Food and Agriculture Organization
of the United Nations

AquaCrop new features and updates
Version 5.0
October 2015

October 2015

Climate

Page

☐ **New features:**

1. <u>Importing climatic data from text files</u> **7**

The 'ETo calculator' has been incorporated in AquaCrop.
Data that can be directly imported in AquaCrop, consist of air temperature (minimum and maximum air temperature), reference evapotranspiration (ETo), rainfall data, and/or climatic data with which ETo can be calculated. By importing the data, AquaCrop will create the corresponding files containing the climatic data (files with extension 'Tnx', 'ETo' and/or 'PLU'), and the climate file (files with extension 'CLI').

2. <u>Aggregation of climatic data</u> **22**

In the ***Climatic data*** and the ***Display of climate characteristics*** menus, mean monthly and yearly totals of climatic data can be plotted and exported. The data help to assess the climatic conditions in which the crop is cultivated.

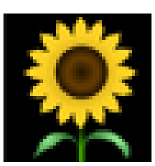
☐ **Updates:**

3. <u>Extension of air temperature files become '.Tnx'</u> **28**

The extension of air temperature files in AquaCrop is changed from '.TMP' to '.Tnx'. Nevertheless, previously created air temperature files with extension '.TMP' can still be used in AquaCrop.

4. <u>Update of CO2 file</u> **29**

The content of the 'MaunaLoa.CO2' file was updated with the latest published results on the NOAA website. Next to the 4 CO2 files from SRES (Special Report on Emissions Scenarios), four different RCP's ('RCP2-6.CO2', RCP4-5.CO2', 'RCP6-0.CO2' and 'RCP8-5.CO2') has been added to the data base of AquaCrop. As the SRES set, the four RCPs (Representative Concentration Pathways) represent a broad range of climate outcomes.



Crop

☐ **Updates:**

5. <u>Update of the *Crop characteristics* menu</u> **31**

In the ***Crop characteristics*** and ***Display of Crop characteristics*** menus, the crop parameters are grouped in different tabular sheets. A new tabular sheet (Mode) has been added to make the alteration between calendar and growing degree-days mode more visible to the user. Additionally some tabular sheets have been updated.

Irrigation

☐ **New features:**

6. Generation of irrigation events for flooded rice

An option is available to generate irrigation applications when the water level between the soil bunds drops below a pre-defined minimum value. This is useful for generating irrigation schedules for paddy rice.

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Field management

☐ **New features:**

7. Field surface practices

The user can adjust the CN based on the soil profile characteristics (CN_{soil}), by considering field management and crop type which might affect surface runoff. The following options are available:

Field surface practices:

- do NOT affect surface runoff (as in previous versions);
- affect surface runoff (new feature). The user specifies the percentage increase/decrease (CN_{man}) of CNsoil;
- prevent surface runoff (as in previous versions);
- soil bunds (as in previous versions).

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☐ **Updates:**

8. Create field management file

So far, only climate, crop, irrigation management, soil profile, groundwater, field data and project files could be created directly. The option has been extended to create field management files (select the **<Create Field management file>** command in the ***Select field management file*** menu).

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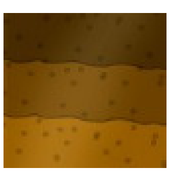

Soil profile

☐ **Updates:**

9. Default soil profile characteristics

Update of default Ksat and CN values, available in 12 default 'soil profile' files (corresponding with the twelve soil textural classes) in the DATA subdirectory of AquaCrop:

- default values for the hydraulic conductivity at saturation (Ksat) were adjusted by considering the indicative values in the Hydraulic Properties Calculator (Saxton and Rawls, 2006) for the 12 soil textural classes;
- because (i) the classification of the soils in hydrologic soil groups have been adjusted to the guidelines of USDA, and (ii) a 5 percent ratio of the initial abstraction (I_a) to storage (S) is now considered in AquaCrop (instead of 20%), the default CN values had to be updated. The default CN for the four distinguished hydrologic soil

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groups are the average values for the ‘small grain’ hydrologic soil-cover complex with good hydrologic conditions as provided by USDA in the National Engineering Handbook (USDA, 2004).

Initial conditions

☐ **New features**

10. <u>Initial conditions at start of simulation period</u> **52**

In the ***Initial conditions*** Menu, the user specifies the soil water content and soil salinity in the soil profile, which determines the status of the soil water and salt balance at the start of the first day of the simulation period. In AquaCrop Version 5.0, the user can also specify the initial Canopy Cover (CC) and effective rooting depth (Z), as well as the above-ground biomass (B) already produced before the start of the simulation period. This is required if for example due to the absence of climatic data, the simulation period starts after the germination of the crop.

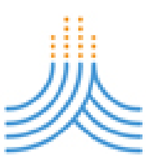
11. <u>Program settings: Simulation run parameters</u> **60**

As in the previous versions of AquaCrop, the simulated soil water content and soil salinity at the end of a previous simulation run can be taken as the initial conditions for the next run. To deal with ‘hot starts’ within the growing cycle, the user can also ‘keep’ or ‘reset’ the initial conditions when running successive simulations within the growing cycle in the ***Program settings: Simulation run parameters*** menu.

☐ **Updates:**

12. <u>Create file with initial conditions</u> **62**

So far, only climate, crop, irrigation management, soil profile, groundwater, field data and project files could be created directly. The option has been extended to create files with initial conditions (select the **<Create File initial conditions>** command in the ***Select file initial conditions*** menu).



Simulation

☐ **New features:**

13. <u>Updating results when running a simulation</u> **63**

AquaCrop does not simulate:

- pests, diseases, frost, hail, … destroying part of the green canopy cover (CC) and the above-ground biomass (B) during the season;
- subsurface horizontal water flow, moving water in or out of the soil profile (seepage).

As a consequence CC, B and/or the soil water profile (θ-z) after such an event might be different from what is observed. Therefore AquaCrop Version 5.0 offers the possibility to update CC, B and θ-z at the end of the event day by considering observations or estimates

	made on that day. After the update, AquaCrop resumes the simulation with the adjusted CC, B and/or θ-z. **14. <u>Simulations with 'Hot starts'</u>** When a simulation finishes within the growing cycle, the final simulation results are saved for the next simulation run. It consists of the water and salinity content in the soil profile, and the status of crop development and production simulated at the last day of the simulation run. If the first day of the next run, neatly succeeds the last day of the previous run, AquaCrop Version 5.0 recognises a 'hot start' and loads the saved final simulation results of the previous run. As such the conditions at the end of the previous run become the initial conditions for the simulation run. Hot starts are useful when running AquaCrop to obtain a first crop yield estimate before the end of the ongoing season, or to assess the irrigation requirement for the next part of the season. The procedure consists in running a series of successive simulations with different climate files, and eventually different irrigation management files.	**69**
	☐ **Updates:** **15. <u>Evaluation of simulation results</u>** When running a simulation, the user can evaluate the simulated Canopy Cover (CC), above-ground Biomass (B) and the soil water content (SWC) with the help of field data stored in an observation file. The statistical indicators are: the Pearson correlation coefficient (r); the root mean square error (RMSE); the normalized root mean square error (CV(RMSE)); the Nash-Sutcliffe model efficiency coefficient (EF); and the Wilmott's index of agreement (d). In AquaCrop Version 5.0 an interpretation of the assessment is provided by means of a color code, ranging from 'very good' (●●●) to 'very poor' (●●●). Since strict guidelines do not exist and depend on what is simulated, the color code is somewhat arbitrary and should be regarded as a first indication. The content and structure of the output file, which contains the evaluation of the simulation results are updated as well. The option to save the results is now handled on exit of the ***Simulation Run*** menu, together with the options to save the daily and seasonal simulation results.	**79**
	16. <u>Simulation of surface runoff</u> In AquaCrop, the estimation of the amount of rainfall lost by surface runoff is based on the curve number method developed by the US Soil Conservation Service. To estimate the amount of water lost by surface runoff, a Curve Number (CN) and initial abstraction (I_a) are considered. A 5 percent ratio of the initial abstraction (I_a) to storage (S) is now considered in AquaCrop. Additionally, the CN which is a	**86**

	soil profile characteristic, can now be adjusted by considering field surface practices (Field management).
	
	17. <u>Output files</u>
	On exit of the ***Simulation run*** menu, the option is available to save (i) daily results, (ii) seasonal results, and (iii) evaluation of the simulation results:
	- The output of the seasonal results are saved in one file. The user can specify if this file is required as output;
	- The output of the daily results are saved in 8 different files. Each of the files contain all the output of the different runs in case of a multiple runs project. A file with 'Climate input data' has been added. The user can select which files are required as output;
	- The results of the evaluation of the simulation is available in two files:
	    - Evaluation – data: This file provides a table with the simulated green canopy cover (CC), above-ground dry biomass (B) and soil water content (SWC) for each day of the simulation period. Next to the simulated values, the field data with their standard variation are specified for the days of their measurement.
	    - Evaluation – statistics: This file provides several statistical indicators evaluating the simulation of CC, B and SWC.
	The user can specify which of the evaluation files are required as output.
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Reference Manual	**18. <u>Update of Chapter 2 'Users guide' of the AquaCrop Reference Manual</u>** (276 pages).	**90**
ANNEX 1. ETo calculation procedures		**91**

1. Importing climatic data from text files

For each day of the simulation period, AquaCrop requires:

– the minimum (Tn) and maximum (Tx) air temperature,
– the reference evapotranspiration (ETo),
– the rainfall data, and
– the mean annual atmospheric CO_2 concentration.

The required climatic data are stored in respectively temperature files (files with extension 'Tnx'), ETo files (extension 'ETo'), rainfall files (extension 'PLU') and CO_2 files (extension 'CO2').

A covering climate file (file with extension 'CLI') contains the names of the Tnx, ETo, PLU and CO2 file (Fig. 1.1). The climatic data itself is stored in the Tnx, ETo, PLU and CO2 files.

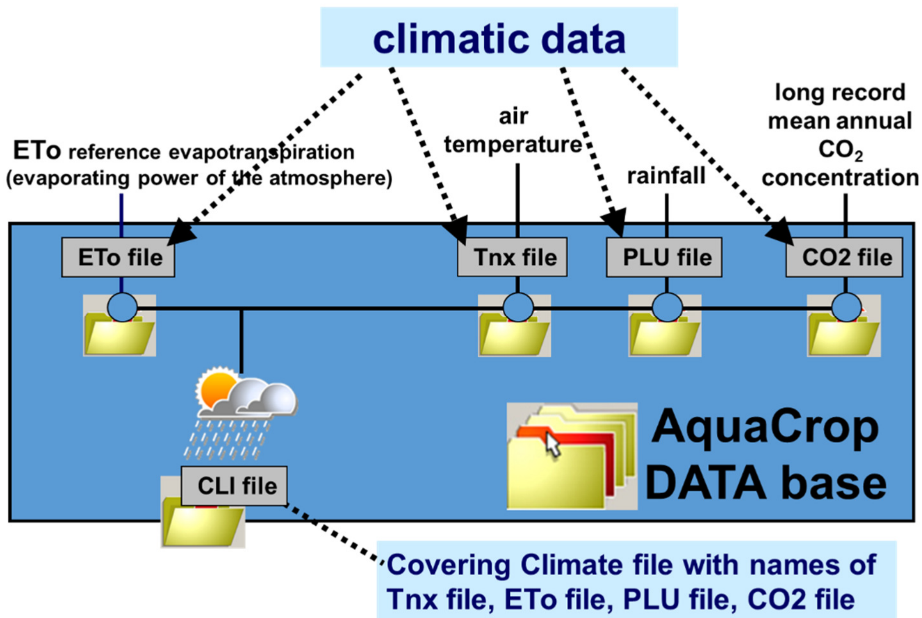


Figure 1.1 – Climate files (*.CLI) and files with climatic data (*.ETo, *.Tnx, *.PLU, *.CO2) available in AquaCrop data base.

1.1 Option to import climatic data

In the ***Select climate file*** menu, the user selects one of the available CLI files or has the option to 'Create a climate file' (file with extension 'CLI'). In AquaCrop Version 5.0, there is now also the option available to 'Import climatic data' from a text file (Fig. 1.2). Data that can be imported, consist of air temperature, ETo, or rainfall data, and/or climatic data with which ETo can be calculated. By importing the data, AquaCrop will create the corresponding files containing the climatic data (files with extension 'Tnx', 'ETo' and/or 'PLU'). Data expressed in the standard units of climatic parameters listed in Table 1.1, can be imported by AquaCrop.

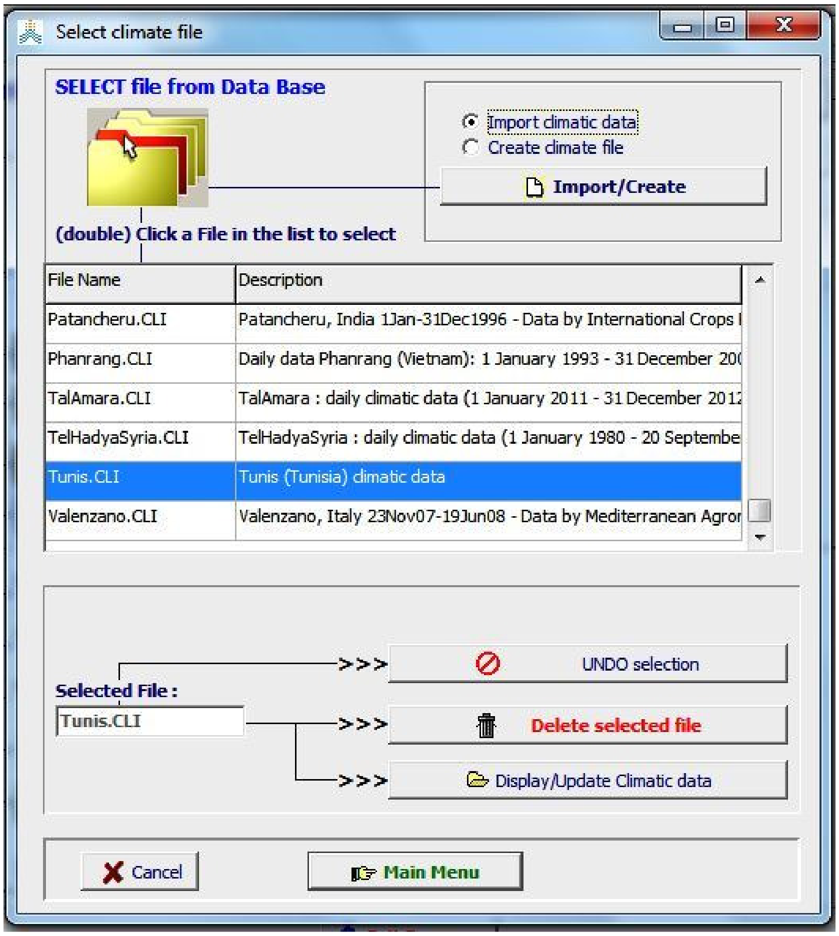


Figure 1.2 – The *Select climatic file* menu, in which the user selects one of the available 'CLI' files or has the option to 'Create a climate file' (new 'CLI' file) or to 'Import climatic data' (by creating 'Tnx', 'ETo' and/or 'PLU' files).

Table 1.1 – Climatic parameters, with their units, recognized by AquaCrop for import.

Climatic parameter (Description and Symbol)	**Units**
Air temperature data	
Maximum air temperature (Tmax)	°C or °F
Mean air temperature (Tmean)	°C or °F
Minimum air temperature (Tmin)	°C or °F
Air Humidity data	
Maximum Relative Humidity (RHmax)	%
Mean Relative Humidity (RHmean)	%
Minimum Relative Humidity (RHmin)	%
Dewpoint temperature (Tdew)	°C or °F
Actual vapour pressure: e(act)	kPa, mbar, psi, atm or mmHG
Temperature of dry bulb (Tdry)	°C or °F
Temperature of wet bulb (Twet)	°C or °F

Wind speed data	
Wind speed at x m above soil surface: u(x)	m/sec, km/day, knot or ft/sec
Radiation and sunshine data	
Actual duration of sunshine in a day (n)	hour
Relative sunshine duration (n/N)	-
Solar or shortwave radiation (Rs)	MJ/m^2.day, W/m^2, J/cm^2.day, mm/day, cal/cm^2.day
Net radiation (Rn)	MJ/m^2.day, W/m^2, J/cm^2.day, mm/day, cal/cm^2.day
ETo, Reference crop evapotranspiration	
Direct import of reference crop evapotranspiration (ETo)	mm/day
Rainfall data	
Rainfall (Rain)	mm or inch

1.2 Free format text files with climatic data (*.txt of *.CXT)

The text file is a file with extension 'txt' (as created by Notepad) or 'CXT' (as used in the ETo calculator), in which climatic data for a specific time range is saved in columns (Table 1.2). It is typically a copy from a spreadsheet but contains only the numerical values (no headings, line numbers, or dates). The file may contain daily, 10-daily or monthly climatic data. The text file consists of climatic data recorded in a specific time range (ranging from a few days up to several years) or of calculated averages for a number of years. The text file has lines and columns:

- Lines: There are as many lines (rows) as day's, 10-day's or months in the imported time range. Each line contains the climatic data (or average) for only one day, 10-day or month of the time range, and this in successive order;
- Columns: The text file can contain up to 10 columns. Each column contains the data of one of the climatic parameters listed in Table 1.1.

Table 1.2 – Example of a text file containing climatic data. It consists of a small part of the 'LosBanos1997_2014.txt' file with daily data for Los Baños (Philippines) at 14.17 °N and 170 m.a.s.l.: Solar radiation (MJ/m^2.day), Maximum and Minimum temperature (°C), wind speed at 10 m above ground level (m/sec), dewpoint temperature (°C), mean relative humidity (%) and rainfall.

12.9	25.7	21.5	5.1	20.1	82.7	0.1
11.3	26.9	20.5	5.2	19.5	82.1	0
13	27.6	20.7	4.3	19.6	78.1	0
15.1	28.1	19.4	3.9	19.4	75.7	0.4
17.7	27	20.6	3.1	19.4	77.6	5
17	27.4	19.9	3.2	18.6	74.7	0.1
15.6	29.3	19.1	3.5	19.7	78	2.5
18.1	28.4	21.1	4.1	19.9	72.6	0
18.6	28.6	21.7	3.2	20	74.6	1.1
15.6	28.3	21.4	3.4	19.7	73.7	0.6

1.3 Import climatic data menu

The ***Import climatic data*** menu contains 5 tabular sheets (Fig. 1.3);

- **'Select file'**: to select the text file, containing the climatic data to be imported;
- **'Time range'**: to specify the time range of the imported climatic data (lines in text file);
- **'Climatic parameters'**: to specify the climatic parameters with their unit to which the imported data belongs (columns of text file);
- **'ETo'**: to specify coefficients for ETo calculation (if relevant);
- **'Import climatic data'**: to create 'Tnx', 'ETo', and/or 'PLU' files (containing the imported climatic data), and to save the created file(s) in the AquaCrop data base.

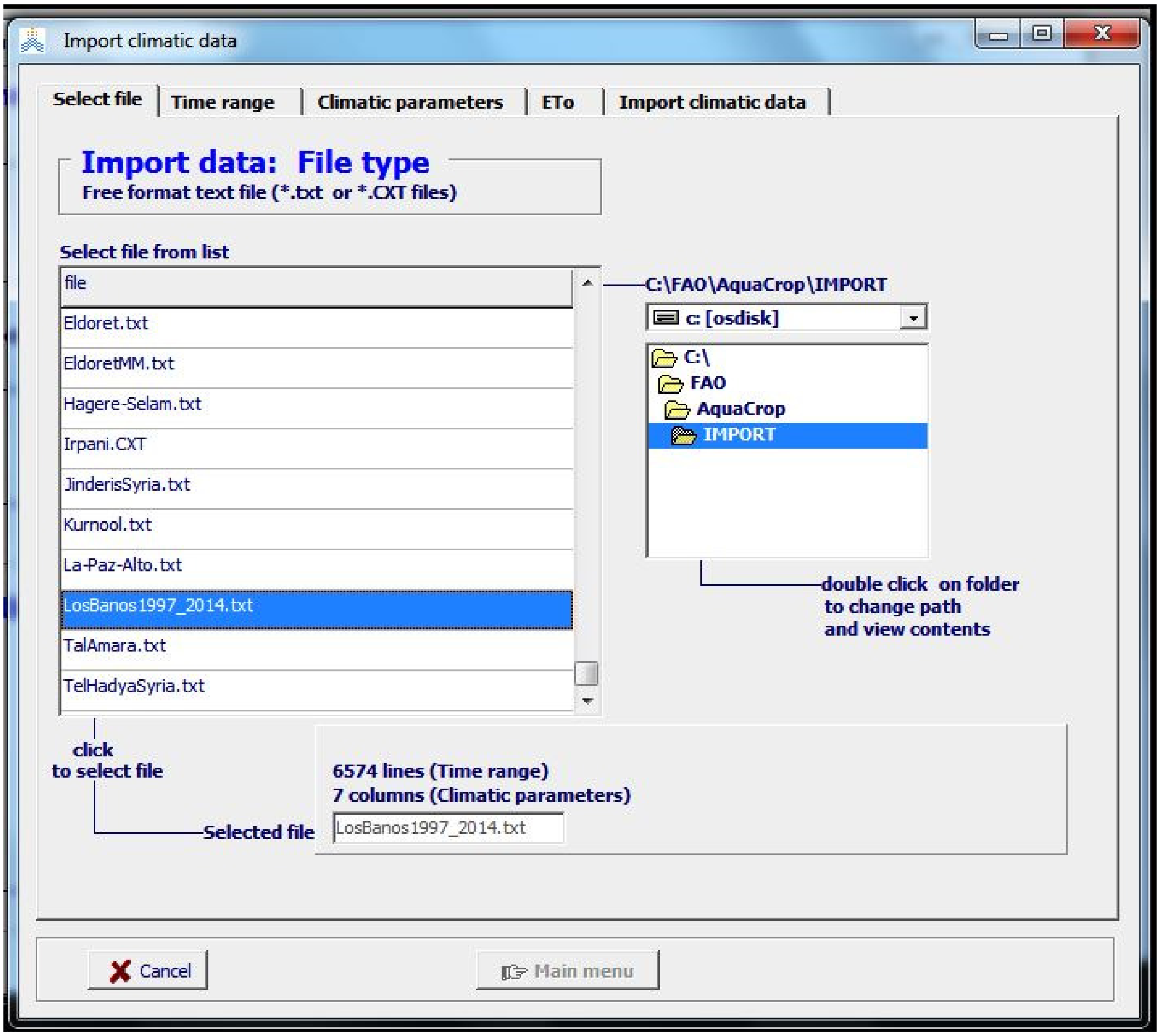


Figure 1.3 – *Import climatic data* menu with its tabular sheets: 'Select file', 'Time range', 'Climatic parameters', 'ETo', and 'Import climatic data'.

1.3.1 Tabular sheet: ‘Select file’

In the tabular sheet ‘Select file’ (Fig. 1.3) the user selects from the displayed list the text file containing the climatic data. All text files (files with extension ‘txt’ or ‘CXT’) stored in the IMPORT sub directory of the AquaCrop folder are listed. By altering the path, the user can retrieve text files from other directories than the default ‘IMPORT’ directory.

Once a text file has been selected, the program displays:

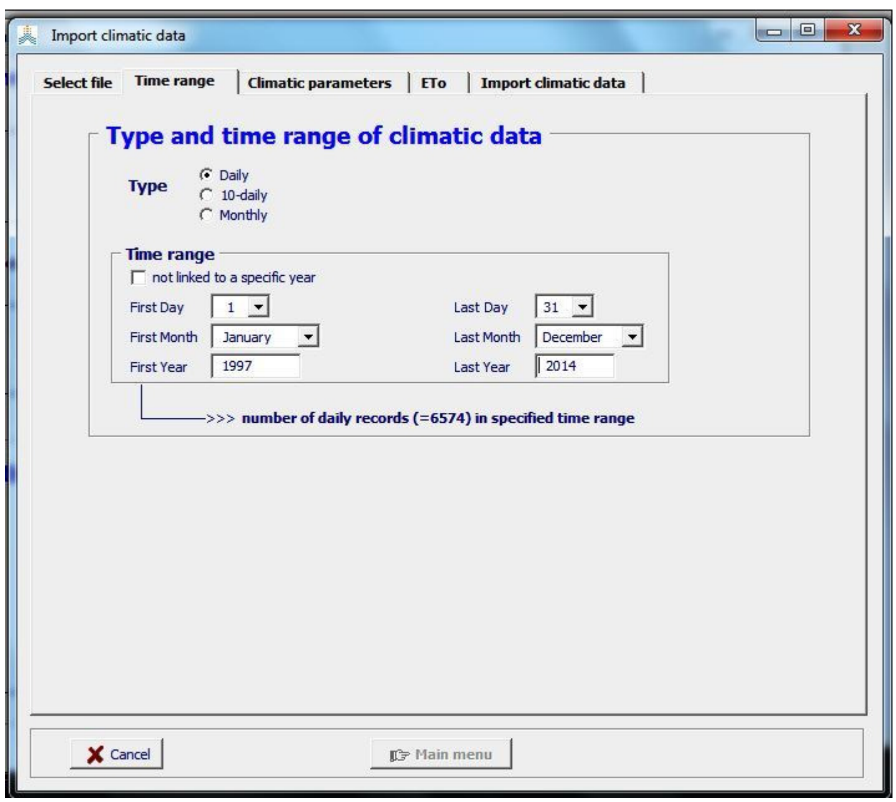
- the number of data lines (rows), which corresponds with the number of days, 10-day’s or months in the time range (from-to) covering the climatic data;
- the number of columns of the text file, which corresponds with the number of climatic parameters available in the text file.

In the example displayed in Figure 1.3, the ‘LosBanos1997_2014.txt’ file has been selected, which contains 6,574 lines and 7 columns with climatic data (i.e. a long record of daily climatic data as specified in Tab. 1.2). The time range and climatic parameters are specified respectively in the ‘Time range’ and ‘Climatic parameters’ tabular sheets.

1.3.2 Tabular sheet: ‘Time range’

In the tabular sheet ‘Time range’ (Fig. 1.4), the user specifies the Type of data (daily, 10-daily or monthly) and the Time range (from date - to date). If the climatic data consists of averages of several years, the data should not be linked to a specific year and the year has not to be specified (Fig 1.4b).

(a)



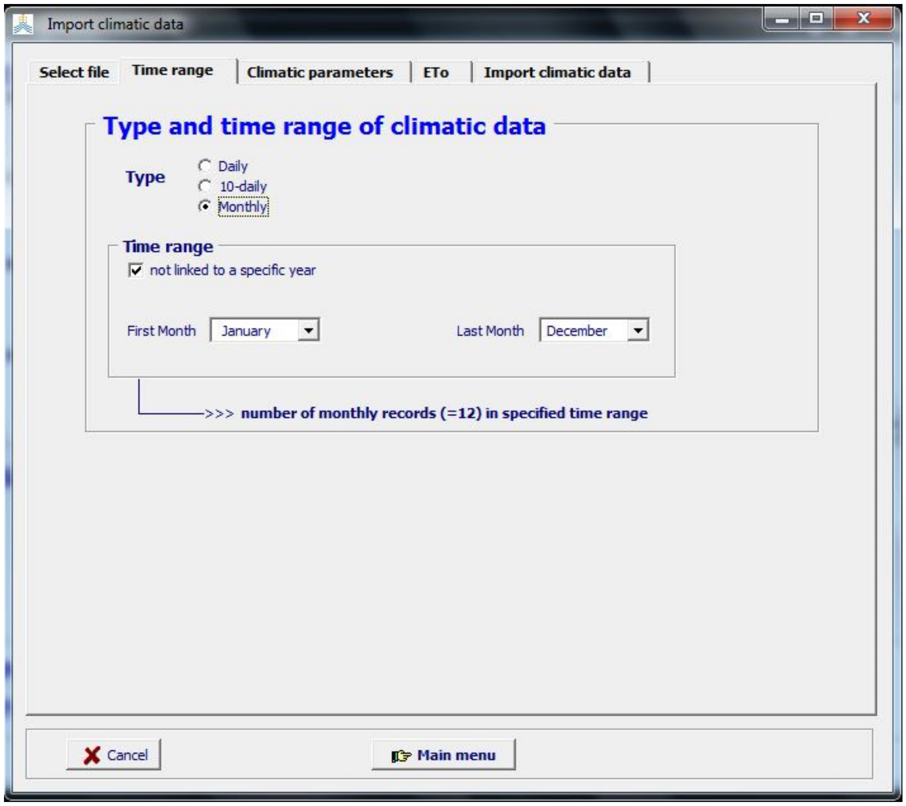
(b)	

Figure 1.4 – The 'Time range' tabular sheet of the *Import climatic data* menu. It is the time range for (a) 'LosBanos1997_2014.txt' (containing a long record of daily data) and (b) 'EldoretMM.txt' containing mean monthly data.

By adjusting the time range in the tabular sheet, the program displays the corresponding number of data records within this range. The number of records should match with the number of rows of the text file containing the meteorological data:

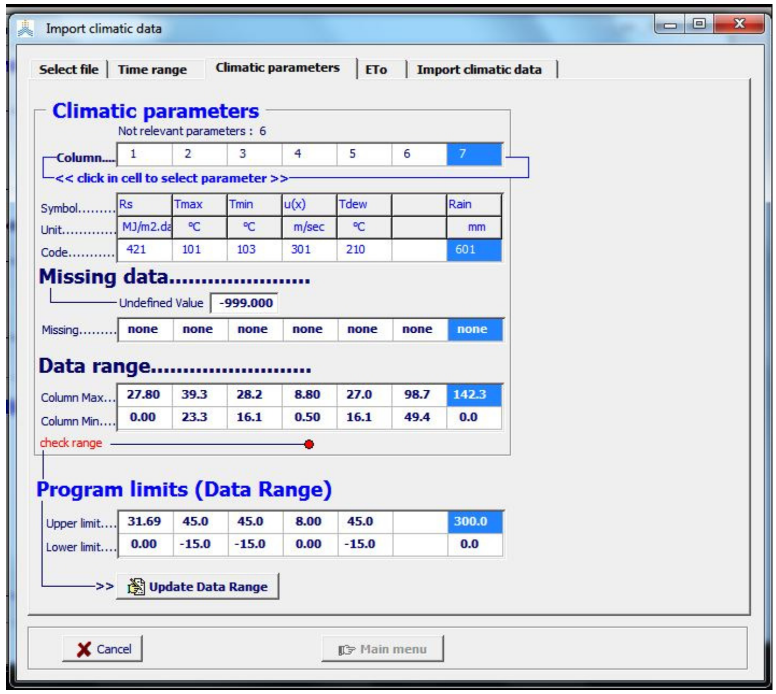
- Fig. 1.4a: This is the example of the selected 'LosBanos1997_2014.txt' file with its 6,574 lines in Fig. 1.3. There are indeed 6,574 days between the specified start (1 January 1997) and end (31 December 2014) of the time range;
- Fig. 1.4b: This the example for the 'ElodretMM.txt' file, containing mean monthly data. The climatic data, which is not linked to a specific year, are specified in 12 monthly records.

If the number of records does not match with the number of rows in the text file, a warning ('Adjust time range') is displayed and the climatic data cannot be imported

1.3.3 Tabular sheet: 'Climatic parameters'

In the tabular sheet 'Climatic parameters' (Fig. 1.5) the user specifies the climatic parameters and its units, of the data stored in the respectively columns.

(a)



(b)

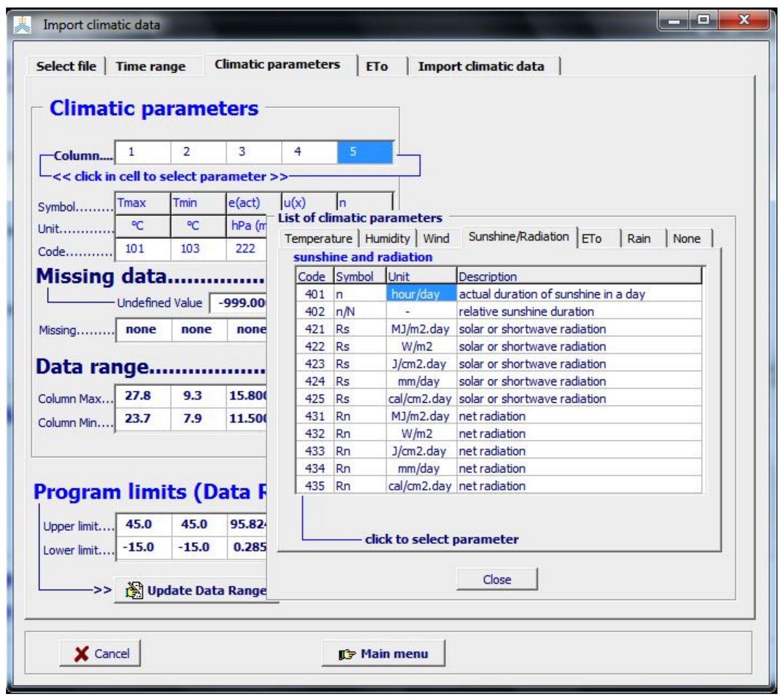


Figure 1.5 – The 'Climatic parameters' tabular sheet of the *Import climatic data* menu for (a) 'LosBanos1997_2014.txt' (containing daily data as specified in Tab. 1.2 and (b) 'EldoretMM.txt' containing mean monthly data (maximum and minimum temperature, actual vapour pressure (mbar), wind speed at 2 m.a.s.l. and hours of bright sunshine).

By clicking in a cell of a column, a list pops up containing the climatic parameters which are recognized by AquaCrop. As listed in Table 1.1, the parameters are stored in 6 folders grouping them in ‘air Temperature’, ‘air Humidity’, ‘Wind speed’, ‘Sunshine/Radiation’, ‘ETo’, and ‘Rain’ data. An additional seventh folder ‘None’ is available, to specify that the column contains not relevant data. If one or more columns of the text file contain a not relevant parameter, the user can decide not to specify explicitly the parameter (as is the case for column 6 in the example of Fig. 1.5a), or select ‘not relevant parameter’ from the ‘None’ folder. In both cases the data in the column is disregarded and not available for import.

When a climatic parameter is specified for a column, the program displays:

- the **Symbol, Unit and program Code** of the selected climatic parameter;
- the **number of Missing data** in each of the columns of the text file;
  The default value (-999.000) for undefined value will be used to identify missing data. The default value can be adjusted to the undefined value used in the specific text file;
  Procedures are available in AquaCrop to estimate ETo with missing air humidity, radiation, sunshine and/or wind speed data. Such procedures are not available to estimate missing minimum and maximum air temperature data, rainfall data and direct imported ETo data. As such records with missing Tmax, Tmin, Rain and ETo data cannot be imported if they contain missing values;
- the **Data range** (minimum and maximum value) for the selected climatic parameter as found in the text file. These should be within the program limits. If the program limits are smaller than the detected data range the data cannot be imported by the program (as wind speed at 10 meter above ground level (column 4) in Fig. 1.5a);
- the **Program limits** (upper and lower limit) used by the program for each of the selected climatic parameters. This feature allows for a range check of the imported data. If the user believes that the program limits are too narrowly or too broadly set, the user can alter the limits in the ***Limits of climatic data*** menu (Fig. 1.6). This menu is displayed by clicking on the **<Update Data Range>** command key at the bottom of in the ‘Climatic parameters’ tabular sheet.

1.3.4 Limits of climatic data menu

The ***Limits of climatic data*** menu (Fig. 1.6) contains the data range (lower and upper limit) assigned by the program to the various climatic parameters. The limits can be adjusted to obtain a more refined or flexible range check of the imported climatic data. The limits differ with the units in which the climatic parameters are expressed.

Upper limit for rainfall data:

Since AquaCrop considers total rainfall, the upper limit for rainfall data differs with the type of rainfall data (daily, 10-daily or monthly values). The default values for the upper limit for rainfall data are 300 mm/day, 1,000 mm/10-day and 2,000 mm/month.

Limits for air temperature, relative humidity and vapour pressure:

The limits for air temperature, relative humidity and vapour pressure are linked. Changing the limits for one parameter will alter the limits for the linked climatic parameters:

Lower limit for $e_a \geq e°(T_{min}) \frac{RH_{min}}{100}$

Upper limit for $e_a \leq e°(T_{max})$

where e_a actual vapour pressure [kPa],
$e°(T_{min})$ saturation vapour pressure at daily minimum temperature [kPa],
$e°(T_{max})$ saturation vapour pressure at daily maximum temperature [kPa],
RH_{min} minimum relative humidity [%].

The default program limits for air temperature are from -15°C up to 45 °C.
The default program limits for relative humidity are from 15% up to 100%.

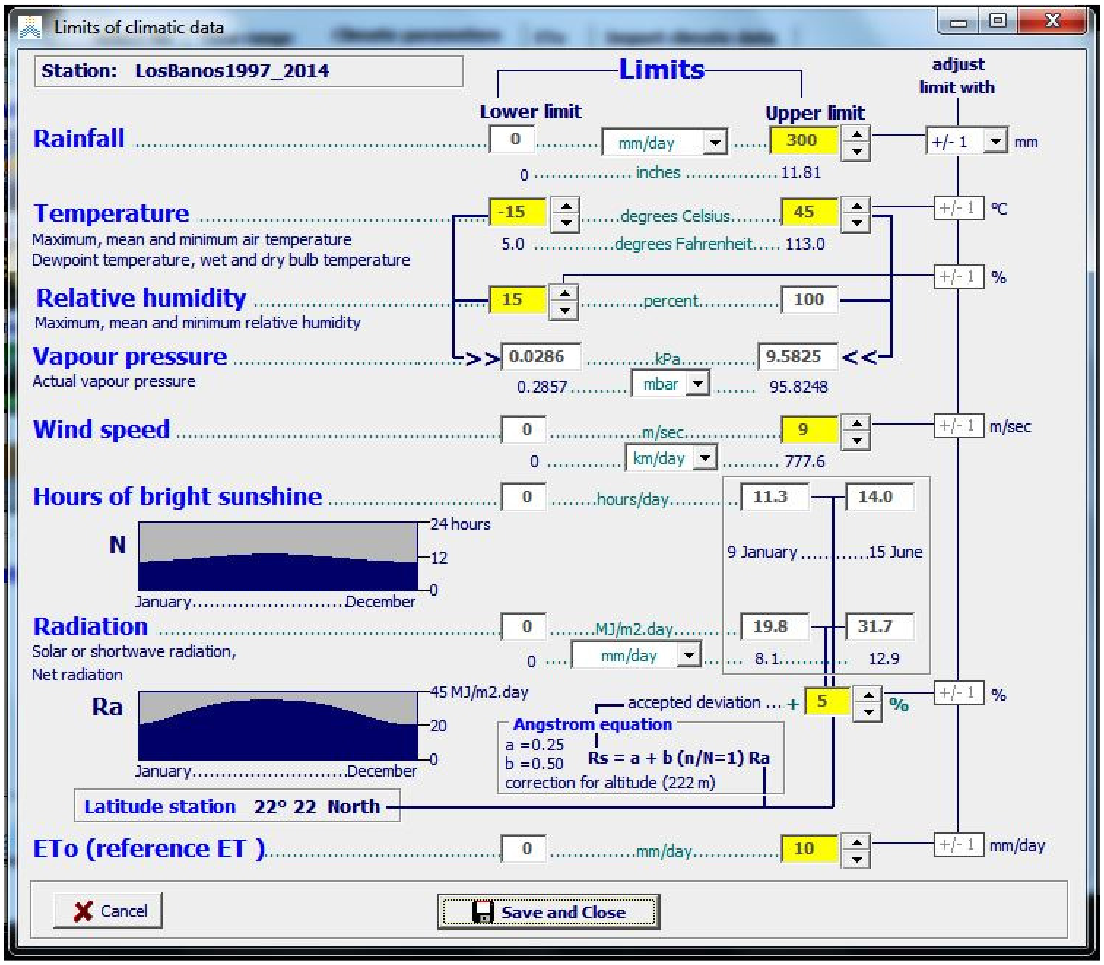


Figure 1.6 – The *Limits of climatic data* menu
with in yellow (shaded edit fields) the upper and lower limits that can be adjusted.

Upper limit for wind speed:
Daily, 10-daily and monthly wind speed are always expressed as the average daily value in m/sec. The default value for the upper limit is 8 m/sec. In Fig. 1.6, the upper limit was increased to 9 m/sec by considering that the wind speed was measured at 10 meter above ground level instead of the standard 2 meter.

Upper limits for sunshine and radiation data:
The latitude of the station and the time of the year determine the maximum hours of bright sunshine or day length (N) and the extra-terrestrial radiation (Ra). This put a limit on the maximum value one can observe on a particular day for the actual hours of bright sunshine (n), the solar (Rs) and net (Rn) radiation. However a degree of over-estimation, that the user still finds acceptable, is allowed. The default value for the acceptable deviation is 5%.

The latitude and altitude are specified in the 'ETo' tabular sheet of the ***Import climatic data*** menu (Fig. 1.7).

Upper limit for direct imported ETo values:
Daily, 10-daily and monthly ETo are always expressed in AquaCrop as the average daily value. When importing 10-day or monthly data, the mean daily ETo (mm/day) of the 10-day period or month should be specified. The default value for the upper limit is 10 mm/day.

1.3.5 Tabular sheet: 'ETo'

If sufficient data is available to estimate ETo with the imported climatic data, extra information required for its calculation is specified in the tabular sheet 'ETo' (Fig. 1.7). The required information consists of:

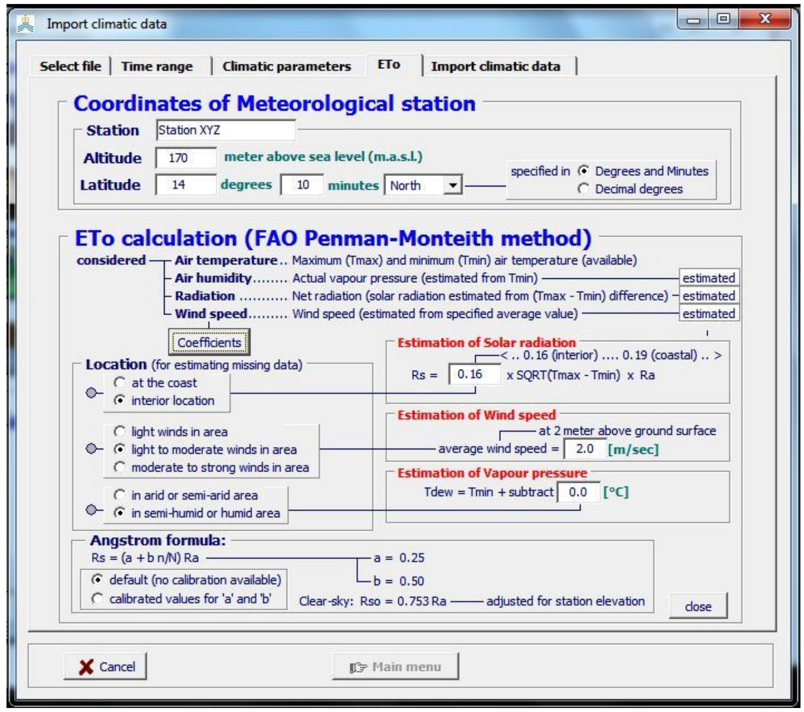
- **Coordinates of the meteorological station** (Altitude and Latitude). They are required for the calculation of the psychrometric constant (γ), extra-terrestrial radiation (Ra) and maximum hours of bright sunshine or day length (N).
  As long as the Altitude and Latitude are identical to their default settings (i.e. 222 m.a.s.l. and 22°22' N), a warning to 'adjust the coordinates' is displayed and the climatic data cannot be imported for ETo calculation;
- **Coefficients required to estimate ETo when solar radiation, wind speed and/or air humidity data are missing**. Default values are assigned to the coefficients by specifying the 'Location' of the meteorological station by means of the radio buttons (Fig. 1.7a);
- **Coefficients of the Angstrom formula** for the calculation of solar radiation if different from the default setting.

Calculation of ETo:
ETo is calculated with the FAO Penman-Monteith method according to the calculation procedures outlined in the FAO Irrigation and Drainage paper Nr. 56 (Allen et al. 1998). The calculation procedures and conversion rules to standard metric unit are given in Annex 1.

To compute ETo, (i) air temperature, (ii) air humidity, (iii) radiation and (iv) wind speed data are required. In the 'ETo' tabular sheet the climatic data considered for its calculation are displayed (Fig. 1.7):

- Fig. 1.7a: for station XYZ, only Tmin and Tmax are available. The required vapour pressure will be estimated from Tmin, and the required solar radiation, will be estimated from the (Tmax-Tmin) difference. For wind speed, the specified average wind speed value will be used;
- Fig. 1.7b: for 'EldoretMM.txt' (a text file with mean monthly data as specified in Fig. 1.5) the required vapour pressure and wind speed are available as direct input (columns 3 and 4). The solar radiation will be derived from the available hours of bright sunshine (column 5) with the Angstrom formula.

(a)



(b)

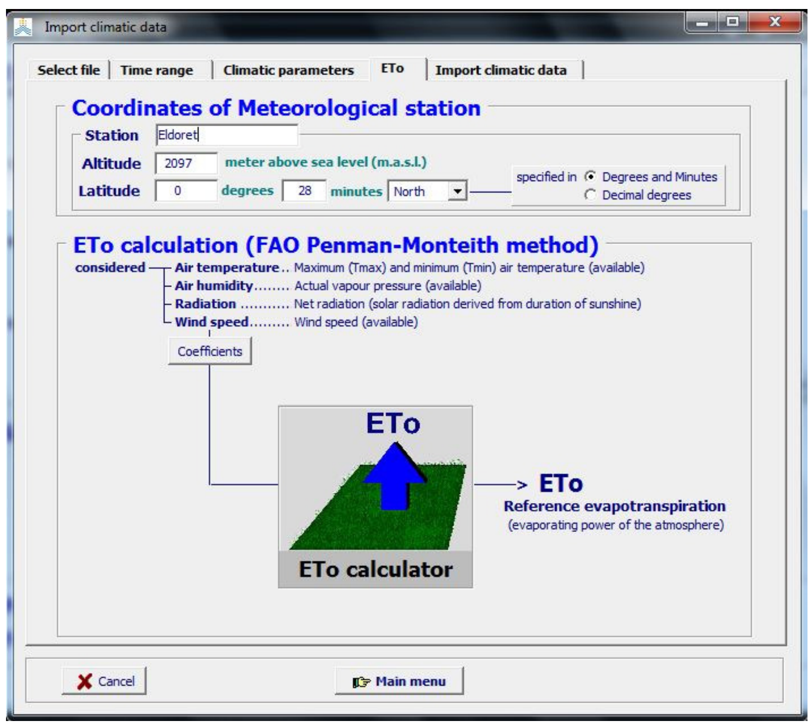


Figure 1.7 – The 'ETo' tabular sheet of the *Import climatic data* menu for (a) station XYZ with only maximum and minimum air temperature and (b) 'EldoretMM.txt' containing mean monthly data as specified in Fig. 1.5.

Coefficients required to estimate ETo when solar radiation, wind speed and/or air humidity data are missing:
Calculation procedures as outlined in the FAO Irrigation and Drainage paper Nr. 56 are used to estimate missing radiation, wind speed and air humidity data:

- The temperature difference method (using the square root of the difference between the maximum and minimum air temperature) is used to estimate **missing solar radiation** (Rs). The adjustment coefficient (k_{Rs}) is empirical and differs for 'interior' or 'coastal' regions.
  In the absence of a calibrated k_{Rs} value, the default values for coastal (0.19) and interior (0.16) locations can be used by selecting the appropriate radio button for the Location of the meteorological station (Fig. 1.7a: 'at the coast' or 'interior location');
- In the case of **missing wind speed**, a general class of average wind speed can be entered by specifying a general value in the Edit field or by selecting an appropriate radio button for the location of the meteorological station (Fig. 1.7a). The default value for wind speed in a region with 'light winds' is 0.5 m/sec. If the wind speed in the area is 'light to moderate', 2 m/sec is considered as default, and when the regional wind speed is 'moderate to strong', the default value becomes 4 m/sec;
- Where **humidity data are lacking** or are of questionable quality, an estimate of actual vapour pressure can be obtained by assuming that dewpoint temperature (Tdew) is near the daily minimum air temperature (Tmin). The relationships Tdew ≈ Tmin holds for humid and sub-humid locations. For arid regions, the air might not be saturated when its temperature is at its minimum. In these situations, Tdew might be better approximated by subtracting 2 up to 3°C from Tmin. In the absence of a calibration, the default values for the region can be used by selecting the appropriate radio button for the location of the meteorological station (Fig. 1.7a: 'in arid or semi-arid area' or 'in semi-humid or humid area'). The default value that will be subtracted from Tmin are 2 °C for (semi-)arid and 0 °C for (semi-)humid areas.

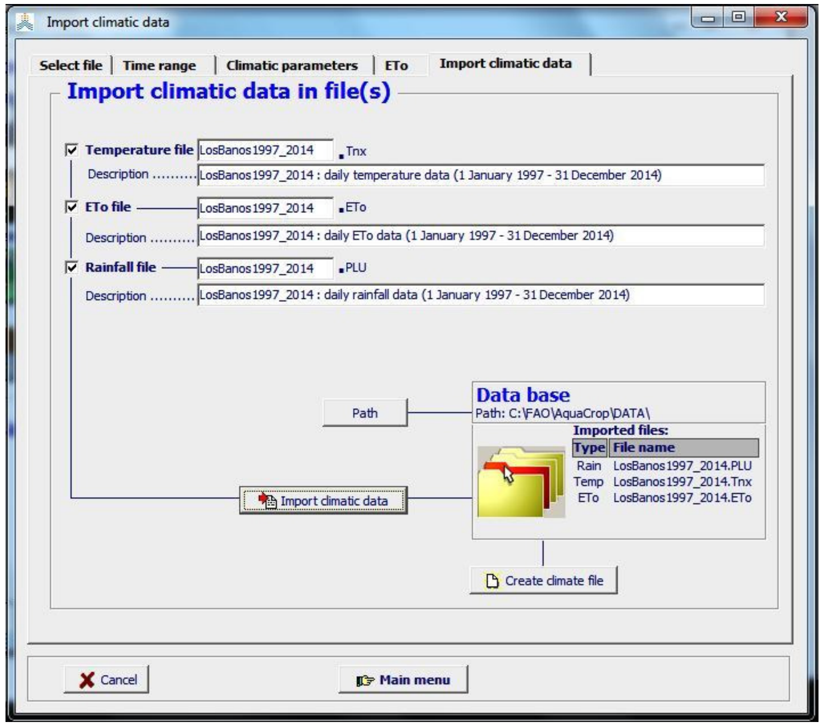
Coefficients of the Angstrom formula:
When net radiation (Rn) is not specified, AquaCrop use the Angstrom formula in the ETo calculation to estimate incoming solar radiation (Rs). When no calibration has been carried out for improved 'a' and 'b' constants of the formula, the default values (a = 0.25 and b = 0.50) are recommended. To estimate outgoing long wave radiation the ratio between the incoming solar radiation (Rs) and the clear sky solar radiation (Rso) is required. The adjustment for station elevation in the calculation of Rso, is recommended. If calibrated values for 'a' and 'b' are available they can be specified in the 'ETo' tabular sheet by selecting the 'calibrated values for 'a' and 'b'' radio button (Fig. 1.7a).

1.3.6 Tabular sheet: 'Import climatic data'

In the tabular sheet 'Import climatic data' (Fig. 1.8), the user can adjust:

- The folder in which the files with climatic data needs to be stored. By selecting the **<Path>** command key, the user can alter the directory from its default path which is the 'DATA' subdirectory of the AquaCrop folder;
- The default specified 'File Name' and 'Description' of the Temperature (file with extension 'Tnx'), ETo (extension 'ETo'), and Rainfall file (extension 'PLU').

(a)



(b)

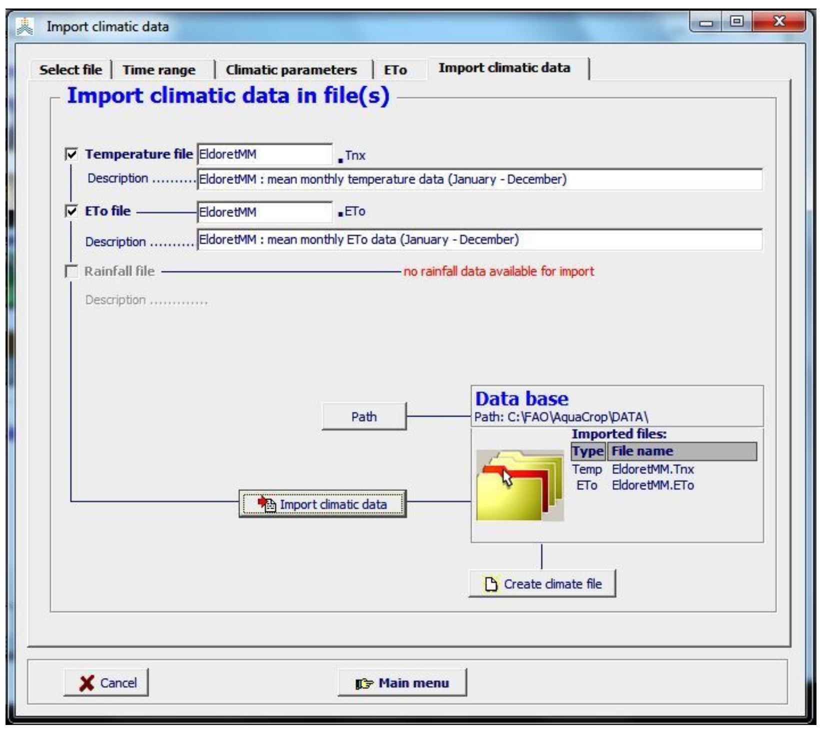


Figure 1.8 – The 'Import climatic data' tabular sheet of the *Import climatic data* menu for (a) 'LosBanos1997_2014.txt' (containing a long record of daily data as specified in Tab. 1.2) and (b) 'EldoretMM.txt' containing mean monthly data as specified in Fig.1.5.

Temperature files (files with extension 'Tnx'), ETo files (with extension 'ETo') and Rainfall files (with extension 'PLU'):
Temperature, ETo and Rainfall files can only be created if (i) the Time range is well set, (ii) sufficient climatic data is available, (iii) the climatic data is within the program limits, and (iv) the coordinates of the meteorological station are adjusted (only required when ETo is calculated):

- Fig. 1.8a: for 'LosBanos1997_2014.txt' (a text file containing a long record of daily data as specified in Tab. 1.2), a temperature file ('LosBanos1997_2014.Tnx' containing the imported daily Tmin and Tmax values), an ETo file ('LosBanos1997_2014.ETo' containing calculated daily ETo estimates by considering measured minimum and maximum air temperature, dew point temperature, solar radiation and wind speed), and a rainfall file ('LosBanos1997_2014.PLU' containing the imported daily rainfall data) could be created and were imported (since selected) in the data base;
- Fig. 1.8b: for 'EldoretMM.txt' (a text file with mean monthly data as specified in Fig. 1.5), a temperature file ('EldoretMM.Tnx' containing the imported mean monthly Tmin and Tmax values), and an ETo file ('EldoretMM.ETo' containing the calculated mean monthly ETo values) could be created. In Fig. 1.8b the 'EldoretMM.Tnx' and 'EldoretMM.ETo' file were selected for import. Due to missing rainfall data, a rainfall file cannot be created, and data cannot be imported.

Covering climate file (file with extension 'CLI'):
Once data has been imported in the data base, a covering climate file can be created, by selecting the **<Create climate file>** command in the 'Import climatic data' tabular-sheet of the ***Import climatic data*** menu (Fig. 1.8) or by selecting the 'Create climate file' option in the ***Select climatic file*** menu (Fig. 1.2).

1.4 Create climate file

Once climatic data has been imported, a covering climate file (file with extension 'CLI') can always be created by selecting the option 'Create climate file' in the ***Select climatic file*** menu (Fig. 1.2), or the **<Create climate file>** command in the 'Import climatic data' tabular-sheet of the ***Import climatic data*** menu (Fig. 1.8).

With reference to the climatic data imported from the 'LosBanos1997_2014.txt' (a text file containing a long record of daily data as specified in Table 1.2), an example for the creation of the covering climate file 'LosBanos1997_2014.CLI' is given in Fig. 1.9. It contains:

- the 'LosBanos1997_2014.PLU' file: with the daily imported rainfall data from the 'LosBanos1997_2014.txt' file;
- the 'LosBanos1997_2014.ETo' file: with daily ETo estimates calculated with the FAO Penman-Monteith method, from the maximum and minimum air temperature, dewpoint temperature, wind speed and solar radiation data as specified in 'LosBanos1997_2014.txt';
- the 'LosBanos1997_2014.Tnx' file: with the daily imported minimum and maximum air temperature data from the 'LosBanos1997_2014.txt' file;
- the (default) 'MaunaLoa.CO2' file.

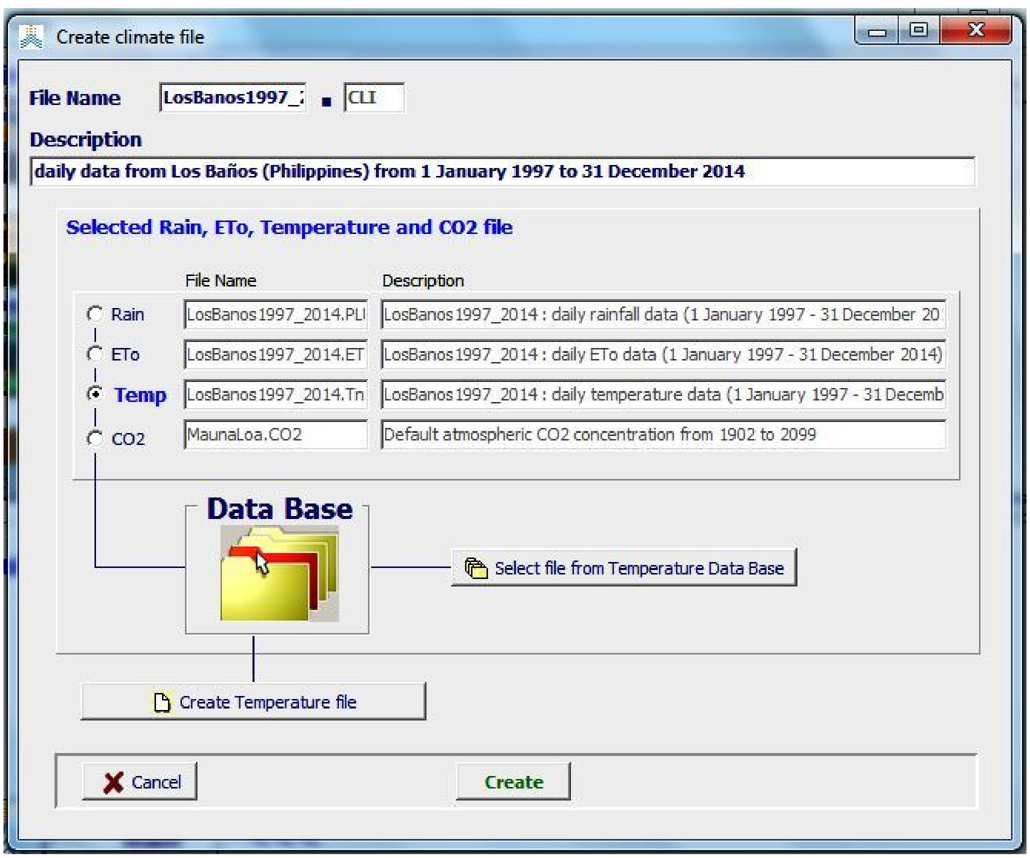
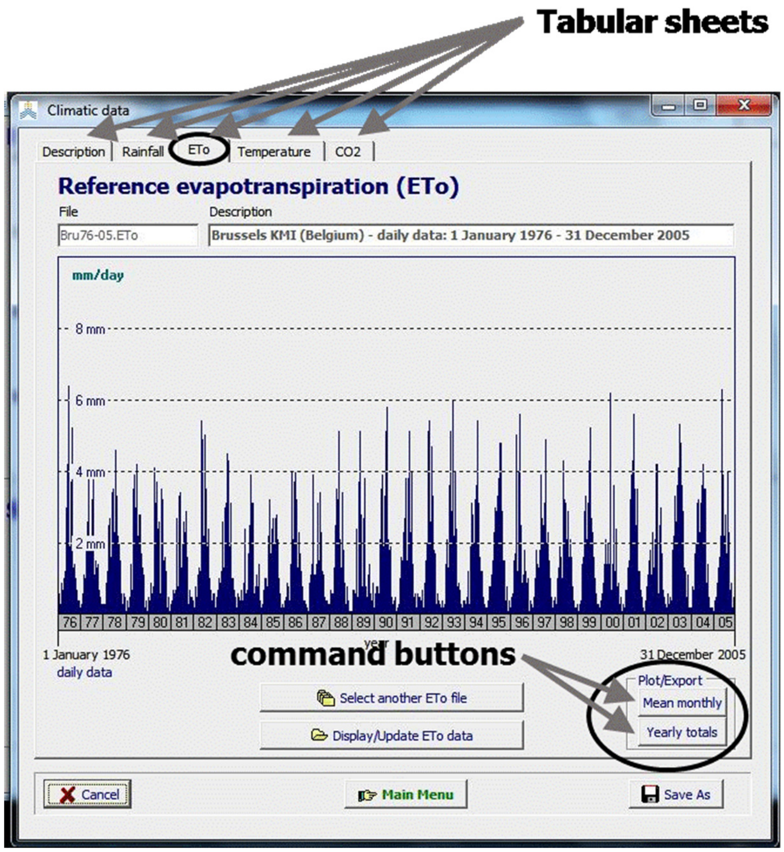


Figure 1.9 – Creating a covering climate file ('LosBanos1997_2014.CLI') for imported climatic data from the 'LosBanos1997_2014.txt' file.

2. Aggregation of climatic data

In the ***Climatic data*** and the ***Display of climate characteristics*** menus, mean monthly and yearly totals of climatic data can be plotted, by selecting one of the commands in the lower right corner of the Rainfall, ETo or Temperature tabular sheet (Fig. 2.1, Table 2.1). The data help to evaluate the climatic conditions in which the crop is cultivated.



Figurer 2.1 – Command buttons in the lower right corner of the 'ETo' tabular sheet of the *Climatic data* menu, to plot mean monthly and yearly totals

Table 2.1 – Command buttons available in the lower right corner of the tabular sheets of the *Climatic data* and the *Display of climate characteristics* menus

Tabular sheet	Command buttons	Description
Rainfall	– Mean monthly (with the option to display rainfall with or without mean ETo) – Yearly totals	Plot of • mean monthly rainfall, • mean monthly rainfall, ETo and half of ETo, (Fig. 2.2), • total yearly rainfall (Fig. 2.3) within the period of available climatic data;
ETo	– Mean monthly (with the option to display as 'mm/day' or 'mm/month')	Plot of • mean monthly ETo (mm/day) (Fig. 2.4),

	– Yearly totals	• mean monthly ETo (mm/month), • total yearly ETo within the period of available climatic data
Temperature	– Mean monthly (with the option to display as growing degree-days) – Yearly values (with the option to display as growing degree days)	Plot of • mean monthly air temperatures (Fig. 2.5), • monthly growing degree-days (2.6), • mean yearly air temperatures, • total yearly growing degree-days (Fig. 2.7) within the period of available climatic data. When the data is displayed as growing degree-days, the base and upper temperatures for crop development for the selected crop are considered

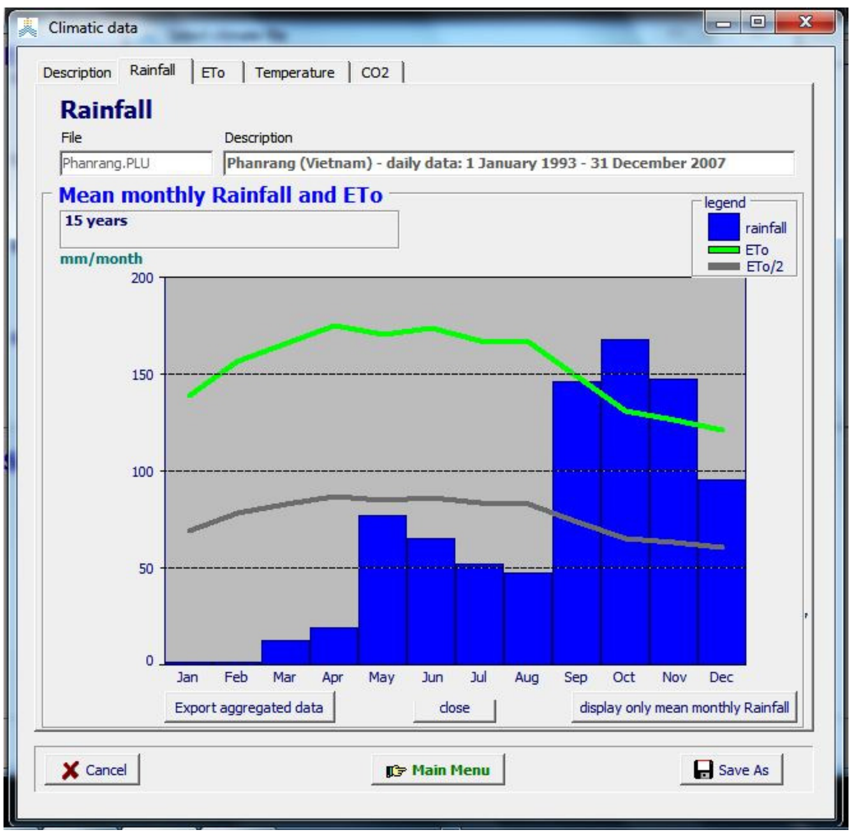


Figure 2.2 – Mean monthly Rainfall and ETo in Phanrang (Vietnam) for the 1993 – 2007 period in the 'Rainfall' tabular sheet of the *Climatic data* menu

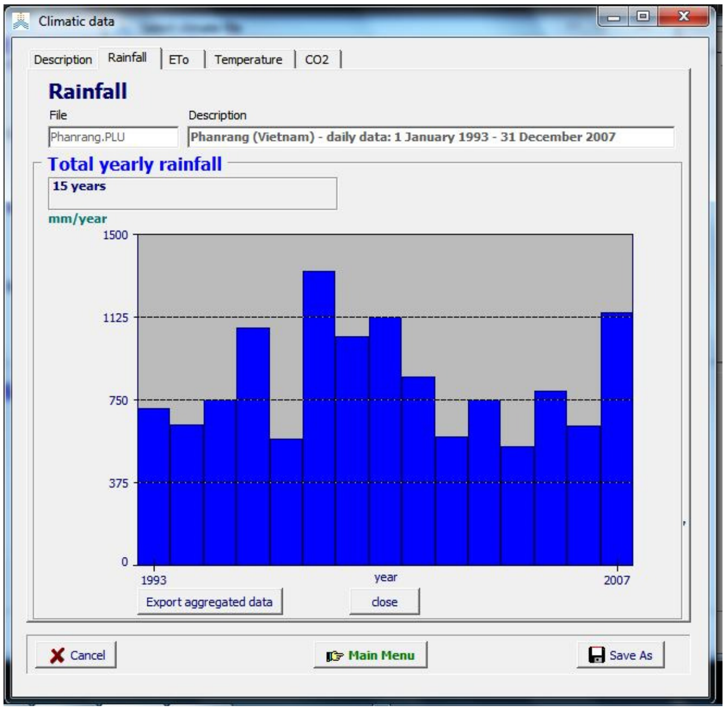


Figure 2.3 – Total yearly rainfall in Phanrang (Vietnam) for the 1993 – 2007 period in the 'Rainfall' tabular sheet of the *Climatic data* menu

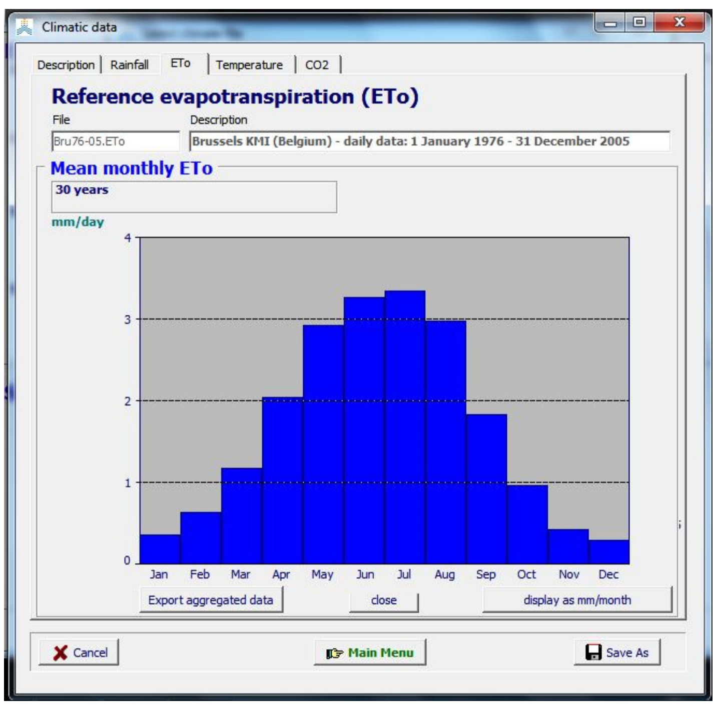


Figure 2.4 – Mean monthly ETo in Brussels (Belgium) for the 1976 – 2005 period in the 'ETo' tabular sheet of the *Climatic data* menu

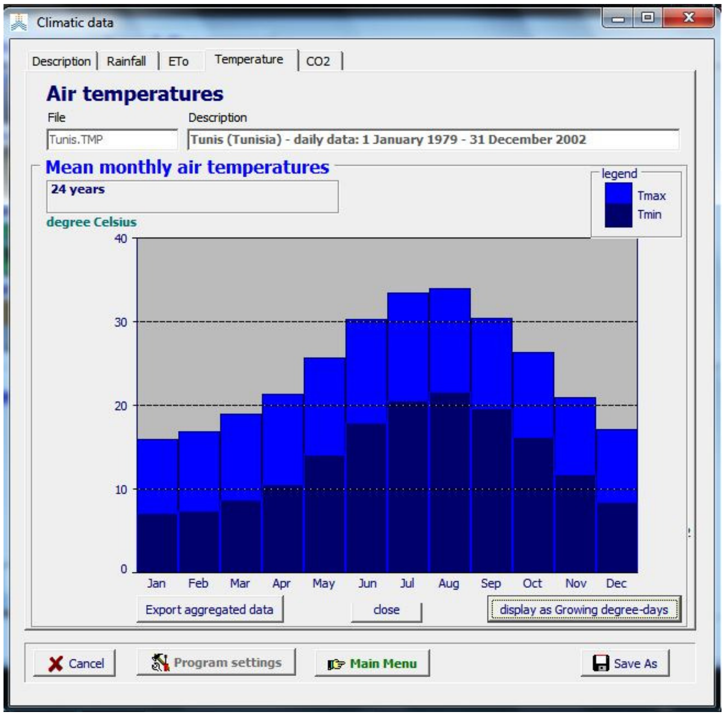


Figure 2.5 – Mean monthly air temperatures in Tunis (Tunisia) for the 1979 – 2002 period in the 'Temperature' tabular sheet of the *Climatic data* menu

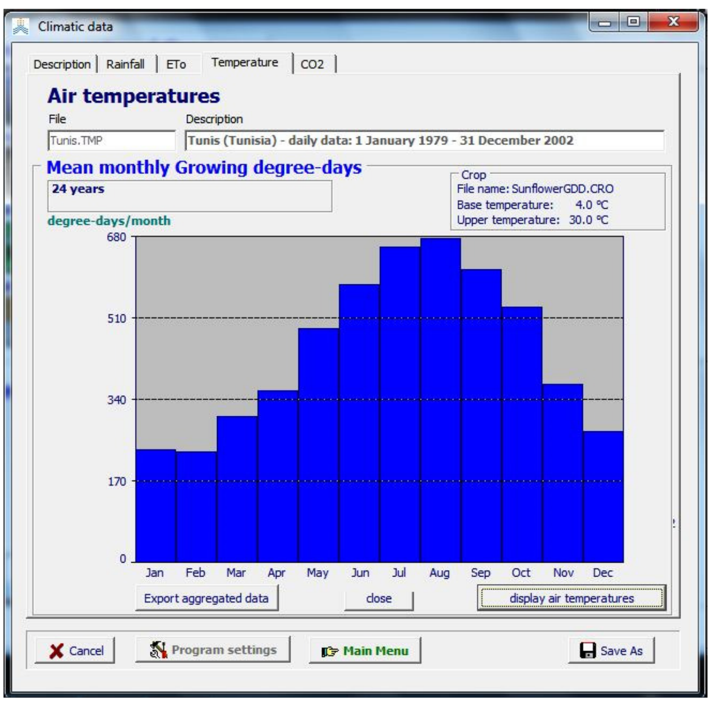
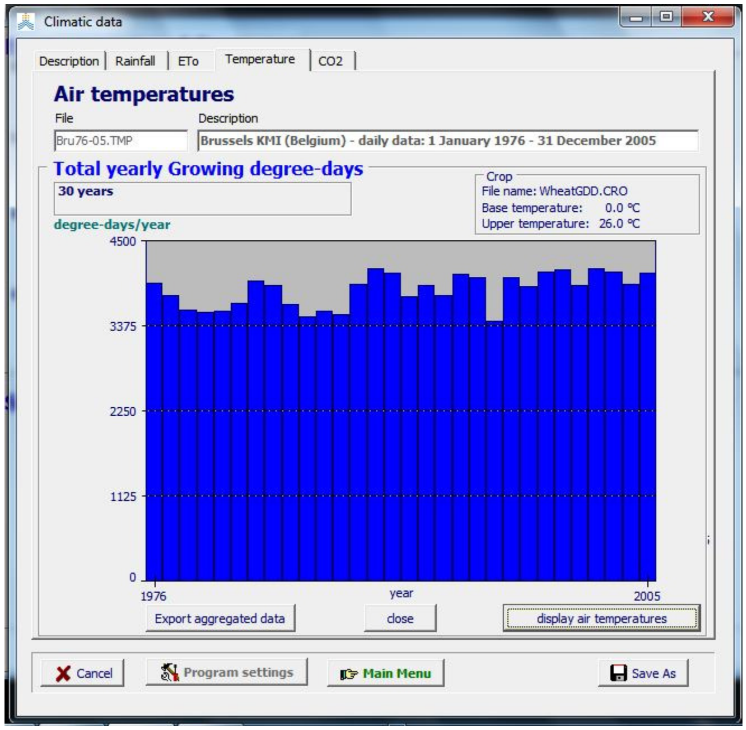


Figure 2.6 – Mean monthly Growing degree-days for a crop with a base temperature for crop development of 4 °C and an upper temperature of 30 °C, in Tunis (Tunisia) for the 1979 – 2002 period in the 'Temperature' tabular sheet of the *Climatic data* menu



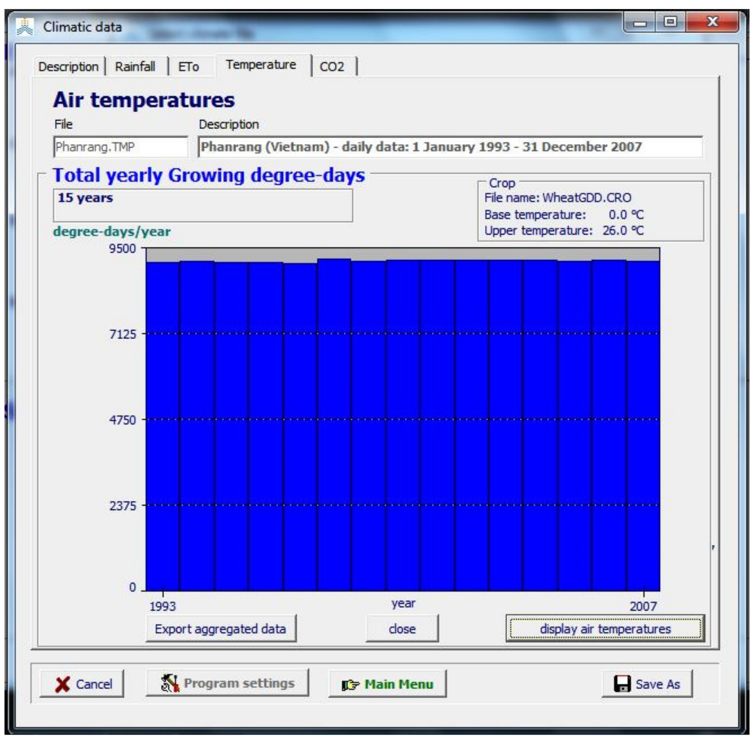


Figure 2.7 – Total yearly Growing degree-days for a crop with a base temperature for crop development of 0 °C and an upper temperature of 26 °C, as displayed in the 'Temperature' tabular sheet of the *Climatic data* menu for (top) Brussels (Belgium) for the 1976 - 2005 period, and (bottom) Phanrang (Vietnam) for the 1993 – 2007 period

The mean monthly and yearly totals of rainfall, ETo, air temperatures and growing degree-days can be exported for further analysis (e.g. frequency analysis) via the 'Export aggregated data' command at the lower left corner of the box in which mean monthly and yearly totals are displayed (Fig. 2.2 to 2.7). In the ***Export aggregated climatic data*** menu, the data to be exported, the name of the files containing the aggregated data, and the path are specified (Fig. 2.8). By default the output is saved in the OUTP directory of AquaCrop.

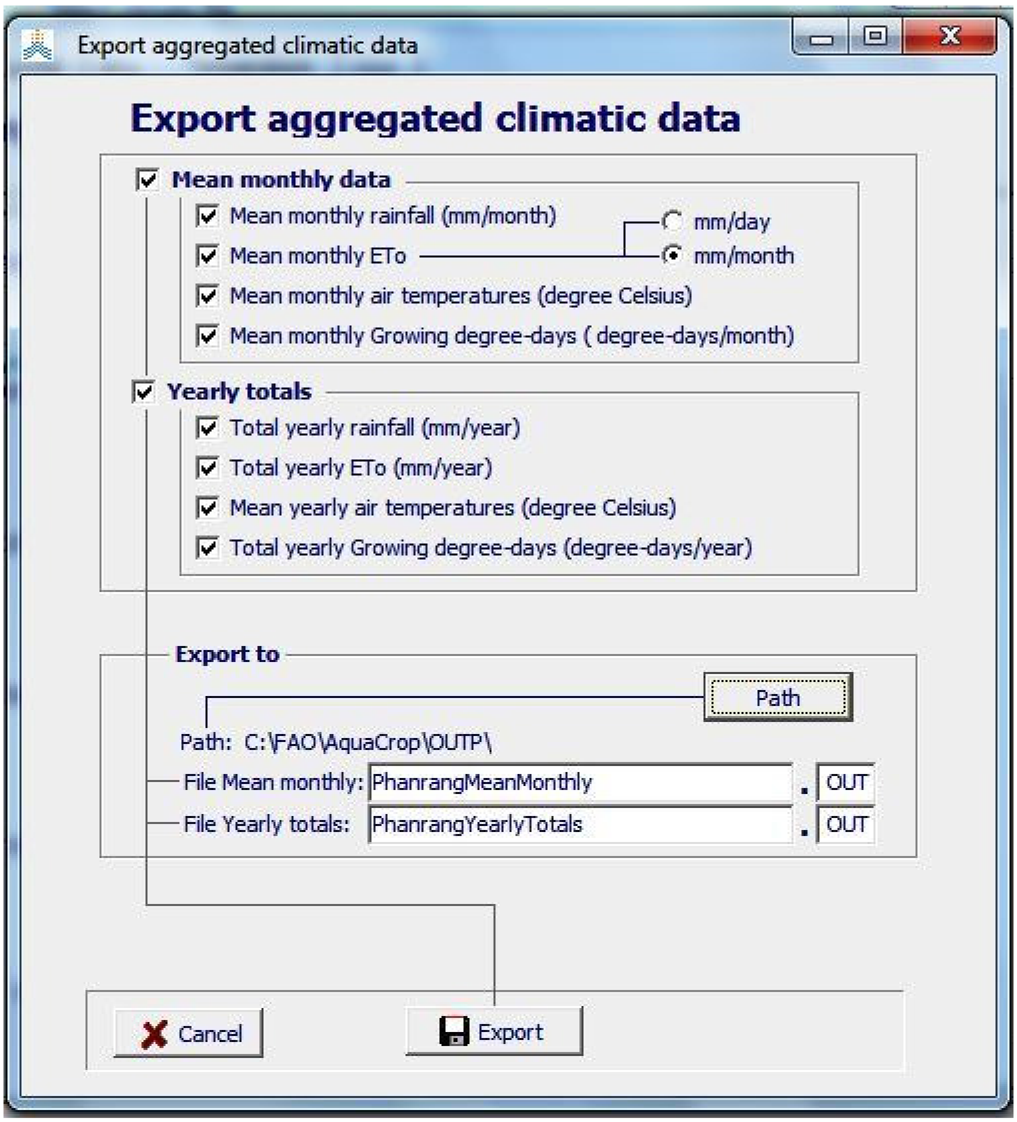


Figure 2.8 – The *Export aggregated climatic data* menu

3. Extension of air temperature files becomes '.Tnx'

To avoid confusion between the air temperature files in AquaCrop and Windows temporary files (both files have the extension '.TMP'), the extension of air temperature files in AquaCrop is changed from '.TMP' to '.Tnx'. Due to restrictions in the transfer of Windows temporary files between computers, sending AquaCrop air temperature files with extension '.TMP' as attachment in e-mails, was not possible.

In version 5.0, newly created air temperature files in AquaCrop get automatically the extension '.Tnx'. Nevertheless, previously created air temperature files with extension '.TMP' can still be used in AquaCrop. Files with extension '.TMP' or '.Tnx' in the data base of AquaCrop can be used and are recognized as air temperature files (Fig. 3.1).

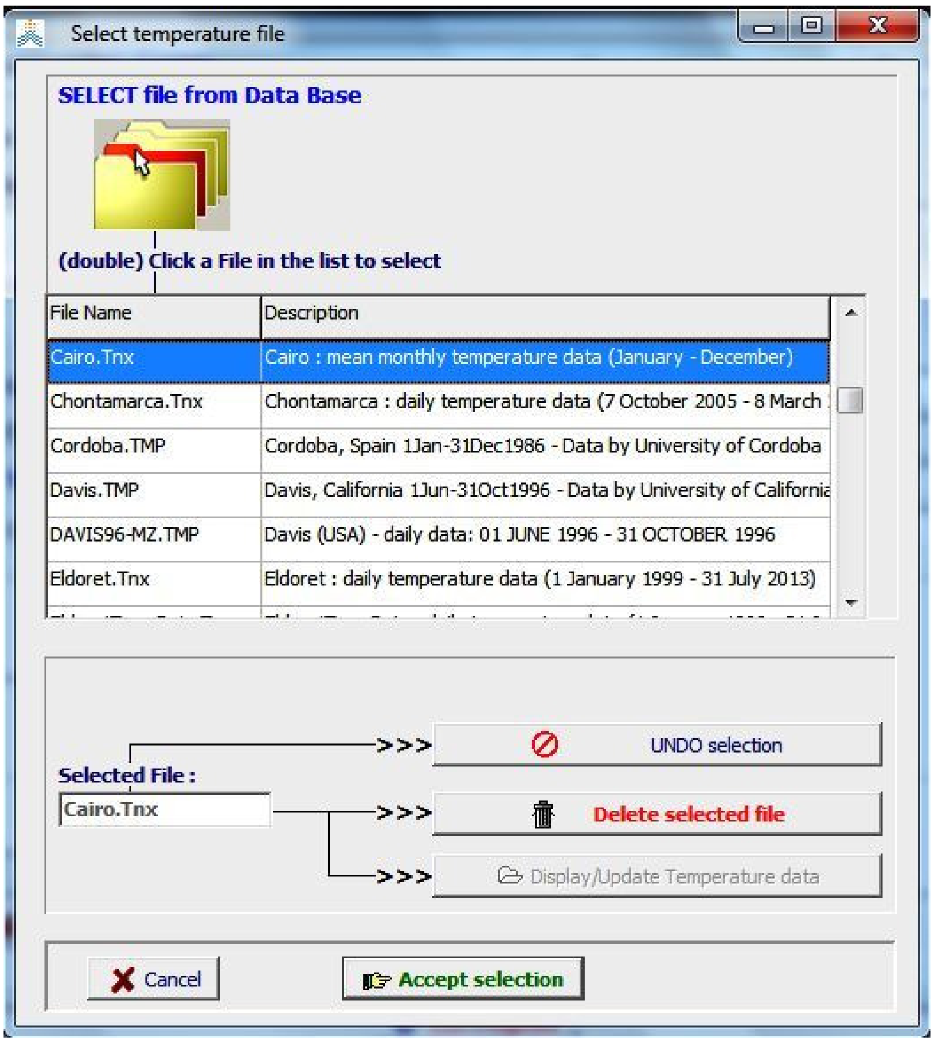


Figure 3.1 – *Select temperature file* menu in which air temperature files with extension '.Tnx' or '.TMP' can be selected

4. Update of CO2 files

4.1 MaunaLoa.CO2

The annual mean concentrations of CO_2 measured at the Mauna Loa Observatory are available in the 'MaunaLoa.CO2' file in the SIMUL subdirectory of AquaCrop (Tab. 4.1). 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 2.0 ppm is still assumed, which might be valid for the next decade. The observed CO_2 concentrations till 2013 were updated with the latest published results on the NOAA website: http://co2now.org/Current-CO2/CO2-Now/noaa-mauna-loa-co2-data.html

Table 4.1 – The default CO_2 concentrations in ppm in the MaunaLoa.CO2 file

Year	Annual Mean [CO_2]	Year	Annual Mean [CO_2]	Year	Annual Mean [CO_2]
1902	297.40	1966	321.37	1991	355.48
1905	298.20	1967	322.18	1992	356.27
1912	300.70	1968	323.05	1993	356.95
1915	301.30	1969	324.62	1994	358.63
1924	304.50	1970	325.68	1995	360.62
1926	305.00	1971	326.32	1996	362.37
1929	305.20	1972	327.46	1997	363.47
1932	307.80	1973	329.68	1998	366.5
1934	309.20	1974	330.17	1999	368.14
1936	307.90	1975	331.08	2000	369.41
1938	310.50	1976	332.06	2001	371.13
1939	310.10	1977	333.78	2002	373.22
1940	310.50	1978	335.4	2003	375.77
1944	309.70	1979	336.78	2004	377.49
1948	310.70	1980	338.7	2005	379.80
1953	311.90	1981	340.11	2006	381.90
1954	314.10	1982	341.22	2007	383.77
1958	315.29	1983	342.84	2008	385.59
1959	315.98	1984	344.4	2009	387.37
1960	316.91	1985	345.87	2010	389.85
1961	317.65	1986	347.19	2011	391.63
1962	318.45	1987	348.98	2012	393.82
1963	318.99	1988	351.45	2013	396.48
1964	319.61	1989	352.89	2014	398.55
1965	320.03	1990	354.16	2020	410.55
				2099	568.55

4.2 CO2 files for future years

For crop yield estimates for future years, other CO2 files from SRES (Special Report on Emissions Scenarios), containing data derived from emissions scenarios are available in the DATA subdirectory of AquaCrop ('A1B.CO2', 'A2.CO2', 'B1.CO2' and 'B2.CO2'). The CO_2 projections presented in those files assume different socio-economic storylines.

Next to the 4 CO2 files from SRES, four different RCP's ('RCP2-6.CO2', RCP4-5.CO2', 'RCP6-0.CO2' and 'RCP8-5.CO2') has been added to the data base of AquaCrop (Fig. 4.1). As the SRES set, the RCPs (Representative Concentration Pathways) represent a broad range of climate outcomes. Each RCP results from different combinations of economic, technological, demographic, policy, and institutional futures.

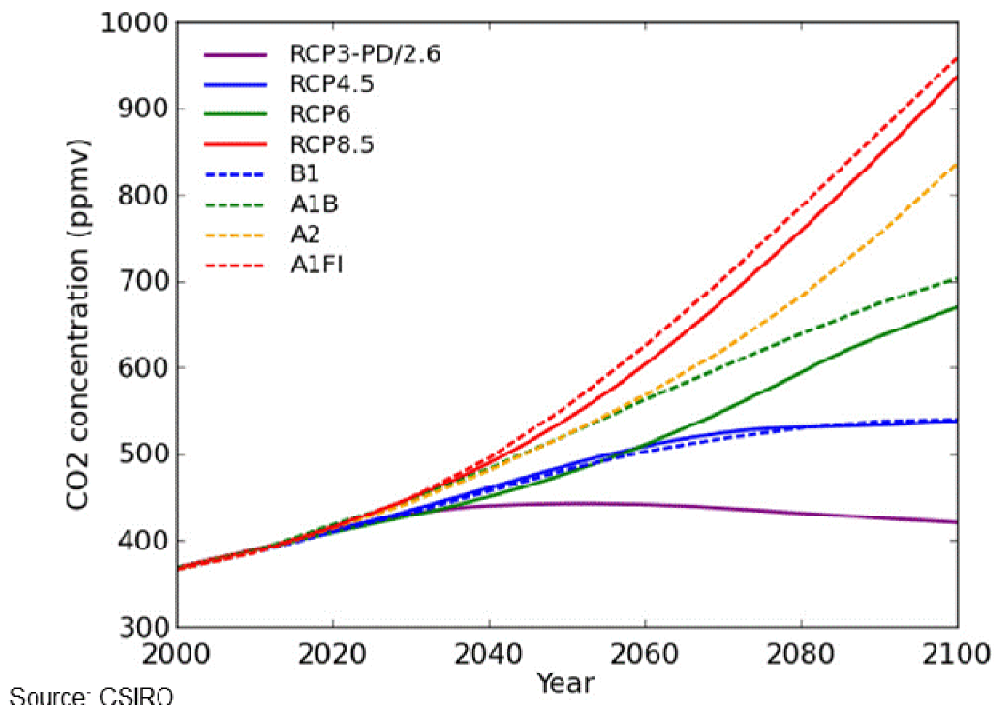


Figure 4.1 – Plot of the different CO2 concentrations according to the four different SRES and four different RCP's scenarios available in the data base of AquaCrop

5. Update of the *Crop characteristics* menu

In the ***Crop characteristics*** and ***Display of Crop characteristics*** menus, the crop parameters are grouped in different tabular sheets. A new tabular sheet has been added and some sheets have been updated (Tab. 5.1).

Table 5.1 – Updates in the Tabular sheets of the *Crop characteristics* and *Display of Crop characteristics* menu

Tabular sheet	Updates
– **Description:** - File description - Type of edit fields (cells) - Protected file (if applicable) Switch between 'Limited' and 'Full' set	
– **Mode**	'Mode': New tabular sheet, in which the switch between the calendar and the growing degree-days mode is available
– **Development:** - Initial canopy cover - Canopy development - Flowering and yield formation - Root deepening ~~- Temperatures~~	'Temperatures': Sheet removed ▪ The switch between the calendar and the growing degree-days mode is now available in the 'Mode' tabular sheet; ▪ The update of the base and upper threshold temperatures for crop development is now available in the 'Temperature' stress tabular sheet
– **ET** ***(only available in Full set)*** - Coefficients - Water extraction pattern	
– **Production** - Crop water productivity - Harvest Index	
– **Water stress** ***(only available in Full set)*** - Canopy expansion - Stomatal closure - Early canopy senescence - Aeration stress - Harvest Index o Before flowering o During flowering	'Aeration stress': Sheet updated

o During yield formation o Overview	
– **Temperature stress** ***(only available in Full set)*** - Crop development - Biomass production o Ks curve o Cold stress in growing cycle - Pollination	‘Crop development’: New tabular sheet in which the base and upper thresholds temperatures for crop development can be updated ‘Cold stress in growing cycle’: new tabular sheet in which the degree of cold stress on biomass production is displayed
– **Salinity stress** ***(only available in Full set)*** - Ks curve - Effects of soil salinity stress	
– **~~Biomass – stress~~ Fertility stress** - Canopy - Water productivity - Transpiration - Biomass - Biomass – stress relationship - Ks curves - Crop parameters	‘Fertility stress’: sheet renamed (before it was called ‘biomass stress’)
– **Calendar**	

5.1. Tabular-sheet: 'Mode'

After fine-tuning the growing cycle to the environment (typically done in calendar days), and considering the characteristics of the crop cultivar, it is advised to switch from the calendar mode to the growing degree-days (GDD) mode. By running AquaCrop in GDD mode, the length and duration of the crop development stages are automatically adjusted to the temperature regimes of the distinctive years of the simulation run.

To make the switch more visible to the user, an extra tabular sheet 'Mode' is now available. In this tabular sheet, the user can change the mode of crop development (Fig. 5.1). In previous AquaCrop versions, the switch was available in the 'Temperatures' tabular sheet (which has been removed) of the 'Development' tabular sheet.

To assess the importance of running in growing degree-days, the coefficient of variation (CV) of the monthly GDD's (for the complete years available in the temperature file), can be displayed in the 'Mode' tabular sheet (Fig. 5.2). CV is defined as the ratio of the standard deviation to the mean, and is expressed in percentage. The months of the growing cycle are colored green in the graph. When the mean of GDDays are close to zero (typically in the winter months of temperate climates), the coefficient of variation becomes sensitive to small changes in the mean.

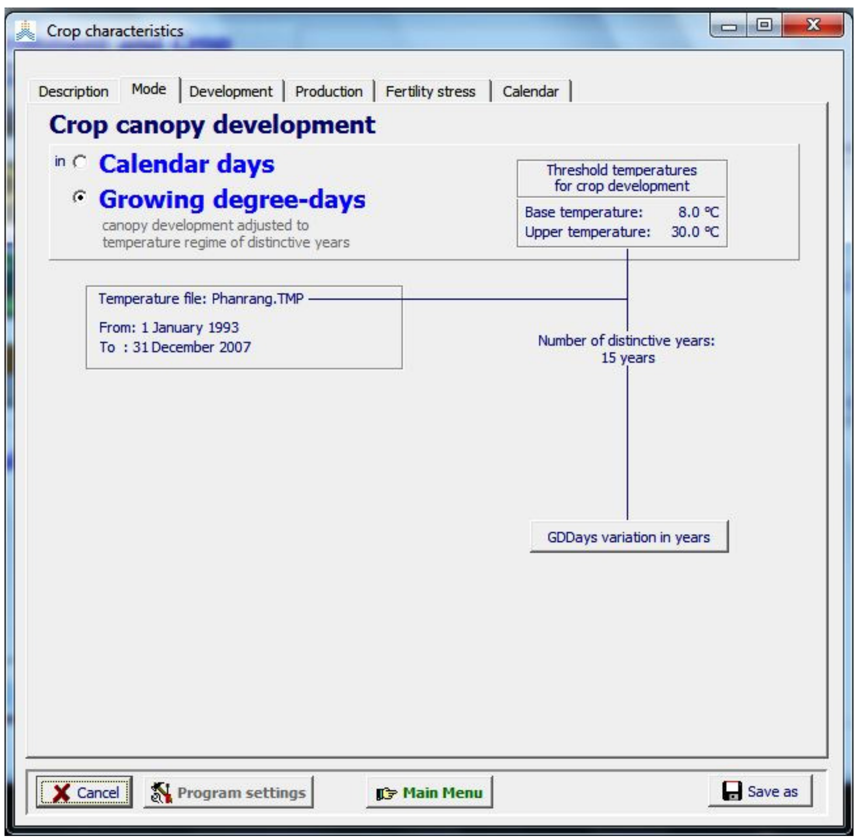


Figure 5.1 – The 'Mode' tabular sheet in the *Crop characteristics* menu

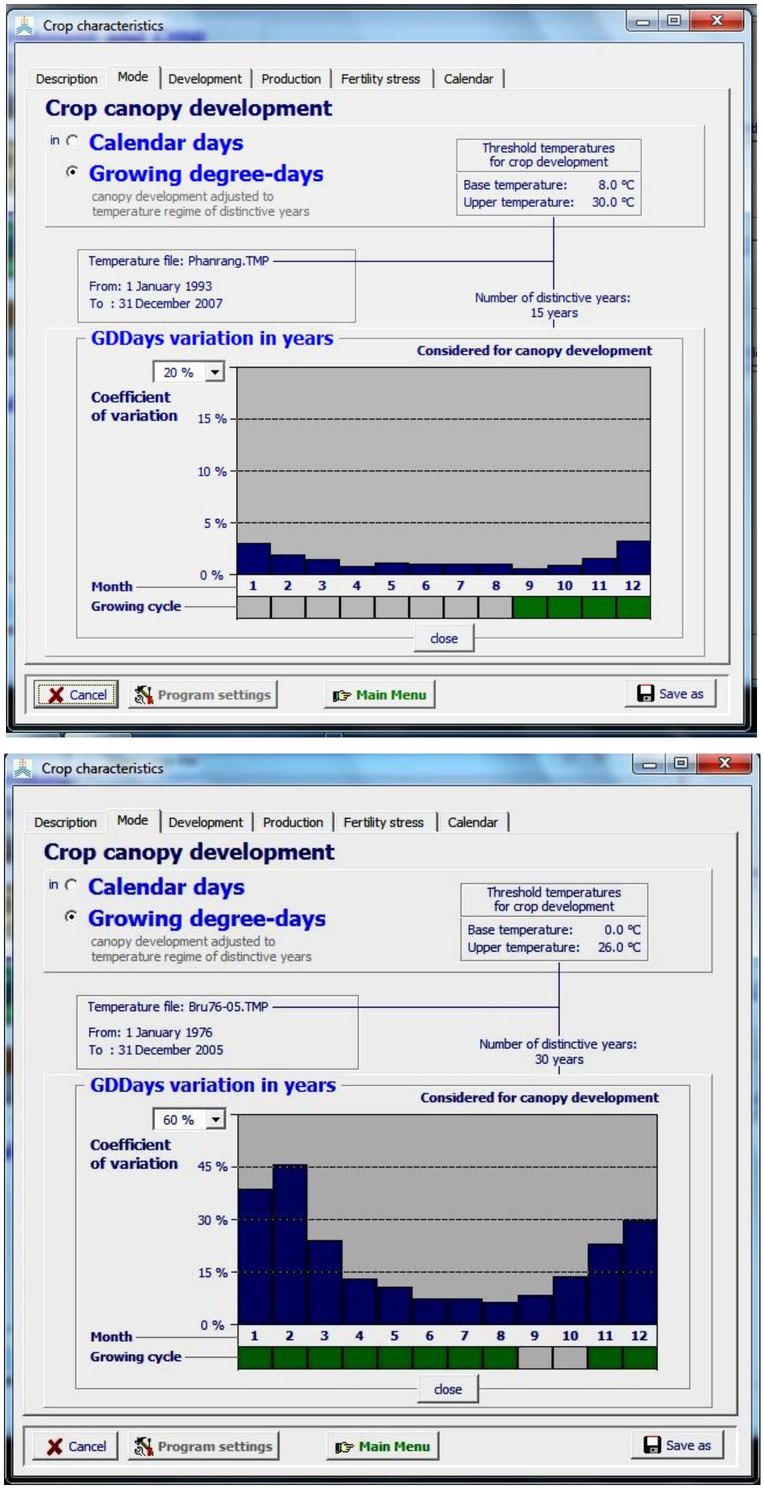


Figure 5.2 – Display of the variations in growing degree-days in the distinctive months (top) of the 15 years of the Phanrang (Vietnam) temperature file, and (bottom) of the 30 years of the Brussels (Belgium) temperature file in the tabular sheet 'Mode'. The base an upper temperatures are those for rice (Phanrang) and winter wheat (Brussels)

5.2 Tabular sheet: 'Temperature' stresses *(only available in full set)*

5.2.1 Tabular sheet: 'Crop development'

In the 'Crop development' sheet of the 'Temperature' stress tabular sheet, the base and upper thresholds temperatures for canopy development can be updated (Fig. 5.3). The corresponding growing degrees for each day of the temperature file, or for the length of the growing cycle, are displayed.

In previous versions of AquaCrop, the thresholds could be updated (when in full set) in the 'Temperatures' sheet (which has been removed) of the 'Development' tabular sheet.

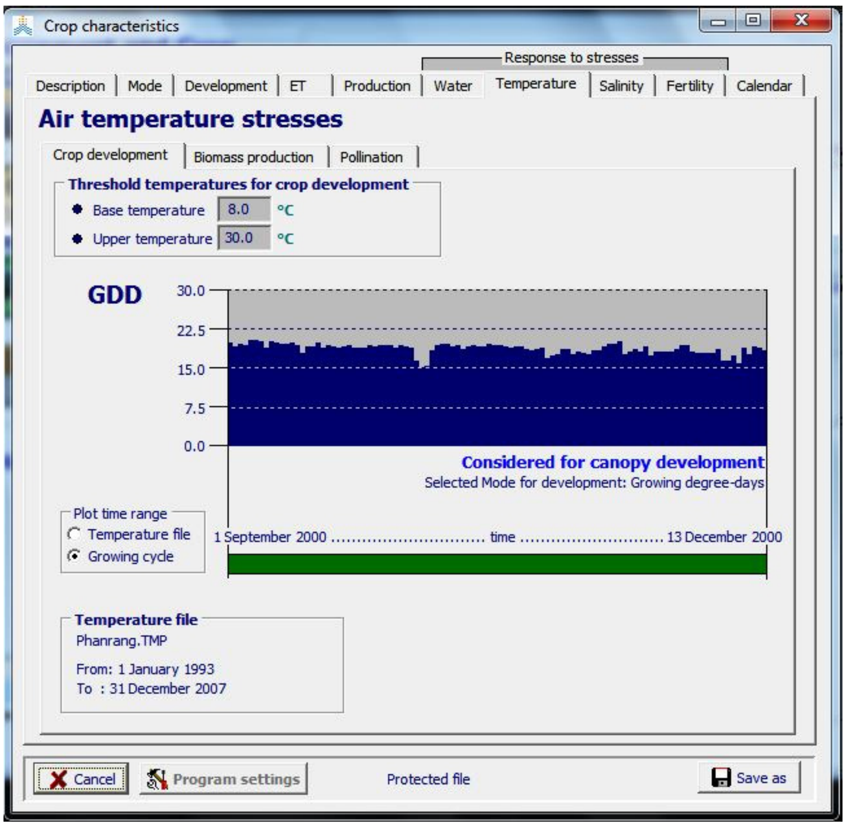
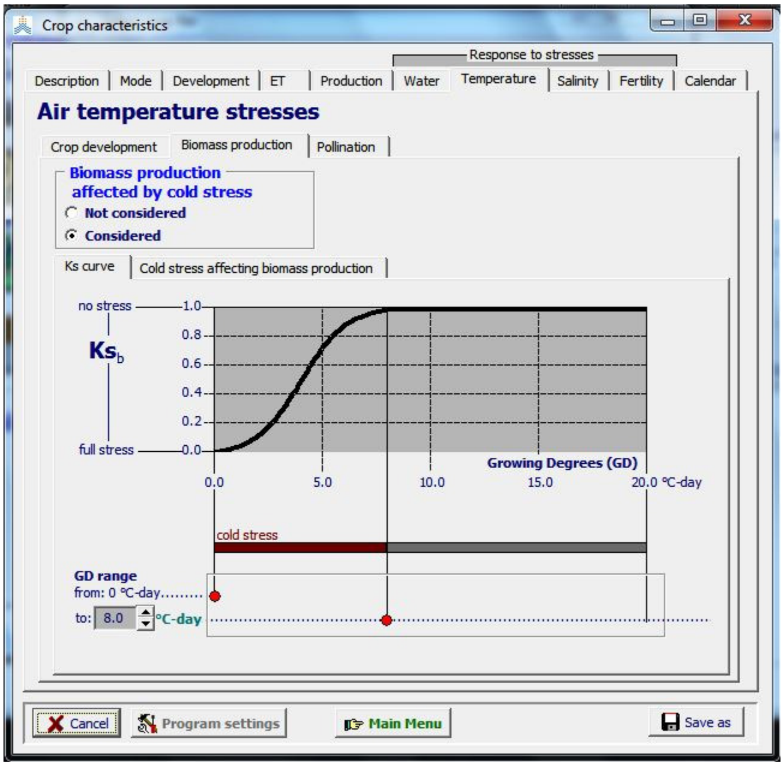


Figure 5.3 – The Base and Upper threshold temperatures for crop development in the 'Crop development' sheet of the 'Temperature' stress tabular sheet, and the corresponding growing degrees in Phanrang (Vietnam) for each day of the growing cycle.

5.2.2 Tabular sheet: 'Biomass production'

As in previous versions of AquaCrop, the number of growing degree-days below which cold stress starts to affect the biomass production can be adjusted in the 'Biomass production' sheet of the 'Temperature' stress tabular sheet (Fig. 5.4). Additionally the percentage of cold stress affecting the biomass production is now displayed for each day of the temperature file, or for the length of the growing cycle.



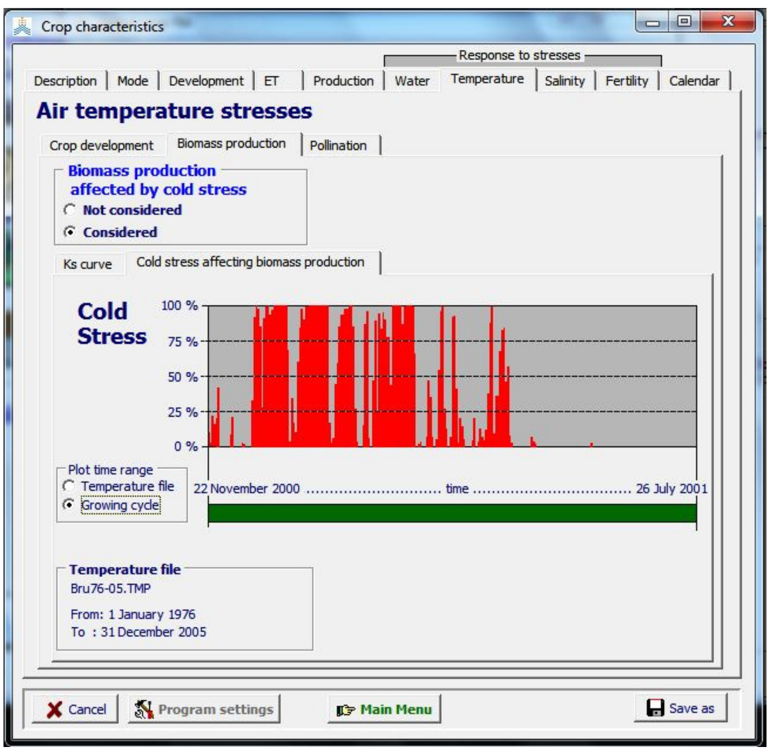


Figure 5.5 – (top) The temperature threshold (expressed in growing degree-days) for biomass production in the 'Biomass production' sheet of the 'Temperature' stress tabular sheet, and (bottom) the corresponding percentage of cold stress in Brussels (Belgium) during the growing cycle

6. Generation of irrigation events for flooded rice

At run time irrigations can be generated by specifying a 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.

In AquaCrop Version 5.0, an extra time criterion ‘Water layer between bunds’ has been added (Tab. 6.1). It generates an irrigation, each time when the water level between the soil bunds (if present) drops below a specified minimum threshold value (Fig. 6.1).

Table 6.1. – 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	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

The ‘Water layer between bunds’ time criterion, can only generate irrigations if:

- soil bunds are present (this is one of the field surface practices in Field management);
- ‘Fixed net application’ is the depth criterion; and
- The specified threshold for the depth of the surface water layer that should be maintained between the soil bunds, is smaller than the bund height.

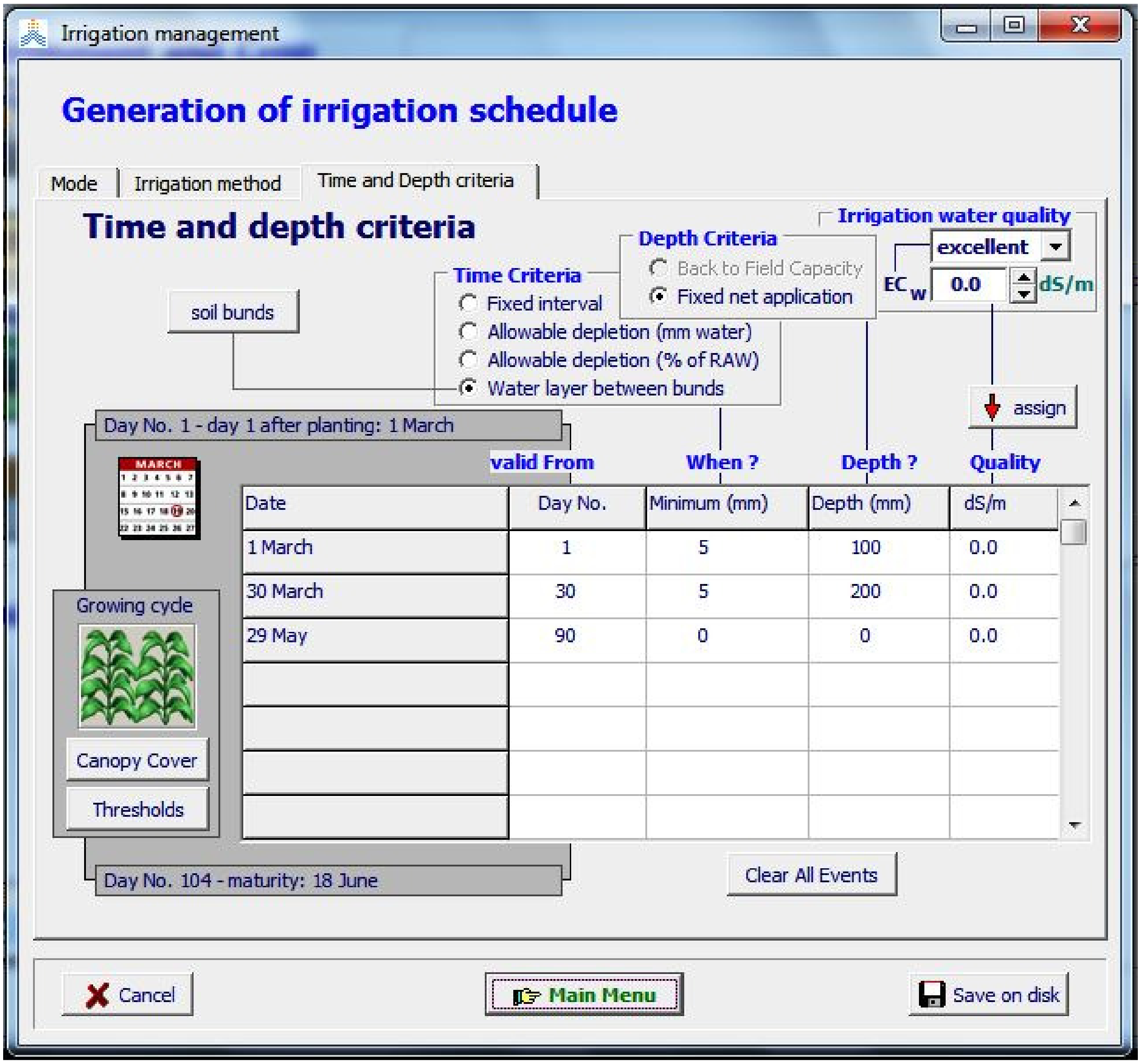


Figure 6.1 – An irrigation schedule for flooded rice, where the fixed application depth increases from 100 mm to 200 mm after 30 days, and irrigation ceases at 90 days after transplanting to prepare for harvesting

7. Field surface practices

In AquaCrop, the estimation of the amount of rainfall lost by surface runoff is based on the curve number (CN) method, developed by the US Soil Conservation Service. The CN value is specified as a soil profile characteristic (CN_{soil}). In the ***Soil profile characteristics*** menu, the user can select the default CN_{soil} (based on the Ksat of the top horizon), or specify a CN_{soil} different from the default by considering soil profile characteristics other than the Ksat of the top horizon. The default CN_{soil} for the hydrologic soil group to which the soil profile belongs, is the average CN for the 'small grain' hydrologic soil-cover complex, with good hydrologic conditions (USDA, 2004).

Since field management and crop type might affect surface runoff, the user can adjust CN_{soil} in the 'Field surface practices' tabular-sheet of the ***Field management*** menu (Fig. 7.1). Four options are available.

7.1 Field surface practices do NOT affect surface runoff

(as in previous AquaCrop versions). Surface runoff is based exclusively on the soil profile characteristic (CN_{soil}; Tab. 7.1). Since land cover most likely was not considered when specifying CN_{soil} in the ***Soil profile characteristics*** menu, crop covers different from the 'small grain' type, might require and adjustment of the CN_{soil} (see option 2).

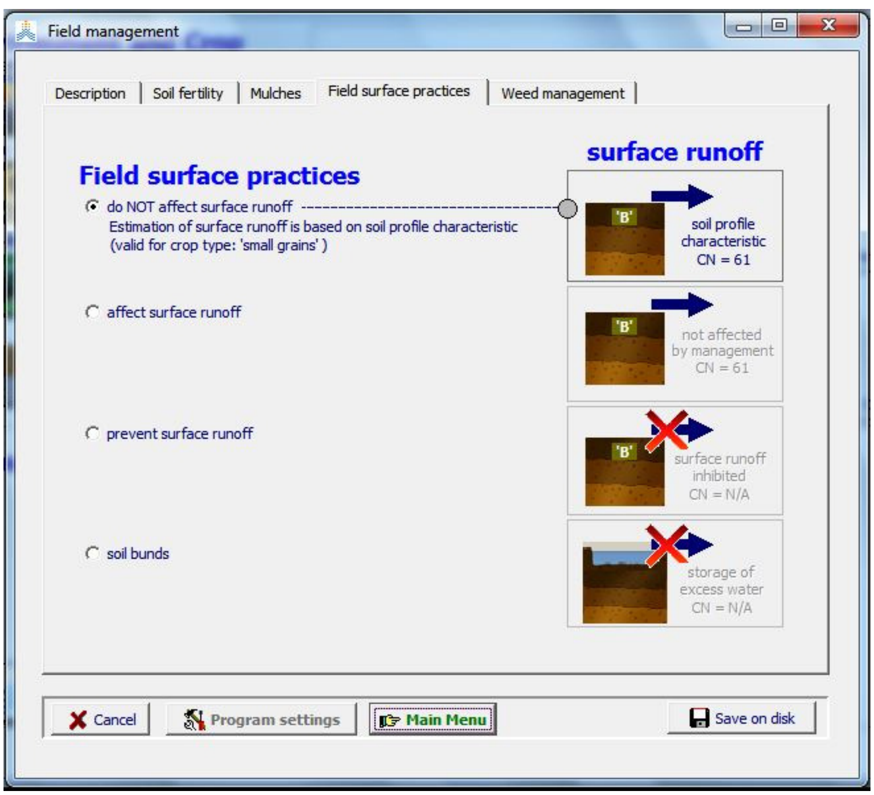


Figure 7.1 – The 'Field surface practices' tabular-sheet of the *Field management* menu, with the 4 options to adjust surface runoff.

Table 7.1 – Default CN_{soil} (assuming an initial abstraction of 5 % of S) for the four hydrologic soil groups, and the range for the saturated hydraulic conductivity (Ksat) of the top horizon, on which the specification of the hydrologic soil group and CN_{soil} is based. The defaults are the averages CN for the 'small grain' hydrologic soil-cover complex, with good hydrologic conditions of the USDA.

Hydrologic soil group	Saturated hydraulic conductivity (K_{sat}) mm/day	Default CN_{soil} (soil profile characteristic)
A	> 864	46
B	864 – 347	61
C	346 – 36	72
D	≤ 35	77

7.2 Field surface practices affect surface runoff (new in version 5.0).

CN_{soil}, which is based on soil profile characteristics, can be adjusted by considering the crop type (if different from 'small grain'), treatment and hydrologic conditions. The adjustment is expressed as the percentage increase or decrease of the specified CN_{soil}. When information is available, the user can also enter directly the adjusted CN value, which is then converted in the percent increase/decrease of CN_{soil} (Fig. 7.2).

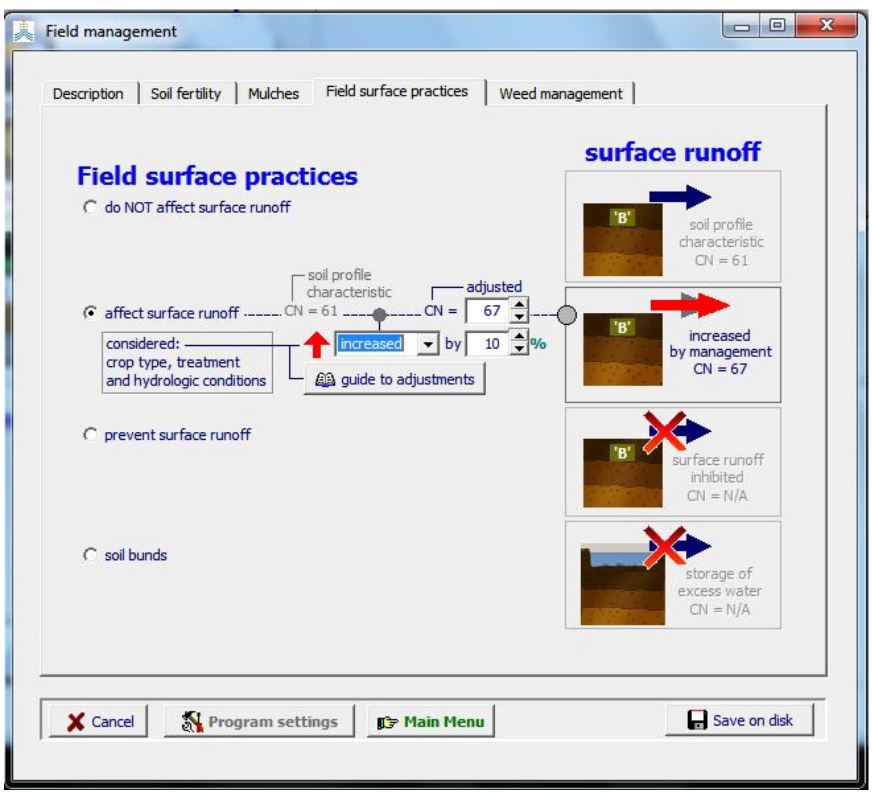


Figure 7.2 – Adjustment of CN_{soil} (based on soil profile characteristics), when field surfaces practices affect surface runoff, in the 'Field surface practices' tabular-sheet of the *Field management* menu.

By selecting the **<guide to adjustments>** command, indicative values for the percent increase/decrease are displayed in the ***CN adjustment*** menu (Fig. 7.3). Values for all hydrologic soil groups are displayed (for reference), but adjustments can only be selected for the group to which the soil profile belongs. Adjustments are available for various treatments, hydrologic conditions (i.e. conditions that affect infiltration and runoff) and for five crop types: (i) row crops, (ii) small grain, (iii) close-seeded or broadcast legumes, (iv) pasture, grassland for grazing, and (v) grassland moved for hay (protected from grazing). The adjustments are based on the CN values provided by the USDA for various hydrologic soil-cover complexes (Tab. 7.2), and were converted in the percentage increase/decrease by considering the default CN for each of the hydrologic soil group (Tab. 7.1).

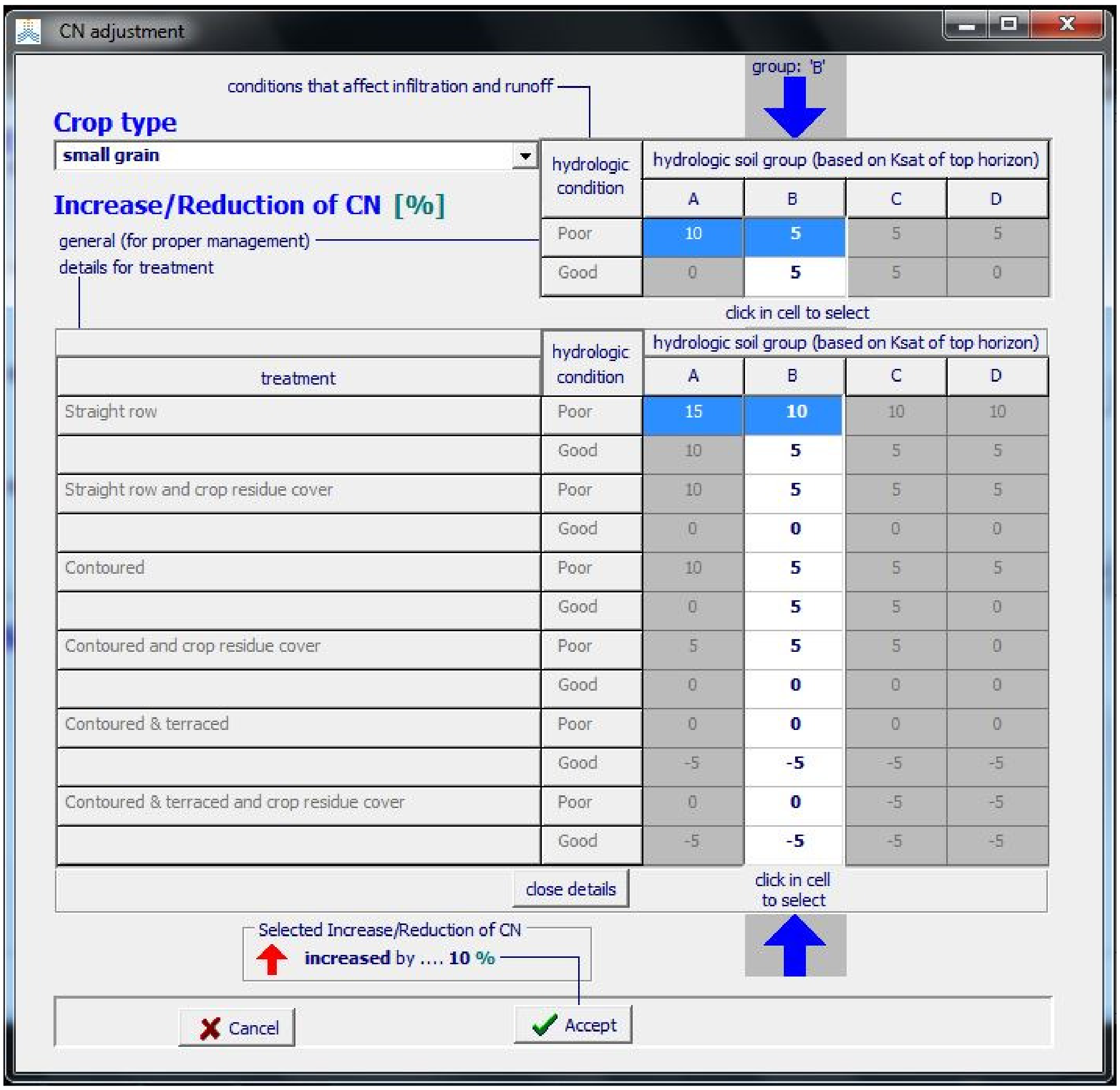


Figure 7.3 – Selection of the percent increase/decrease of the CN based on soil profile characteristics, by considering the crop type, treatment and hydrologic condition in the *CN adjustment* menu.

Table 7.2 – Runoff Curve Numbers (assuming an initial abstraction of 5 % of S), for agriculture lands (source National Engineering Handbook of the USDA, USDA 2004).

A. Row crops

Cover/treatment	Hydrologic Condition	Increase/Decrease of CN in percentage Hydrologic soil group			
		A	B	C	D
Straight row	Poor	61	74	84	88
	Good	55	70	80	85
Straight row and crop residue cover	Poor	60	72	83	87
	Good	51	65	75	80
Contoured	Poor	59	71	78	84
	Good	52	65	75	81
Contoured and crop residue cover	Poor	57	70	77	83
	Good	51	64	74	80
Contoured & terraced	Poor	53	64	72	75
	Good	48	60	70	74
Contoured & terraced and crop residue cover	Poor	52	63	71	74
	Good	47	59	68	72

B. Small grain

Cover/treatment	Hydrologic Condition	Increase/Decrease of CN in percentage Hydrologic soil group			
		A	B	C	D
Straight row	Poor	52	67	78	84
	Good	50	65	77	83
Straight row and crop residue cover	Poor	51	65	77	81
	Good	46	61	72	78
Contoured	Poor	50	64	75	80
	Good	47	63	74	78
Contoured and crop residue cover	Poor	48	63	74	78
	Good	46	61	72	77
Contoured & terraced	Poor	47	61	71	75
	Good	45	59	70	74
Contoured & terraced and crop residue cover	Poor	46	60	70	74
	Good	44	57	68	72

C. Close-seeded or broadcast legumes

Cover/treatment	Hydrologic Condition	Increase/Decrease of CN in percentage Hydrologic soil group			
		A	B	C	D
Straight row	Poor	53	68	80	85
	Good	44	61	74	80
Straight row and crop residue cover	Poor	-	-	-	-
	Good	-	-	-	-
Contoured	Poor	51	65	77	80
	Good	40	57	70	77
Contoured and crop residue cover	Poor	-	-	-	-
	Good	-	-	-	-
Contoured & terraced	Poor	50	63	72	77
	Good	36	55	67	72
Contoured & terraced and crop residue cover	Poor	-	-	-	-
	Good	-	-	-	-

D. Pasture, grassland, or range-continuous forage for grazing

Cover/treatment	Hydrologic Condition	Increase/Decrease of CN in percentage Hydrologic soil group			
		A	B	C	D
	Poor	56	71	81	85
	Fair	34	57	71	78
	Good	24	47	64	72

E. Meadow-continuous grass, protected from grazing and generally mowed for hay

Cover/treatment	Hydrologic Condition	Increase/Decrease of CN in percentage Hydrologic soil group			
		A	B	C	D
	Good	17	44	60	70

7.3 Field surface practices prevent surface runoff (as previous)

Practices, such as tied-ridges and closed-end furrows, will prevent surface runoff.

7.4 Soil bunds (as in previous AquaCrop versions)

Soil bunds not only prevent surface runoff, but store excess water between the bunds. The height of the soil bunds has to be specified in meter.

8. Create field management file

When creating a field management file, the user has to specify only a few characteristics (Fig.8.1):

– **Soil fertility:** the level of potential biomass production that can be expected with the given soil fertility and in the absence of any other stress. When the crop is calibrated for soil fertility stress, the corresponding soil fertility stress is displayed;
– **Mulches:** the level of soil surface cover by mulches and the type of the mulches;
– **Field surface practices:** Specify if field practices prevent surface runoff, and if present, the height of soil bunds;

With the help of this information AquaCrop generates the complete set of field management characteristics. The parameters are displayed and the values can be adjusted in the ***Field management*** menu.

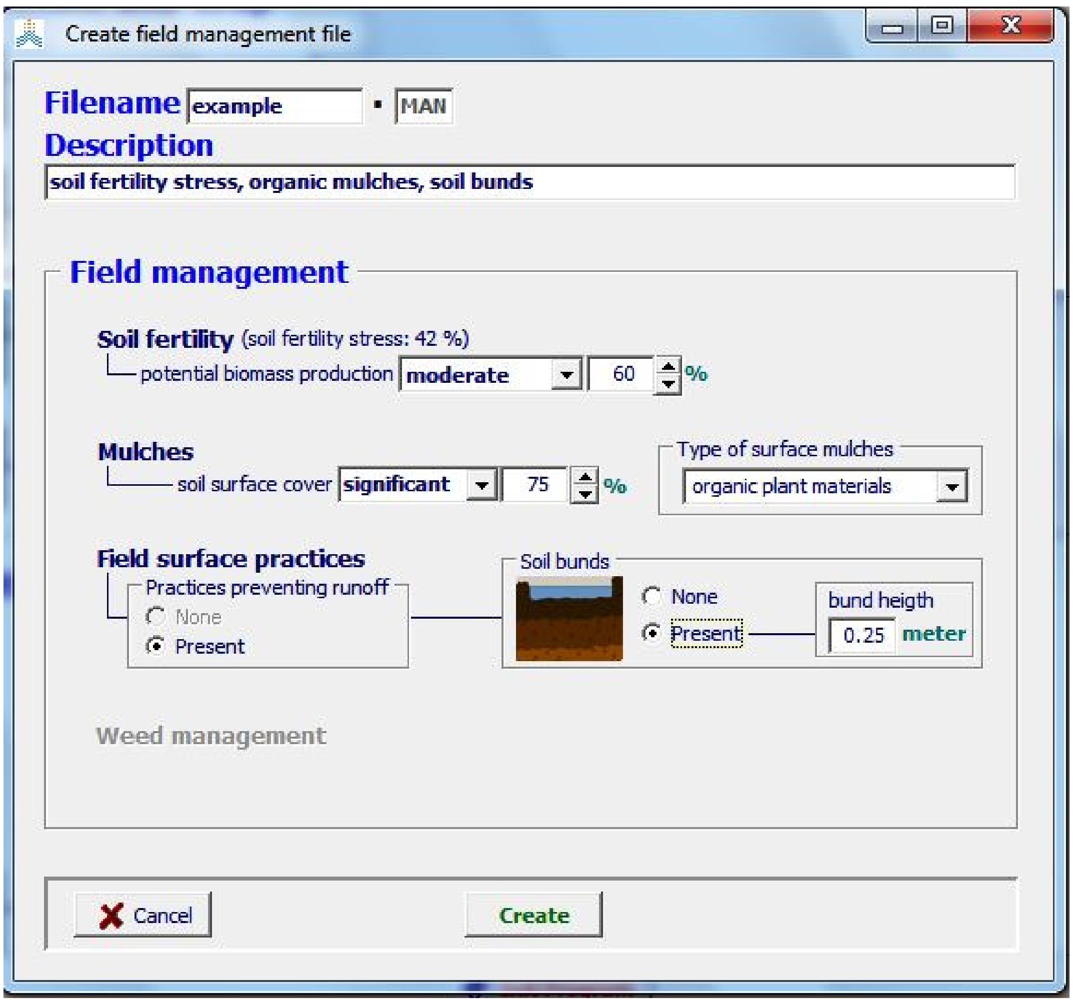


Figure 8.1 – Create *field management file* menu

9. Default soil profile characteristics

Good indicative values for the soil water content at saturation (SAT), field capacity (FC) and permanent wilting point (PWP) are already available in 12 'soil profile' files (corresponding with the twelve soil textural classes) in the DATA subdirectory of AquaCrop. The indicative values were obtained by sampling the Hydraulic Properties Calculator developed by Saxton and Rawls (2006, USDA). The estimating equations (based on soil texture) were developed by correlations of an extensive data set (1,722 samples) provided by the USDA/NRCS National Soil Survey Laboratory.

Updates are available in AquaCrop Version 5.0 for (i) the saturated hydraulic conductivity (Ksat) and (ii) the Curve Number (CN) for estimating surface runoff.

9.1 Saturated hydraulic conductivity (Ksat)

The default values for the hydraulic conductivity at saturation (Ksat), available in the 12 'soil profile' files, are updated in version 5.0. The updated values were obtained by sampling 260 times the textural triangle of the Hydraulic Properties Calculator, and by averaging the values for each textural class (Table 9.1). Since Ksat varies strongly in space and time, even in a single field, as a result of variations in soil structure, bulk density, biological activity and soil management, the default Ksat values reported in the files are only indicative,

Table 9.1 – 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 Version 5.0.

Soil textural class	soil water content (θ)			TAW	Ksat
	SAT	FC	PWP		
	vol %	vol %	vol %	mm/m	mm/day
Sand	36	13	6	70	3,000
Loamy sand	38	16	8	80	2,200
Sandy loam	41	22	10	120	1,200
Loam	46	31	15	160	500
Silt loam	46	33	13	200	575
Silt	43	33	9	240	500
Sandy clay loam	47	32	20	120	225
Clay loam	50	39	23	160	125
Silty clay loam	52	44	23	210	150
Sandy clay	50	39	27	120	35
Silty clay	54	50	32	180	100
Clay	55	54	39	150	35

The updated Ksat values are about twice as large as the values reported in the 'soil profiles' files of previous AquaCrop versions. The updated Ksat will increase the speed of infiltration and alter the magnitude of surface runoff, but will not affect the water retention in the root zone (which is based on TAW). Since the updated Ksat values come with an updated estimate of the surface runoff, the expected increase in surface runoff (due to the increased Ksat values), might be oppressed by the updated classification of soils in hydrologic soil groups and the calculation of the surface runoff (Fig. 9.1).

9.2 Hydrologic soil groups and default Curve Numbers (CN)

In AquaCrop, the estimation of the amount of rainfall lost by surface runoff is based on the curve number method developed by the US Soil Conservation Service (USDA, 1964; Rallison, 1980; Steenhuis et al., 1995):

$$RO = \frac{\left[P - I_a\right]^2}{P + S - I_a} \quad \text{(Eq. 9.1)}$$

$$S = 254\left(\frac{100}{CN} - 1\right) \quad \text{(Eq. 9.2)}$$

where RO amount of water lost by surface runoff [mm];
P rainfall amount [mm];
I_a initial abstraction [mm] or the amount of water that can infiltrate before runoff occurs;
S potential maximum soil water retention [mm], Eq. 9.2;
CN Curve Number

In previous versions of AquaCrop:

a) the initial abstraction (I_a) in Eq. 9.1 was fixed at 0.2 S since this was generally assumed;
b) the default CN values for several soil classes, were derived from average values provided by Smedema and Rycroft (1983) for 4 soil groups. The soil classification (based on Ksat) was somewhat arbitrary selected (CN was 65, for Ksat > 250 mm/day; CN was 75, for 50 < Ksat < 250 mm/day; CN was 80, for 10 < Ksat < 50 mm/day; and CN was 85 for Ksat < 10 mm/day);
c) the user could specify a CN value different from the default, by considering slope, land use and cover.

Updates in AquaCrop 5.0:

a) the initial abstraction (I_a) in Eq. 9.1 is fixed at 0.05 S. Recent research (Hawkins et al., 2002) found that this may be a more appropriate value for I_a. CN values assuming an initial abstraction of 20% S ($CN_{0.20}$), can be converted to their corresponding values with an initial abstraction of 5% S ($CN_{0.05}$) by (Jiang, 2001; Hawkins, 2009):

$$CN_{0.05} = \frac{100}{1.879\left[\left(100/CN_{0.20}\right) - 1\right]^{1.15} + 1} \quad \text{(Eq. 9.3)}$$

where $CN_{0.20}$ is the CN value used in previous AquaCrop versions.

b) the default CN for the four distinguished hydrologic soil groups are the average values for the 'small grain' hydrologic soil-cover complex with good hydrologic conditions as provided by USDA in the National Engineering Handbook (USDA, 2004). The same criteria used by USDA for the assignment of hydrologic soil groups (based on Ksat) are used in AquaCrop for the classification of the soils in the hydrologic soil groups (Table 9.2). The comparison between the CN's in the previous and the new version of AquaCrop indicates, that the estimation of surface runoff might not change dramatically (Fig. 9.1).

Table 9.2 – Hydrologic soil groups, the corresponding range for the saturated hydraulic conductivity (Ksat) of the top horizon, and default CN values (assuming an initial abstraction of 5 % of S) for antecedent moisture class II (AMCII).

Hydrologic soil group	Saturated hydraulic conductivity (K_{sat}) mm/day	CN default value for AMC II
A	> 864	46
B	864 – 347	61
C	346 – 36	72
D	≤ 35	77

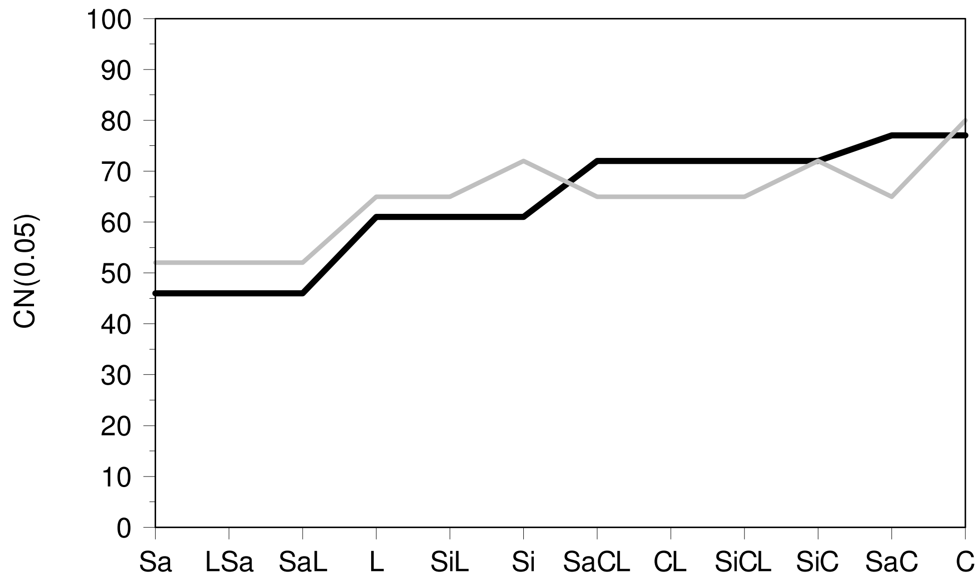


Figure 9.1 – CN values (assuming an initial abstraction of 5% S) used in the previous (gray line) and in the new (black line) version of AquaCrop for the various soil textural classes: Sa (sand), LSa (loamy sand), SaL (sandy loam), L (loam), SiL (silt loam), Si (silt), SaCL (sandy clay loam), CL (clay loam), SiCL (silty clay loam), SiC (silty clay), SaC (sandy clay) and C (clay).

c) the user can still specify a CN value different from the default (Fig. 9.2), but should thereby not consider the effect of land use and cover, since these effects are now considered when specifying the field management. Hence a clear distinction is made between the CN value based on soil profile characteristics (CN_{soil}: which is a soil parameter), and the adjustment of CN_{soil} as a result of field management practices (which is a field management parameter).

The user should be aware that previous defined CN values in existing 'soil profile' files, were calculated with an initial abstraction of 20% S. Therefore, when selecting a 'soil profile' file created in previous AquaCrop versions, a warning is displayed in the ***Soil profile characteristics*** menu, stating that the 'specified CN might need to be adjusted to new runoff settings in Version 5.0'. To convert the specified $CN_{0.20}$ in previous 'soil profile' files to the corresponding $CN_{0.05}$ value, the user can find the value in Table 9.3 or use Eq. 9.3 for the conversion.

Table 9.3 – $CN_{0.20}$ values (assuming an initial abstraction of 20% S) with the corresponding $CN_{0.05}$ values (assuming an initial abstraction of 5% S).

$CN_{0.20}$	$CN_{0.05}$	$CN_{0.20}$	$CN_{0.05}$	$CN_{0.20}$	$CN_{0.05}$
100	100	80	72	60	46
98	98	78	70	58	44
96	95	76	67	56	41
94	93	74	64	54	39
92	90	72	61	52	37
90	87	70	59	50	35
88	84	68	56	48	33
86	81	66	53	46	31
84	78	64	51	44	29
82	75	62	48	42	27

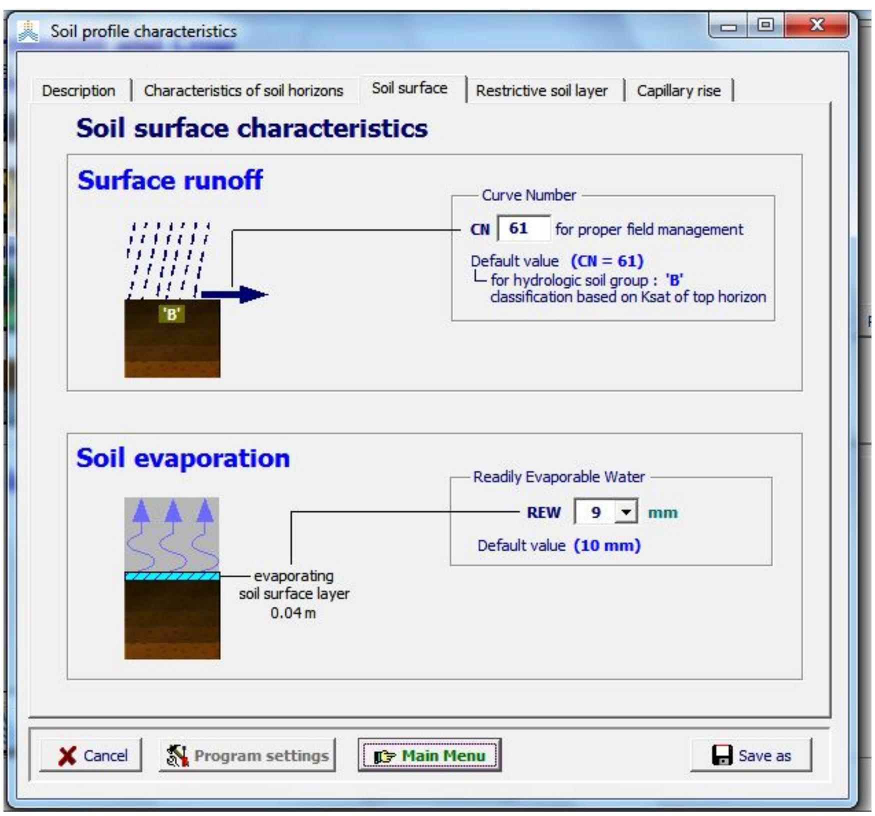


Figure 9.2 – Specification of the CN value for proper field management and display of the default based on Ksat of the top horizon in the *Soil profile characteristics* menu.

Updated soil profile characteristics in the default profile files

In Tables 9.4 to 9.15 the content of the 12 default soil profile files ('*.SOL'), available in the DATA subdirectory of AquaCrop Version 5.0, are displayed.

Table 9.4 – The 'Sand.SOL' file in the DATA subdirectory

```
deep uniform 'very sandy' soil profile
        5.0      : AquaCrop Version (March 2015)
       46        : CN (Curve Number)
        4        : Readily evaporable water from top layer (mm)
        1        : number of soil horizons
       -9.00     : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb           description
  ---(m)-   ----(vol %)-----  (mm/day)  ----------------------------------------------------
    4.00    36.0  13.0   6.0  3000.0    -0.341200  0.440738             sand
```

Table 9.5 – The 'LoamySand.SOL' file in the DATA subdirectory

```
deep uniform 'loamy sand' soil profile
        5.0       : AquaCrop Version (March 2015)
       46         : CN (Curve Number)
        5         : Readily evaporable water from top layer (mm)
        1         : number of soil horizons
       -9.00      : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb           description
  ---(m)-   ----(vol %)-----  (mm/day)  ----------------------------------------------------
    4.00    38.0  16.0   8.0  2200.0    -0.333200  0.365805        loamy sand
```

Table 9.6 – The 'SandyLoam.SOL' file in the DATA subdirectory

```
deep uniform 'sandy loam' soil profile
        5.0       : AquaCrop Version (March 2015)
       46         : CN (Curve Number)
        7         : Readily evaporable water from top layer (mm)
        1         : number of soil horizons
       -9.00      : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb           description
  ---(m)-   ----(vol %)-----  (mm/day)  ----------------------------------------------------
    4.00    41.0  22.0  10.0  1200.0    -0.323200  0.219363        sandy loam
```

Table 9.7 – The 'Loam.SOL' file in the DATA subdirectory

```
deep uniform 'loamy' soil profile
        5.0      : AquaCrop Version (March 2015)
       61        : CN (Curve Number)
        9        : Readily evaporable water from top layer (mm)
        1        : number of soil horizons
       -9.00     : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb           description
  ---(m)-   ----(vol %)-----  (mm/day)  ---------------------------------------------------
    4.00    46.0  31.0  15.0   500.0    -0.453600  0.837340             loam
```

Table 9.8 – The 'SiltLoam.SOL' file in the DATA subdirectory

```
deep uniform 'silty loam' soil profile
        5.0      : AquaCrop Version (March 2015)
       61        : CN (Curve Number)
       11        : Readily evaporable water from top layer (mm)
        1        : number of soil horizons
       -9.00     : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb           description
  ---(m)-   ----(vol %)-----  (mm/day)  ----------------------------------------------------
    4.00    46.0  33.0  13.0   575.0    -0.446850  0.904118         silt loam
```

Table 9.9 – The 'Silt.SOL' file in the DATA subdirectory

```
deep uniform 'silt' soil profile
        5.0      : AquaCrop Version (March 2015)
       61        : CN (Curve Number)
       11        : Readily evaporable water from top layer (mm)
        1        : number of soil horizons
       -9.00     : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb           description
  ---(m)-   ----(vol %)-----  (mm/day)  ----------------------------------------------------
    4.00    43.0  33.0   9.0   500.0    -0.453600  0.837340             silt
```

Table 9.10 – The 'SandyClayLoam.SOL' file in the DATA subdirectory

```
deep uniform 'sandy clay loam' soil profile
        5.0      : AquaCrop Version (March 2015)
       72        : CN (Curve Number)
        9        : Readily evaporable water from top layer (mm)
        1        : number of soil horizons
       -9.00     : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb           description
  ---(m)-   ----(vol %)-----  (mm/day)  ----------------------------------------------------
    4.00    47.0  32.0  20.0   225.0    -0.576700 -0.511485   sandy clay loam
```

Table 9.11 – The 'ClayLoam.SOL' file in the DATA subdirecotry

```
deep uniform 'clay loam' soil profile
        5.0      : AquaCrop Version (March 2015)
       72        : CN (Curve Number)
       11        : Readily evaporable water from top layer (mm)
        1        : number of soil horizons
       -9.00     : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb           description
  ---(m)-   ----(vol %)-----  (mm/day)  ----------------------------------------------------
    4.00    50.0  39.0  23.0   125.0    -0.572700 -0.859573         clay loam
```

Table 9.12 – The 'SiltyClayLoam.SOL' file in the DATA subdirectory

```
deep uniform 'silty clay loam' soil profile
        5.0      : AquaCrop Version (March 2015)
       72        : CN (Curve Number)
       13        : Readily evaporable water from top layer (mm)
        1        : number of soil horizons
       -9.00     : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb           description
  ---(m)-   ----(vol %)-----  (mm/day)  ----------------------------------------------------
    4.00    52.0  44.0  23.0   150.0    -0.516600  1.622512   silty clay loam
```

Table 9.13 – The 'SandyClay.SOL' file in the DATA subdirectory

```
deep uniform 'sandy clay' soil profile
        5.0      : AquaCrop Version (March 2015)
       77        : CN (Curve Number)
       10        : Readily evaporable water from top layer (mm)
        1        : number of soil horizons
       -9.00     : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb           description
  ---(m)-   ----(vol %)-----  (mm/day)  ----------------------------------------------------
    4.00    50.0  39.0  27.0    35.0    -0.569100 -1.613423        sandy clay
```

Table 9.14 – The 'SiltyClay.SOL' file in the DATA subdirectory

```
deep uniform 'silty clay' soil profile
        5.0      : AquaCrop Version (March 2015)
       72        : CN (Curve Number)
       14        : Readily evaporable water from top layer (mm)
        1        : number of soil horizons
       -9.00     : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb           description
  ---(m)-   ----(vol %)-----  (mm/day)  ----------------------------------------------------
```

```
    4.00    54.0  50.0  32.0   100.0    -0.556600  1.336132        silty clay
```

Table 9.15 – The 'Clay.SOL' file in the DATA subdirectory

```
deep uniform 'heavy clay' soil profile
        5.0     : AquaCrop Version (March 2015)
       77       : CN (Curve Number)
       14       : Readily evaporable water from top layer (mm)
        1       : number of soil horizons
       -9.00    : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
  Thickness  Sat   FC    WP     Ksat       CRa       CRb          description
  ---(m)-   ----(vol %)-----  (mm/day)  ----------------------------------------------------
    4.00    55.0  54.0  39.0    35.0    -0.608600  0.594642           clay
```

References

Hawkins, R.H., Jiang, R., Woodward, D.E., Hjelmfelt, A.T., Van Mullem, J.A. 2002. "Runoff Curve Number Method: Examination of the Initial Abstraction Ratio". *Proceedings of the Second Federal Interagency Hydrologic Modeling Conference, Las Vegas, Nevada* (U.S. Geological Survey). Retrieved 24 November 2013.

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USDA, 2004. Hydrologic Soil-Cover complexes. Chapter 9 of PART 630 Hydrology. National Engineering handbook. Department of agriculture of the United Sates.

USDA, 2007. Hydrologic Soil Groups. Chapter 7 of PART 630 Hydrology. National Engineering handbook. Department of agriculture of the United Sates.

10. Initial conditions at start of simulation period

10.1 Initial conditions menu

In the ***Initial conditions*** Menu, the user specifies the soil water content and soil salinity in the soil profile, which determines the status of the soil water and salt balance at the start of the first day of the simulation period. The initial conditions can be measured at the field. If field data is not available, the simulation can start at a day at which soil water conditions can be well estimated, such as early spring when the soil water content is likely to be at field capacity after long winter rains. Another appropriate starting time of the simulation might be at the end of a long dry period when the soil water content is likely to be close to permanent wilting point. Since the simulation period has not to coincide with the growing cycle, putting the start of the simulation period at an appropriate date well before planting, is a good method to become well estimated initial conditions at the moment of crop germination.

In version 5.0, the user can also specify the initial Canopy Cover (CC) and effective rooting depth (Z), as well as the above-ground biomass (B) already produced before the start of the simulation period. This is required if for example due to the absence of climatic data, the simulation period starts after the germination of the crop. In previous versions of AquaCrop, the CC and Z had not to be specified since it was assumed that they were are their maximum values that could have been reached at the end of the day before the start of the simulation period. It was thereby assumed that the crop didn't experience any stress before the start of the simulation period. Since this is not necessary true, there is now the option in Version 5.0, to specify the initial status of CC and Z in the ***Initial conditions*** Menu, when stresses have affected crop development before the simulation period. In the same menu, the above-ground biomass already produced before the start of the simulation period (if any), can be specified. The initial conditions of CC, B and Z can be measured at the field or estimated with the help of remote sensing.

In the AquaCrop version 5.0, the user specifies as initial conditions at the start of the first day of the simulation period:

- the soil water content (Fig. 10.1) at various depths in the soil profile;
- the soil salinity (Fig. 10.2) at various depths in the soil profile;
- the initial canopy cover (CC), if different from the maximum canopy cover that could have been reached without water stress (which is the default), at the start of the simulation period (Fig. 10.3);
- the biomass already produced at the start of the simulation period (Fig. 10.4), if different from zero (which is the default);
- the initial rooting depth (Z), if different from the maximum rooting depth that could have been reached without water stress (which is the default), at the start of the simulation period (Fig. 10.5).

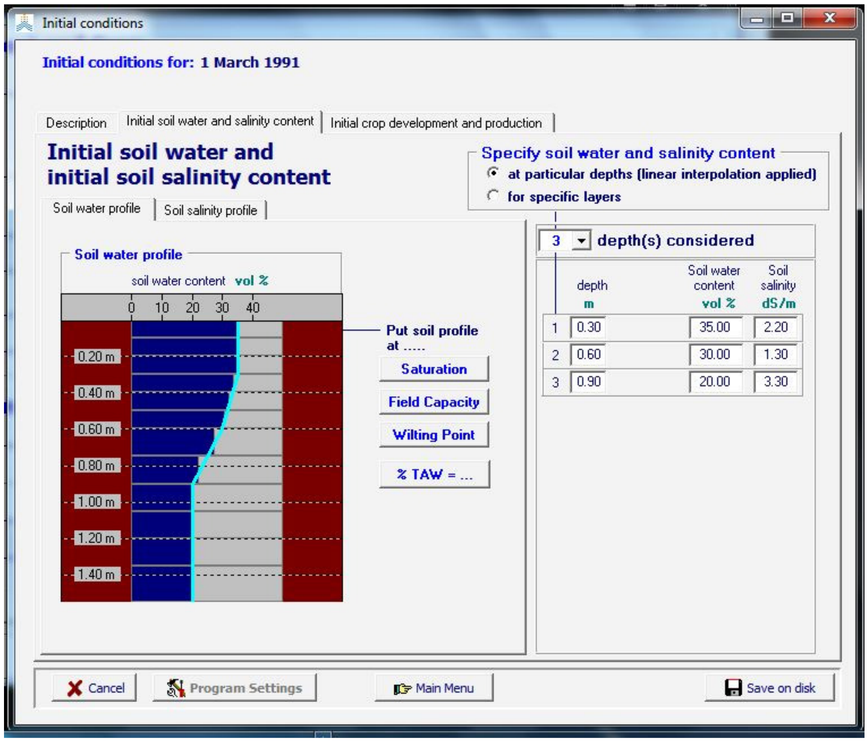


Figure 10.1 – Specification of the soil water content at various depths at the start of the simulation period in the *Initial conditions* Menu

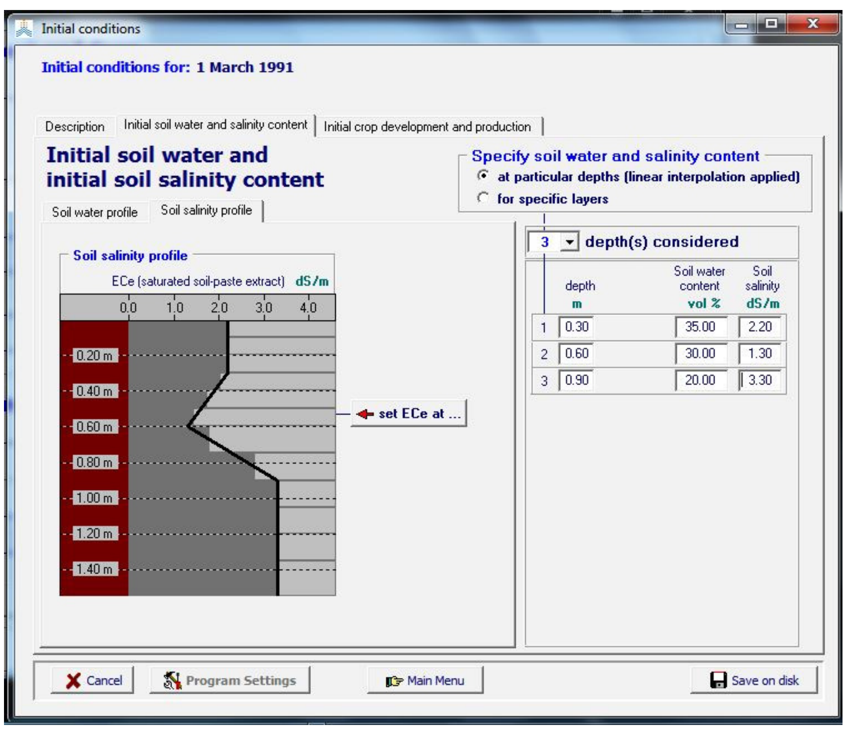


Figure 10.2 – Specification of the soil salinity content at various depths at the start of the simulation period in the *Initial conditions* Menu

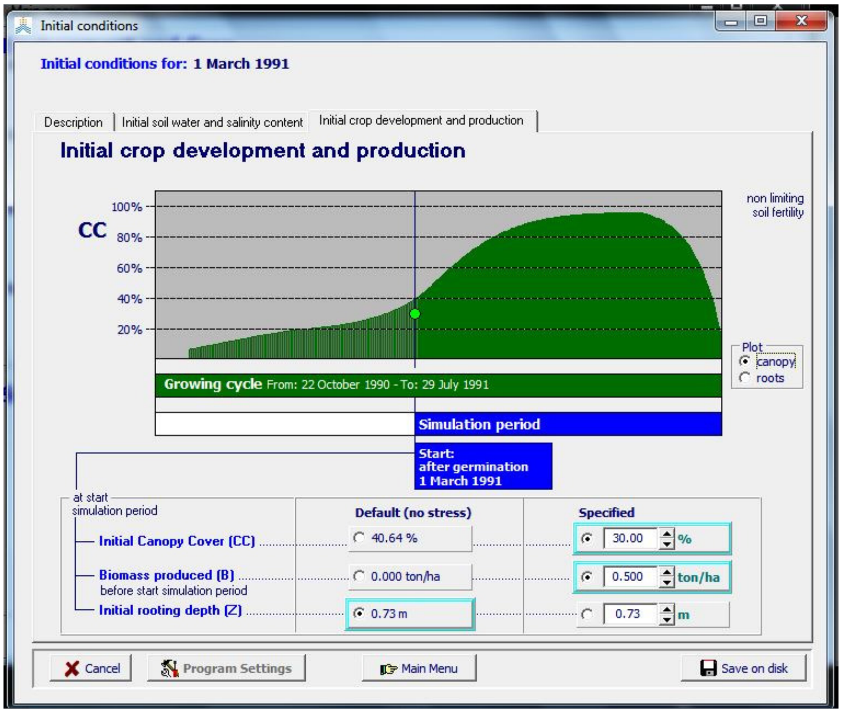


Figure 10.3 – Specification of the green Canopy Cover (CC) and produced Biomass (B) at the start of the simulation period in the *Initial conditions* Menu for a simulation period which starts after germination.

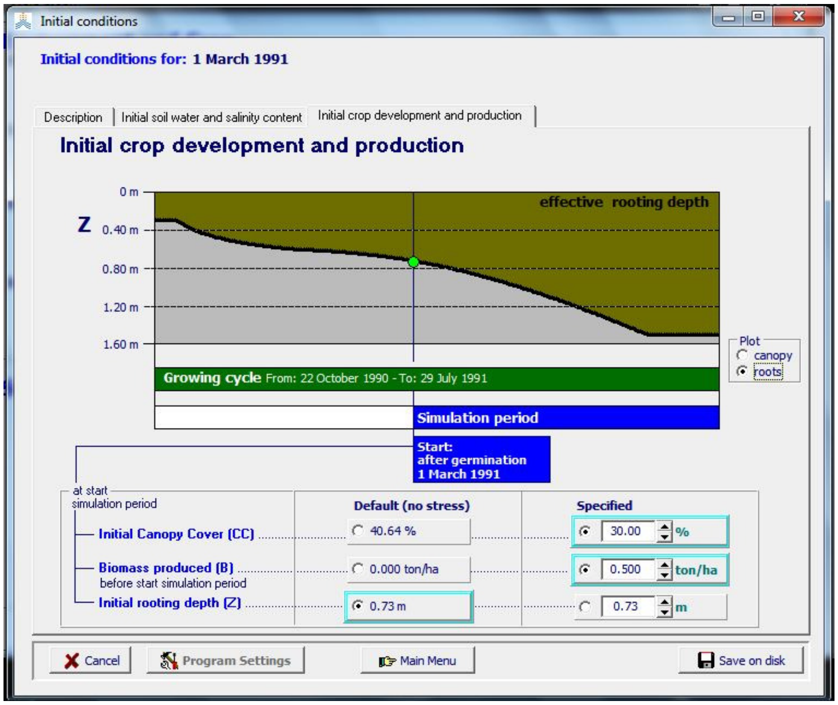


Figure 10.4 – Specification of the rooting depth (Z) at the start of the simulation period in the *Initial conditions* Menu for a simulation period which starts after germination.

10.2 File with initial conditions (*.SW0)

The information specified in files with the initial conditions (files with extension SW0) consist of:

- The soil water content and soil salinity in the soil profile (at a specified number of soil layers or depths). The soil water content is expressed in volume % and the soil salinity is given by the Electrical Conductivity of the saturated soil-paste extract (ECe) expressed in dS/m;
- The depth of the water layer on top of the soil surface and its water quality at the start of the simulation run, if the field is surrounded by soil bunds. The depth of the water layer is expressed in millimetre, and the quality of the water between the soil bunds is given by its Electrical Conductivity (ECw) expressed in dS/m;
- The initial canopy cover (CC) if different from the maximum canopy cover that could have been reached without water stress at the start of the simulation period. This might be required when the simulation period starts after germination or after the recovering of the crop after transplanting. The initial canopy cover (CC) is expressed in %. However, the specified CC:
    - cannot be larger than the maximum canopy cover (CCmax) that could have been reached without water stress at the start of the simulation period. If so the specified CC will be disregarded and a CC equal to CCmax will be assumed at the start of the simulation period;
    - cannot be smaller than the CC at germination or at transplanting (CCmin). If so the specified CC will be disregarded and a CC equal to CCmin will be assumed at the start of the simulation period;
    - cannot be different from 0 % if the simulation period starts before or after the growing cycle. If so the specified CC will be disregarded and no crop (CC equal to 0.0 %) will be assumed at the start of the simulation period.
- The biomass produced (ton/ha) before the start of the simulation period (if any);
- The initial effective rooting depth if different from the maximum effective rooting depth that could have been reached without water stress at the start of the simulation period. This might be required when the simulation period starts after germination or after the recovering of the crop after transplanting. The initial effective rooting depth is expressed in meter. However, the specified Z:
    - cannot be larger than the maximum effective rooting depth (Zmax) that could have been reached without water stress at the start of the simulation period. If so the specified Z will be disregarded and a Z equal to Zmax will be assumed at the start of the simulation period;
    - cannot be smaller than the Z at germination or at transplanting (Zmin). If so the specified Z will be disregarded and a Z equal to Zmin will be assumed at the start of the simulation period;
    - cannot be different from 0.00 m if the simulation period starts before or after the growing cycle. If so the specified Z will be disregarded and no crop (Z equal to 0.00 m) will be assumed at the start of the simulation period.

In the absence of a file with initial conditions, it is assumed that in the soil profile (i) the soil water content is at field capacity and (ii) salts are absent at the start of the simulation. If the simulation starts after sowing/planting of the crop but still inside the growing cycle, the initial canopy cover and effective rooting depths are taken as the maximum that could have been reached without water stress at the start of the simulation period. Outside the period of the growing cycle, the initial canopy cover and effective rooting depth are always zero (no crop). It is also assumed as default that no biomass was produced before the start of the simulation period.

The structure of SW0 files are given in Table 10.1 and examples are provided in Table 10.2 to 10.5.

Table 10.1 – Structure of the file with initial conditions (files with extension SW0)

Line	Description	Format
1	First line is a description of the file content	String of characters
2	Version number of AquaCrop	Real (1 digit)
3	Canopy Cover (%) at start of the simulation period. If undefined (-9.00), the maximum canopy cover that could have been reached without water stress at the start of the simulation period is assumed.	Real (2 digits)
4	Biomass produced (ton/ha) before the start of the simulation period	Real (3 digits)
5	Effective rooting depth (m) at start of the simulation period. If undefined (-9.00), the maximum effective rooting depth that could have been reached without water stress at the start of the simulation period is assumed.	Real (2 digits)
6	Water layer (mm) stored between soil bunds (if present)	Real (1 digit)
7	Electrical conductivity (dS/m) of water layer stored between soil bunds (if present)	Real (2 digits)
8	A number (0 or 1) used as a code to specify if the initial conditions are specified for specific layers, or at particular depths of the soil profile: 0: code indicating that the data are specified for specific layers (Example Table 10.2, 10.3 and 10.4); 1: code indicating that the data are specified at particular depths of the soil profile (Example Table 10.5).	Integer
9	Number of different layers/depth considered (Maximum = 12)	Integer
10	Empty line	-
11	Title (list of parameters)	String of characters
12	Dotted line (‘====================================’)	String of characters
	Code = 0 (in line 8): For specific soil layers (Example Table 10.2, 10.3 and 10.4)	
13	For the 1st soil layer: – Thickness of the soil layer in meter – Soil water content in volume % – Soil salinity (ECe) in dS/m	 Real (2 digits) Real (2 digits) Real (2 digits)
14 ..	Repeat for each soil layer	

	Code = 1 (in line 8): At particular soil depths (Example Table 10.5)	
13	At the 1st soil depth: – Soil depth in meter – Soil water content in volume % – Soil salinity (ECe) in dS/m	 Real (2 digits) Real (2 digits) Real (2 digits)
14 ..	Repeat for each soil depth	

Table 10.2 – Example for water stored between bunds

```
Uniform silty soil at Field capacity with soil bunds
   4.1   : AquaCrop Version (March 2014)
  -9.00  : initial canopy cover that can be reached without water stress will be used as default
   0.000 : biomass (ton/ha) produced before the start of the simulation period
  -9.00  : initial effective rooting depth that can be reached without water stress will be used as default
 150.0   : water layer (mm) stored between soil bunds (if present)
   0.00  : electrical conductivity (dS/m) of water layer between bunds
   0     : soil water content specified for specific layers
   1     : number of layers considered

Thickness layer (m)     Water content (vol%)     ECe(dS/m)
==============================================================
           4.00              33.00              0.00
```

Table 10.3 – Example for which the simulation period starts after germination, with specification of the initial canopy cover, biomass and effective rooting depth at the start of the simulation period.

```
Initial conditions for Field SN123 on 21 April 2014
 4.1   : AquaCrop Version (May 2014)
  40.00  : initial canopy cover (%) at start of simulation period
   3.500 : biomass (ton/ha) produced before the start of the simulation period
   0.50  : initial effective rooting depth (m) at start of simulation period
   0.0   : water layer (mm) stored between soil bunds (if present)
   0.00  : electrical conductivity (dS/m) of water layer stored between soil bunds (if present)
   0     : soil water content specified for specific layers
   1     : number of layers considered

Thickness layer (m)     Water content (vol%)     ECe(dS/m)
==============================================================
           3.00              30.00              0.00
```

Table 10.4 – Example of initial conditions specified for specific soil layers

initial conditions for specific layers in Field AZ123 on 21 March 2010
4.1 : AquaCrop Version (March 2014)
-9.00 : initial canopy cover that can be reached without water stress will be used as default
0.000 : biomass (ton/ha) produced before the start of the simulation period
-9.00 : initial effective rooting depth that can be reached without water stress will be used as default
0.0 : water layer (mm) stored between soil bunds (if present)
0.00 : electrical conductivity (dS/m) of water layer between bunds
0 : soil water content specified for specific layers
3 : number of layers considered

Thickness layer (m)	Water content (vol%)	ECe(dS/m)
0.40	30.00	1.00
0.40	20.00	2.00
0.40	18.00	2.50

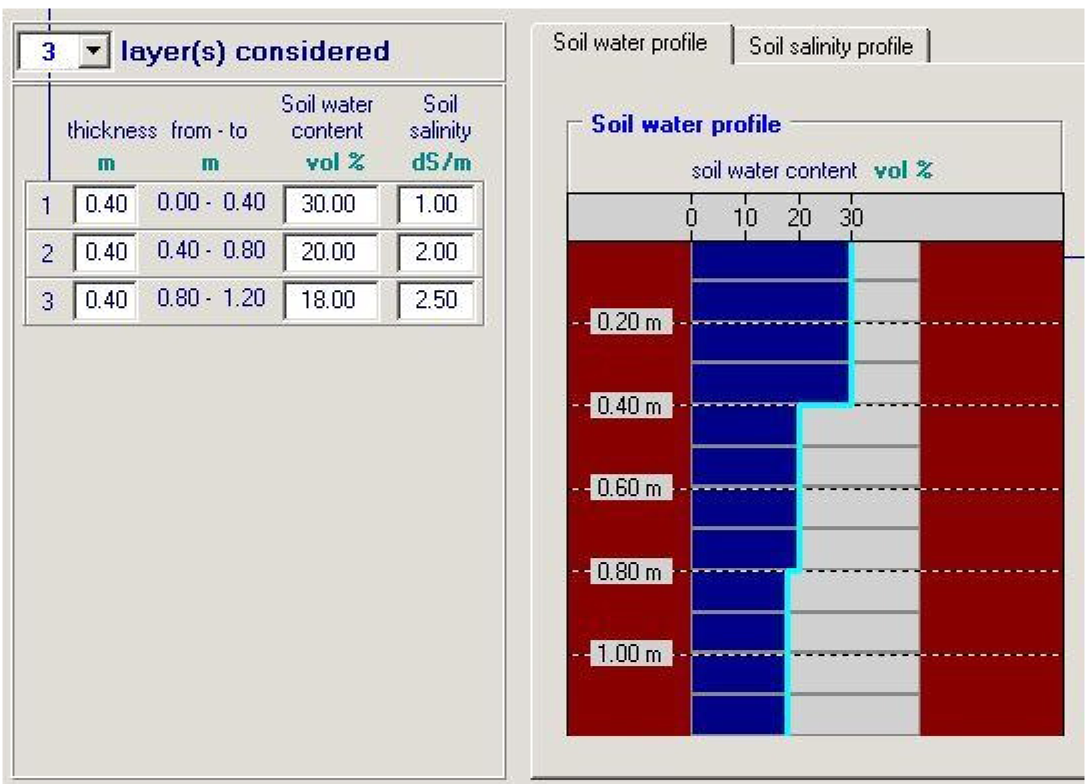
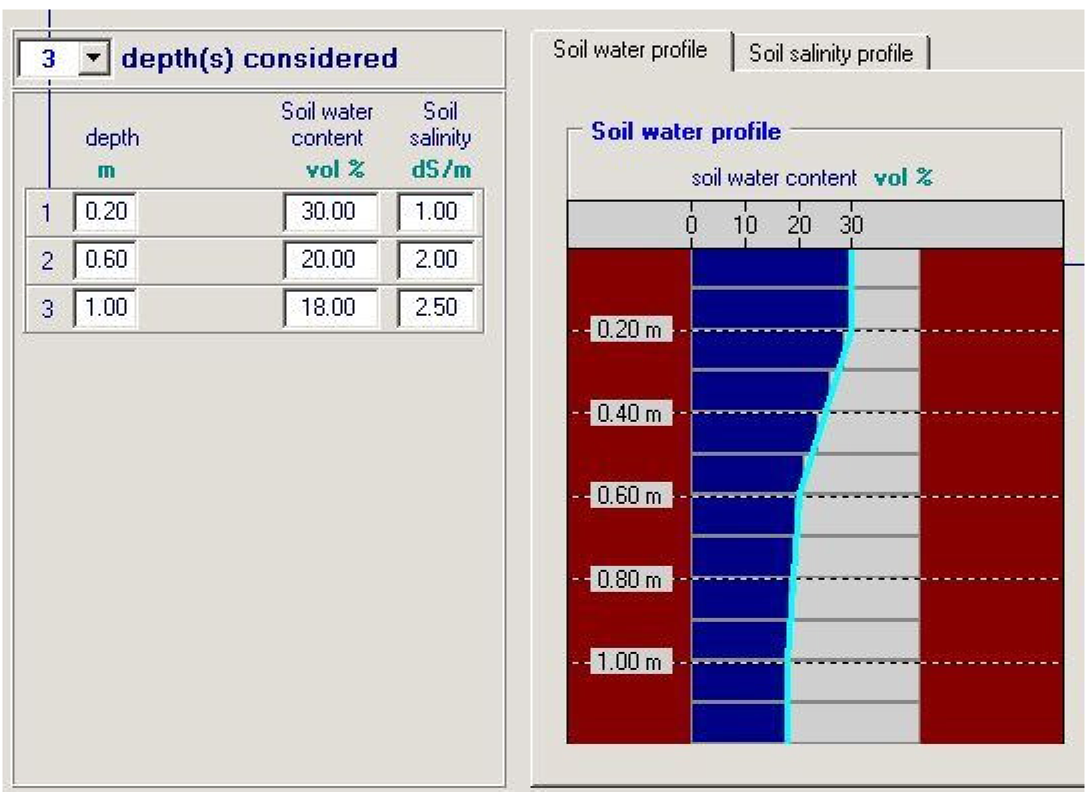


Table 10.5 – Example of initial conditions specified at particular soil depths

initial conditions at particular depths in Field AZ123 on 21 March 2010
4.1 : AquaCrop Version (March 2014)
-9.00 : initial canopy cover that can be reached without water stress will be used as default
0.000 : biomass (ton/ha) produced before the start of the simulation period
-9.00 : initial effective rooting depth that can be reached without water stress will be used as default
0.0 : water layer (mm) stored between soil bunds (if present)
0.00 : electrical conductivity (dS/m) of water layer between bunds
1 : soil water content specified at particular depths
3 : number of soil depths considered

Soil depth (m)	Water content (vol%)	ECe (dS/m)
0.20	30.00	1.00
0.60	20.00	2.00
1.00	18.00	2.50



11. Program settings: Simulation run parameters

(*Initial conditions* menu)

11.1 When running successive simulation runs within growing cycle

When running successive simulation runs, within the same growing cycle, a 'hot start' is possible in AquaCrop Version 5.0. In a hot start, which is the default option in the ***Program settings: Simulation run parameters*** menu (Fig. 11.1), the soil water and salinity content, and the status of crop development and production, simulated at the end of a simulation run, become the initial conditions for the next run. Hot starts apply as long as:

- the user does not alter, between the successive simulation runs, the selected soil and crop file and the initial conditions specified in the ***Initial conditions*** Menu;
- the end of the previous run is still within the growing cycle; and
- the first day of the simulation period, follows neatly the last day of the previous run.

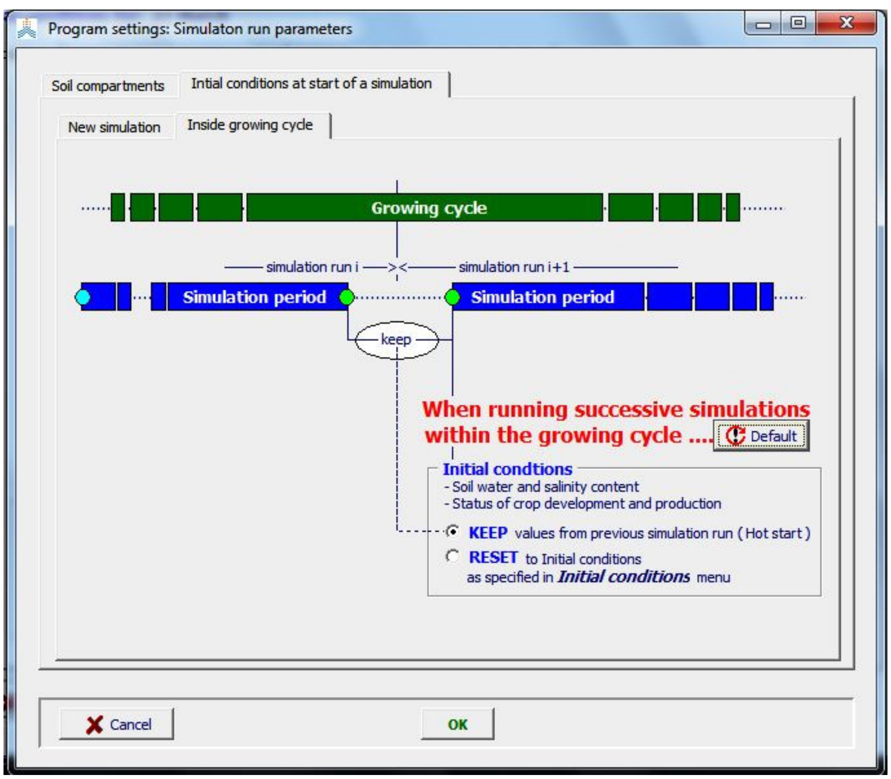


Figure 11.1 – Default option for the program parameter for the initial conditions, when running successive simulation runs within the growing cycle, in the *Program settings: Simulation run parameters* menu.

Hot starts are useful when running AquaCrop to obtain a first yield estimate before the end of the ongoing season, or to assess the irrigation requirement for the next part of the season. The procedure consists in running a series of successive simulations with different climate files, and eventually different irrigation management files.

11.2 When starting a new simulation at start or outside growing cycle

As in the previous versions of AquaCrop, the simulated soil water content and soil salinity at the end of a previous simulation run can be taken as the initial conditions for the next run. This option is not restricted to successive simulation runs within the same growing cycle. Since this is not the default option, it requires a change to the settings of the program, which has to be done in the ***Program settings: Simulation run parameters*** menu (Fig. 11.2). The **<KEEP values from previous simulation run>** setting applies as long as the soil file remains the same, and the option is not reset to its default (**<RESET to specified initial conditions>**).

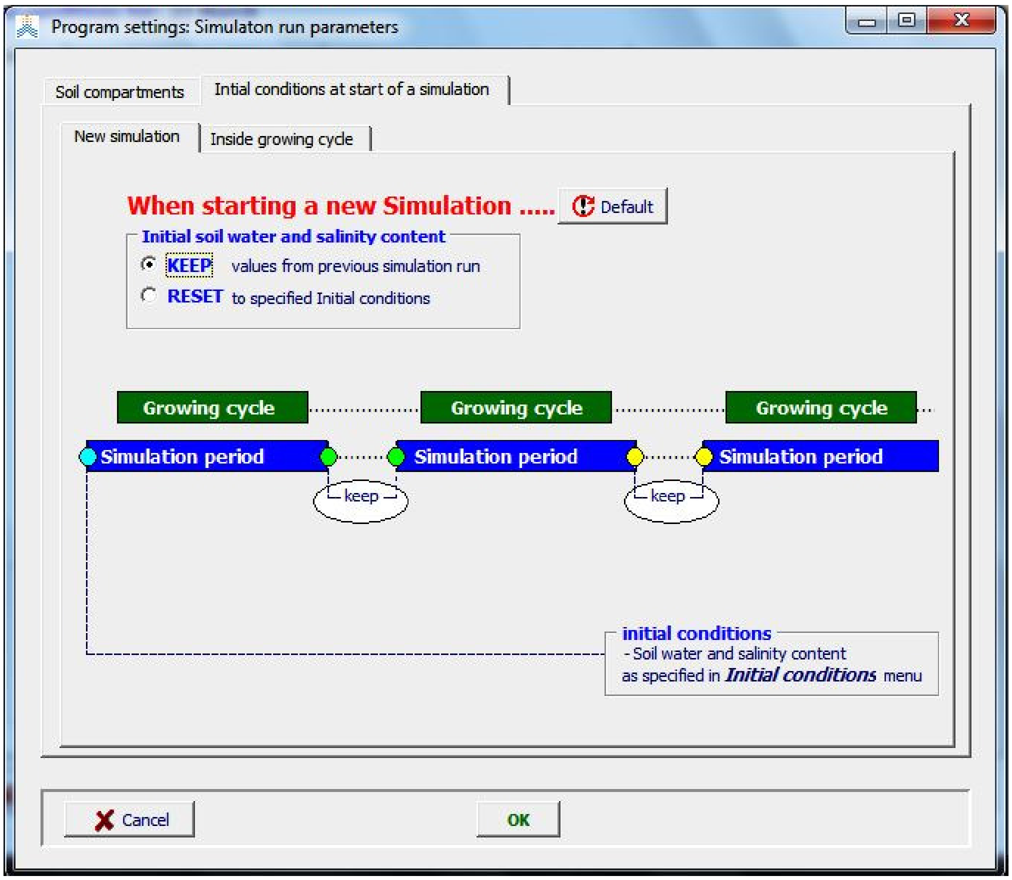


Figure 11.2 – Specification of the program parameter for the initial soil water and soil salinity content in the *Program settings: Simulation run parameters* menu.

Running with the "KEEP" option is for example useful for simulating the building up of salts over successive irrigation seasons. By taking whole years as the successive simulation periods, the effect of winter rains leaching salts out of the root zone is considered in the simulation of the salt balance over the years.

12. Create file with initial conditions

When creating an initial conditions file, the user specifies in the various tabular sheets of the ***Create Initial conditions file*** menu (Fig. 12.1), the initial conditions at the start of the first day of the simulation period:

- the soil water content at various depths in the soil profile;
- the soil salinity at various depths in the soil profile;
- the depth of the water layer on top of the soil surface and its water quality, if the field is surrounded by soil bunds;
- the initial canopy cover (CC), if different from the maximum canopy cover that could have been reached without water stress at the start of the simulation period;
- the biomass already produced at the start of the simulation period, if different from zero;
- the initial rooting depth (Z), if different from the maximum rooting depth that could have been reached without water stress at the start of the simulation period.

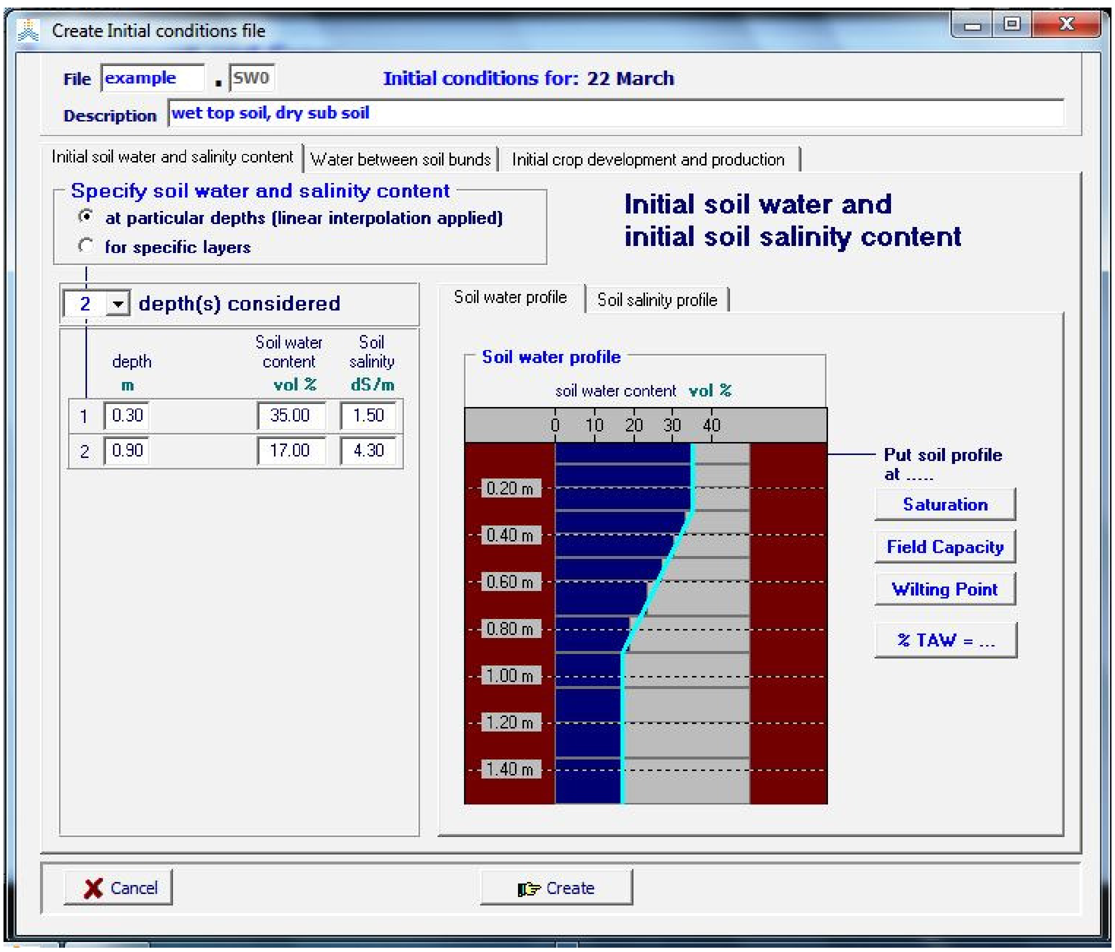


Figure 12.1 – The *Create Initial conditions file* menu

13. Updating results when running a simulation

13.1 Need for an update of simulation results

AquaCrop does not simulate:

- pests, diseases, frost, hail, … destroying part of the green canopy cover (CC) and the above-ground biomass (B) during the season;
- subsurface horizontal water flow, moving water in or out of the soil profile (seepage).

As a consequence CC, B and/or the soil water profile (θ-z) after such an event might be different from what is observed. Therefore AquaCrop Version 5.0 offers the possibility to update CC, B and θ-z at the end of the event day by considering observations or estimates made on that day. After the update, AquaCrop resumes the simulation with the adjusted CC, B and/or θ-z.

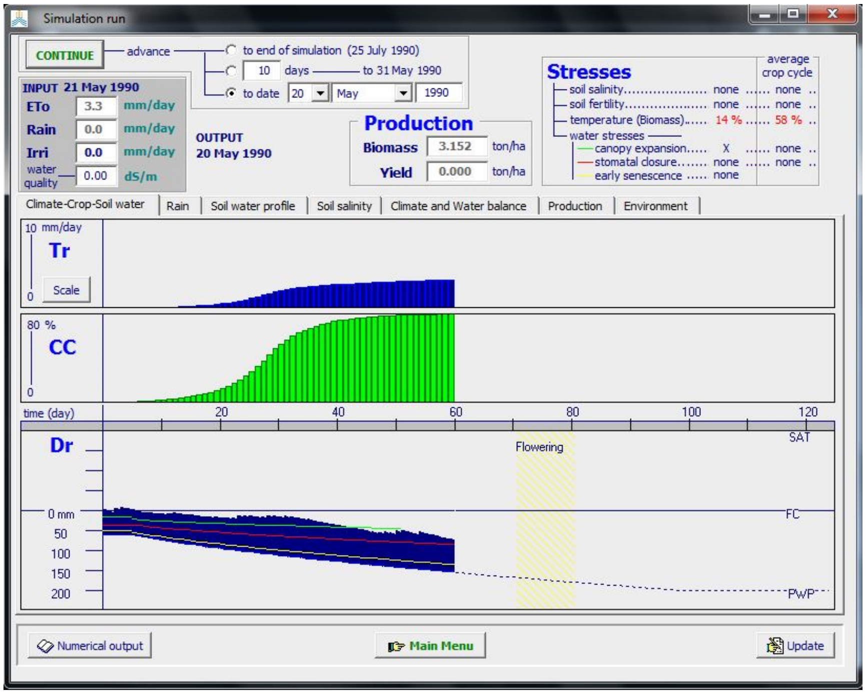
Before such changes are made, the user should check if the mismatch between observations and simulation results is not the result of a wrong setting of non-conservative crop parameters and/or a poor description of the environment in which the crop develops. Only events not simulated in AquaCrop may justify an update. Therefore the user should assure that:

- the rainfall data is collected at or nearby the field;
- the evaporating power of the atmosphere (ETo) is correctly determined;
- the air temperature (which might affects crop development and production) is well defined;
- the crop phenology and life cycle length is fine-tuned to the environment and the crop species;
- the moment of germination or transplanting is correctly specified;
- the moment and duration of flowering is well selected in case of a determinant fruit/grain crop;
- field management, affecting soil surface run-off, reducing soil evaporation (mulches) and crop development and production (soil fertility) is well specified;
- the moment and the net application depth of the various irrigation events are correctly specified;
- the physical soil characteristics of the various soil horizons are well defined;

13.2 Updating simulation results

By specifying in the advance panel, at the top left corner of the ***Simulation run*** menu, the date (selected option: 'to date') at which an update is required at the start of a simulation run, the simulation will be halted at that day (Fig. 13.1a). By clicking subsequently on the **<Update>** command in the menu bar at the bottom of the screen, the user gets access to the ***Update simulation results*** menu. In this menu the user can change for that day, the status of the soil water content in the soil profile (Fig. 13.2a), the green Canopy Cover and the above-ground dry biomass (Fig 13.2b). When returning to the ***Simulation run*** menu, any update will be considered after resuming the simulation (Fig. 13.1b).

(a)



(b)

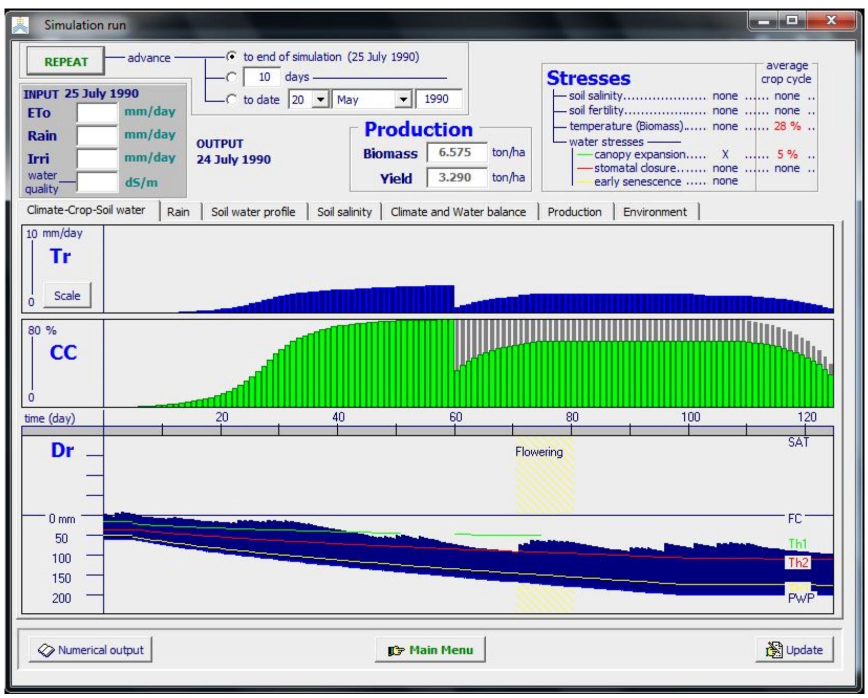
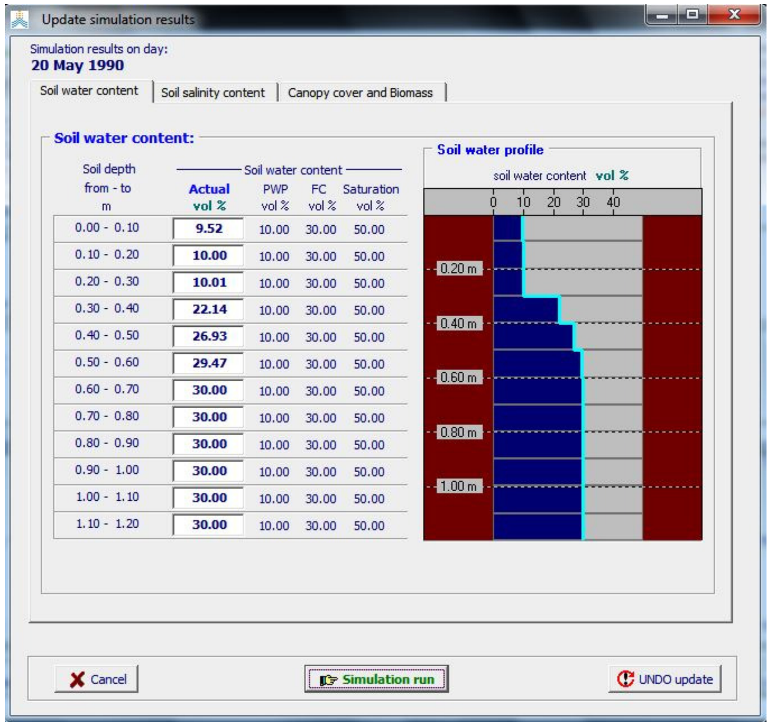


Figure 13.1 – Simulated Crop transpiration (Tr), green Canopy cover (CC) and root zone depletion (Dr) displayed in the ***Simulation run*** menu (a) before the update on 20 May 1990 (in the ***Update simulation results*** menu), and (b) and at the end of the simulation run.

(a)



(b)

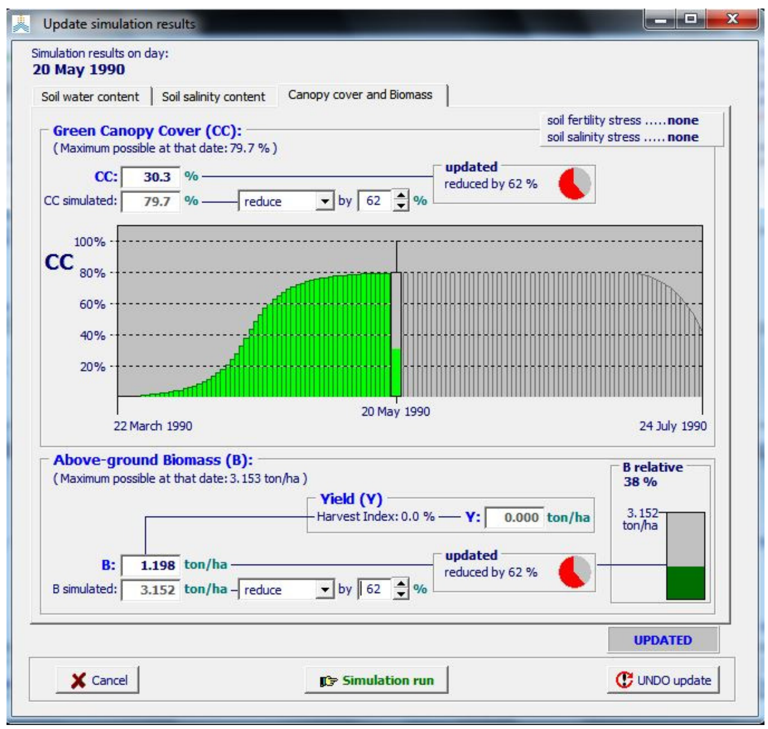


Figure 13.2 – The (a) actual soil water content and (b) green Canopy Cover and above-ground Biomass on 20 May 1990, as simulated and/or updated in the ***Update simulation results*** menu.

13.3 Guidelines for the update of CC, B and/or θ

- It is possible to adjust the simulated CC with a value larger than the maximum CC that can be reached on that day. However since this is the maximum CC that can be obtained under the given environmental conditions, it is advised to verify first the non-conservative parameters in the crop file (the crop phenology and life cycle length might not be fully fine-tuned to the environment), air-temperature data in the climate file (too low air temperature might have reduced the speed of canopy expansion) and/or soil fertility settings in the field management file (soil fertility stress might be different from what is assumed) before making such changes;
- Before germination or transplanting any update of CC is disregarded. Verify, if required, the moment of germination or transplanting;
- If the crop is a determinant fruit/grain crop (i.e. a crop in which life cycle a clear distinction is made between the vegetative and reproduction stage), AquaCrop disregard any increase in CC after mid flowering (which is the end of the vegetative stage), even when the maximum CC (CC_x) was not yet reached. Verify, if required, the moment and duration of flowering;
- It is possible to adjust the simulated B with a value larger than the maximum B that can be produced on that day. However since this maximum B is the one that can be obtained under optimal conditions for the given weather conditions, it is advised first to verify the non-conservative parameters in the crop file (crop phenology and life cycle length might not be fully fine-tuned to the environment), and/or air temperature data in the climate file (too low air temperature might have reduced the biomass production) before making such changes;
- Yield (Y) cannot be updated directly during the simulation run. However, by considering the displayed HI, the user can calculate the corresponding B (i.e. Y/(0.01*HI)) and adjust the simulated B accordingly. Note however that before the reproductive stage HI is always zero;
- The simulated soil water contents (θ) in each of the (maximum 12) soil compartments (as displayed in the 'Soil water profile' tab-sheet of the ***Simulation run*** menu) can be updated. For reference the soil water content at Permanent Wilting Point (θ_{PWP}) and at saturation (θ_{SAT}) of the soil horizon at that depth, and the depth of the center of the soil compartment below soil surface are displayed. It is possible to adjust θ out of the $\theta_{PWP} – \theta_{SAT}$ range. However since θ can only fluctuate between this range, it is advised to check the physical soil characteristics of the various soil horizons before making changes out of the range. Note that at the top of the soil profile θ can drop below θ_{PWP} since the surface layer can become air dry due to soil evaporation. The soil water content at air-dry is half of the water content at permanent wilting point ($\theta_{air\ dry} = \theta_{PWP}/2$).

13.4 Structure of 'ExchangeData.SIM' file in the SIMUL folder

To allow updates, AquaCrop records the simulated CC, B and θ-z in a specific file. This is done each time when the program waits to advance to the next step (this is the case when a simulation does not go right to the end but advances with time steps of 'n' days, or when the user request to advance the simulation to a particular date in the season). While AquaCrop waits to resume the simulation in the next time step, the recorded data are displayed and can be updated in the ***Update simulation results*** Menu (accessed by means of the **<Update>** command in the menu bar of the

Simulation run Menu. After the update and before resuming the simulation in the next time step(s), AquaCrop reads the updated data and adjust CC, B and/or θ-z accordingly.

The file in which the simulated CC, B and θ-z are recorded is the 'ExchangeData.SIM' file in the SIMUL folder of AquaCrop. The content and structure of the file are given in Table 13.1, while an example of file content is given in Table 13.2. The file contains next to the values that can be altered (the actual CC (first number at line 2), the actual B (first number of line 3), and the actual θ's (first numbers of lines 4 till end)), a lot of information for reference.

Table 13.1 – Content and structure of 'ExchangeData.SIM' file in the SIMUL folder of AquaCrop opened when an update is requested

Line	Content
1	**<u>Date and Project information:</u>** • Day; • Month; • Year; • Run number (i.e. 1 for Single run projects or in the absence of a project) • Project file name ('(None)' if absent)
2	**<u>Green Canopy Cover (CC):</u>** • Simulated CC [%]; • Maximum CC [%] that can be reached on that day by considering the canopy development (without water stress) as specified in the Crop file, but adjusted to soil fertility stress as specified in the field management file.
3	**<u>Dry above-ground Biomass (B) and Harvest Index (HI):</u>** • Simulated B [ton/ha]; • Maximum B [ton/ha] that can be produced on that day by considering crop development under optimal conditions without any stress (water stress, soil fertility stress, salinity stress, ..) for the given climatic conditions; • HI [%] by considering its building up during the growing cycle (as specified in the crop file) and its adjustment to water and/or air temperature stress.
4 till end	**<u>Soil water content (θ) at various depths in the soil profile:</u>** • Simulated θ [volume %]; • Soil water content [volume %] at permanent wilting point (θ_{PWP}) for the soil horizon at that depth; • Soil water content [volume %] at field capacity (θ_{FC}) for the soil horizon at that depth; • Soil water content [volume %] at saturation (θ_{SAT}) for the soil horizon at that depth; • Depth [m] in the soil profile.

Table 13.2 – Example of 'ExchangeData.SIM' file of the SIMUL folder of AquaCrop before an update.

```
   20   5  1990    1  (None)
   79.6524   79.6524
    3.1523    3.1528      0.00
    9.5161   10.0000   30.0000   50.0000   0.05
   10.0000   10.0000   30.0000   50.0000   0.15
   10.0113   10.0000   30.0000   50.0000   0.25
   22.1355   10.0000   30.0000   50.0000   0.35
   26.9343   10.0000   30.0000   50.0000   0.45
   29.4654   10.0000   30.0000   50.0000   0.55
   30.0000   10.0000   30.0000   50.0000   0.65
   30.0000   10.0000   30.0000   50.0000   0.75
   30.0000   10.0000   30.0000   50.0000   0.85
   30.0000   10.0000   30.0000   50.0000   0.95
   30.0000   10.0000   30.0000   50.0000   1.05
   30.0000   10.0000   30.0000   50.0000   1.15
```

If CC, B or the soil water content (θ) at various depths are updated in the ***Update simulation results*** menu, the content of the 'ExchangeData.SIM' file is altered (Table 13.3). The altered file contains only the values that can been changed (CC, B and θ's) and codes to signal an updated. CC, B and θ's are followed by '1' if an update was made, and by '0' if the values remained unaltered. At the start of the next time step, AquaCrop reads only the updated values.

Table 13.3 – Example of 'ExchangeData.SIM' file of the SIMUL folder of AquaCrop after an update.

```
updated
   30.2679 1
    1.1979 1
    9.5161 0
   10.0000 0
   10.0113 0
   22.1355 0
   26.9343 0
   29.4654 0
   30.0000 0
   30.0000 0
   30.0000 0
   30.0000 0
   30.0000 0
   30.0000 0
```

14. Simulations with 'Hot starts'

14.1 Hot starts within the growing cycle

When a simulation finishes within the growing cycle, the final simulation results are saved for the next simulation run. It consists of the water and salinity content in the soil profile, and the status of crop development and production simulated at the last day of the simulation run. If the first day of the next run, neatly succeeds the last day of the previous run, AquaCrop (version 5.0) recognises a 'hot start' and loads the saved final simulation results of the previous run. As such the conditions at the end of the previous run become the initial conditions for the simulation run.

A hot start is the default option when running successive simulations within the growing cycle (Fig. 14.1).

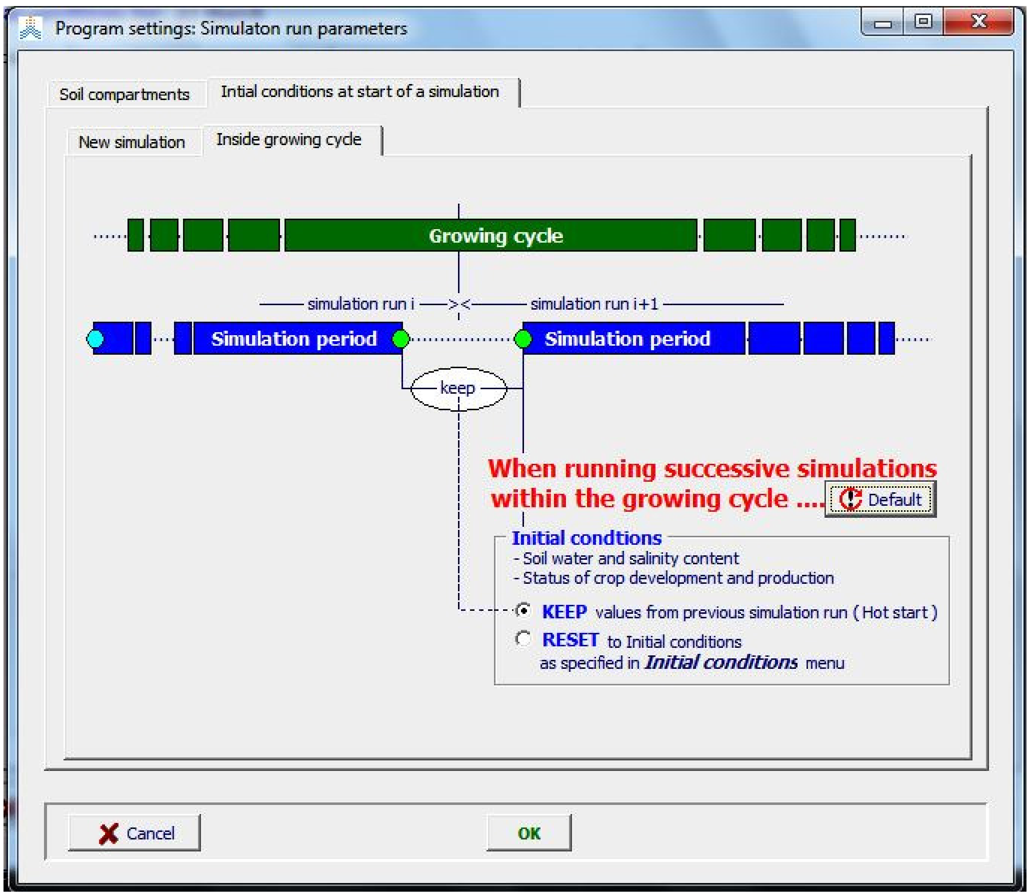


Figure 14.1 – Default option for the initial conditions when running successive simulation runs within the growing cycle ('KEEP values from previous simulation run (Hot start)'), in the *Program settings: Simulation run parameters* menu.

14.2 Examples of 'hot starts'

Hot starts are useful when running AquaCrop to obtain a first yield estimate before the end of the ongoing season, or to assess the irrigation requirement for the next part of the season. The procedure consists in running a series of successive simulations with different climate files, and eventually different irrigation management files.

In the example of Fig. 14.2, the first simulation runs till day i of the season with observed weather data for that period, the second simulation runs for the next n days with a weather forecast, and the third simulation runs from day (i+n+1) till the end of the growing cycle with historical climatic data. By repeating the exercise with different historical climatic data for simulation run 3, the range within which the yield or the irrigation requirement can vary is obtained. As the season advances, the series of observed weather data become longer, and the estimates become more accurate.

When assessing the irrigation requirement for the remaining part of the season, each of the three simulation runs can have its own irrigation management file. For example, it can consists of a file with the observed 'irrigation schedule' in run 1, (ii) a file with criteria to 'generate an irrigation schedule' in run 2, and a file with the option to 'determine net irrigation requirement' in run 3.

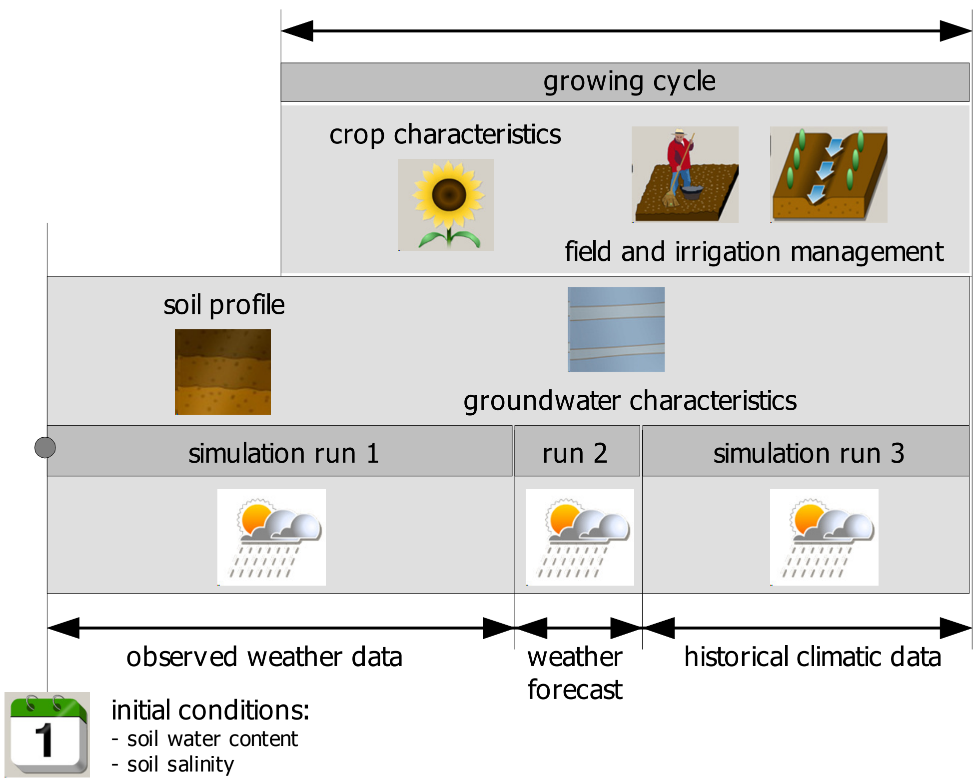


Figure 14.2 – Three successive simulations within one growing cycle, each with its own climate file.

14.3 Running successive simulations within the growing cycle (no projects)

Step 1. – Select a crop;

Step 2. – Specify the planting/sowing date;

Step 3. – Specify the environment. The description of the environment consists in accepting the default settings or in selecting an appropriate Climate file, Irrigation management file, Field management file, Soil profile file, Groundwater file, and/or Initial conditions file (Fig. 14.3);

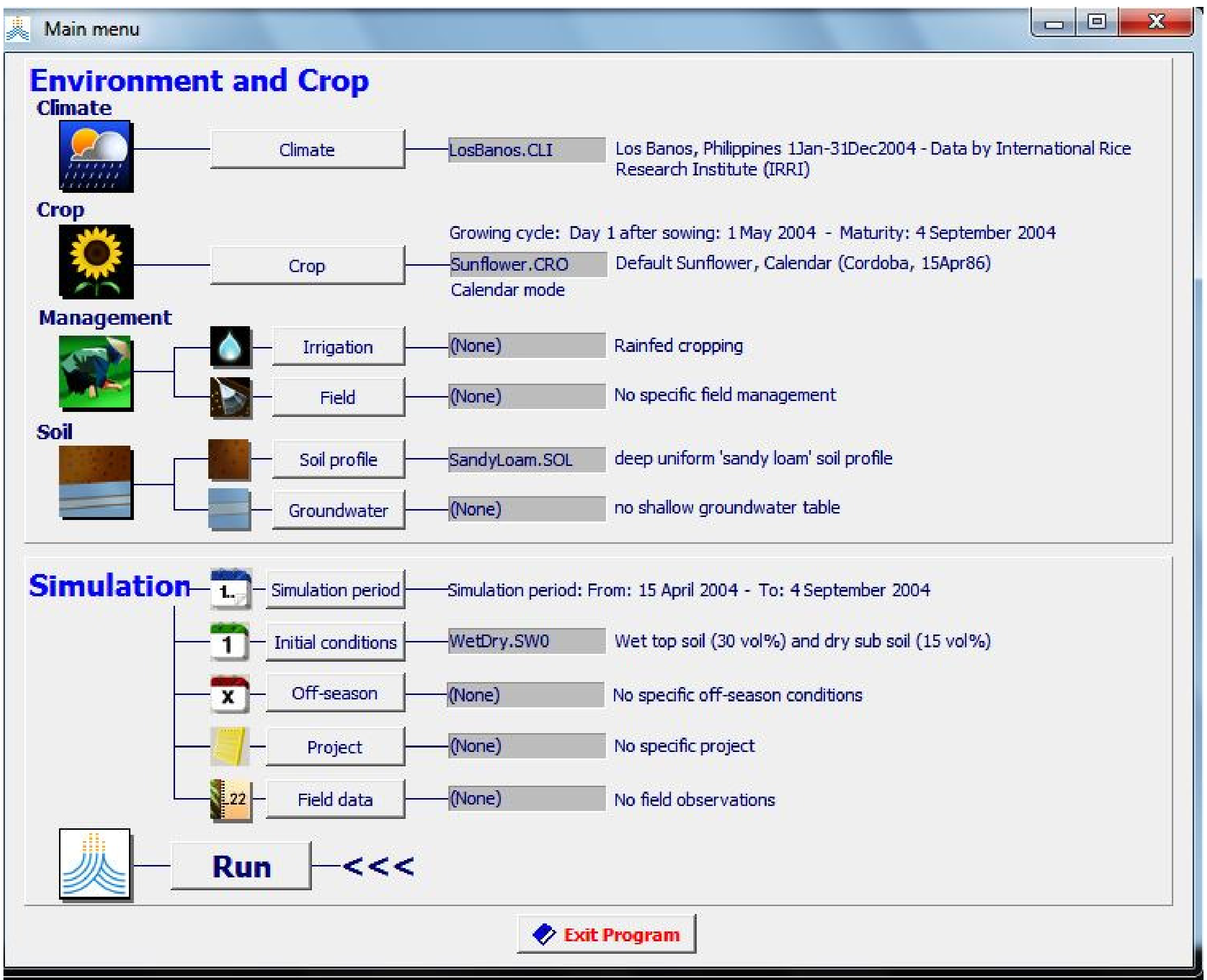


Figure 14.3 – Display of the selected crop, sowing date and environmental conditions in the *Main menu* of AquaCrop.

Step 4. – Specify the simulation period for the first run (Fig. 14.4):

- From (first day): The simulation period may start before, at, or after the planting/sowing date. It is the day for which the specified conditions in the ***Initial conditions*** menu are valid;
- To (last day): When running a series of successive runs within the growing cycle, it is recommended to select the end of the growing cycle (or a later day) as the last day of the simulation period. This facilitates the settings for the successive simulation run(s) in Step 10;

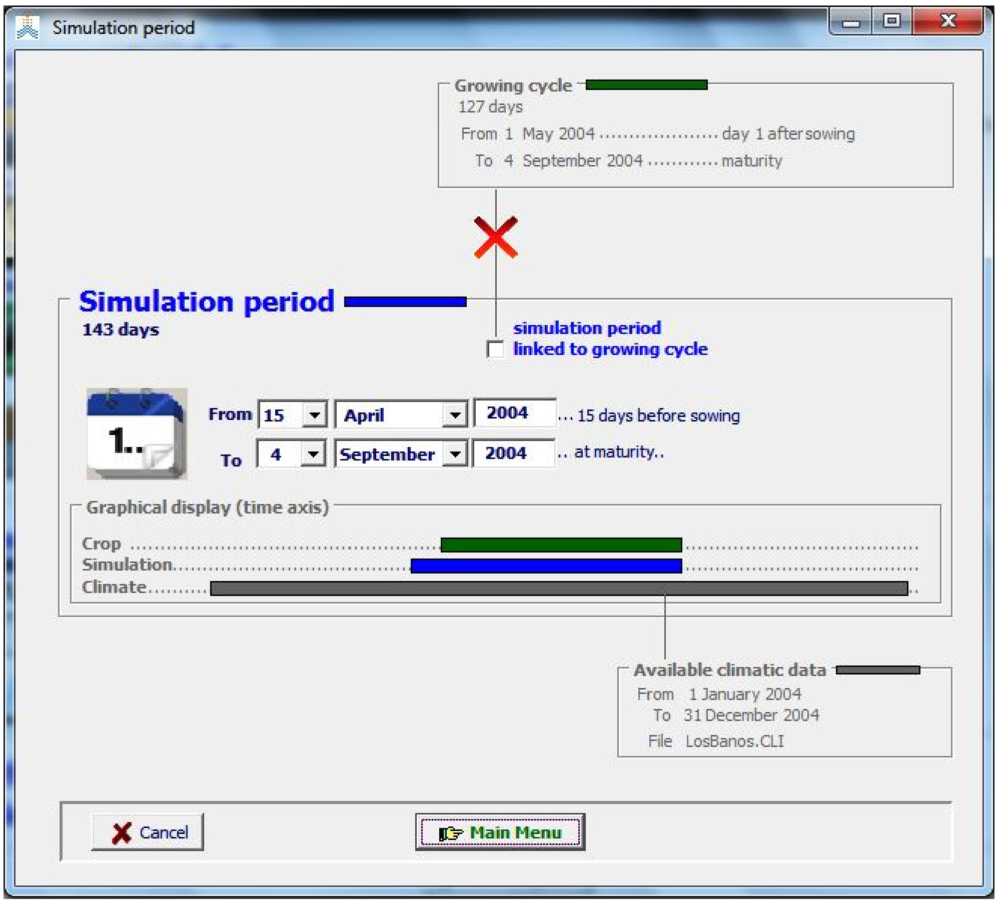


Figure 14.4 – Specification of the first and last day of the first simulation run, within a series of successive runs within the growing cycle, in the *Simulation period* menu.

Repeat till end of growing cycle (Step 5 till 10):

Step 5. – Start the simulation by selecting the **<Run>** command in the ***Main menu***;

Step 6. – Specify in the advance panel, at the top left corner of the ***Simulation run*** menu (Fig. 14.5a), either a date (selected option: 'to date: ') or the number of days with which the simulation has to advance (selected option: 'n days'). A hot start will be possible for the next run, when the advance date is smaller than the last day of the growing cycle. When in simulation run the conditions for a hot start at the start of the run are fulfilled, the '●: hot start' message is displayed in the advance panel (Fig. 14.5b);

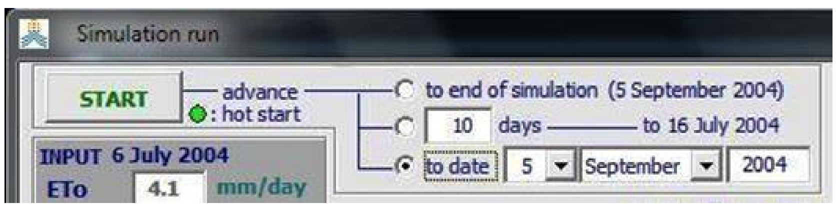
(a)	
(b)	

Figure 14.5 –Specification of the date, at the start of a simulation, to which the simulation run has to advance, in the advance panel of the *Simulation run* menu.

Step 7. – Start the simulation, which will stop at the date specified in the advance panel (Fig. 14.6);

Step 8. – Exit the ***Simulation run*** menu, and return to the ***Main Menu***. If the simulation was halted within the growing cycle (after the sowing/plant day and before the end of the growing cycle), a hot start will be possible in the next run and the simulated final conditions are kept. In the ***Main menu*** the message 'hot start pending' will be displayed below the Simulation period.

Step 9. – Adjust if required the environmental conditions in the ***Main menu*** (e.g. select another climate, irrigation management and/or field management file);

Step 10. – Specify the simulation period for the successive run (Fig. 14.7):

- From (first day): To fulfil the requirements for a 'hot start', the first day of a next simulation period should be equal to the last day of the previous run. To facilitate the selection, AquaCrop displays this 'hot start' day in the ***Simulation period*** menu. By checking the 'hot start' check-box, the last day of previous run becomes the first day of the next run;
- To (last day): The last day needs not to be redefined if it was already set at the end of the growing cycle (or a later day) in the initial selection (Step 4 and Fig. 14.4).

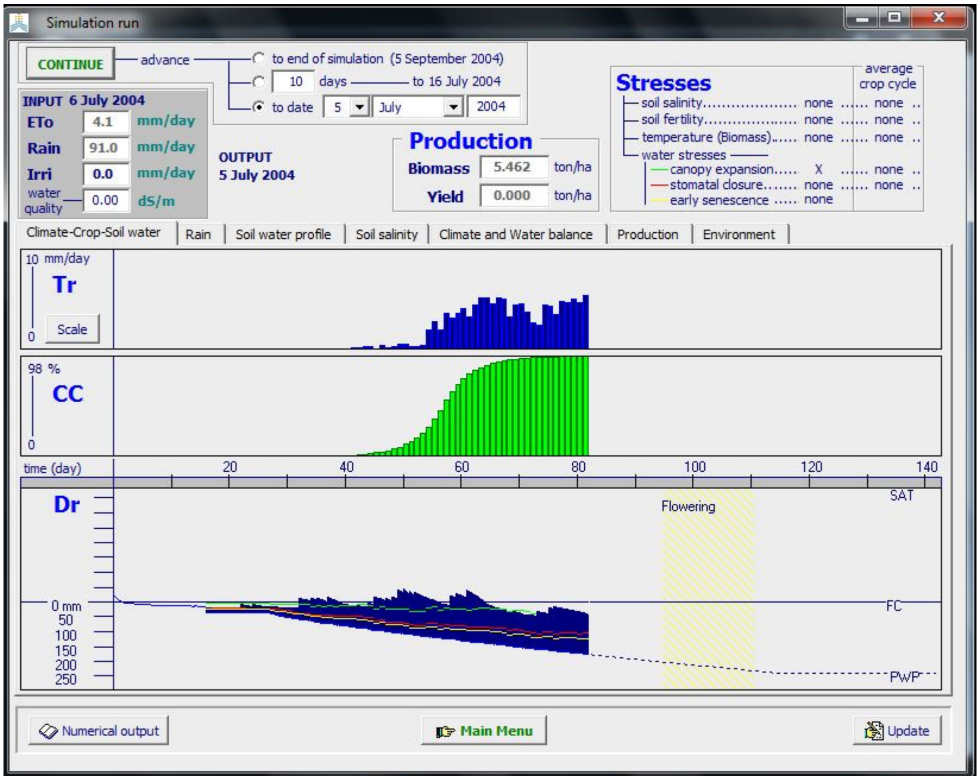


Figure 14.6 – End of the simulation within the growing cycle.

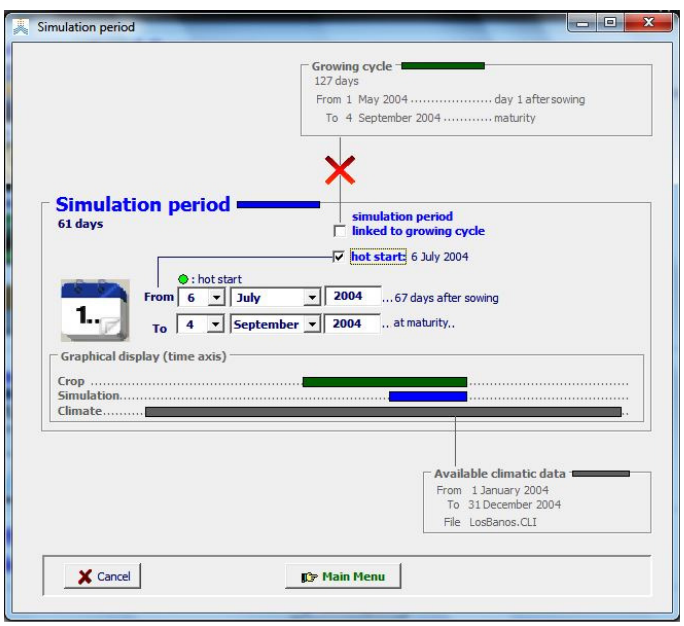


Figure 14.7 – Specification of the first and last day of a successive simulation period within the growing cycle, in the *Simulation period* menu.

14.4 Running successive simulations within the growing cycle with the help of projects

Actual shortcoming: - When creating single projects in AquaCrop, (i) the first day of the simulation period cannot be taken later than the sowing/planting plant, and (ii) the end of the simulation period is automatically taken as the last day of the growing cycle (crop maturity). This still needs to be adjusted, but as long as this is not yet done the procedure is somewhat cumbersome and not straightforward.

Step 1. – Create as much single projects as planned simulations within the growing cycle.

It consists in selecting a crop file with a planting date and in specifying the environment. The description of the environment consists in selecting an appropriate Climate file, Irrigation management file, Field management file, Soil profile file, Groundwater file, and/or Initial conditions file. To fulfil the conditions for a hot start between the successive simulation runs, the crop file, the planting date, the soil profile and groundwater file in all projects should be identical.

In the project which will be used for the first of a series of successive simulation runs, the simulation starts at the day for which the conditions specified in the ***Initial conditions*** menu are valid. The last day of the simulation period is automatically crop maturity.

For the second, third, … project, keep at this stage the same settings for the simulation period as for the first run, but select the appropriate climate files, irrigation management files, and/or field management files (which may be different from the files specified in the first project). These files describe the specific environment (valid from their starting day, which still need to be adjusted in Step 2) during their part of the simulation.

Step 2. – Update in each of the created projects, the (i) first and (ii) last day of the simulation period (Fig. 14.8 and 14.9). The first day follows the last day of the previous run, and the last day is the day before the first day of the next run of the series of successive runs within the growing cycle.

An alternative for step 2 consists in adjusting the first and last day of the simulation period directly in the project files (see Section 2.21 'input files' of Chapter 2 of the reference manual of AquaCrop for the structure of the project file). Note that AquaCrop uses day numbers to specify the start and end of the simulation period and of the growing cycle. The day number refers to the days elapsed since 0^{th} January 1901 at 0 am. The calculation procedure is given in Table 14.1 and the code in Table 14.2.

Step 3. – Run the projects one after the other. Since the first day of the next run neatly follows the last day of the previous runs, a 'hot start' is recognized and applied as long as the successive runs of the series remain within the same growing cycle.

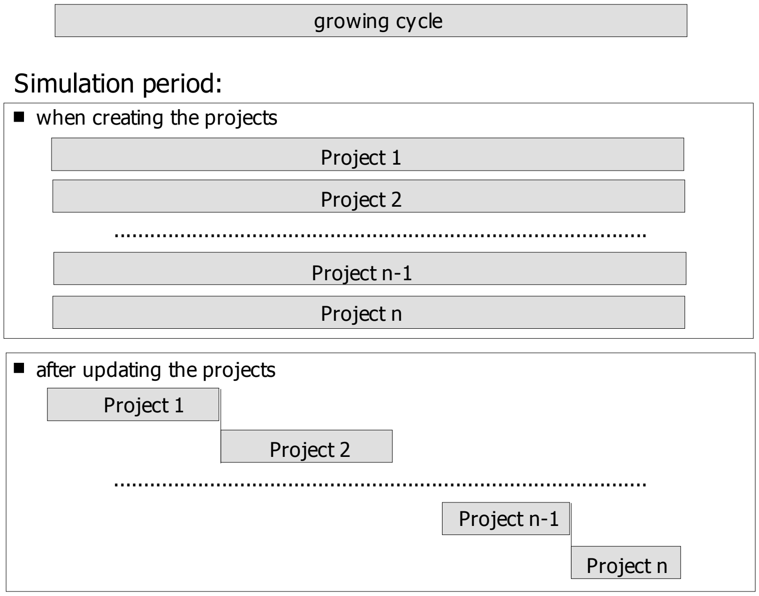


Figure 14.8 – Specification of the first and last day of the simulation period in a series of successive simulation runs within the growing cycle.

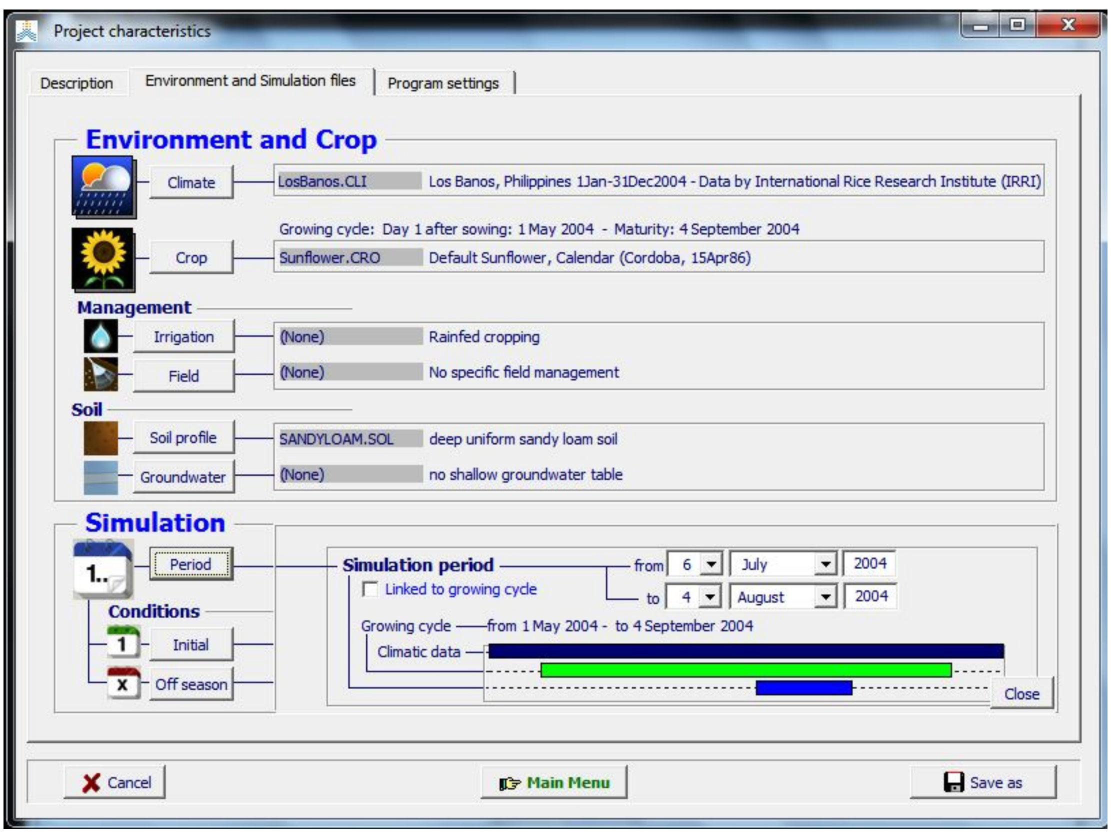


Figure 14.9 – Update of the first and last day of the simulation period of a project, in the *Project characteristics* menu.

Table 14.1 – Number of days elapsed since 0^{th} January 1901, 0 am

Validity: The method is valid from 1901 to 2099 only (time range in AquaCrop)
Rules 1. Subtract 1901 from the year 2. Multiply by 365.25 3. According to the month add: - January : 0 - February : 31 - March : 59.25 - April : 90.25 - May : 120.25 - June : 151.25 - July : 181.25 - August : 212.25 - September : 243.25 - October : 273.25 - November : 304.25 - December : 334.25 4. Add the number of the day within the month 5. Take the integer
Example For 24 August 1982

1. Subtract 1901 from the year	1982 – 1901 = 81
2. Multiply by 365.25	81 x 365.25 = 29585.25
3. Add 212.25 for August	29585.25 + 212.25 = 29797.5
4. Add the number of the day	29797.5 + 24 = 29821.5
5. Take the integer	29821

Table 14.2 – Calculation code to derive a day-number from a given date (day/month/year)

```
CONST ElapsedDays :
ARRAY[1..12]      of      double      =      (0,31,59.25,90.25,120.25,151.25,181.25,
212.25,243.25,273.25,304.25,334.25);

INPUT: Dayi  : DD (Integer); Monthi : MM (Integer); Yeari   : YYYY (Integer);
OUTPUT:   DayNr (LongInt);
PROCEDURE DetermineDayNr (Dayi,Monthi,Yeari : INTEGER;
                                             VAR DayNr : Longint);
BEGIN
DayNr := TRUNC((Yeari - 1901)*365.25 + ElapsedDays[Monthi] + Dayi + 0.05);
END; (* DetermineDayNr *)
```

14.5 Conditions for a hot start

Hot starts can be initiated when the default option is selected for the initial conditions of successive simulation runs within the growing cycle. It is the 'KEEP values from previous simulation run (Hot start)' in the ***Program settings: Simulation run parameters*** menu (Fig. 14.1)

A hot start is pending when a simulation finishes before the end of the growing cycle (maturity) was reached. Simulation results, valid at the last day of the run, will be saved for the next run.

A hot start is recognized and applied at the start of a simulation run, if:

- the end of the previous run was before the end of the growing cycle;
- the first day of the simulation period, follows neatly the last day of the previous run;

and if between the previous and actual simulation run:

- the initial conditions were not altered in the ***Initial conditions*** Menu;
- the selected soil file and the soil characteristics were not altered;
- the selected crop file and the crop characteristics were not altered.

15. Evaluation of simulation results

15.1 Evaluation of simulation results menu

When running a simulation, users can evaluate the simulation results with the help of field data stored in an observation file (see 2.19 Field observations in the reference manual). The user gets access to the ***Evaluation of simulation results*** menu by selecting the **<Field data>** command in the command panel of the ***Simulation run*** menu (Fig. 15.1).

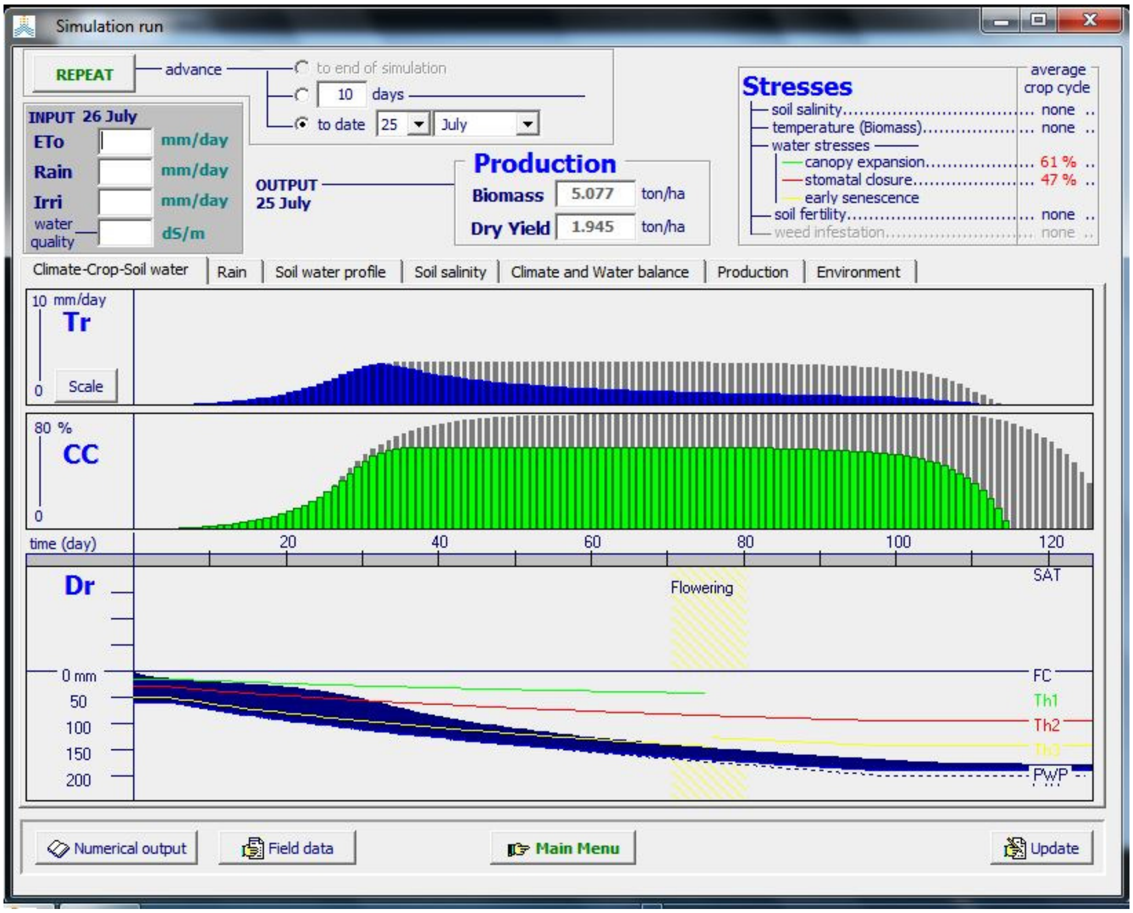


Figure 15.1 – The *Simulation run* menu with the <Field data> command in the command panel

- **Graphical and numerical displays**

For each of the 3 sets of field observations (Canopy Cover, Biomass and Soil water content) the user finds in the ***Evaluation of simulation results*** menu:

1. A graphical display where the simulated and observed (with their standard deviations) values are plotted (Fig. 15.2);
2. A numerical display where the simulated and observed values (with their standard deviations) are displayed; and
3. Statistical indicators evaluating the simulation results (Fig. 15.3).

- **Save results**

On exit of the Simulation Run menu, the option is available to save the evaluation of the simulation results in 2 output files (Fig. 15.4):

Data output file: which contain for each day of the simulation period the simulated green canopy cover (CC), biomass (B) and soil water content (SWC), and the observed field data (with their standard deviation);

Statistics output file: which contain the statics of the evaluation of the simulation results for Canopy Cover, biomass and soil water content (see section 15.2).

- **Statistical indicators**

The statistical indicators (see section 15.2) available to assess the simulation results with field data are:

- Pearson correlation coefficient (r);
- Root mean square error (RMSE);
- Normalized root mean square error (CV(RMSE));
- Nash-Sutcliffe model efficiency coefficient (EF);
- Wilmott's index of agreement (d).

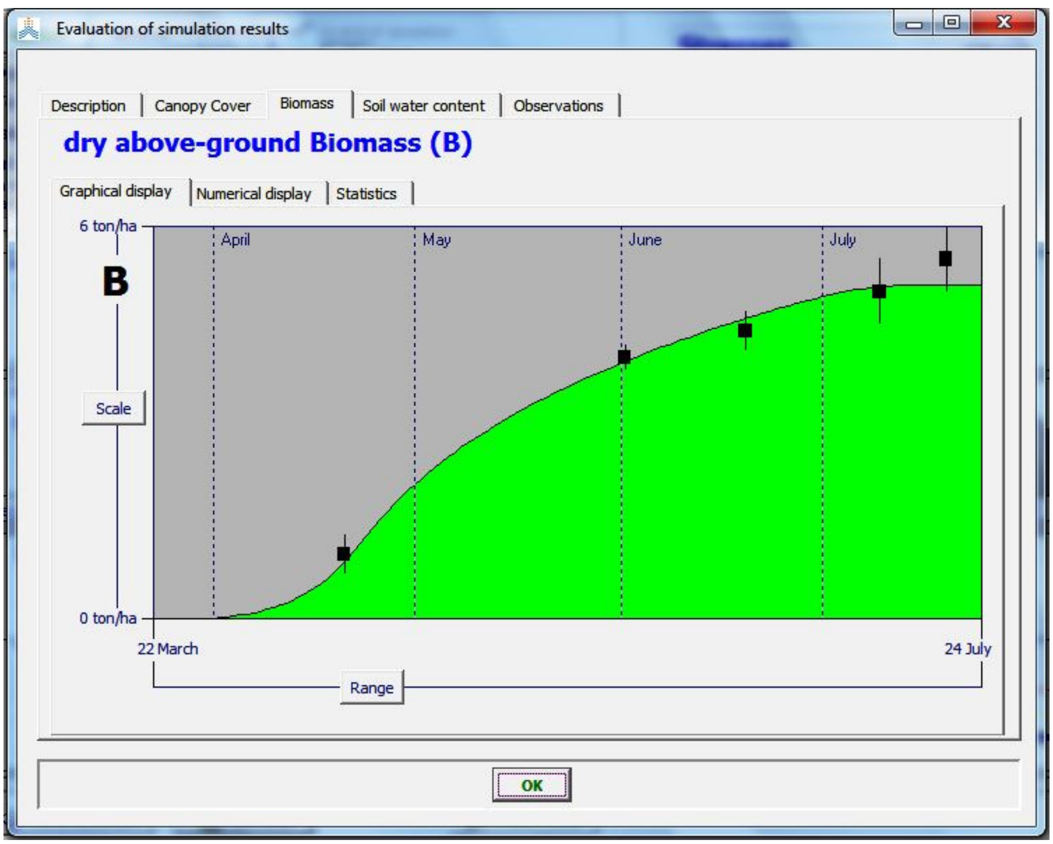


Figure 15.2 – Simulated (line) and observed (dots) dry above-ground Biomass with their standard deviations (vertical lines) in the *Evaluation of simulation results* menu.

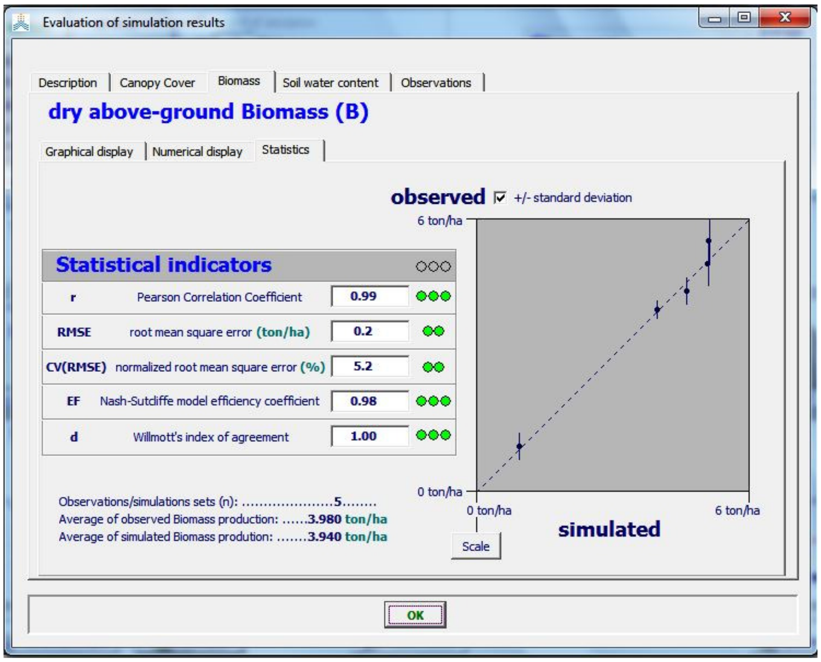


Figure 15.3 – Statistical indicators for the assessment of the simulated dry above-ground Biomass in the *Evaluation of simulation results* menu

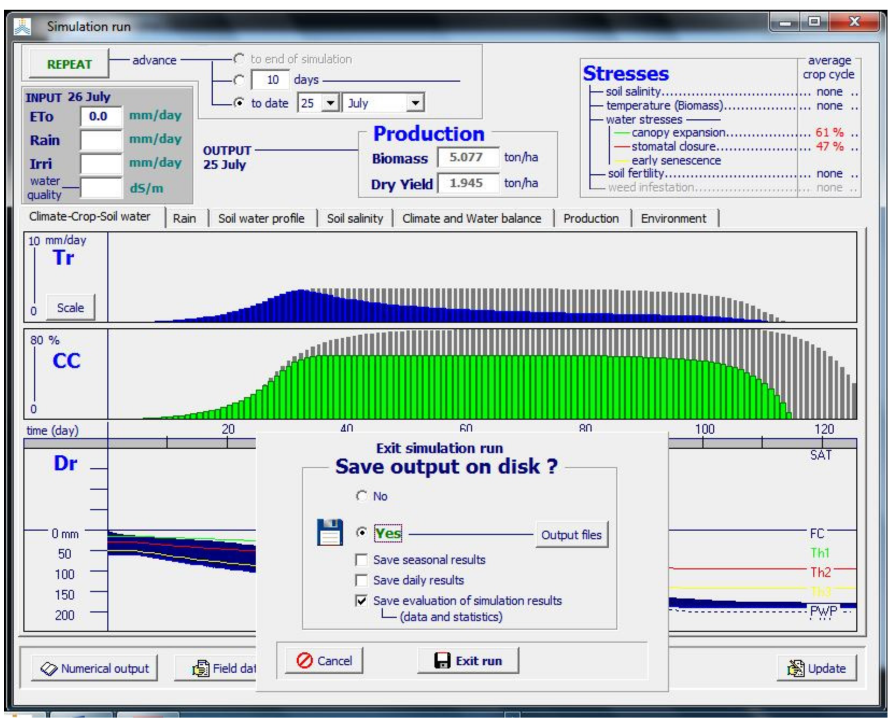


Figure 15.4 – Presented options for saving output on disk, when exiting the *Simulation run* menu.

15.2 Statistical indicators

Evaluation of model performance is important to provide a quantitative estimate of the ability of the model to reproduce an observed variable, to evaluate the impact of calibrating model parameters and compare model results with previous reports (Krause et al., 2005). Several statistical indicators are available to evaluate the performance of a model (Loague and Green, 1991). Each has its own strengths and weaknesses, which means that the use of an ensemble of different indicators is necessary to sufficiently assess the performance of the model (Willmott, 1984; Legates and McCabe, 1999). In the equations 15a to 15e, O_i and P_i are the observations and predictions respectively, $\bar{O}$ and $\bar{P}$ their averages and n the number of observations.

Pearson correlation coefficient (r)

The Pearson correlation coefficient ranges from -1 to 1, with values close to 1 indicating a good agreement:

$$= \left[\frac{\sum(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum(O_i - \bar{O})^2 \sum(P_i - \bar{P})^2}}\right] \quad (15a)$$

A major drawback of r and its squared value (r^2) is that only the dispersion is quantified, which means that a model which systematically overestimates (or underestimates) the observations can still have a good r^2 value (Krause et al., 2005). Willmott (1982) also stated that within the context of atmospheric sciences both r and r^2 are insufficient and often misleading when used to evaluate model performance. Analysis of the residual error (the difference between model predictions and observations: $P_i - O_i$) is judged to contain more appropriate and insightful information.

The correlation coefficient (r) ranges from -1 to 1, with values close to 1 indicating a good agreement. The following interpretation for r is used in AquaCrop. It is somewhat arbitrary and hence should be regarded as an indication.

Value for r	Interpretation	Color code
≥ 0.90	Very good	●●● (green)
0.80 – 0.89	Good	●● (green)
0.70 – 0.79	Moderate good	● (green)
0.50 – 0.69	Moderate poor	● (red)
0 – 0.49	Poor	●● (red)
< 0	Very poor	●●● (red)

Root Mean Square Error (RMSE)

The root mean square error or RMSE is one of the most widely used statistical indicators (Jacovides and Kontoyiannis, 1995) and measures the average magnitude of the difference between predictions and observations. It ranges from 0 to positive infinity, with the former indicating good and the latter poor model performance. A big advantage of the RMSE is that it summarizes the mean difference in the units of P and O. It does however not differentiate between over- and underestimation.

$$RMSE = \sqrt{\frac{\sum (P_i - O_i)^2}{n}} \quad (15b)$$

A disadvantage of RMSE is the fact that the residual errors are calculated as squared values, which has the result that higher values in a time series are given a larger weight compared to lower values (Legates and McCabe, 1999) and that the RMSE is overly sensitive to extreme values or outliers (Moriasi et al., 2007). This is in fact a weakness of all statistical indicators where the residual variance is squared, including EF and Willmott's d which are discussed below.

Normalized Root Mean Square Error (CV(RMSE))

Because RMSE is expressed in the units of the studied variable, it does not allow model testing under a wide range of meteo-climatic conditions (Jacovides and Kontoyiannis, 1995). Therefore, RMSE can be normalized using the mean of the observed values ($\bar{O}$). The normalized RMSE (CV(RMSE)) is expressed as a percentage and gives an indication of the relative difference between model and observations.

$$CV\,(RMSE) = \frac{1}{\bar{O}} \sqrt{\frac{\sum (P_i - O_i)^2}{n}}\, 100 \qquad (15c)$$

A simulation can be considered excellent if CV(RMSE) is smaller than 10%, good if between 10 and 20%, fair if between 20 and 30% and poor if larger than 30% (Jamieson, 1991).

The following interpretation for CV(RMSE) (and the corresponding RMSE) is used in AquaCrop. It is somewhat arbitrary and hence should be regarded as an indication.

Value for NRMSE	Interpretation	Color code
≤ 5%	Very good	●●●
6 – 15%	Good	●●
16 – 25%	Moderate good	●
26 – 35%	Moderate poor	●
36 – 45%	Poor	●●
> 46%	Very poor	●●●

Nash-Sutcliffe model efficiency coefficient (EF)

The Nash-Sutcliffe model efficiency coefficient (EF) determines the relative magnitude of the residual variance compared to the variance of the observations (Nash and Sutcliffe, 1970). Another way to look at it is to say that EF indicates how well the plot of observed versus simulated data fits the 1:1 line (Moriasi et al., 2007). EF can range from minus infinity to 1. An EF of 1 indicates a perfect match between the model and the observations, an EF of 0 means that the model predictions are as accurate as the average of the observed data and a negative EF occurs when the mean of the observations is a better prediction then the model.

$$EF = 1 - \frac{\sum (P_i - O_i)^2}{\sum \left(O_i - \bar{O}\right)^2} \qquad (15d)$$

EF is very commonly used, which means that there is a large number of reported values available in literature (Moriasi et al., 2007). However, like r², EF is not very sensitive to systematic over- or underestimations by the model (Krause et al., 2005).

The Nash-Sutcliffe efficiency coefficient (EF) can range from minus infinity to 1. An EF of 1 indicates a perfect match between the model and the observations, an EF of 0 means that the model predictions are as accurate as the average of the observed data and a negative EF occurs when the mean of the observations is a better prediction the model. The following interpretation for EF is used in AquaCrop. It is somewhat arbitrary and hence should be regarded as an indication.

Value for EF	Interpretation	Color code
≥ 0.80	Very good	●●●
0.60 – 0.79	Good	●●
0.40 – 0.59	Moderate good	●
0 – 0.39	Moderate poor	●
(-10) – 0	Poor	●●
< (-10)	Very poor	●●●

Willmott's index of agreement (d)

The index of agreement was proposed by Willmott (1982) to measure the degree to which the observed data are approached by the predicted data. It represents the ratio between the mean square error and the "potential error", which is defined as the sum of the squared absolute values of the distances from the predicted values to the mean observed value and distances from the observed values to the mean observed value (Willmott, 1984). It overcomes the insensitivity of r^2 and EF to systematic over- or underestimations by the model (Legates and McCabe, 1999; Willmott, 1984). It ranges between 0 and 1, with 0 indicating no agreement and 1 indicating a perfect agreement between the predicted and observed data.

$$d = 1 - \frac{\sum (P_i - O_i)^2}{\sum \left(|P_i - \overline{O}| + |O_i - \overline{O}| \right)^2} \qquad (15e)$$

A disadvantages of d is that relatively high values may be obtained (over 0.65) even when the model performs poorly, and that despite the intentions of Willmott (1982) d is still not very sensitive to systemic over- or underestimations (Krause et al., 2005).

The Wilmott's index of agreement (d) ranges between 0 and 1, with 0 indicating no agreement and 1 indicating a perfect agreement between the predicted and observed data. The following interpretation for d is used in AquaCrop. It is somewhat arbitrary and hence should be regarded as an indication.

Value for d	Interpretation	Color code
≥ 0.9	Very good	●●●
0.80 – 0.89	Good	●●
0.65 – 0.79	Moderate good	●
0.50 – 0.64	Moderate poor	●
0.25 – 0.49	Poor	●●
< 0.25	Very poor	●●●

References

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Legates, D. R., and McCabe, G. J. (1999). Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resources Research 35, 233–241.

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Willmott, C. J. (1984). On the evaluation of model performance in physical geography. In Spatial Statistics and Models, Gaile GL, Willmott CJ (eds). D. Reidel: Boston. 443–460.

Willmott, C. J. (1982). Some Comments on the Evaluation of Model Performance. Bulletin American Meteorological Society 63, 1309–1313.

16. Simulation of surface runoff

Surface runoff is simulated with the curve number method developed by the US Soil Conservation Service (USDA, 1964; Rallison, 1980; Steenhuis et al., 1995):

$$RO = \frac{[P - I_a]^2}{P + S - I_a} \qquad \text{(Eq. 16.1)}$$

$$S = 254\left(\frac{100}{CN} - 1\right) \qquad \text{(Eq. 16.2)}$$

where RO daily amount of water lost by surface runoff [mm];
- P daily rainfall [mm];
- I_a initial abstraction [mm] or the amount of water that can infiltrate before runoff occurs;
- S potential maximum soil water retention [mm], Eq. 16.2;
- CN Curve Number

Updated in AquaCrop Version 5.0:
- the initial abstraction (I_a): $I_a = 0.05$ S (in previous versions, I_a was 0.20 S);
- CN is a soil profile characteristic (CN_{soil}), updated (if required) for field surface practices (field management). The adjustment for management (CN_{man}) is expressed as the percentage increase (positive value) or decrease (negative value) of CN_{soil}:

$$CN = CN_{soil} \left(100 + \frac{CN_{man}}{100}\right) \qquad \text{(Eq. 16.3)}$$

As in previous AquaCrop versions, the CN specified as the soil profile characteristic, is the value for the Antecedent Moisture Class II (CN_{AMCII}). At run time the CN value is adjusted to the simulated soil water content of the top soil layer at run time. The relationships to derive CN_{AMCI} (dry top soil layer) and CN_{AMCIII} (wet top soil layer) are updated for the initial abstraction of 0.05 S:

$$CN_{AMCI} = 1.4\ 10^{-14} + 0.507\ CN_{AMCII} - 0.00374\ (CN_{AMCII})^2 + 0.0000867\ (CN_{AMCII})^3$$
$$CN_{AMCIII} = 5.6\ 10^{-14} + 2.33\ CN_{AMCII} - 0.0209\ (CN_{AMCII})^2 + 0.000076\ (CN_{AMCII})^3$$

As in previous AquaCrop versions, the calculation of the surface runoff can be switched off if field surface practices inhibited surface runoff, or in the presence of soil bunds.

17. Output files

On exit of the ***Simulation run*** menu, the option is available to save the simulation results. Distinction is made between files containing daily simulation results, seasonal results, and evaluation of simulation results (Fig. 17.1). The files are stored by default in the OUTP directory of AquaCrop.

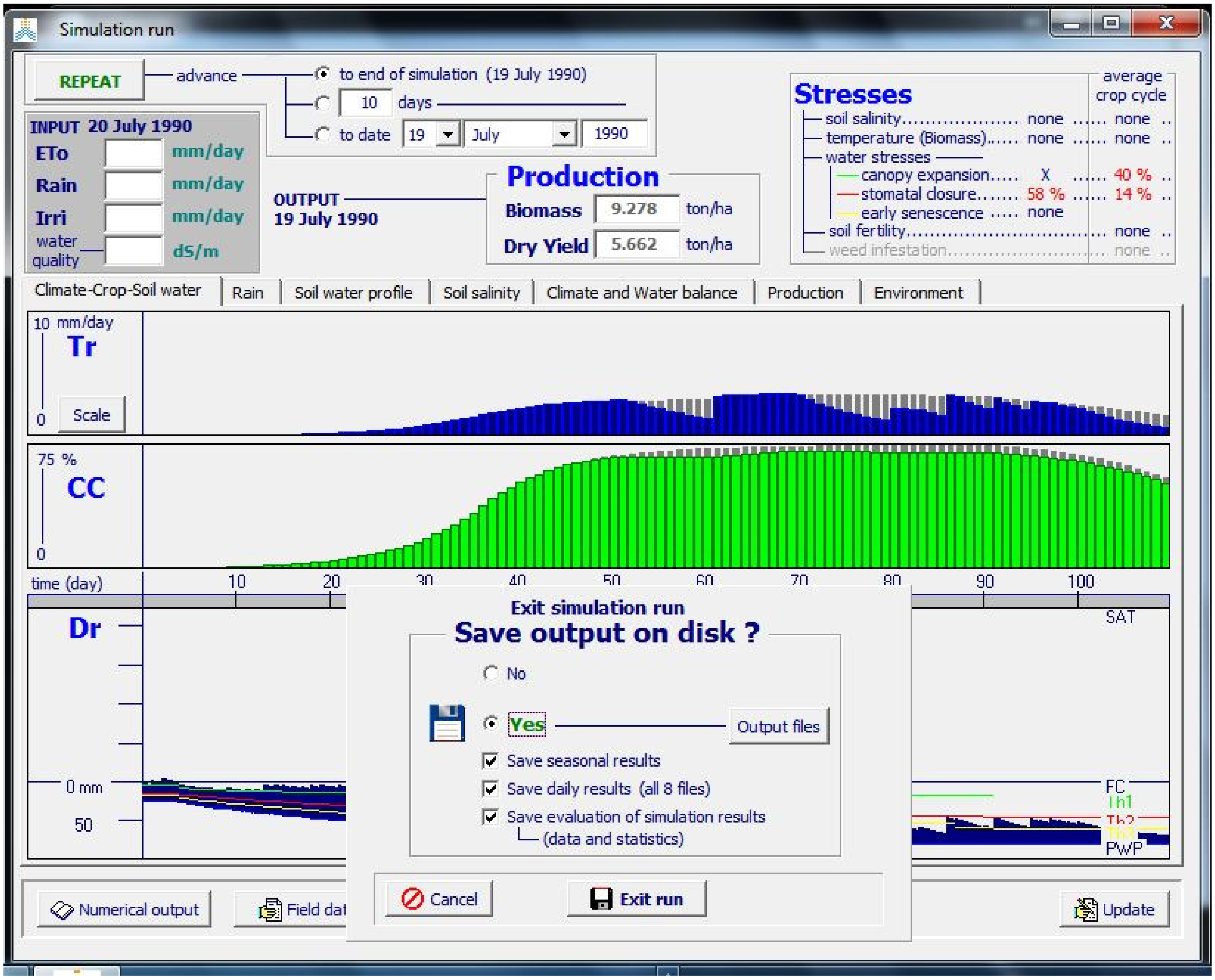

Figure 17.1 – On exit of the *Simulation run* menu, the option to save output on disk becomes available

By selecting the **<Output files>** command in the ***Simulation Run*** menu, the user gets access to the ***Output Files*** menu in which (Fig. 17.2):

- the filenames (and even directories) of the output can be changed (to prevent that the simulation results are overwritten at each run);
- the files can be selected which need to be saved.

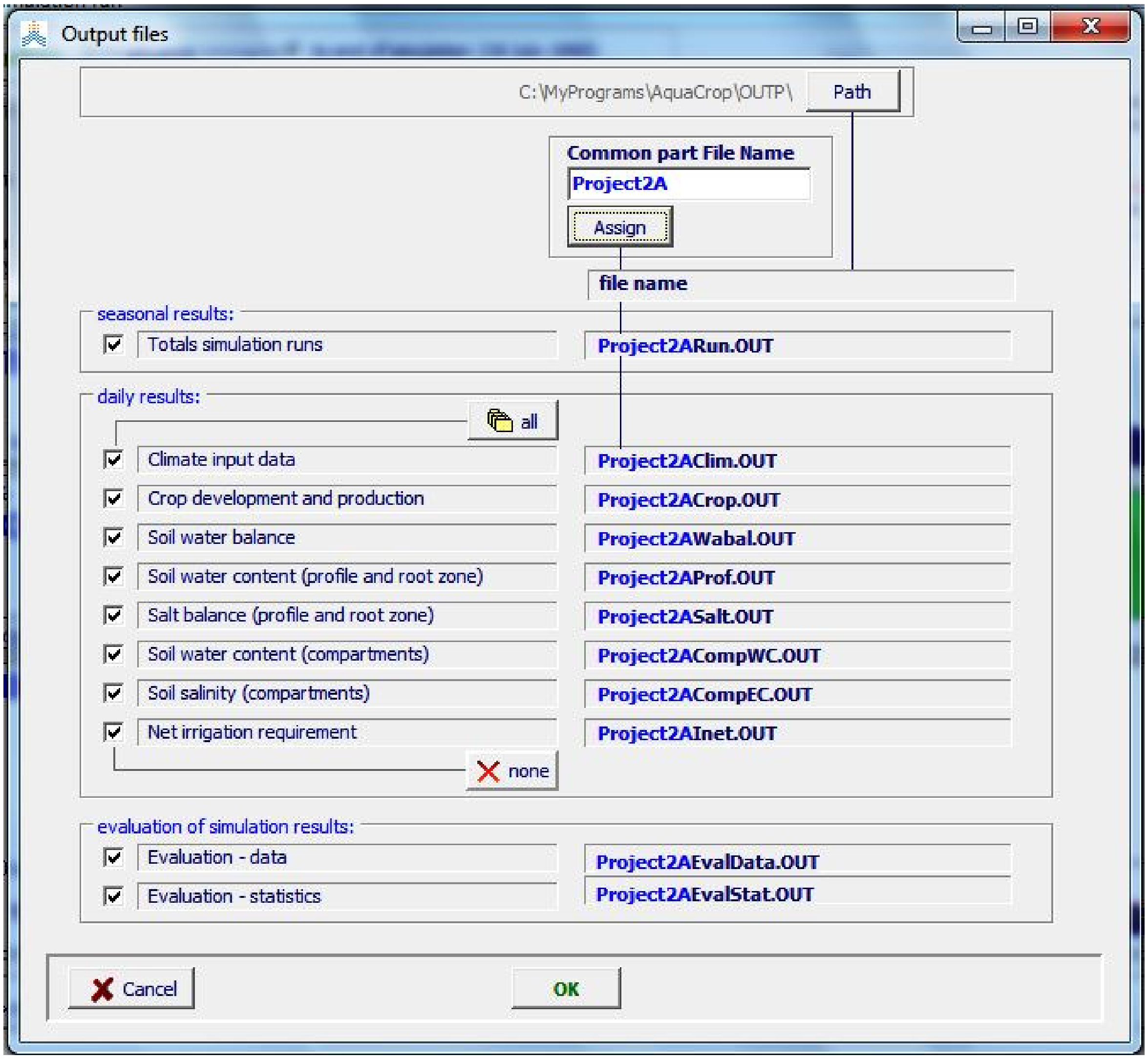

Figure 17.2 – Specification of the path and common part of the file name of output files, and selection of output files to be saved, in the *Output Files* menu.

- **Seasonal results**

The output of the seasonal results are saved in one file. The user can specify if this file is required as output.

- **Daily results**

The output of the daily results are saved in 8 different files (Tab.17.1). The user can select which files are required as output.

- **Evaluation of simulation results**

The results of the evaluation of the simulation is available in two files:

- Evaluation – data: This file provides a table with the simulated green canopy cover (CC), above-ground dry biomass (B) and soil water content (SWC) for each day of the simulation period. Next to the simulated values, the field data with their standard variation are specified for the days of their measurement.

- Evaluation – statistics: This file provides several statistical indicators evaluating the simulation of CC, B and SWC.

The user can specify which of the evaluation files are required as output.

In section 2.23 (Output files) of the reference manual the variables listed in the output files are described. The data in the files can be retrieved in spread sheet programs for further processing and analysis.

Table 17.1 – Default file name and content of the 8 output files with daily simulation results

Default file name	Content
ProjectClim.OUT	6 key variables of climate input data
ProjectCrop.OUT	18 key variables for crop development and production
ProjectWabal.OUT	17 key variables for soil water balance
ProjectProf.OUT	10 key variables for soil water content – Profile/Root zone
ProjectSalt.OUT	10 key variables for soil salinity – Profile/Root zone
ProjectCompWC.OUT	12 key variables for soil water content – Compartments
ProjectCompEC.OUT	12 key variables for soil salinity – Compartments
ProjectInet.OUT	5 key variables for net irrigation requirement

New output file:

Climate input data

Default file name: ProjectCLIM.OUT

Nr	Symbol	Description	Unit
1	Day		-
2	Month		-
3	Year		-
4	DAP	Days after planting/sowing	-
5	Stage	Crop growth stage: 0: before or after cropping; 1: between sowing and germination or transplant recovering; 2: vegetative development; 3: flowering; 4: yield formation and ripening -9: no crop as a result of early canopy senescence	-
6	Rain	Rainfall	mm
7	ETo	Reference evapotranspiration	mm
8	Tmin	Minimum air temperature	°C
9	Tavg	Average air temperature	°C
10	Tmax	Maximum air temperature	°C
11	CO2	Atmospheric CO_2 concentration	ppm

18. Update of Chapter 2 'Users guide' of the AquaCrop Reference Manual

The update consists in providing (more) guidelines:

- **to import climatic data** to calculate the reference evapotranspiration (ETo):
  2.9 Climatic data
- **to describe the environment** in which the crop develops (climate, irrigation and field management, soil profile and groundwater table characteristics):
  2.9 Climatic data
  2.12 Irrigation management
  2.13 Field management
  2.14 Soil profile characteristics
  2.15 Groundwater table characteristics
- **to tune crop parameters** when the cultivar and environment differ from what is assumed in the crop file:
  2.10 Crop characteristics
  2.11 Start of the growing cycle
- **to specify the initial conditions** at the start of the simulation period:
  2.16 Simulation period
  2.17 Initial conditions
- **to create project files** and run simulations:
  2.19 Project characteristics
  2.21 Simulation run
- **to evaluate the simulation results**:
  2.20 Field data
  2.22 Evaluation of simulation results

and to provide a full description of the **input and output files**
  2.23 Input files
  2.25 Output files

Annex 1.
ETo calculation procedures

Calculation methods listed in this annex are outlined in the FAO Irrigation and Drainage Paper n° 56 (Allen et al., 1998).

1. Atmospheric parameters

- **Atmospheric pressure (P)**

The atmospheric pressure, P, is the pressure exerted by the weight of the earth's atmosphere:

$$P = 101.3\left(\frac{293 - 0.0065\,z}{293}\right)^{5.26} \qquad \text{(Eq. 1)}$$

where	P	atmospheric pressure [kPa],
	z	elevation above sea level [m].

- **Psychrometric contant (γ)**

The psychrometric constant, γ, is given by:

$$\gamma = \frac{c_p\ P}{\varepsilon\ \lambda} = 0.664742\,x10^{-3}\ P \qquad \text{(Eq. 2)}$$

where	γ	psychrometric constant [kPa °C^{-1}],
	P	atmospheric pressure [kPa],
	λ	latent heat of vaporization, 2.45 [MJ kg^{-1}],
	c_p	specific heat at constant pressure, 1.013 10^{-3} [MJ kg^{-1} °C^{-1}],
	ε	ratio molecular weight of water vapour/dry air = 0.622.

The value of the latent heat varies as a function of temperature. As λ varies only slightly over normal temperature ranges a single value of 2.45 MJ kg^{-1} is considered in the program. This corresponds with the calculation procedure for the FAO Penman-Monteith equation. The fixed value for λ is the latent heat for an air temperature of about 20°C.

2. Air temperature

- **Mean air temperature (T_{mean})**

The mean air temperature is given by:

$$T_{mean} = \frac{T_{max} + T_{min}}{2} \qquad \text{(Eq. 3)}$$

where T_{mean} mean air temperature [°C],
T_{min} minimum air temperature [°C],
T_{max} maximum air temperature [°C].

- **Calculation rules**

- if T_{max} and T_{min} are available, the mean air temperature (T_{mean}) is calculated by Eq. 3 and the specified mean air temperature is disregarded,
- if T_{mean} and only T_{max} or T_{min} are available, the missing minimum or maximum air temperature is estimated by rearranging Eq. 3,
- if T_{max} or T_{min} is missing and cannot be derived, ET_o cannot be calculated,
- if no temperature data is available, ETo can not be calculated.

3. Air humidity

- **Saturation vapour pressure as a function of air temperature (e°(T))**

$$e^o(T) = 0.6108 \exp\left[\frac{17.27\ T}{T + 237.3}\right] \qquad \text{(Eq. 4)}$$

where e°(T) saturation vapour pressure at the air temperature T [kPa],
T air temperature [°C],
exp[..] 2.7183 (base of natural logarithm) raised to the power [..].

- **Mean saturation vapour pressure for a day, 10-day, or month (e_s)**

Due to the non-linearity of Eq. 4, the mean saturation vapour pressure for a day, 10-day or month is computed as the mean between the saturation vapour pressure at the mean daily maximum and minimum air temperatures for that period:

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \qquad \text{(Eq. 5)}$$

where e_s saturation vapour pressure [kPa],
$e°(T_{max})$ saturation vapour pressure at the mean daily maximum air temperature [kPa],
$e°(T_{min})$ saturation vapour pressure at the mean daily minimum air temperature [kPa].

- **Slope of saturation vapour pressure curve (Δ)**

For the calculation of the reference evapotranspiration, the slope of the relationship between saturation vapour pressure and temperature, Δ, is required. The slope of the curve at a given temperature is given by:

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27\ T}{T + 237.3}\right)\right]}{(T + 237.3)^2} \quad \text{(Eq. 6)}$$

where
- Δ slope of saturation vapour pressure curve at air temperature T [kPa °C^{-1}],
- T air temperature [°C],
- exp[..] 2.7183 (base of natural logarithm) raised to the power [..].

- **Actual vapour pressure (e_a) derived from dewpoint temperature**

$$e_a = e^o(T_{dew}) = 0.6108\ \exp\left[\frac{17.27\ T_{dew}}{T_{dew} + 237.3}\right] \quad \text{(Eq. 7)}$$

where
- e_a actual vapour pressure [kPa],
- T_{dew} dew point temperature [°C].

- **Actual vapour pressure (e_a) derived from psychrometric data**

$$e_a = e^o(T_{wet}) - \gamma_{psy}(T_{dry} - T_{wet}) \quad \text{(Eq. 8)}$$

where
- e_a actual vapour pressure [kPa],
- $e°(T_{wet})$ saturation vapour pressure at wet bulb temperature [kPa],
- γ_{psy} psychrometric constant of the instrument [kPa °C^{-1}],
- T_{dry}-T_{wet} wet bulb depression, with T_{dry} the dry bulb and T_{wet} the wet bulb temperature [°C].

The psychrometric constant of the instrument is given by:

$$\gamma_{psy} = a_{psy}\ P \quad \text{(Eq. 9)}$$

where a_{psy} is a coefficient depending on the type of ventilation of the wet bulb [°C^{-1}], and P is the atmospheric pressure [kPa].

- **Actual vapour pressure (e_a) derived from relative humidity data**

The actual vapour pressure can also be calculated from the relative humidity. Depending on the availability of the humidity data, different equations are used:

For RH_{max} and RH_{min}:

$$e_a = \frac{e^o(T_{min})\frac{RH_{max}}{100} + e^o(T_{max})\frac{RH_{min}}{100}}{2} \quad \text{(Eq. 10)}$$

where e_a actual vapour pressure [kPa],
$e°(T_{min})$ saturation vapour pressure at daily minimum temperature [kPa],
$e°(T_{max})$ saturation vapour pressure at daily maximum temperature [kPa],
RH_{max} maximum relative humidity [%],
RH_{min} minimum relative humidity [%].

For RH_{max}:

$$e_a = e^o(T_{min})\frac{RH_{max}}{100} \quad \text{(Eq. 11)}$$

For RH_{mean} (Smith, 1992):

$$e_a = e^o(T_{mean})\frac{RH_{mean}}{100} \quad \text{(Eq. 12)}$$

Eq. 12 differs from the one presented in the FAO Irrigation and Drainage Paper N° 56. Analysis with several climatic data sets proved that more accurate estimates of e_a can be obtained with Eq. 12 than with the equation reported in the FAO paper if only mean relative humidity is available (G. Van Halsema and G. Muñoz, Personal communication).

- **Vapour pressure deficit (e_s - e_a)**

The vapour pressure deficit is the difference between the saturation (e_s) and actual vapour pressure (e_a) for a given time period.

- **Calculation rules**

If air humidity data are missing or if several climatic parameters are available with which the air humidity can be estimated, the following calculation rules exist:

- If the mean actual vapour pressure (e_a) is missing and air humidity is specified by means of another climatic parameter, e_a is estimated from (in descending order):
    - the specified mean dew point temperature T_{dew} (Eq. 7),
    - the specified mean dry (T_{dry}) and wet bulb (T_{wet}) temperature (Eq. 8),
    - the specified maximum (RH_{max}) and minimum (RH_{min}) relative humidity, and the specified maximum (T_{max}) and minimum (T_{min}) air temperature (Eq. 10). In case RH_{mean} and only RH_{max} or RH_{min} are available, the program estimates the missing minimum or maximum relative humidity by rearranging Eq. 13:

$$RH_{mean} = \frac{RH_{max} + RH_{min}}{2} \quad \text{(Eq. 13)}$$

- the specified maximum (RH_{max}) and minimum (T_{min}) air temperature (Eq. 11),
- the specified mean (RH_{mean}) and mean (T_{mean}) air temperature (Eq. 12).

- If no air humidity data are available, e_a is estimated by assuming that the minimum air temperature (T_{min}) is a good estimate for the mean dew point temperature (T_{dew}). Before using T_{min} in Eq. 7, the number of degrees specified in the ***Data and ETo menu*** (Missing air humidity in the Input data description sheet) will be subtracted from T_{min}.

4. Radiation

• Extraterrestrial radiation (Ra)

The extraterrestrial radiation, R_a, for each day of the year and for different latitudes is estimated from the solar constant, the solar declination and the time of the year by:

$$R_a = \frac{24\,(60)}{\pi} G_{sc}\, d_r \left[\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)\right] \qquad \text{(Eq. 14)}$$

where
- R_a extraterrestrial radiation [MJ m^{-2} day^{-1}],
- G_{sc} solar constant = 0.0820 MJ m^{-2} min^{-1},
- d_r inverse relative distance Earth-Sun (Eq. 16),
- ω_s sunset hour angle (Eq. 18) [rad],
- φ latitude [rad] (Eq. 15),
- δ solar declination (Eq. 17) [rad].

The latitude, φ, expressed in radians is positive for the northern hemisphere and negative for the southern hemisphere. The conversion from decimal degrees to radians is given by:

$$[\text{Radians}] = \frac{\pi}{180} [\text{decimal degrees}] \qquad \text{(Eq. 15)}$$

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

$$d_r = 1 + 0.033 \cos\left(\frac{2\,\pi}{365} J\right) \qquad \text{(Eq. 16)}$$

$$\delta = 0.409 \sin\left(\frac{2\,\pi}{365} J - 1.39\right) \qquad \text{(Eq. 17)}$$

where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December).

The sunset hour angle, ω_s, is given by:

$$\omega_s = \arccos\left[-\tan(\varphi) \tan(\delta)\right] \qquad \text{(Eq. 18)}$$

- **Daylight hours (N)**

$$R_s = \left(a_s + b_s \frac{n}{N} \right) R_a \qquad \text{(Eq. 19)}$$

The daylight hours, N, are given by:

$$N = \frac{24}{\pi} \omega_s \qquad \text{(Eq. 20)}$$

where ω_s sunset hour angle in radians given by Eq. 18.

- **Solar radiation (R_s)**

If the solar radiation, R_s, is not measured, it can be calculated with the Angstrom formula, which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

where	R_s	solar or shortwave radiation [MJ m^{-2} day^{-1}],
	n	actual duration of sunshine [hour],
	N	maximum possible duration of sunshine or daylight hours [hour],
	n/N	relative sunshine duration [-],
	R_a	extraterrestrial radiation [MJ m^{-2} day^{-1}],
	a_s	regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0),
	a_s+b_s	fraction of extraterrestrial radiation reaching the earth on clear days (n = N).

The default values for a_s and b_s are 0.25 and 0.50. If the user has site specific information, calibrated values for a_s and b_s can be specified in the ***Data and ETo menu*** (Calculation method and coefficients).

- **Clear-sky solar radiation (R_{so})**

The calculation of the clear-sky radiation, R_{so}, when n = N, is required for computing net longwave radiation. Depending on the option selected in the ***Data and ETo menu*** (Calculation method and coefficients) Eq. 21 or 22 is used

When adjustment for station elevation is requested:

$$R_{so} = \left(0.75 + 2\ 10^{-5}\ z\right) R_a \qquad \text{(Eq. 21)}$$

where	R_{so}	clear-sky solar radiation [MJ m^{-2} day^{-1}],
	z	station elevation above sea level [m],
	R_a	extraterrestrial radiation [MJ m^{-2} day^{-1}].

When no adjustment for station elevation is requested (calibrated values for a_s and b_s are available):

$$R_{so} = (a_s + b_s)\, R_a \qquad \text{(Eq. 22)}$$

where a_s+b_s fraction of extraterrestrial radiation reaching the earth on clear-sky days (n = N).

- **Net solar or net shortwave radiation (R_{ns})**

The net shortwave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = (1 - \alpha)\, R_s \qquad \text{(Eq. 23)}$$

where R_{ns} net solar or shortwave radiation [MJ m^{-2} day^{-1}],
α albedo or canopy reflection coefficient for the reference crop [dimensionless],
R_s the incoming solar radiation [MJ m^{-2} day^{-1}].

If net solar radiation needs to be calculated when computing ET_o, the fixed value of 0.23 is used for the albedo in Eq. 23.

- **Net longwave radiation (R_{nl})**

$$R_{nl} = \sigma \left[\frac{T_{max,K}{}^4 + T_{min,K}{}^4}{2} \right] \left(0.34 - 0.14 \sqrt{e_a}\right) \left(1.35 \frac{R_s}{R_{so}} - 0.35\right) \qquad \text{(Eq. 24)}$$

where
R_{nl} net outgoing longwave radiation [MJ m^{-2} day^{-1}],
σ Stefan-Boltzmann constant [4.903 10^{-9} MJ K^{-4} m^{-2} day^{-1}],
$T_{max,K}$ maximum absolute temperature during the 24-hour period [K = °C + 273.16],
$T_{min,K}$ minimum absolute temperature during the 24-hour period [K = °C + 273.16],
e_a actual vapour pressure [kPa],
R_s/R_{so} relative shortwave radiation (limited to ≤ 1.0),
R_s measured or calculated (Eq. 20) solar radiation [MJ m^{-2} day^{-1}],
R_{so} calculated (Eq. 21, or Eq. 22) clear-sky radiation [MJ m^{-2} day^{-1}].

When maximum and minimum air temperature are missing, $\left[\frac{T^4_{\max,K} + T^4_{\min,K}}{2}\right]$ in Eq. 24 is replaced by $\left[T^4_{mean,K}\right]$.

- **Net radiation (R_n)**

The net radiation (R_n) is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net longwave radiation (R_{nl}):

$$R_n = R_{ns} - R_{nl} \qquad \text{(Eq. 25)}$$

- **Calculation rules**

If sunshine or radiation data are missing or if several climatic parameters are available with which radiation can be estimated, the following calculation rules exist:

- If net radiation (R_n) is missing, R_n is cacultated by Eq. 25,
- If Rn and solar radiation (R_s) are missing, R_s is derived from (in descending order):
  - the specified hours of bright sunshine n (Eq. 20),
  - the specified relative sunshine hours n/N (Eq. 20),
  - the maximum (T_{max}) and minimum (T_{min}) air temperature by means of the adjusted Hargreaves' radiation formula:

$$R_s = k_{Rs} \sqrt{(T_{max} - T_{min})}\ R_a \qquad \text{(Eq. 26)}$$

where R_a extraterrestrial radiation [MJ m^{-2} d^{-1}],
T_{max} maximum air temperature [°C],
T_{min} minimum air temperature [°C],
k_{Rs} adjustment coefficient [$°C^{-0.5}$].

The value for the adjustment coefficient k_{Rs} is specified in the ***Data and ETo menu*** (Missing radiation data in the Input data description sheet). Indicative default values are 0.16 for interior locations and 0.19 for coastal locations.

5. Wind speed

- **Adjustment of wind speed to standard height**

To adjust wind speed data obtained from instruments placed at elevations other than the standard height of 2 m:

$$u_2 = u_z \frac{4.87}{\ln(67.8\, z - 5.42)} \qquad \text{(Eq. 27)}$$

where u_2 wind speed at 2 m above ground surface [m s^{-1}],
u_z measured wind speed at z m above ground surface [m s^{-1}],
z height of measurement above ground surface [m].

- **Missing wind speed data**

If wind speed data is missing, the default value for u_2 specified in the ***Data and ETo menu*** (Missing wind speed in the Input data description sheet) is used.

6. Reference evapotranspiration (FAO Penman-Monteith)

The relatively accurate and consistent performance of the Penman-Monteith approach in both arid and humid climates has been indicated in both the ASCE and European studies. The FAO Penman-Monteith equation (Allen et al., 1998) is given by:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T+273} u_2\,(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \qquad \text{(Eq. 28)}$$

where	ET_o	reference evapotranspiration [mm day^{-1}],
	R_n	net radiation at the crop surface [MJ m^{-2} day^{-1}],
	G	soil heat flux density [MJ m^{-2} day^{-1}],
	T	mean daily air temperature at 2 m height [°C],
	u_2	wind speed at 2 m height [m s^{-1}],
	e_s	saturation vapour pressure [kPa],
	e_a	actual vapour pressure [kPa],
	e_s-e_a	saturation vapour pressure deficit [kPa],
	Δ	slope vapour pressure curve [kPa °C^{-1}],
	γ	psychrometric constant [kPa °C^{-1}].

In Eq. 28, the value 0.408 converts the net radiation R_n expressed in MJ/m^2.day to equivalent evaporation expressed in mm/day. Because soil heat flux is small compared to R_n, particularly when the surface is covered by vegetation and calculation time steps are 24 hours or longer, the estimation of G is ignored in the ETo calculator and assumed to be zero. This corresponds with the assumptions reported in the FAO Irrigation and Drainage Paper n° 56 for daily and 10-daily time periods. Allen et al. (1989) state that the soil heat flux beneath the grass reference surface is relatively small for that time period.

7. Conversion to standard metric unit

To convert a value (***A***) expressed in a non-standard unit to a value (***Y***) expressed in the standard metric unit, the following equations are used in the software:

- **Temperature: standard unit is degree Celsius**

Temperature unit	Equation to convert to standard unit (°C)
degree Fahrenheit (°F)	***Y*** °C = (***A*** °F - 32) 5/9

- **Vapour pressure: standard unit is kilo Pascal**

Vapour pressure unit	Equation to convert to standard unit (kPa)
millibar	***Y*** kPa = 0.1 ***A*** mbar
pound per square inch (psi)	***Y*** kPa = 6.89476 ***A*** psi
atmospheres (atm)	***Y*** kPa = 101.325 ***A*** atm
millimetre of mercury (mmHg)	***Y*** kPa = 0.133322 ***A*** mmHg

- **Wind speed: standard unit is meter per second (m/s)**

Wind speed unit	Equation to convert to standard unit (m/s)
kilometre per day (km/day)	***Y*** m/s = (***A*** /86.40) km/day
nautical mile/hour (knot)	***Y*** m/s = 0.5144 ***A*** knot
foot per second (ft/s)	***Y*** m/s = 0.3048 ***A*** ft/sec

- **Radiation: standard unit is megajoules per square meter per day (MJ/m^2.day)**

Radiation unit	Equation to convert to standard unit (MJ/m^2.day)
watt per m^2 (W/m^2)	***Y*** MJ/m^2.day = 0.0864 ***A*** W/m^2
joule per cm^2 per day (J/cm^2.day)	***Y*** MJ/m^2.day = 0.01 ***A*** J/cm^2.day
equivalent evaporation (mm/day)	***Y*** MJ/m^2.day = 2.45 ***A*** mm/day
calorie per cm^2 per day (cal/cm^2.day)	***Y*** MJ/m^2.day = 4.1868 10^{-2} ***A*** cal/cm2.day

- **Evapotranspiration: standard unit is millimeter per day (mm/day)**

Evaporation unit	Equation to convert to standard unit (mm/day)
equivalent radiation in megajoules per square metre per day (MJ/m^2.day)	***Y***mm/day = 0.408 ***A*** MJ/m^2.day

References

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