **Determination of the weather conditions**

On the irrigation chart, the 10-day indicative irrigation intervals in the absence of rainfall are presented for each decade of the growing period for four different weather conditions: cool, normal, warm and hot (Fig. 6.2.2c).

In the absence of rainfall, the weather conditions in a decade are determined by the evapotranspiration demand (ETo) of the atmosphere. The higher the ETo in a decade, the shorter the irrigation interval. Since ETo is not directly available at field level, the maximum air temperature (Tmax) is presented on the irrigation chart to help the user select the appropriate weather condition.

The relationship between the 10-day Tmax and ETo over 20 successive years (2000 – 2019), indicates whether Tmax is a good indicator of ETo for the relevant month (Fig. 6.2.2d).

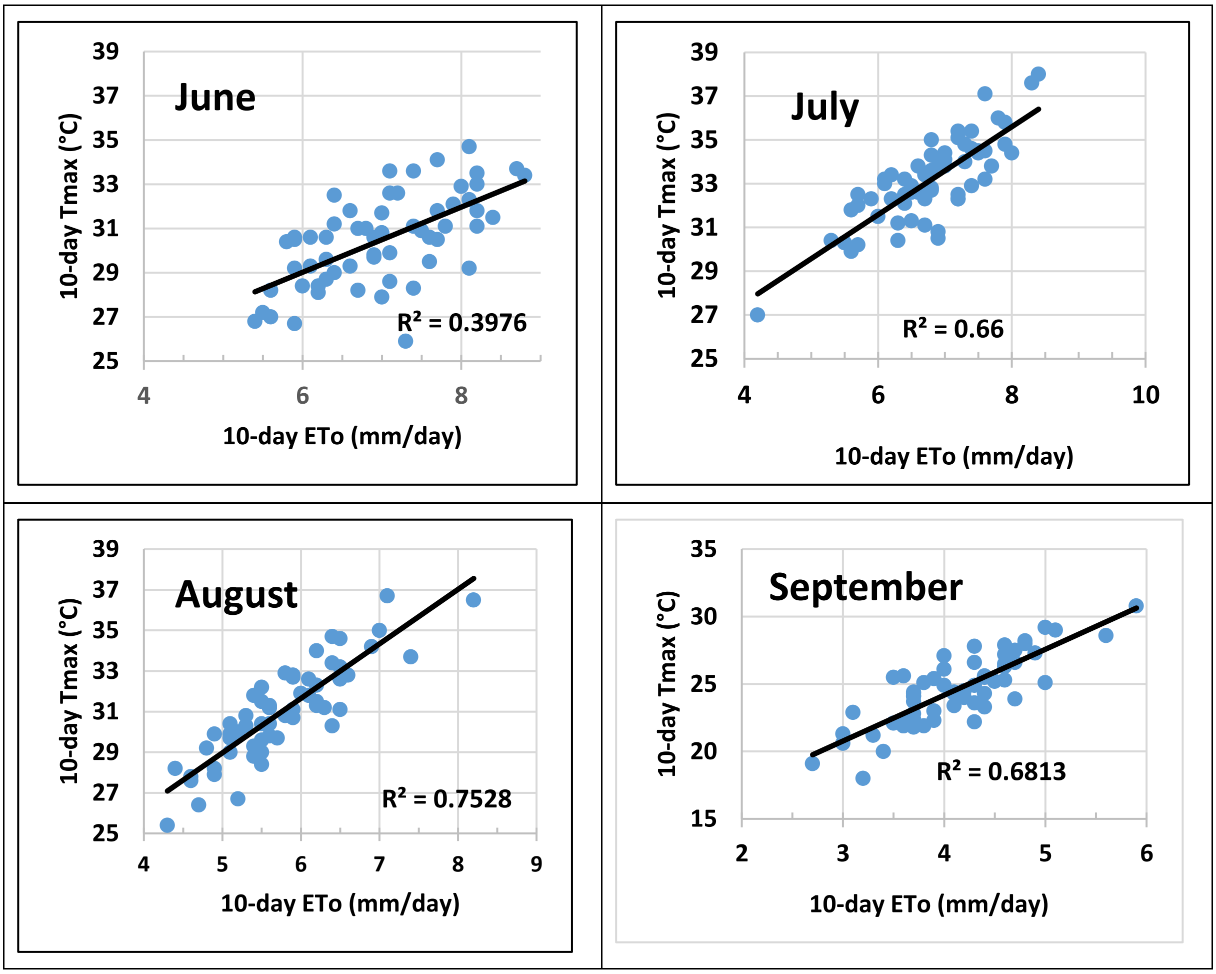


Figure 6.2.2d – The relationship between the 10-day Tmax and ETo over 20 successive years (2000 – 2019) for Bayannur

To provide an indication of the variation in maximum air temperature (Tmax) throughout the growing season, a frequency analysis on Tmax was performed. A plot of the variation of Tmax throughout the growing season for various probabilities is obtained (Fig. 6.2.2e). (i) by selecting in the ***Frequency analysis (10-Day, Month)*** menu the "daily maximum air temperature (°C)" as parameter, and (ii) by considering the same probabilities used to determine the irrigation interval.

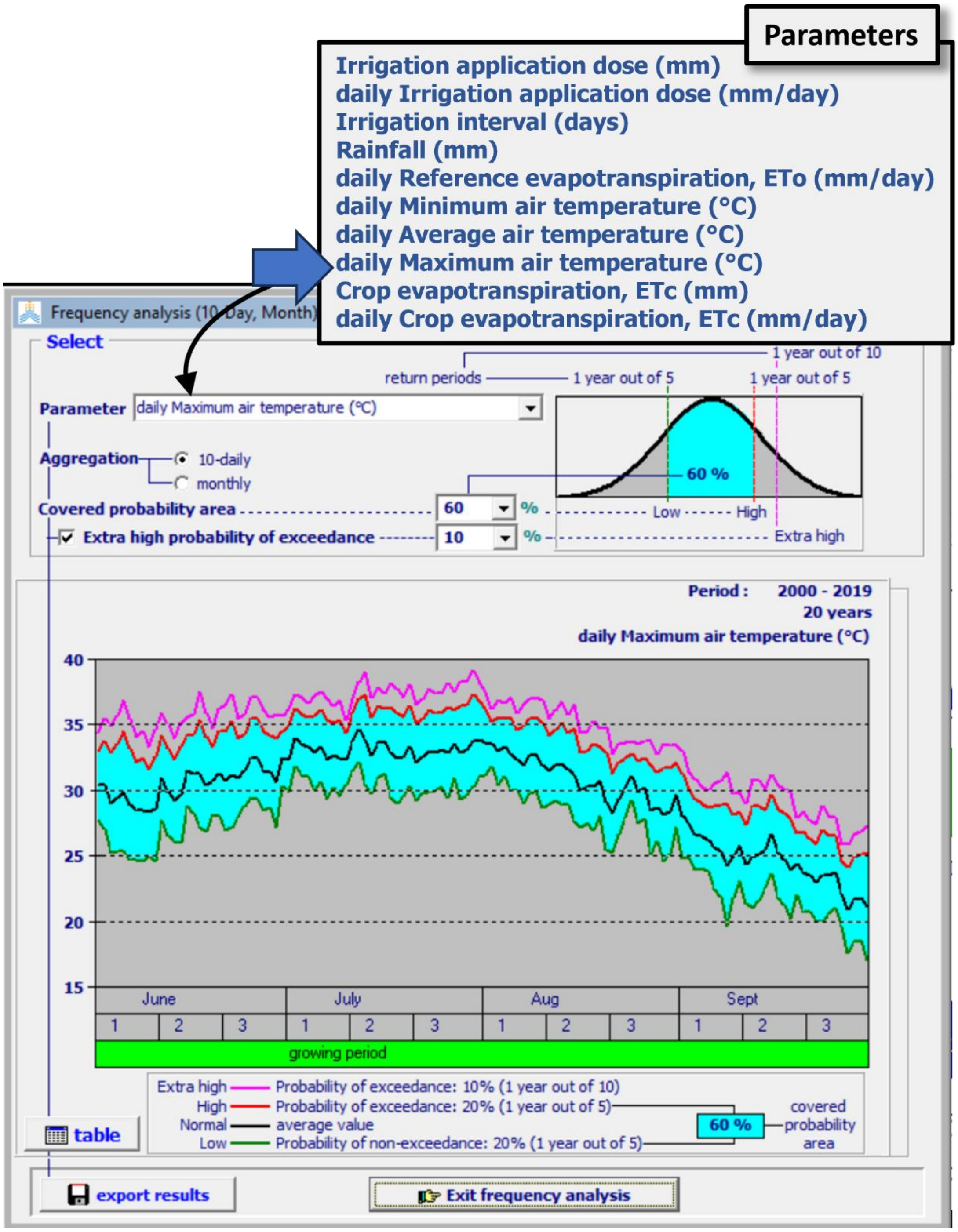


Figure 6.2.2e – Variation of the daily maximum air temperature (Tmax) throughout the growing period for various probabilities.

- **Irrigation Chart**

Irrigation guidelines for sunflower for the region of Bayannur
planting: end May- early June
harvest: end September
soil type: silt loam

Linear move/ Center pivot
gross application dose 25 mm
80% field application efficiency

Weather conditions	June			July			August			September		
	ini	mid	end	ini	mid	end	ini	mid	end	ini	mid	End
	irrigation interval (in absence of rain)											
Hot	3	2 days								3 days		X
Warm	4	3 days			2 days			3 days				X
Normal	6	4 days			3 days			4 days				X
Cool	8	6 days		5	4 days			5 days				x
Growth stage	establish		vegetative					flowering		yield formation		
Sensitivity to water stress	sensitive		moderate tolerant					sensitive		moderate sensitive		

Weather conditions Bayannur for sunflower growing period

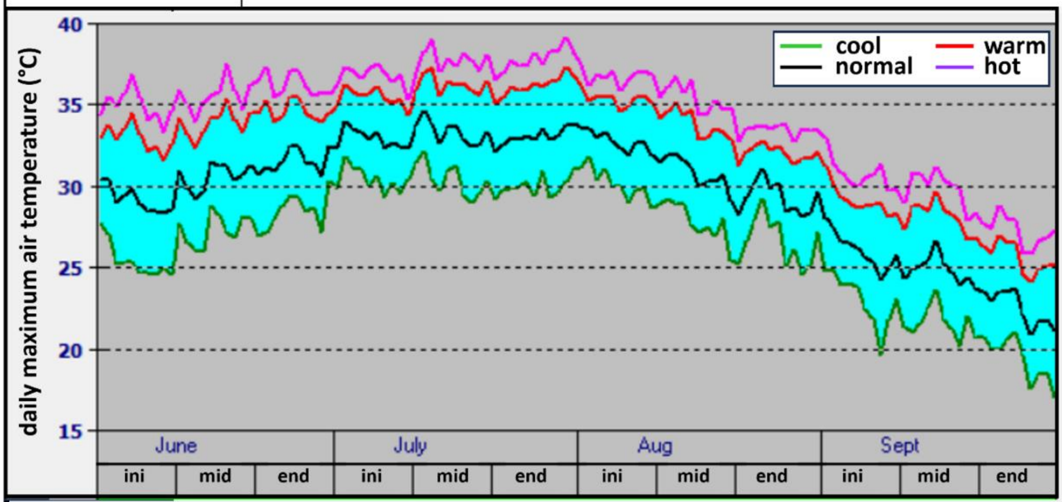


Figure 6.2.2f – Centre pivot/Linear move Irrigation chart for sunflowers for the region of Bayannur. specifying (1) the crop and environment in question, (2) the irrigation interval in the absence of rainfall for various weather conditions, (3) the crop's sensitivity to water stress and (4) the maximum air temperature at the four different weather conditions

(1) the crop and environment in question

The irrigation chart is valid for a specific crop (sunflowers), growing period (planting: end May – early June; harvest: end September), climate region (Bayannur, China), soil type (silt loam), and irrigation method (the crop is irrigated by a Linear move/Centre pivot with a fixed gross application dose of 25 mm, and an irrigation application efficiency (Ea) of 80 %).

(2) the irrigation interval in the absence of rainfall for various weather conditions

The listed intervals for the four different weather conditions are valid in the absence of rainfall and for a gross application dose of 25 mm by the Centre pivot/linear move system.

Although the irrigation intervals listed in the Chart (Fig. 6.2.2f) assume that for each irrigation application the specified gross irrigation dose of 25 mm is applied, farmers may irrigate with other irrigation doses or adjust the application dose during the season. Under such conditions, the chart still provides valid guidelines for irrigation planning as long as the link between the application dose and interval is respected. If a smaller dose is applied than the 25 mm, the irrigation interval should be decreased proportionally as well. If a farmer increases the proposed irrigation interval with a certain percentage, the farmer has also to increase the irrigation dose with that percentage.

Variations of the irrigation application dose should remain moderate. Uniformity of the water application on the field will suffer if the application dose becomes too small. If the applied amount of water is much larger than the listed application dose, some of the irrigation water will be lost as deep percolation. This will not only contaminate the water, but may also cause valuable nutrients to be flushed out of the root zone.

(3) the crop's sensitivity to water stress

This section provides information concerning the sensitivity of the crop to water stress. In case of water shortage, this information is useful to further adjust the irrigation calendar while still maximising production:

- ***When the crop is not or moderately sensitive to water stress:***
  By postponing irrigation applications during periods when the crop is not or moderately sensitive to water stress, irrigation water can be saved. A slight to moderate increase of the irrigation interval will not greatly affect crop yield.
- ***When the crop is sensitive to very sensitive to water deficits:***
  Delaying irrigation applications during these periods should be avoided.

(4) the maximum air temperature at the four different weather conditions

By observing the actual maximum air temperature (Tmax), the graph of Tmax values under the four different weather conditions helps the user determine the appropriate irrigation interval at any point during the growing season. During the growing period, Tmax was a good indicator of the atmospheric evaporative demand (Fig. 6.2.2d).

□ Adjusting the irrigation interval to rainfall

When rainfall on a particular day or during successive rainy days is larger than or as large as the net irrigation dose

Under such conditions, rainfall replaces an irrigation event, and there is no need to irrigate (Fig. 6.2.2g). Once the rains are over, guidelines for the irrigation interval are given in the respective rows.

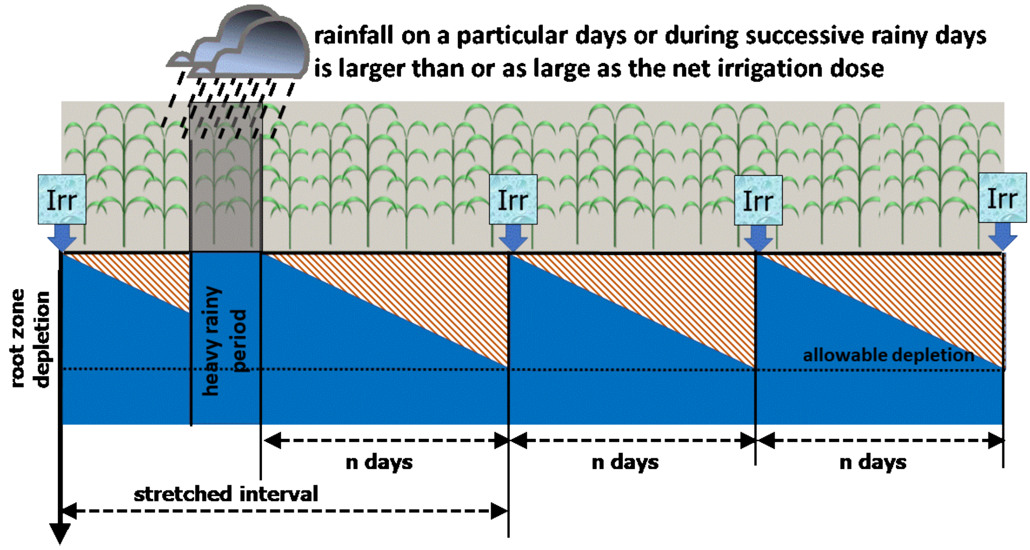


Figure 6.2.2g – Adjustment of the irrigation interval in case of important rainfall

Rainfall is smaller than the irrigation dose

Under such conditions the next irrigation application can be delayed with one or more days (Fig. 6.2.2h).

The number of days by which the irrigation interval can be extended is determined by multiplying the irrigation interval in the absence of rainfall (n days) with the ratio between the rainfall amount (P) and the net application dose (d_{net}). The number of extra days should be smaller than or equal to the number of days since the last irrigation (d days).

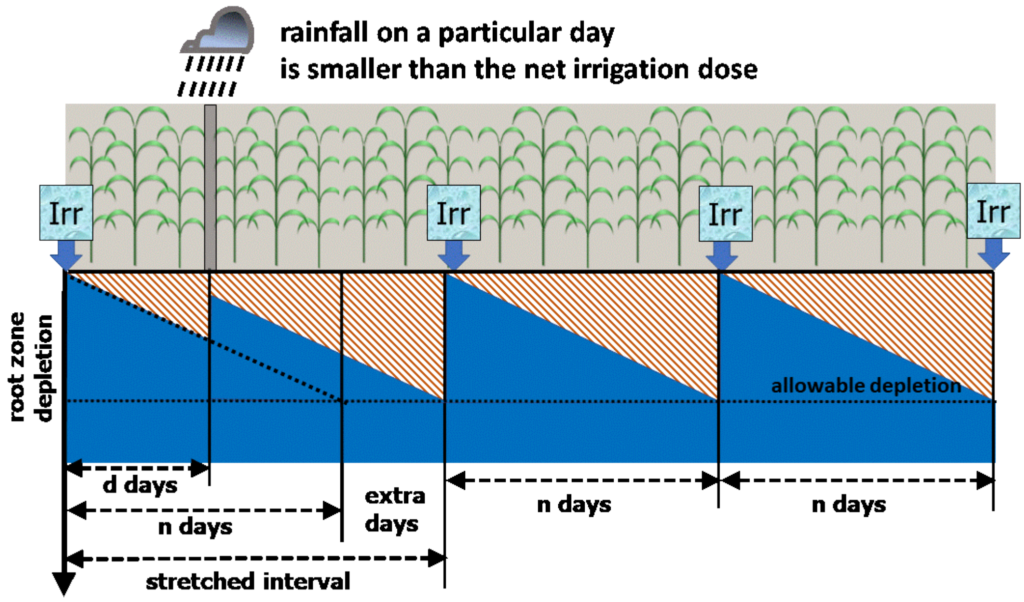


Figure 6.2.2h – Adjustment of the irrigation interval in case of small rainfall

6.2.3 *Chart with a fixed irrigation interval*

When applying small irrigation doses with micro-irrigation techniques (drip, sprinkler), the interval is often fixed at one or a few days. In this case, the irrigation application dose should be adjusted to the changes in crop evapotranspiration (ETc) during the growing season. AquaCrop can calculate the amount of water needed for each irrigation event to bring the soil water content in the root zone back to a specific level.

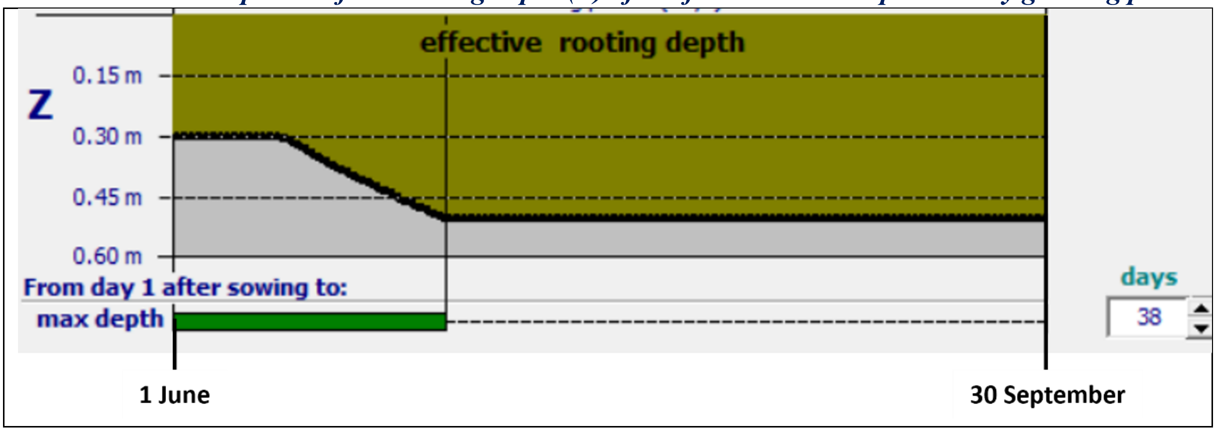
An example is worked out for sunflower for the region of Bayannur (41.1 N; 108.0 E; 1073 m) in Inner-Mongolia (China). For this example it is assumed that the crop is irrigated by drip, with a field application efficiency (Ea) of 95%. In the absence of rainfall water is applied every day (i.e. irrigation interval is 1 day).

□ **Input**

The climate data (Box 6.2.2a), growing period, soil profile characteristics and groundwater (Box 6.1.1b), and field management practices used, are identical to those employed for the chart with a fixed irrigation application dose as specified in Section 6.2.2. Because the chart guides irrigation application in the absence of rainfall, the rainfall file in the climate file has also been replaced in this example by the file "NoRain.PLU" (assuming zero rainfall for each of the 12 months of an unidentified year).

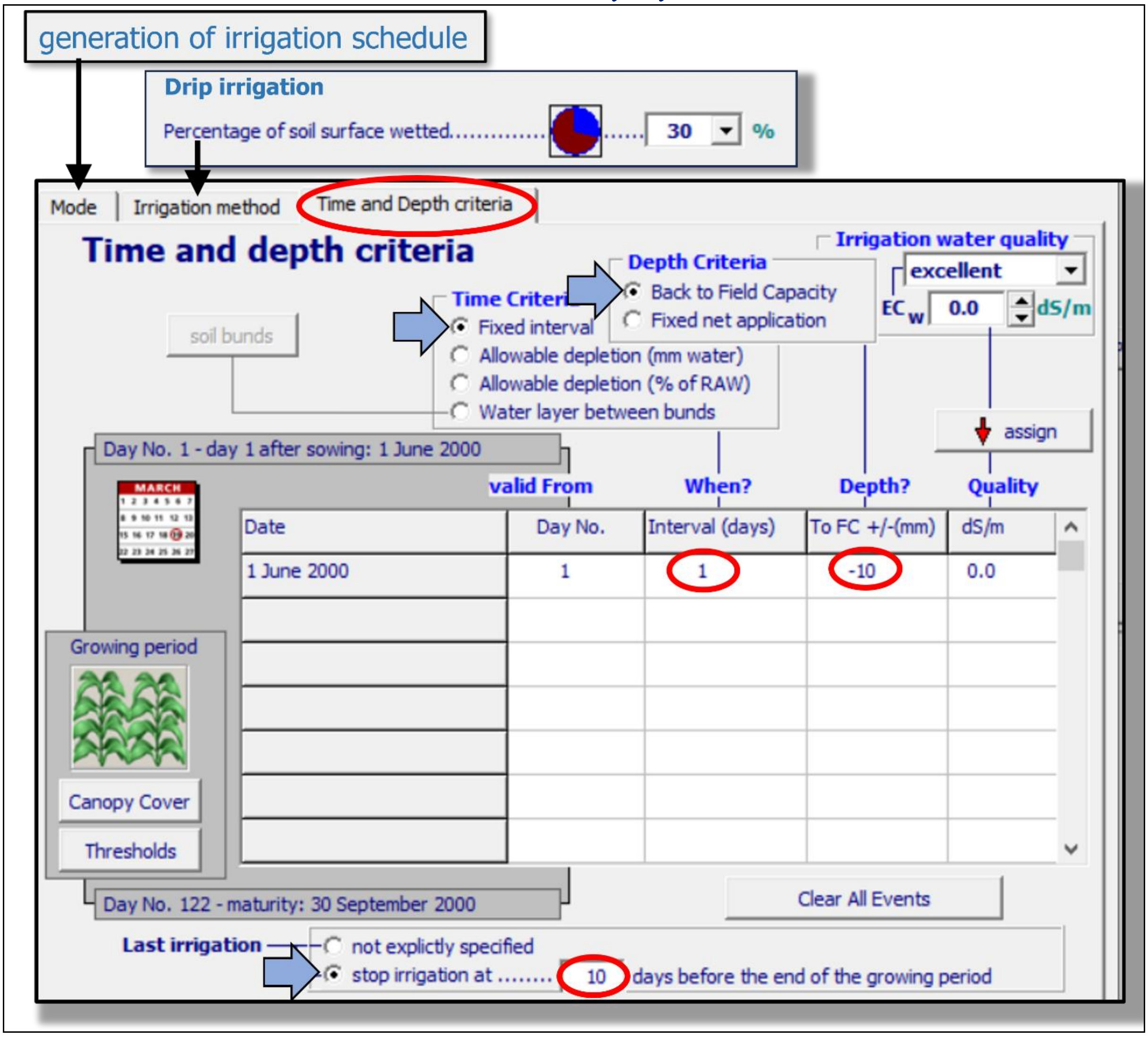
With drip irrigation, however, the root zone will remain relatively small during the dry growing period. Therefore, it was assumed that the maximum effective root depth is only 0.5 m, and the crop file was adjusted accordingly. By considering an average root zone expansion of 1 cm/day, the maximum effective rooting depth of 1 meter was reached after 38 days (Box 6.2.3a).

Box 6.2.3a – Development of the rooting depth (Z) of sunflower under drip in the dry growing period.



The drip irrigation strategy consisted of restoring daily the root zone to field capacity in the absence of rainfall. However, it allows rainfall to be stored in the root zone on rainy days, with a depletion of 10 mm being considered. Due to the crop development and changing weather conditions (ETo), the crop evapotranspiration and the applied irrigation dose will change during the growing season. The irrigation stopped at 10 days before the end of the growing period (Box 6.2.3b).

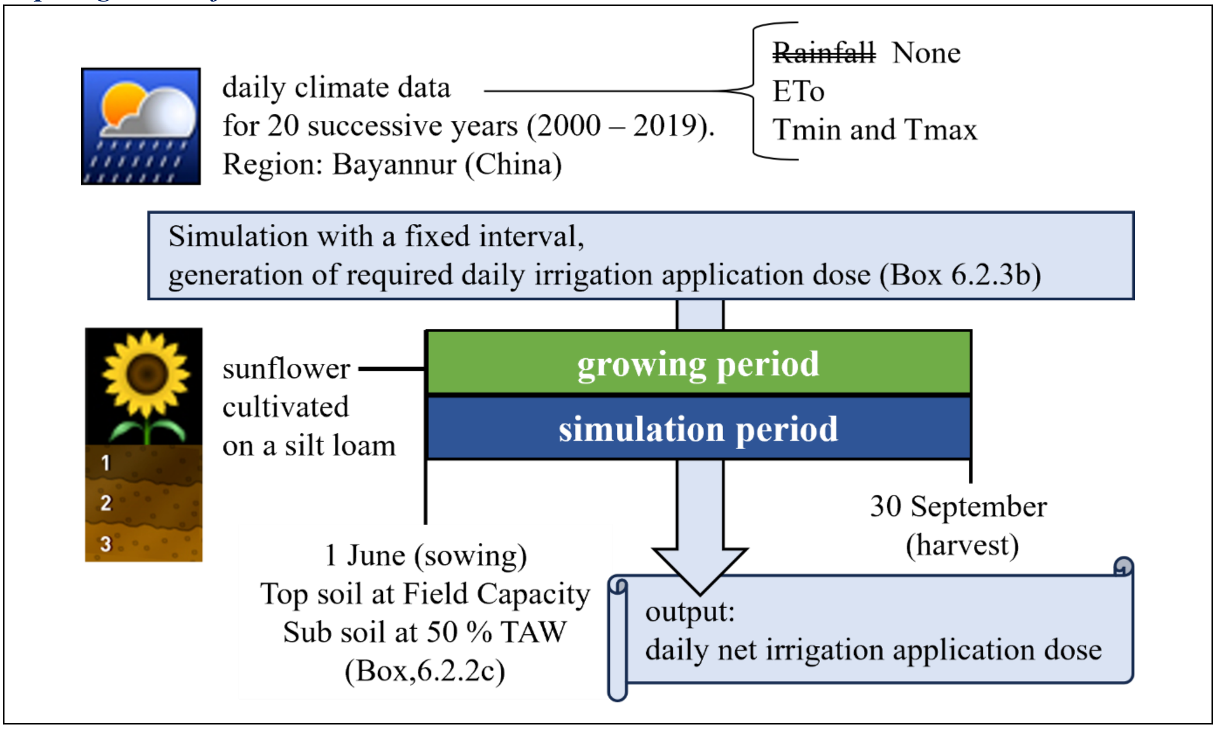
Box 6.2.3b – At each irrigation event the soil water content in the root zone is put back to field capacity minus 10 mm, so that rainwater can be stored on rainy days.



□ **Simulation with a fixed irrigation interval**

A project was created to determine the daily irrigation application dose for the drip irrigated sunflowers for the region of Bayannur in Inner-Mongolia (China), for 20 successive years (2000 – 2019). The simulation period coincided with the growing period of the sunflowers. At the start of the simulation, the same initial soil moisture content was assumed as in section 6.2.2 (Box 6.2.2c). Because of rain or pre-irrigation, Field Capacity was assumed for the topsoil (0.30 m) at the start of the irrigation season, while the subsoil was at 50% TAW (Box 6.2.3c).

Box 6.2.3c – Project determining the daily net irrigation application dose in 20 successive years for drip irrigated sunflowers



The seasonal output in the ***Simulation run*** menu showed that the total irrigation amount varied over the 20 successive years (Fig. 6.2.3a). Since precipitation has not been taken into account, this is entirely due to the variation in the evapotranspiration demand (ETo) over the years.

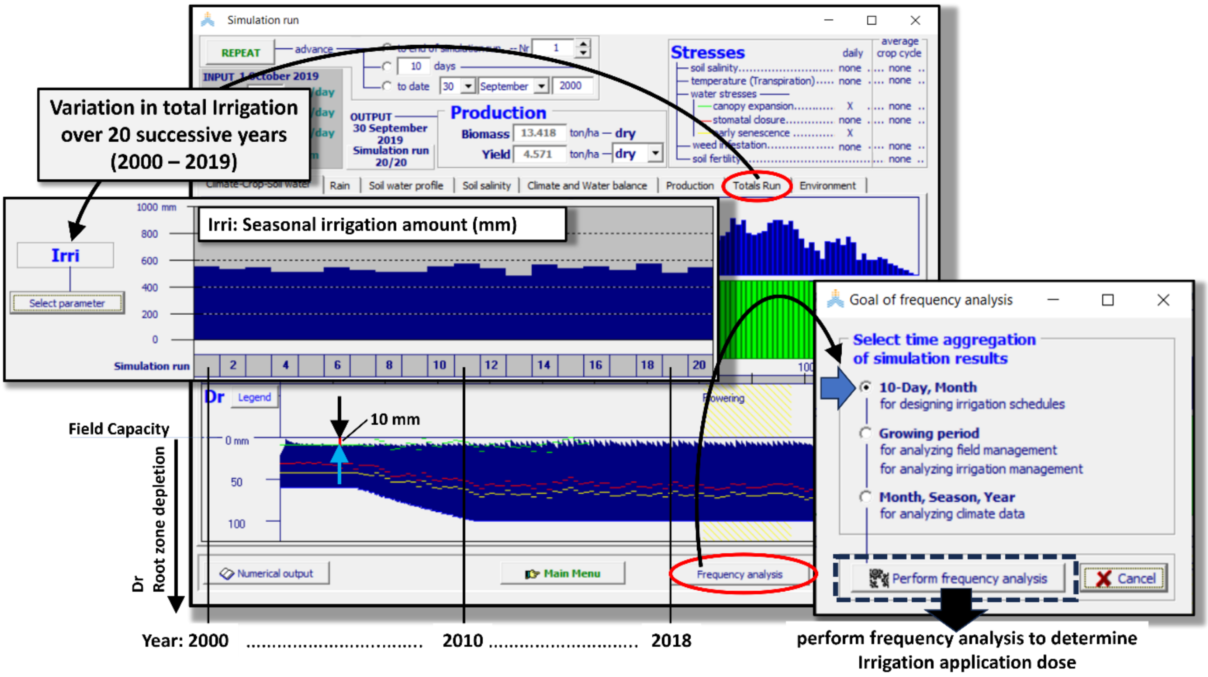
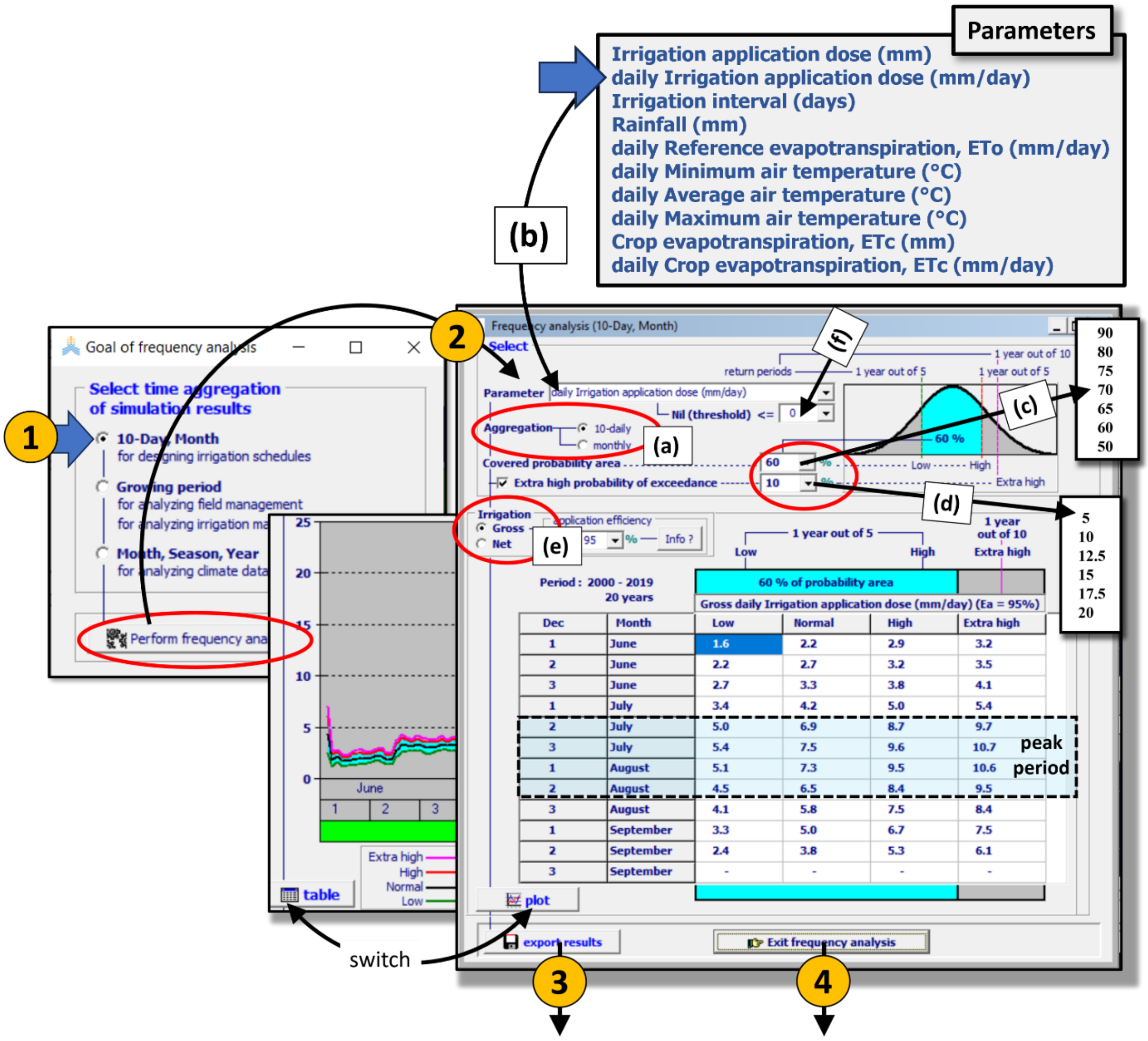


Figure 6.2.3a – Variation of the total applied irrigation amount over the 20 successive years and the <Frequency analysis> button in the "Simulation run" menu, which provides access to a series of menus for performing a frequency analysis on the irrigation application dose.

□ **Determination of the irrigation application dose**

After (1) selecting *'10-Day, Month'* in the ***Goal of frequency analysis*** menu, and clicking on the **<Perform frequency analysis>** button, (2) the ***Frequency analysis (10-Day, Month)*** menu is displayed. From this menu, the user can (3) export the results and (4) return to the ***Simulation run*** menu (Fig. 6.2.3b).



Dec	Month	Low	Normal	High	Extra high
1	June	1.6	2.2	2.9	3.2
2	June	2.2	2.7	3.2	3.5
3	June	2.7	3.3	3.8	4.1
1	July	3.4	4.2	5.0	5.4
2	July	5.0	6.9	8.7	9.7
3	July	5.4	7.5	9.6	10.7
1	August	5.1	7.3	9.5	10.6
2	August	4.5	6.5	8.4	9.5
3	August	4.1	5.8	7.5	8.4
1	September	3.3	5.0	6.7	7.5
2	September	2.4	3.8	5.3	6.1
3	September	-	-	-	-

Figure 6.2.3b – Determination of the average daily drip irrigation application dose for each decade of the growing period for various probabilities of occurrence and the corresponding return periods.

In the ***Frequency analysis (10-Day, Month)*** menu, the user selects (Fig. 6.2.3b):

a) the desired time aggregation (*10-daily*);
b) the "*Daily Irrigation application dose (mm/day)*" as parameter;
c) the covered probability area (ranging from 50 to 90 %), which determines the return periods for the low and high irrigation application dose in the 10-day period (Box 6.1.2b);
d) an extra low probability of exceedance (ranging from 5 to 20 % probability of non-exceedance);
e) if the net or gross irrigation application dose should be analyzed. In the example the gross dose was considered with an application efficiency (Ea) of 95%.

By clicking on the **<plot>** or **<table>** button in the ***Frequency analysis (10-Day, Month)*** menu (Fig. 6.2.3b), the user can switch between the probability table for the selected parameters and the corresponding plot.

Different covered probability areas (option (c) in Fig. 6.2.3b) can be selected in the ***Frequency analysis (10-Day, Month)*** menu. By selecting a covered probability area, also the corresponding probabilities of exceedance and non-exceedance and the return period are defined (Box 6.1.2b). In this example the covered probability area was 60%. Consequently:

- the 10-day low irrigation application dose have a probability of non-exceedance of 20 %, this means that in 1 year of 5, the required irrigation application dose will be less;
- the 10-day high irrigation application dose have a probability of exceedance of 20 %, this means that the application doses are valid in 4 years out of 5.

In the example, a gross irrigation application dose of 8.4 to 9.6 mm per day during the peak period (mid July – mid August) and in the absence of rainfall, will cover the crop water need in 4 years out of 5 (Fig. 6.2.3b). A gross irrigation application dose of 9.5 to 10.7 mm per day in this period secures the crop water needs in 9 years out of 10.

The content of the corresponding output file of the Frequency analysis is presented in Box. 6.2.3d.

Box. 6.2.3d – The output file of the 10-day frequency analysis of the daily gross irrigation application dosed for sunflowers at Bayannur at various probabilities of exceedance.

```
AquaCrop 7.3 (July 2026) - Output created on (date) : …   at (time) : …

Gross daily Irrigation application dose (mm/day) (Ea = 95%), (Aggregated 10-daily), Nil <= 0,
period 2000 - 2019 (20 years),
Low/high: 20% probability of (non-)exceedance (1 year out of 5) - Covered probability area: 60%,
Extra high: 10% probability of exceedance (1 year out of 10)

Aggregated 10-daily
                                                                 ----- global probability -----
      Decade      Month      Years       %Nil    Average      StDev        Low     Normal       High  ExtraHigh
                                                  mm/day     mm/day     mm/day     mm/day     mm/day     mm/day
           1          6          -          -          -          -        1.6        2.2        2.9        3.2
           2          6          -          -          -          -        2.2        2.7        3.2        3.5
           3          6          -          -          -          -        2.7        3.3        3.8        4.1
           1          7          -          -          -          -        3.4        4.2        5.0        5.4
           2          7          -          -          -          -        5.0        6.9        8.7        9.7
           3          7          -          -          -          -        5.4        7.5        9.6       10.7
           1          8          -          -          -          -        5.1        7.3        9.5       10.6
           2          8          -          -          -          -        4.5        6.5        8.4        9.5
           3          8          -          -          -          -        4.1        5.8        7.5        8.4
           1          9          -          -          -          -        3.3        5.0        6.7        7.5
           2          9          -          -          -          -        2.4        3.8        5.3        6.1
           3          9          -          -          -          -       -999       -999       -999       -999
```

Weather conditions	June			July			August			September		
	ini	mid	end	ini	mid	end	ini	mid	end	ini	mid	end
	gross application dose (in absence of rain) in mm per day											
Hot	3	4		5	10	11 mm		10	8 mm		6	X
Warm	3		4	5	9	10 mm		8		7	5	X
Normal	2	3 mm		4	7	8	7 mm		6	5	4	X
Cool	2 mm		3 mm		5 mm				4	3	2	X
Growth stages	establish		vegetative					flowering		yield formation		
Sensitivity to water stress	sensitive		moderate tolerant					sensitive		moderate sensitive		

Figure 6.2.3c – Daily gross application doses in the absence of rain during the growing period of the sunflowers.

On the irrigation chart, the indicative daily gross irrigation application doses, in the absence of rainfall, are presented for each decade of the growing period for four different weather conditions: cool, normal, warm and hot (Fig. 6.2.3c).

In the absence of rainfall, the weather conditions in a decade are determined by the evapotranspiration demand (ETo) of the atmosphere. The higher the ETo in a decade, the larger the irrigation dose. Since ETo is not directly available at field level, the maximum air temperature (Tmax) is presented on the irrigation chart to help users select the appropriate weather condition. In section 6.2.2 it was demonstrated that Tmax for the growing period is a good indicator of ETo (Fig. 6.2.2d).

- **Irrigation chart**

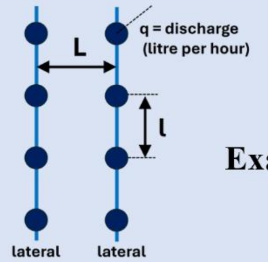
Irrigation guidelines for sunflower for the region of Bayannur

planting: end May- early June
harvest: end September
soil type: silt loam

Drip irrigation
daily irrigation interval
90% field application efficiency

Weather conditions	June			July			August			September		
	ini	mid	end	ini	mid	end	ini	mid	end	ini	mid	end
	gross application dose (in absence of rain) in mm per day											
Hot	3	4		5	10	11 mm		10	8 mm		6	X
Warm	3		4	5	9	10 mm		8		7	5	X
Normal	2	3 mm		4	7	8	7 mm		6	5	4	X
Cool	2 mm		3 mm		5 mm				4	3	2	X
Growth stages	establish		vegetative					flowering		yield formation		
Sensitivity to water stress	sensitive		moderate tolerant					sensitive		moderate sensitive		

Q discharge per unit of surface litre/hour.m²	gross application dose (mm/day)									
	2	3	4	5	6	7	8	9	10	11
	application time in hours and minutes (H:MM) per day									
2	1:00	1:30	2:00	2:30	3:00	3:30	4:00	4:30	5:00	5:30
3	0:40	1:00	1:20	1:40	2:00	2:20	2:40	3:00	3:20	3:40
4	0:30	0:45	1:00	1:15	1:30	1:45	2:00	2:15	2:30	2:45
5	0:25	0:35	0:45	1:00	1:10	1:25	1:35	1:45	2:00	2:10
6	0:20	0:30	0:40	0:50	1:00	1:10	1:20	1:30	1:40	1:50



Q: discharge per unit of surface

$$Q = \frac{q}{(l \times L)} \text{ litre per hour per m}^2$$

Example: $\left.\begin{array}{l} l = 0.50\text{m} \\ L = 0.80 \text{ m} \\ q = 2 \text{ l/h} \end{array}\right\}$ 5 litre/hour.m²

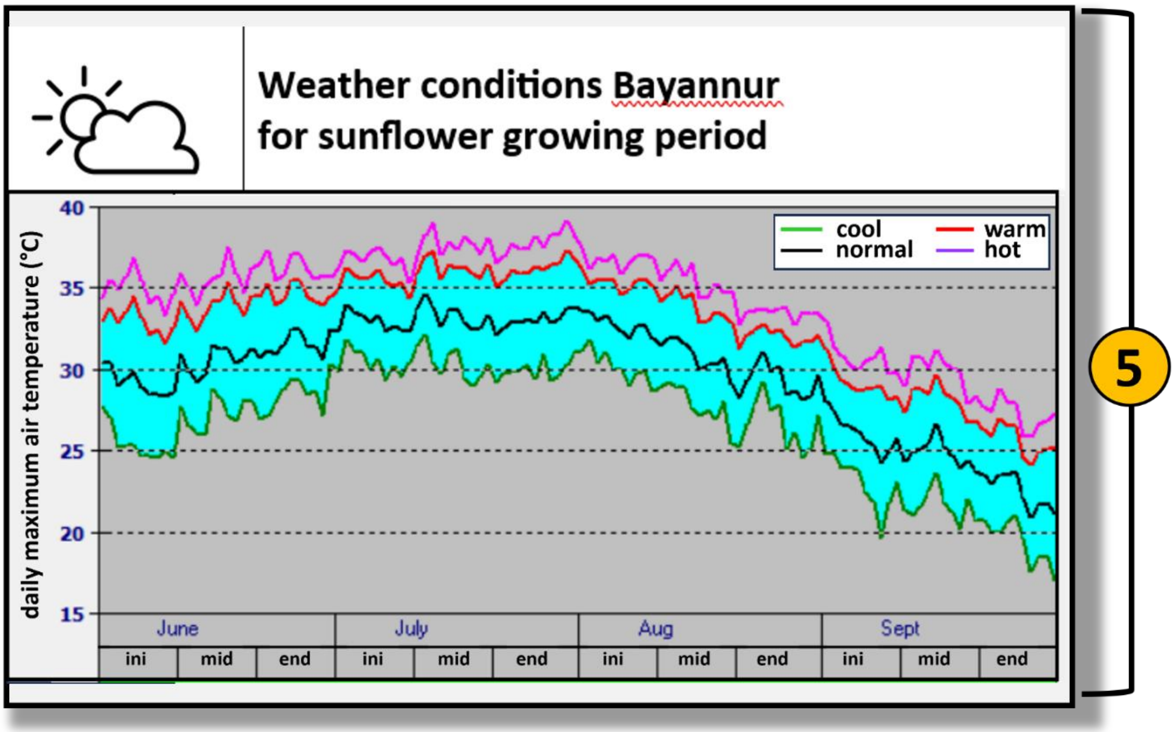


Figure 6.2.3d – Information on the drip Irrigation chart for sunflowers for the region of Bayannur. listing on the front side (1) the crop and environment in question, (2) the daily gross irrigation application dose in the absence of rainfall for various weather conditions, (3) the crop's sensitivity to water stress and (4) the irrigation application times for the considered gross irrigation application doses; and on the back side (5) the maximum air temperature at the four different weather conditions

(1) <u>the crop and environment in question</u>

The irrigation chart is valid for a specific crop (sunflowers), growing period (planting: end May – early June; harvest: end September), climate region (Bayannur, China), soil type (silt loam), and irrigation method (the crop is irrigated by drip with an irrigation application efficiency (Ea) of 95 %).

(2) <u>the daily gross application dose in the absence of rainfall for various weather conditions</u>

The listed daily gross application doses for the four different weather conditions are valid in the absence of rainfall and for an application efficiency (Ea) of 95%.

Although the gross application doses were derived by assuming that water is applied daily, farmers may irrigate with a longer irrigation interval. Under such conditions, the chart still provides valid guidelines for irrigation planning as long as the irrigation interval does not become too large.

(3) <u>the crop's sensitivity to water stress</u>

This section provides information concerning the sensitivity of the crop to water stress. In case of water shortage, this information is useful to further adjust the irrigation calendar while still maximising production:

- ***When the crop is not or moderately sensitive to water stress:***

By reducing the irrigation application dose during periods when the crop is not or moderately sensitive to water stress, irrigation water can be saved. A slightly to moderate reduction of the irrigation application dose will not strongly affect crop yield.

- ***When the crop is sensitive to very sensitive to water deficits:***
  Reducing the irrigation application dose during these periods should be avoided.

(4) <u>irrigation application times for the considered gross irrigation application doses</u>

Based on the discharge per unit surface (Q) of the drip irrigation system and the required gross application amounts (varying between 2 and 11 mm per day), the corresponding irrigation duration (in hours and minutes) can be found in the table. By taking into account the emitter discharge (q) and the distances between the emitters (l) and the lateral lines (L), the discharge per unit area (Q) can be determined.

(5) <u>the maximum air temperature at the four different weather conditions</u>

By observing the actual maximum air temperature (Tmax), the graph of Tmax values across the four different weather conditions helps the user select the appropriate daily gross irrigation application dose for any point during the growing season. During the growing period, Tmax was a good indicator of the atmospheric evaporative demand (Fig. 6.2.2d).

□ **Adjusting the irrigation interval to rainfall**

On rainy days, the gross irrigation application dose should be reduced by the rainfall amount. If the amount of precipitation exceeds somewhat the daily irrigation application, the irrigation interval can be extended until the total precipitation is less than the sum of the daily applications for the skipped days. However, the number of skipped days should remain moderate, since an important part of an heavy rainfall event is likely to be lost by deep percolation.