AquaCrop update
Version 4.0
June 2012



June 2012

FAO
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Land and Water Division
Rome, Italy

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Installation guidelines

- **Uninstall previous version of AquaCrop**

If the directory where AquaCrop was installed (default directory was so far: C:\Program Files\FAO\AquaCrop) is different from the one where it will be installed (new default directory is C:\FAO\AquaCrop) the user will have first to uninstall AquaCrop from the PC before installing the new version. The switch in the default directory is the result of problems with WINDOWS Vista and 7.

Data created by the user in previous versions will not be destroyed by the uninstall procedure. After the installation of the new version, the files can be moved to the new DATA folder.

- **Standard installation procedure**

Zipped files containing the executable program for installing Version 4.0 of AquaCrop can be downloaded from the FAO website:

http://www.fao.org/nr/water/aquacrop.html

1. Copy the zipped file to the PC;
2. Unzip; and
3. Run SETUP.EXE.

When running the installation file, a series of windows will pop up. By selecting 'Next >' in each of the windows, AquaCrop will be installed by default in the FAO subfolder (which will be created when not available) of the C drive (i.e. C:\FAO\AquaCrop).

- **Once installed**

When AquaCrop is properly installed, the user will find in the AquaCrop directory:

- the AquaCrop executable file (AquaCrop.EXE);
- some files with extension PAR (these are settings for program parameters);
- the default crop and soil file;
- the list of soil characteristics for default soil types (Soils.DIR);
- the DATA subdirectory, with the calibrated and validated crop files by FAO and some examples files with environmental data (climate, soil, ..);
- the OUTP subdirectory, where simulation results will be stored by default;
- the OBS subdirectory to store measured field data (to assess the simulations);
- the SIMUL subdirectory, with the Mauna Loa CO2 file.

1. Modifications in menus of AquaCrop

1.1 Initial canopy cover

The initial canopy cover (CC_o) is required to describe canopy expansion (Chapter 3 – Section 3.3.2 Canopy development). It is the product of plant density (number of plants per hectare) and the canopy size of the seedling (cc_o).

Type of planting method

- Direct sowing: CCo refers to the initial canopy cover at 90% emergence and is obtained by multiplying plant density by the canopy size of the average seedling at 90% emergence (cc_o);
- Transplanting: CCo refers to the initial canopy cover after transplanting and is obtained by multiplying plant density by the canopy size of the transplanted seedling (cc_o).

Since the canopy size of the transplanted seedling is likely to be larger than the canopy size of the germinating seedling, the user has to confirm the proposed default size or adjust the value, when altering the method of planting (Fig. 1.1).

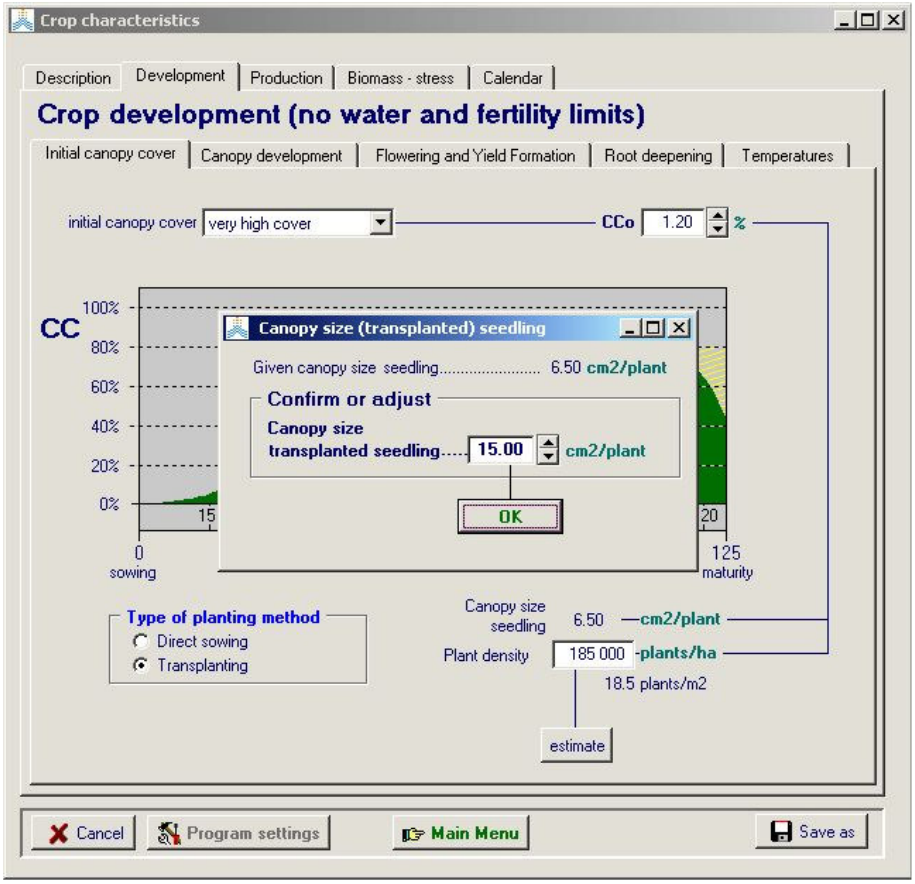


Figure 1.1 – Update of the canopy size of the transplanted seedling when altering the planting method from direct sowing to transplanting in the ***Canopy size (transplanted) seedling*** menu

1.2 Display of crop parameters

Two types of display mode of crop parameters can be selected when selecting the **<Display/Update Crop characteristics>** command in the ***Main Menu***:

- **Limited set:** Crop parameters describing mainly phenology and life cycle length are displayed. These parameters might require an adjustment when selecting a cultivar different from the one considered for crop calibration, or when the environmental conditions differ from the conditions assumed at calibration or when the planting method is altered. The displayed parameters are cultivar specific or might be affected by the field management, conditions in the soil profile, or the climate (especially when simulating in calendar day mode).
- **Full set:** All crop parameters are displayed

Since crop responses to soil fertility or soil salinity stress are not conservative but need to be calibrated by the user for each specific case, the 'Biomass-stress' tab sheet is displayed when selecting the 'Limited set' in the ***Crop characteristics*** menu (Fig. 1.2).

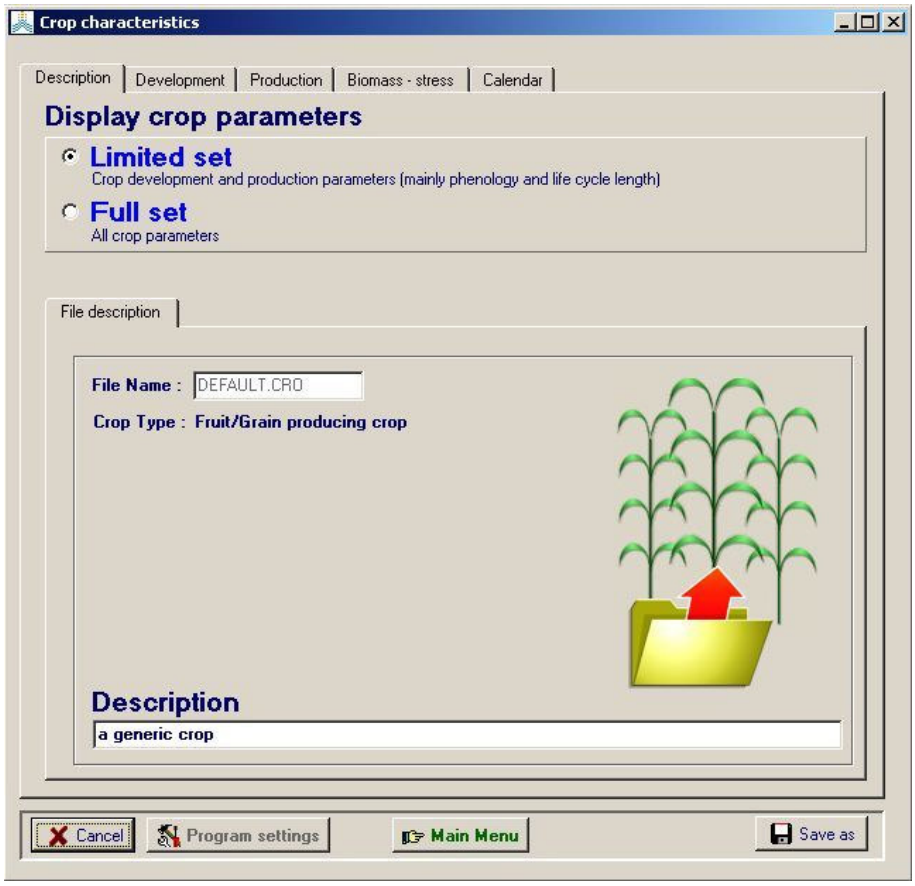


Figure 1.2 – ***Crop characteristics*** menu (limited set)

1.3 Field management menu

1.3.1 Soil fertility

For limited soil fertility, the biomass production declines as result of the effect of soil fertility on (i) canopy development (CC) and hence on crop transpiration and on (ii) biomass water productivity (WP*). The maximum biomass production that can be expected as a result of soil fertility stress is specified by:

- selecting one of the classes ranging from non limiting to very poor (Tab. 2.12a), or
- specifying directly the biomass production in the ***Field management*** menu.

The selected biomass production is the production that can be expected for the given climatic conditions in absence of any other stress. The crop response on soil fertility will be different if additionally stresses occur during the season.

Table 2.12a – Classes, corresponding default values, and ranges for soil fertility.

Class	Default value	Range
Non limiting	100 %	99 – 100 %
Near optimal	80 %	76 – 98 %
Moderate	60 %	56 – 75 %
About half	50 %	45 – 55 %
Poor	40 %	35 – 44 %
Very poor	25 %	34 – 20 %

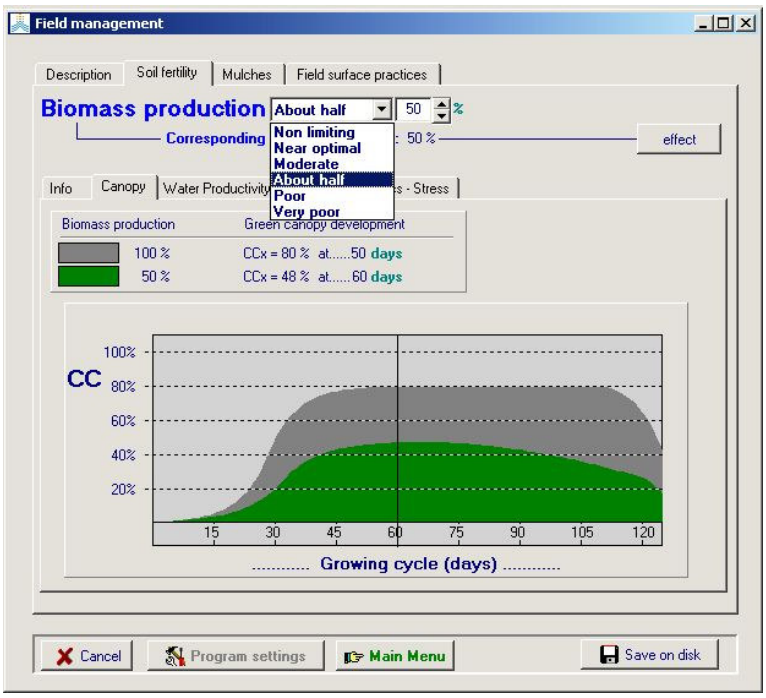
AquaCrop displays for the selected maximum biomass production (i) the canopy development, (ii) the water productivity corresponding to the amount of biomass produced, (iii) the expected maximum biomass production, (iv) the calibrated biomass – stress relationship, and (v) the adjusted values for particular cop parameters (Fig. 1.3a).

The biomass – stress relationship (Fig. 1.3a), calibrated in the ***Crop characteristic*** menu, determines the corresponding soil fertility stress and as such the values for the stress coefficients ($Ks_{exp,f}$, Ks_{WP}, Ks_{CCx}, $f_{CDecline}$).

The soil fertility module is designed using fundamental concepts,
although at present it is based on a qualitative assessment.

Consult the Reference manual or Section 4 of this note ('Calibrating crop response to soil fertility stress') for the calibration procedure.

(a)



(b)

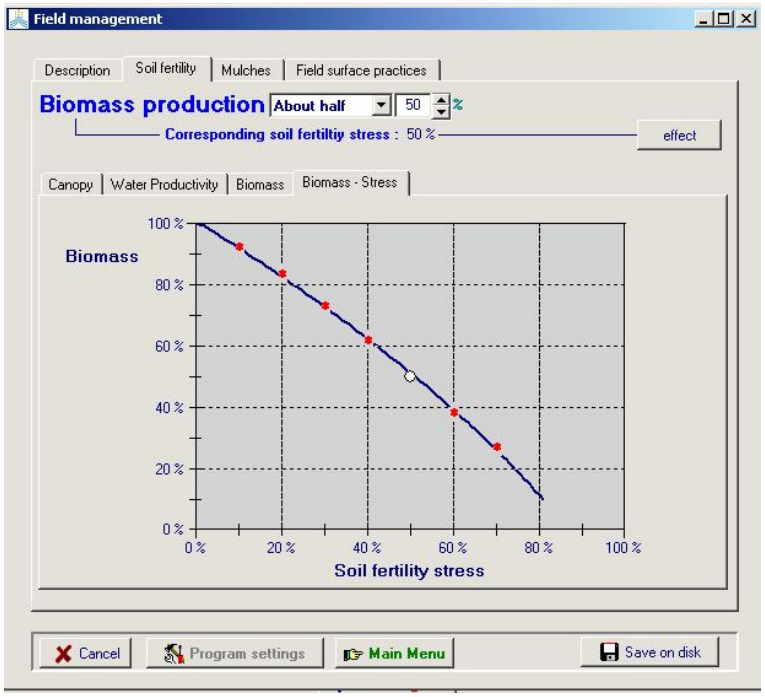


Figure 1.3a – Display of (a) the response of green canopy development for the selected relative biomass production (50 %) and (b) the biomass-stress relationship in the ***Field management*** menu

1.3.2 Mulches

Mulches covering the soil surface will affect soil evaporation. Depending on the type of mulches and the fraction of the soil surface covered, the reduction in soil evaporation might be more or less substantially. The user specifies:

- the degree of soil cover;
- the type of surface mulches.
    - Synthetic plastic mulches, which reduce completely the evaporation of water from the soil surface (100 %)
    - Organic mulches, which consists of unincorporated plant residues or foreign material imported to the field such as a straw, and reduce the soil evaporation by 50%,
    - User specified mulches, for which the reduction in soil evaporation needs to be specified by the user.

The corresponding total reduction in soil evaporation and the relative soil evaporation (or soil water evaporation coefficient and crop transpiration coefficient), are displayed (Fig. 1.3b).

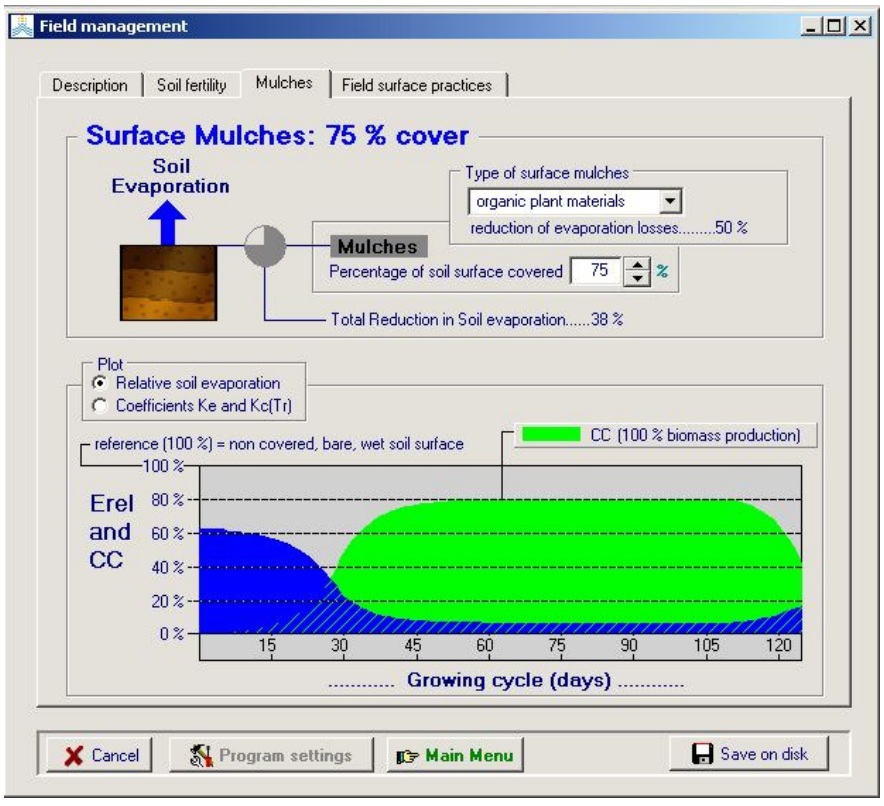


Figure 1.3b – Display of the effect of mulches on soil evaporation

2. Fine tuning of effect of elevated CO_2 concentrations on WP*

2.1 Effect of elevated CO_2 on biomass water productivity (WP*)

In AquaCrop the normalized biomass water productivity (WP*) is adjusted when running a simulation with an atmospheric CO_2 concentration different from the reference value (i.e. 369.41 ppm measured at Mauna Loa, Hawaii for the year 2000). The adjustment is obtained by multiplying WP^* with the correction coefficient f_{CO2} as specified by Steduto et al. (2007). The coefficient considers the difference between the reference value and the actual atmospheric composition:

$$WP^*_{adj} = f_{CO2}\, WP^* \qquad \text{(Eq. 2.1)}$$

$$f_{CO2} = \frac{\left(C_{a,i} / C_{a,o}\right)}{1 + b\left(C_{a,i} - C_{a,o}\right)} \qquad \text{(Eq. 2.2)}$$

where f_{CO2} correction coefficient for WP* for CO_2;
WP* Water Productivity normalized for climate (ETo) and [CO_2];
WP^*_{adj} WP* adjusted for actual atmospheric composition;
$C_{a,o}$ reference atmospheric CO_2 concentration (369.41 ppm);
$C_{a,i}$ actual atmospheric CO_2 concentration (ppm); and
b 0.000138 (Steduto et al., 2007).

In version 3.1+, Eq. 2.2 was updated to consider the discrepancy between the observed (FACE experiments) and theoretical adjustment (Steduto et al., 2007) of WP*:

$$f_{CO2} = \frac{\left(C_{a,i} / C_{a,o}\right)}{1 + \left(C_{a,i} - C_{a,o}\right)\left[(1-w)b_{Sted} + w\left(\frac{A}{100}b_{Sted} + \left(1 - \frac{A}{100}\right)b_{FACE}\right)\right]} \qquad \text{(Eq. 2.3)}$$

where b_{Sted} 0.000138 (Steduto et al., 2007);
b_{FACE} 0.001165 (derived from FACE experiments);
w weighing factor;
A percentage achieved of the required crop and management adjustments (fixed at 50 %).

The weighing factor (w) makes that Eq.2.3 gradually replaces Eq.2.2 starting from year 2000 and becomes fully applicable at year 2100:

$$0 \le \quad w = \frac{(i - 2000)}{100} \quad \le 1 \qquad \text{(Eq. 2.4)}$$

where i is the year for which the simulation applies. By keeping the range for w between 0 and 1, Eq. 2.3 comes in effect only for years later than 2000 and remains valid for years beyond 2100.

2.2 Introduction of a crop sink strength coefficient (f_{sink})

The percentage A in Eq. 3 considers that the theoretical adjustment (Eq. 2.2) might not be entirely valid when (i) soil fertility is not properly adjusted to the higher productivity under elevated CO_2 concentration, and/or (ii) the sink capacity of the current crop variety is unable to take care of the elevated CO_2 concentration.

In version 4.0 of AquaCrop, the percentage A (which is fixed at 50 % in Version 3.1+) is replaced by a crop sink strength coefficient (f_{sink}) which can be adjusted by the user in accordance with the expected soil fertility management and the cultivar (Fig. 2.2). In version 4.0, Eq. (2.3) is replaced by:

$$f_{CO2} = \frac{\left(C_{a,i} / C_{a,o}\right)}{1+\left(C_{a,i}-C_{a,o}\right)\left[(1-w)b_{Sted} + w\left(f_{\sin k}\ b_{Sted} + (1-f_{\sin k})b_{FACE}\right)\right]} \qquad \text{(Eq. 2.5)}$$

where f_{sink} is the crop sink strength coefficient which can vary between 0 and 1 when expressed as a fraction.

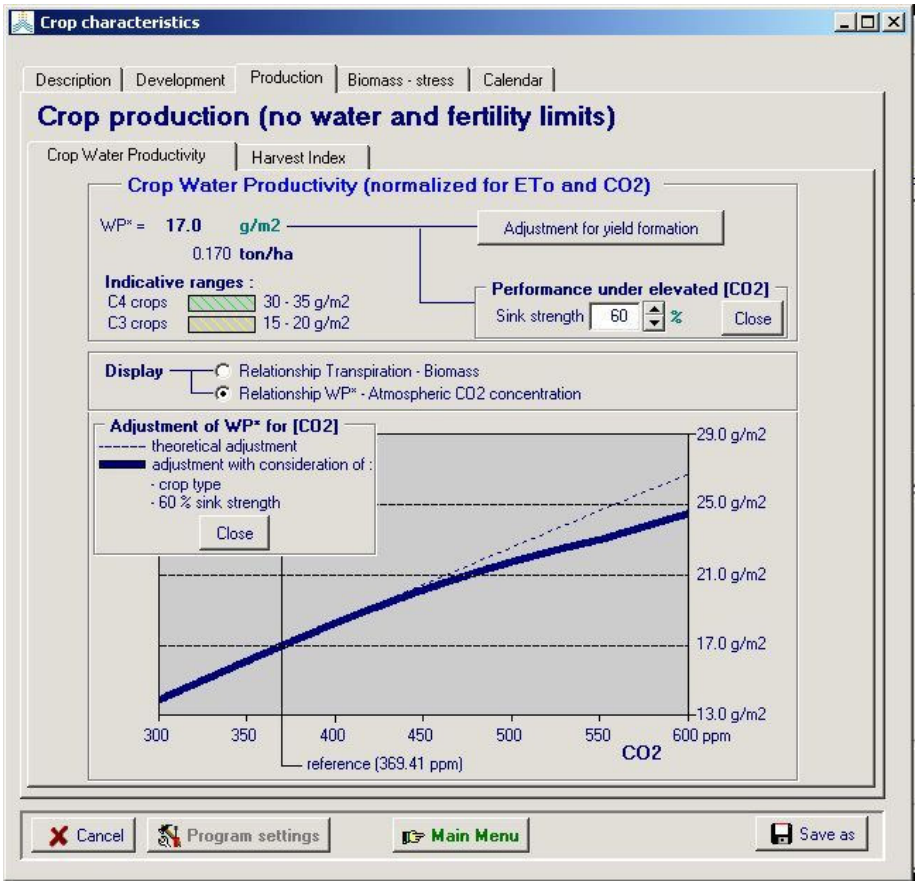


Figure 2.2 – The water productivity adjusted to atmospheric CO_2 concentration by considering crop type and crop sink strength (i.e. f_{sink} expressed in percentage) in the ***Crop characteristics*** menu

The crop sink strength coefficient (f_{sink}) can be altered according to the sink strength of the crop considered, which is determined by crop characteristics and field management. The value can be as high as one (the theoretical approach) or as low as zero (based on an analysis of crop responses in FACE environments by Vanuytrecht et al., 2011). If projections of future agricultural productivity are to be made in areas where nutrient deficiency is excepted f_{sink} should be reduced. If projections are to be made for species with improved cultivars with a higher responsiveness to [CO_2] are likely to be bred (e.g. high value crops like vegetables) the values for f_{sink} can be high.

References:

Steduto, P., T.C. Hsiao and E. Fereres 2007. On the conservative behavior of biomass water productivity. Irrig. Sci. 25: 189-207.

Vanuytrecht, E., D. Raes and P. Willems. 2011. Considering sink strength to model crop production under elevated atmospheric CO2. Agricultural and Forest Meteorology 151: 1753-1762.

2.3 The weighing factor (w) for various CO_2 concentrations

To calculate the correction coefficient f_{CO2} (Eq. 2.3 and 2.5), the difference between the reference atmospheric CO_2 concentration ($C_{a,o}$) and the actual atmospheric composition ($C_{a,i}$) is considered. To avoid conflicting results, the build-in weighing factor (w) in the Equations (2.3) and (2.5) needs to be expressed in atmospheric composition instead of in years. Hence Eq. 2.4 is replaced by:

$$0 \leq \quad w = \left(1 - \frac{(550 - C_{a,i})}{(550 - C_{o,i})}\right) \quad \leq 1 \qquad \text{(Eq. 2.6)}$$

where $C_{a,o}$ reference atmospheric CO_2 concentration (369.41 ppm);
$C_{a,i}$ actual atmospheric CO_2 concentration (ppm); and

For $C_{a,i}$ smaller than or equal to $C_{a,o}$, the weighing factor is zero (w = 0), while for $C_{a,i}$ larger than or equal to 550 ppm, w becomes 1. The threshold of 550 ppm is selected as the representing value for the elevated [CO_2] maintained in the FACE experiments.

3. Generating planting date based on air temperature

Climate change is likely to increase the air temperature in many regions. To estimate the planting dates for future years for spring crops in cool climates, AquaCrop offers the possibility to generate the sowing/planting date based on air temperature. By selecting one or another criterion, the likely planting/sowing date is generated by appraising the air temperature data specified in the selected 'Air temperature' data file. By specifying the first and last day in a 'Search window', only temperature data within the specified window is evaluated.

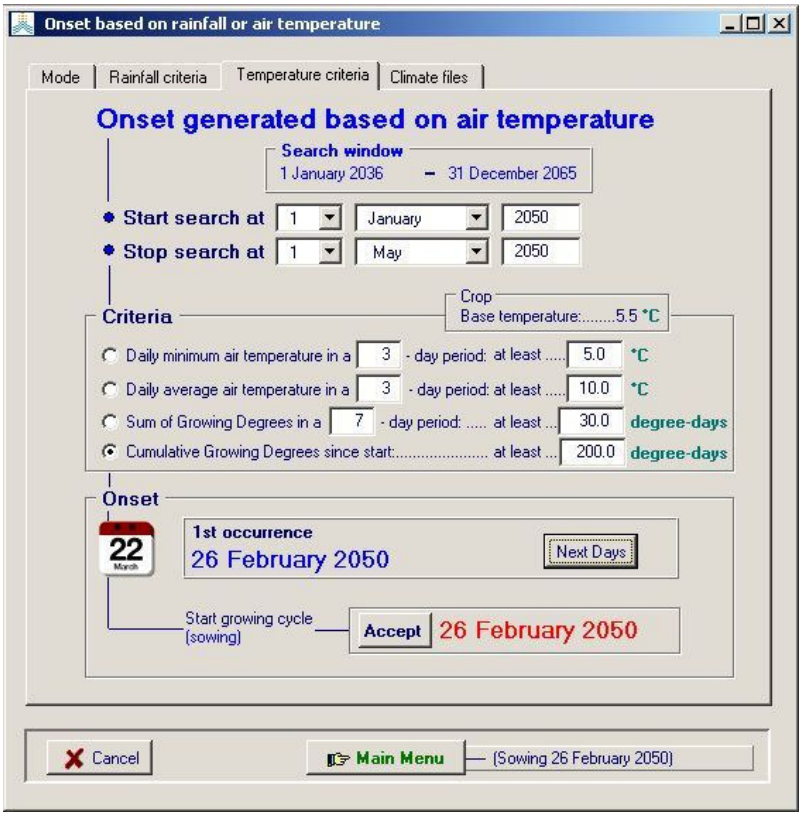


Figure 3 – Selection of a temperature criterium
in the ***Onset based on rainfall or air temperature*** menu

The following criteria can be selected to determine the onset of the growing cycle based on air temperature:

- The daily minimum air temperature, in each day of a given number of successive days, is equal to or exceeds a specified minimum air temperature;
- The daily average air temperature, in each day of a given number of successive days, is equal to or exceeds a specified average air temperature;
- The sum of Growing Degrees in a given number of successive days is equal to or exceeds the specified growing degree days;
- The cumulative Growing Degrees since the start of the search period are equal to or exceed the specified growing degree days.

The first occurrence of the onset date is the first date for which the selected criterion holds. The next 10 occurrences of onset days are displayed when clicking on the **<Next days>** command.

4. Calibrating crop response to soil fertility and salinity stress

4.1 Stress coefficients

The calibration consists in linking an observed reduction in total above ground biomass (B) in a Stressed field with the soil fertility stress in that field. The observed reduction in biomass is the result of an integration of effects of the stress on several processes. The soil fertility stress affects green canopy development (CC) and hence indirectly crop transpiration (Tr), and the biomass water productivity (WP*). In Table 4.1 the stress coefficients (Ks) and decline coefficient (f) used for the simulation of the crop response to soil fertility stress are listed.

Table 4.1 – Stress coefficients for simulating crop response to soil fertility and salinity stress

Coefficient	Description	Target crop parameter
For simulating the effect of both soil fertility and soil salinity stress		
$Ks_{exp,f}$	Stress coefficient for canopy expansion	Canopy Growth Coefficient (CGC)
Ks_{CCx}	Stress coefficient for maximum canopy cover	Maximum canopy cover (CCx)
$f_{CDecline}$	Stress decline coefficient of the canopy cover	Canopy Cover (CC) once maximum canopy cover has been reached
For simulating the effect of soil fertility stress		
Ks_{WP}	Stress coefficient for biomass water productivity	Biomass water productivity (WP*)
For simulating the effect of soil salinity stress		
$Ks_{sto,salt}$	Stress coefficient for stomatal closure	Crop transpiration (Tr)

4.2 Field observations for calibration

Since the crop response is specific to the type of stress and the environment in which the crop develops, the crop response to soil fertility stress cannot be described with conservative crop parameters, but needs to be calibration for each specific case.

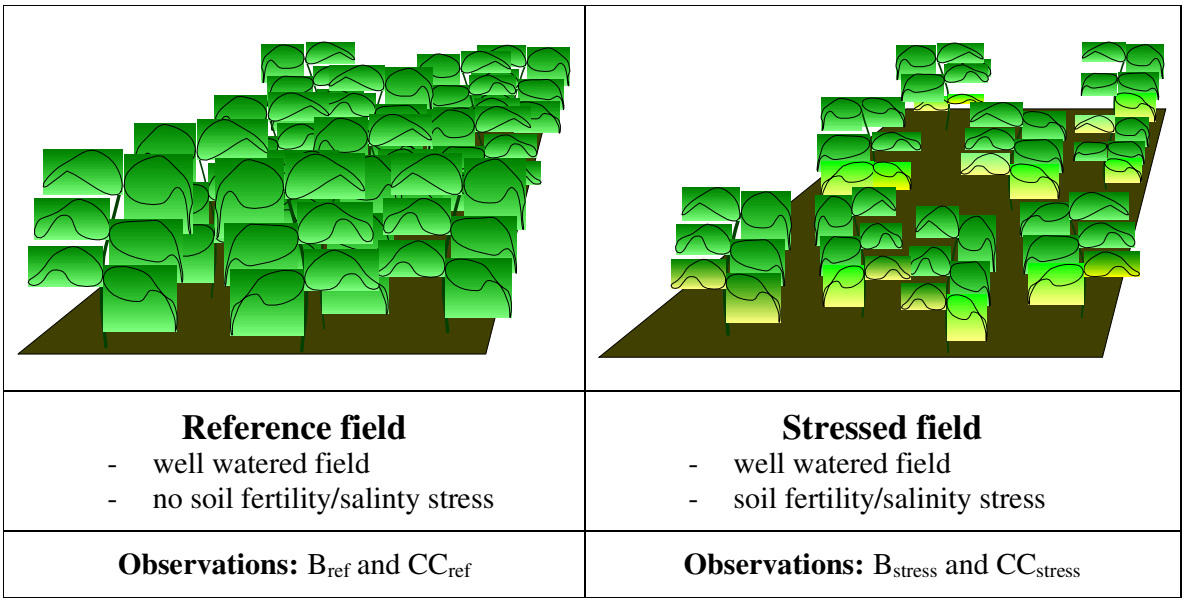


Figure 4.2 – The calibration of crop response to soil fertility or soil salinity stress is based on field observations of differences in Biomass production (B) and green Canopy Cover (CC) between a Reference and Stressed field.

The calibration, which is done in the ***Crop characteristic*** menu, requires access to observed green Canopy Cover (CC) and biomass production (B) in two well watered fields: one with and the other without soil fertility or soil salinity stress. The field with no stress is regarded as the 'Reference field', while the field with limited soil fertility or soil salinity stress is denoted as the 'Stressed field'. The fields are well watered to avoid the effect of soil water stress on crop development and production. The calibration requires that the crop in the Stressed field shows a well noted response to the limited soil fertility or soil salinity stress (Fig. 4.2).

4.3 The effect of stress is not yet considered

Protected crop files (provided by FAO), do not consider the effect of soil fertility/salinity stress on biomass, and need to be calibrated before the effect can be simulated. In the ***Crop characteristics*** menu the user selects the type of stress for which the crop response will be calibrated (Fig. 4.3a).

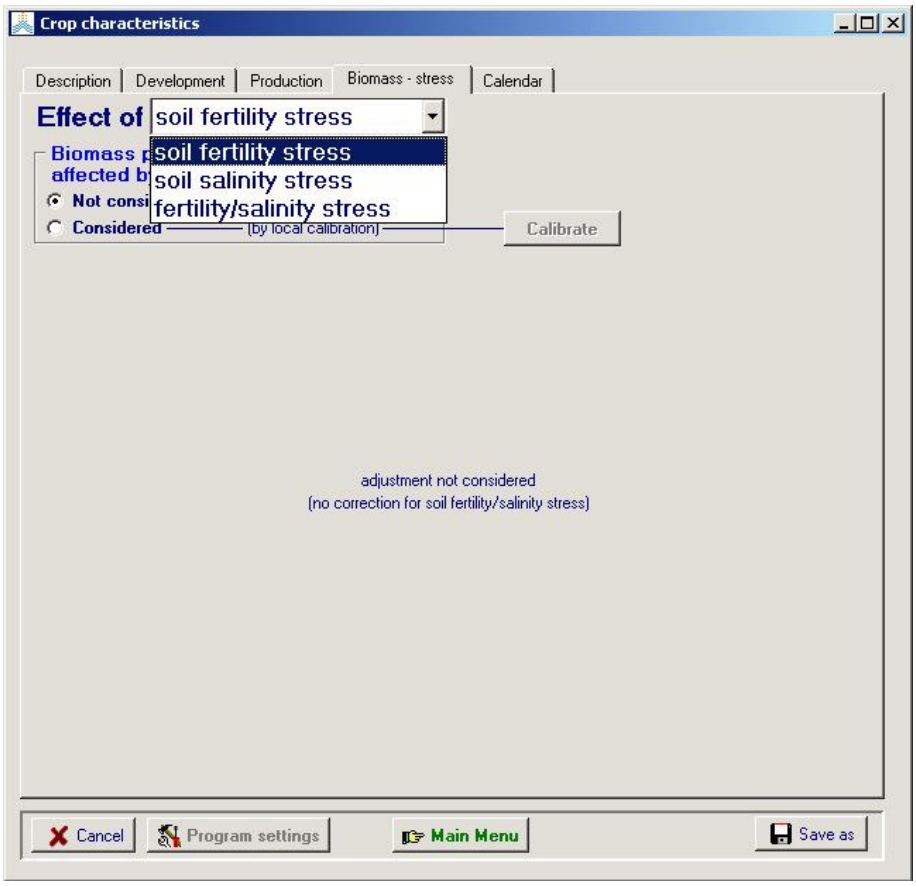


Figure 4.3a – Display in the ***Crop characteristics*** menu of a crop for which the effect of soil fertility stress is not considered

By selecting 'Considered' on the 'Biomass-stress' tab sheet in the ***Crop characteristics*** menu (Fig. 4.3a), AquaCrop will display the ***Calibration soil fertility stress, Calibration soil salinity stress,*** or the ***Calibration soil fertility/salinity stress*** menu in which the calibration can be started (Fig. 4.3b).

In the 'Field observations' tab sheet of the ***Calibration soil fertility stress, Calibration soil salinity stress,*** or the ***Calibration soil fertility/salinity stress*** menu the user specifies (with reference to the Reference field) the observations as surveyed in the Stressed field (Fig. 4.3b):

1. the observed relative Biomass production, by selecting a class (varying from 'near optimal' to 'very poor') or by specifying the relative biomass;
2. the observed Maximum canopy cover (CCx) , by selecting a class (varying from 'close to reference' to 'very strong reduced') or by specifying the observed CCx;
3. the observed Canopy decline in the season once CCx is reached, by selecting a class (varying from 'small' to 'strong').

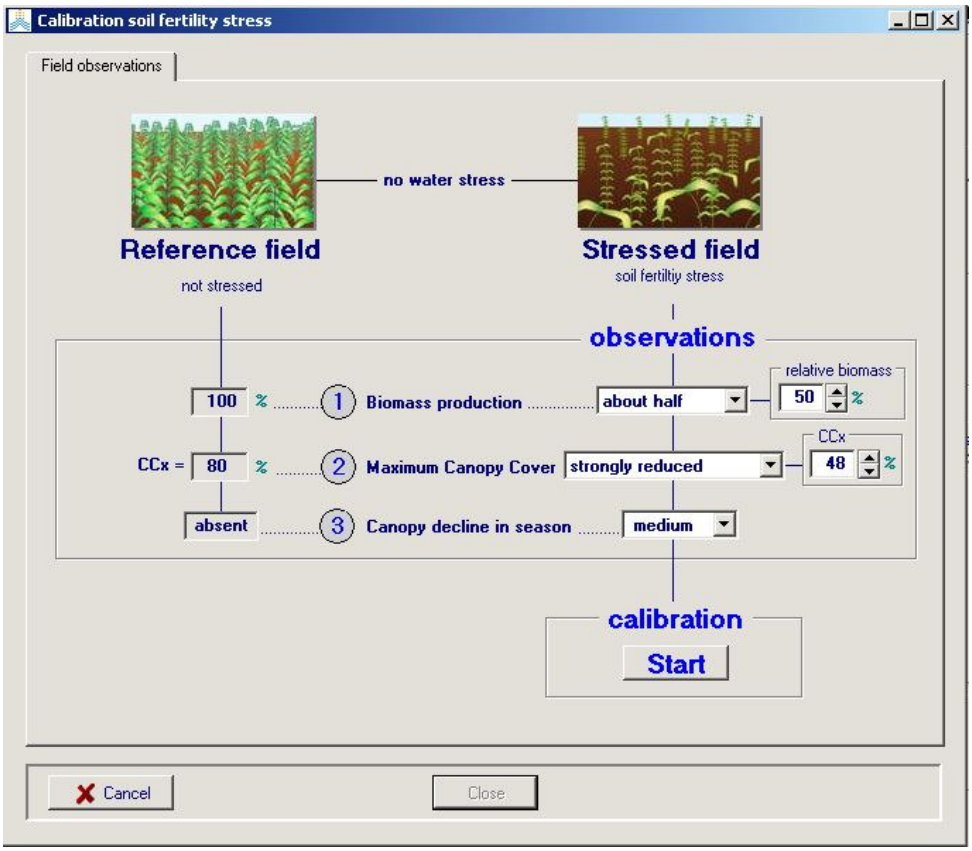


Figure 4.3b – Specification of field observations as observed in the 'Stressed field' in the ***Calibration soil fertility stress*** menu

By clicking on the **<Start>** button in the 'Field observations' tab sheet of the ***Calibration soil fertility stress, Calibration soil salinity stress,*** or the ***Calibration soil fertility/salinity stress*** menu (Fig. 4.3b), AquaCrop selects values for the stress coefficients ($Ks_{exp,f}$, Ks_{CCx}, Ks_{WP}, $Ks_{sto,salt}$, $f_{CDecline}$) and alters as such the simulated green canopy cover (CC), crop transpiration (Tr) and/or biomass water production (WP*) for the Stressed field.

By trying different values for the various stress coefficients, and by respecting the specified observations (Fig. 4.3b), AquaCrop calculates the corresponding CC, crop transpiration (Tr) and Biomass production (B) until the simulated relative biomass production is equal to the observed relative production in the Stressed field.

The results are displayed in two tab sheets:
- 'Crop response to soil fertility stress' (Fig. 4.3c); and
- 'Crop response to soil salinity stress' (Fig. 4.3d).

The effect of soil fertility and soil salinity stress on canopy development (CCx, CGC, and canopy decline) is assumed to be identical. But soil fertility stress differs from soil salinity stress because soil fertility stress results in a reduced biomass water production (Fig. 4.3c) while soil salinity stress induces stomatal closure (Fig. 4.3d).

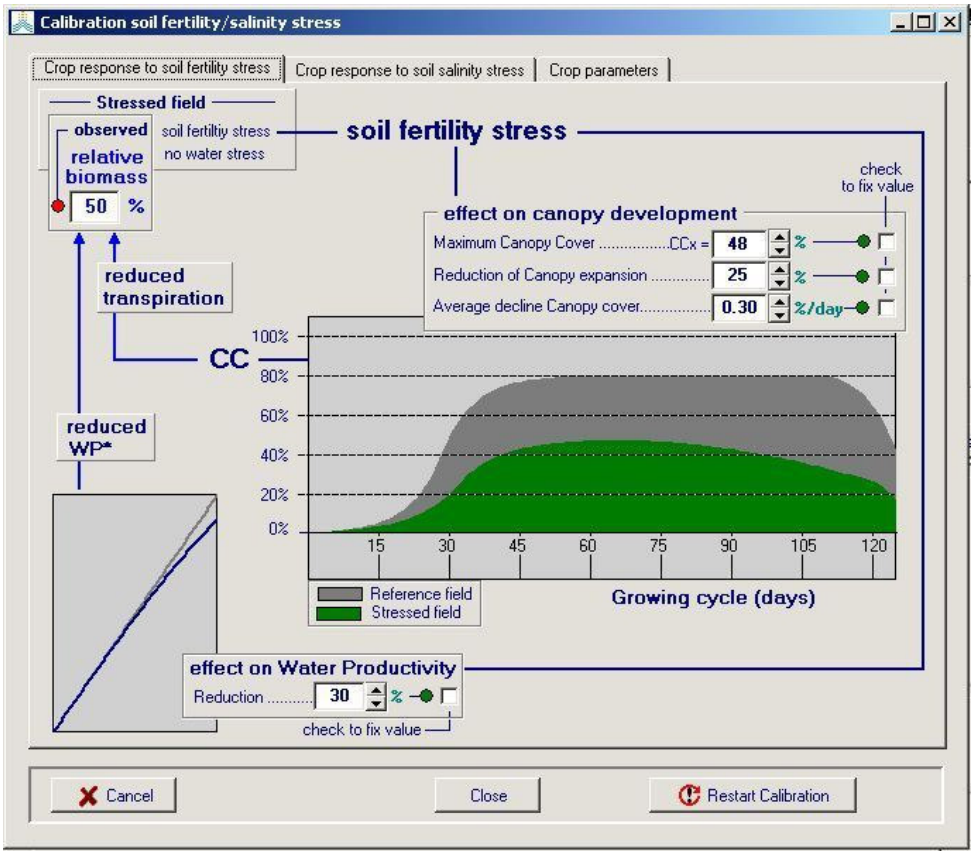


Figure 4.3c – The simulated relative biomass (similar as observed on the stressed field) obtained by considering the effect of soil fertility stress on (i) canopy development (CCx, CGC and canopy decline) and (ii) biomass Water Productivity (WP*), as displayed in the tab sheet 'Crop response to soil fertility stress' of the ***Calibration soil fertility/salinity stress*** menu

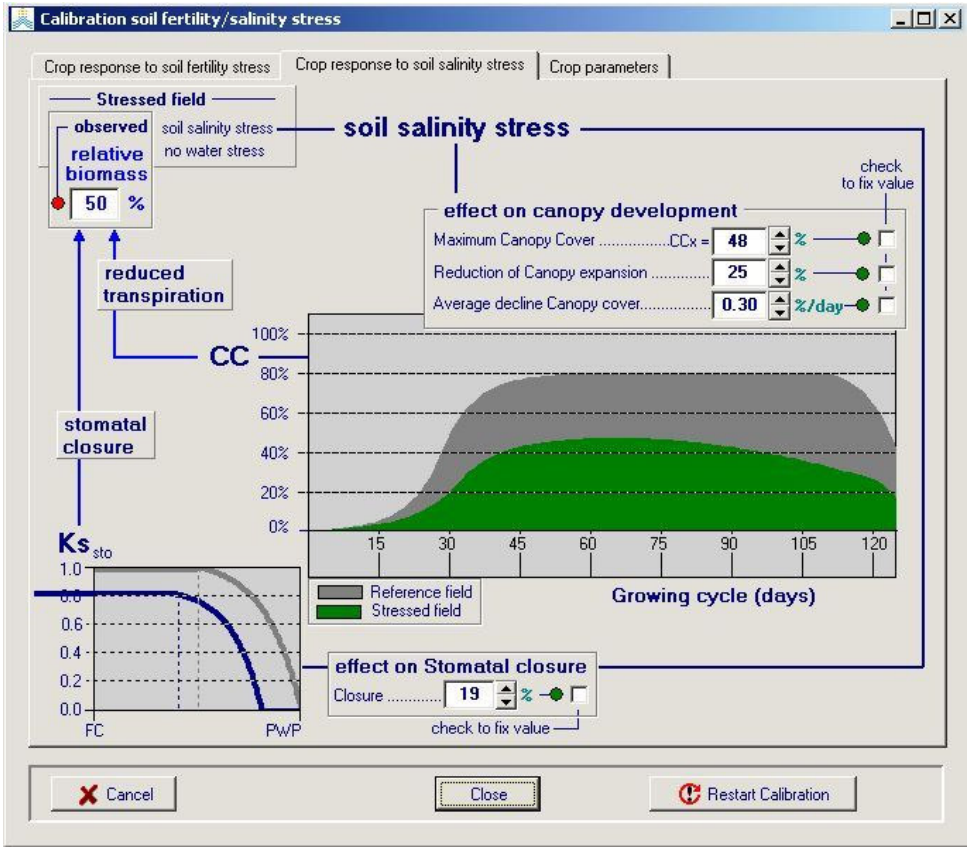


Figure 4.3d – The simulated relative biomass (similar as observed in the stressed field) obtained by considering the effect of soil salinity stress on (i) canopy development (CCx, CGC and canopy decline) and (ii) stomatal closure (Ks_{sto}), as displayed in the tab sheet 'Crop response to soil salinity stress' of the ***Calibration soil fertility/salinity stress*** menu.

In the 'Crop parameters' tab sheet of the ***Calibration soil fertility/salinity stress*** menu, the reduction in Canopy development, biomass Water Productivity (WP*), and in crop Transpiration are displayed. The corresponding simulated Biomass production (B), the 5 Ks-curves and the Crop parameters (adjusted to the stress) can be consulted as well (Fig. 4.3e).

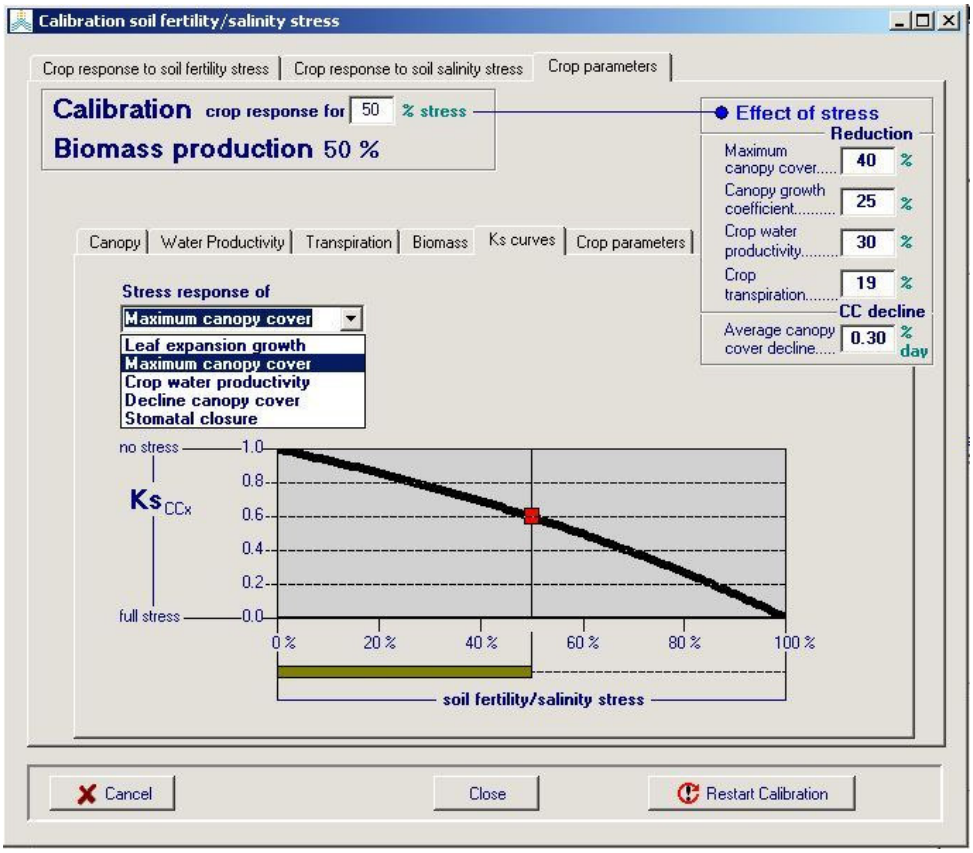


Figure 4.3e – The Ks curve for Maximum canopy cover as displayed in the ***Calibration soil fertility/salinity stress*** menu

The calibration determines the shape of the 4 Ks-curves and of the decline coefficient (f). The shape is given by the values of Ks or f, at 3 different levels of stress:

1. For non-limiting soil fertility or for soil salinity not affecting biomass production, the stress is 0 % and the 4 soil fertility stress coefficients (Ks) are 1, and the decline coefficient ($f_{CDecline}$) is zero;
2. When the soil fertility or soil salinity stress is complete (100% stress), crop production is no longer possible and the Ks coefficients are zero and the decline coefficient ($f_{CDecline}$) is at its maximum rate i.e. 1 % per day.
3. The stress in the Stressed field is derived from the observed relative biomass (Brel):

$$stress = 100\,(1 - B_{rel}) \qquad \text{(Eq. 4.3)}$$

By considering the effect on its target parameter (CCx, CGC, WP*, Tr, and canopy decline), the corresponding values for Ks and f are obtained for the defined stress level.

For example, if B is reduced in the Stressed field by 50 % and CCx by 40 %, Ks_{CCx} is 0.6 at the soil fertility/salinity stress of 50 % (Fig. 4.3e).

Once a curve is calibrated, the Ks corresponding to other soil fertility/salinity stresses can be obtained from the curves. With reference to Fig. 4.3e, CCx will be reduced by 20 % (Ks_{CCx} = 0.80) for a soil fertility/salinity stress of 27 %, and by 60 % (Ks_{CCx} = 0.40) for a stress of 69 %.

The user can fine tune the calibration by altering in the ***Calibration soil fertility/salinity stress*** menu (Fig. 4.3c or 4.3d): (i) the maximum canopy cover (CCx), (ii) the reduction of canopy expansion, (iii) the average decline of the Canopy cover, (iv) the biomass water productivity (WP*), or the effect on stomatal closure. Changing one of the above values will alter the values of the other parameters since AquaCrop always looks for the equilibrium between the simulated and observed and specified relative biomass production in the Stressed field. By clicking on one or more of the 5 check boxes, the user can fix the value of one or more parameters (Fig. 4.3c and 4.3d).

By clicking on the **<Restart calibration>** button key, the user returns to the 'Field observation' tab sheet (Fig. 4.3b).

4.4 The effect of stress is considered

For crop files where the effect of soil fertility/salinity stress on biomass is considered, AquaCrop displays in the ***Crop characteristics*** menu the effect on canopy development, biomass water productivity, crop transpiration, and biomass production for several stress levels (mild up to severe stress). In the menu the relationship between Biomass and soil fertility and between Biomass and soil salinity stress are displayed as well (Fig. 4.4). The relationships are obtained by (i) considering for various stress levels the effect on CCx, CGC, canopy decline, crop transpiration (Tr) and WP*, and (ii) calculating the corresponding canopy development, crop transpiration and reduction in relative biomass production by assuming no water stress. The effect of the various considered stress levels on CCx, CGC, canopy decline, Tr and WP* are described in the various calibrated Ks and reduction curves (Fig. 4.3e). Since the shape of each Ks curve might differ, and the effect of stress on WP* increases when the canopy cover increases, the relationships are not linear and differ between soil fertility and soil salinity stress.

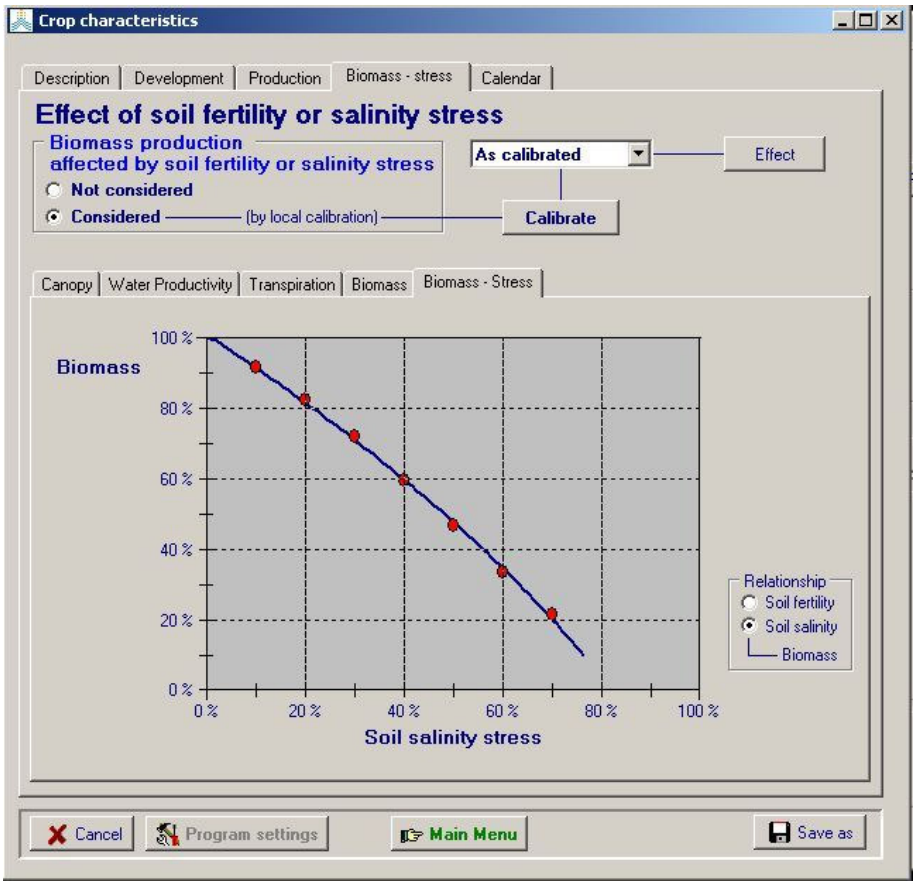


Figure 4.4 – Display in the ***Crop characteristics*** menu of a crop for which the effect of soil fertility and soil salinity stress on biomass is considered.

For crop files where the effect of soil fertility/salinity stress on biomass is considered, the calibration can be fine tuned by clicking on the **<Calibrate>** button key in the ***Crop characteristics*** menu which will display the ***Calibration soil fertility/salinity stress*** menu (Fig. 4.3c). By clicking on the **<Restart calibration>** button key in the ***Calibration soil fertility/salinity stress*** menu, the user returns to the 'Field observation' tab sheet (Fig. 4.3b).

5. Soil salinity

5.1 Salt balance

Salts enter the soil profile as solutes with the irrigation water or through capillary rise from a shallow groundwater table. It is assumed that rainfall does not contain dissolved salts. The extent to which salts accumulate in the soil depends on the irrigation water quality and quantity that infiltrates into the soil, frequency of wetting, the adequacy of leaching, the importance of soil evaporation and crop transpiration, the soil physical characteristics of the various layers of the soil profile, and the salt content and depth of the groundwater table. Salts are transported out of the soil profile (leached) by means of the drainage water.

AquaCrop uses the calculation procedure presented in BUDGET (Raes et al., 2001; Raes, 2002; De Nys et al., 2005;Raes et al., 2006) to simulate salt movement and retention in the soil profile.

5.1.1 Movement and accumulation of salts in the soil profile

Vertical downward salt movement in a soil profile is described by assuming that salts are transferred downwards by soil water flow in macro pores. This is simulated in AquaCrop by the drainage function (see Chapter 3, section 3.7 Soil water balance). The exponential drainage function (Eq. 3.7a) describes the vertical solute movement till field capacity is reached. If the soil water content is at or below field capacity, AquaCrop assumes that all macro pores are drained and hence inactive for solute transport.

Since the solute transport in the macro pores bypass the soil water in the matrix, a diffusion process has to be considered to describe the **transfer of solutes** from macro pores to the micro pores in the soil matrix. The driving force for this horizontal diffusion process is the salt concentration gradient that exists between the water solution in the macro pores and micro pores. To avoid the building up of high salt concentrations at a particular depth, a **vertical salt diffusion** is also considered. The driving force for this vertical redistribution process is the salt concentration gradient that builds up at various soil depths in the soil profile.

Vertical upward salt movement is the result of capillary rise from a saline groundwater table and water movement in response to soil evaporation**.** The vertical upward salt movement depends on the wetness of the top of the soil profile and the salinity and depth of the groundwater table (see point 6 of this note 'Capillary rise'). Due to soil evaporation water will evaporate at the soil surface while the dissolved salts remain in the top compartment.

5.1.2 Cells

To describe the movement and retention of soil water and salt in the soil profile, AquaCrop divides the soil profile in various soil compartments (12 by default) with thickness Δz (Fig. 5.1a). To simulate the convection and diffusion of salts, a soil compartment is further divided into a number of cells where salts can be stored (Fig. 5.1b).

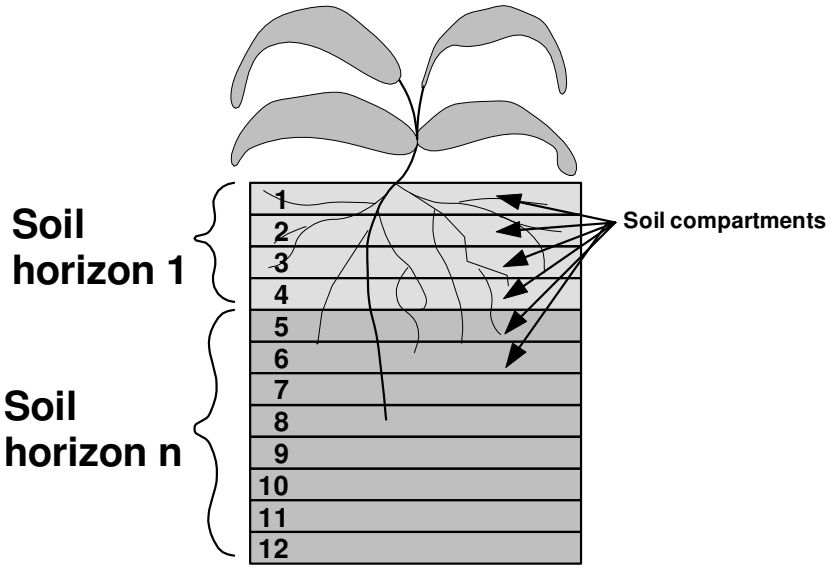


Figure 5.1a – A soil profile with several soil horizons and 12 soil compartments

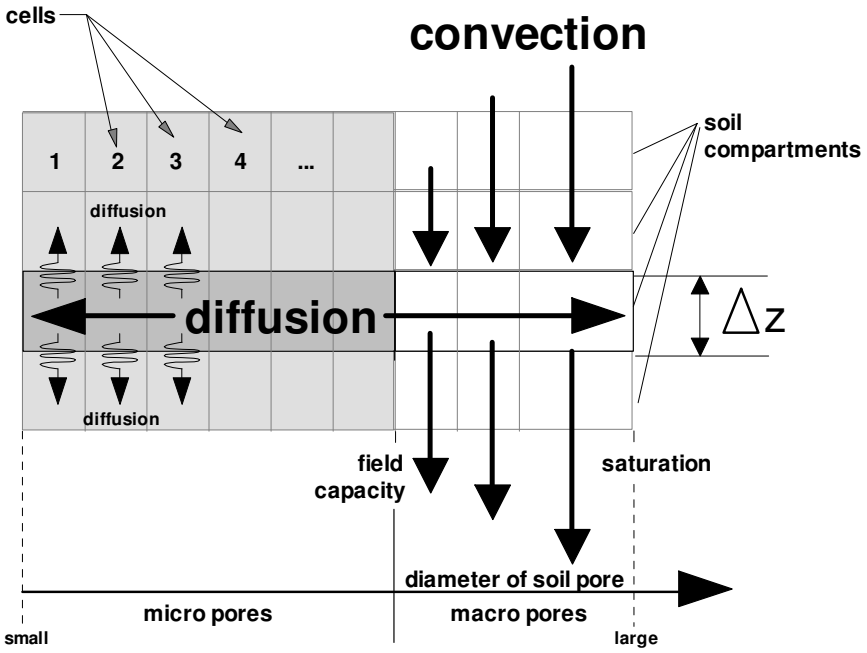


Figure 5.1b - Convection and diffusion of salts in the cells of a soil compartment

The number of cells (n), which may range from 2 to 11, depends on the soil type of the soil horizon. Since salts are strongly attached to the clay particles a clayey horizon will contain more cells than a sandy horizon. The inverse of the saturated hydraulic conductivity (Ksat) is used as an index for the number of cells. The number of cells in a compartment is obtained by considering the Ksat of the soil horizon to which the compartment belongs:

$$2 \leq n = ROUND\left(1.6 + \frac{1000}{Ksat}\right) \leq 11 \qquad \text{(Eq. 5.1a)}$$

where Ksat is the saturated hydraulic conductivity (mm/day) of the soil horizon. The volume of a cell, which is a fraction of the total pore volume, is given by:

$$W_{cell} = 1000 \frac{\theta_{sat}}{n} \Delta z \qquad \text{(Eq.5.1b)}$$

where W_{cell} is the volume of the cell in mm(water), θ_{sat} the soil water content at saturation (m^3/m^3) of the soil horizon, n the number of cells, and Δz the thickness of the soil compartment (m). A cell is in fact a representation of a volume of pores with a particular mean diameter. Cells with a low number have small diameters, while cells with a high number have large diameters (Fig. 5.1b).

Salts can be transported by diffusion horizontally and vertically from one cell to its adjacent cells if there exists a concentration gradient and if the cells are active, it is when they contain soil water. Hence, the number of active cells depends on the wetness of the soil. If the soil is dry, only cells with small pore diameters (low numbers) will accommodate water and the diffusion process will be limited. When the soil water content increases, more and more cells are active and become involved in the diffusion process. Once the soil water content is above field capacity, the macro pores are active as well and salts can now also be conducted vertically downward in the soil profile together with the movement of the soil water. If the soil is saturated all macro pores contains water and the convection rate is at its maximum.

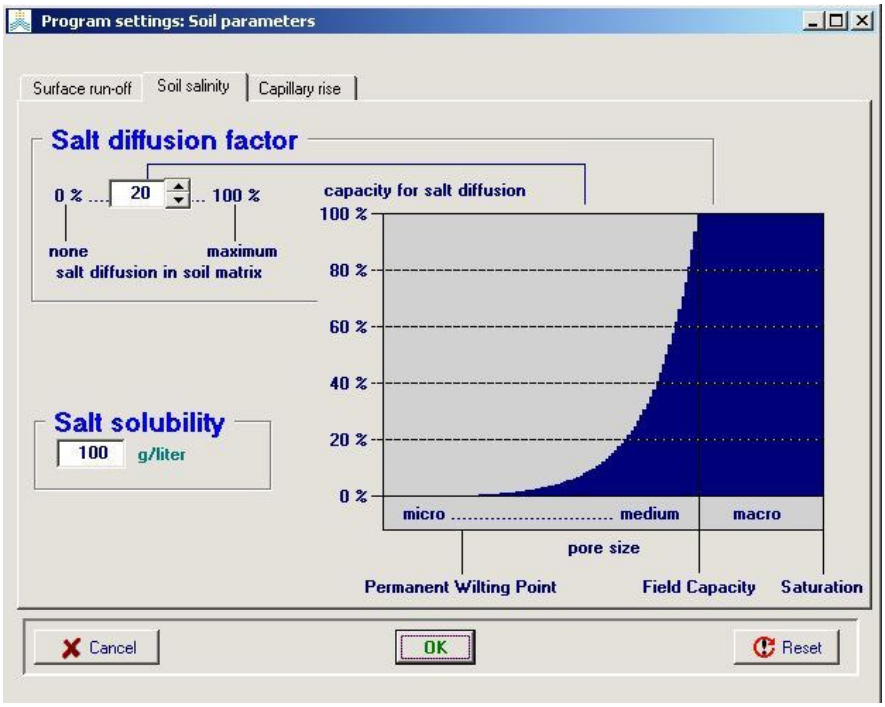


Figure 5.1c – Program parameters for soil salinity (Salt diffusion coefficient, f_{diff}, and Salt solubility) in the ***Program settings: Soil parameters*** menu.

The salt concentration in a cell can never exceed a threshold value. The threshold value is determined by the solubility of the salt and is a program parameter (Fig. 5.1c). If the salt concentration in a cell exceeds the threshold value, salts will precipitate and will be temporarily removed from the soil solution. Salts return to the solution as soon as the salt concentration in the cell drops below the threshold value.

5.1.3 Salt diffusion

The salt diffusion between two adjacent cells (cell j and cell j+1) is given by the differences in their salt concentration which is expressed by the electrical conductivity (EC) of their soil water. At the end of the time step t+Δt the EC of the soil water in cell j is:

$$EC_{j,t+\Delta t} = EC_{j,t} + f_{diff}\left(\frac{EC_{j,t}\,W_{cell,j} + EC_{j+1,t}\,W_{cell,j+1}}{W_{cell,j} + W_{cell,j+1}} - EC_{j,t}\right) \qquad \text{(Eq. 5.1c)}$$

where EC is the electrical conductivity of the soil water in the cell (dS/m), W_{cell} the volume of the cell (mm), and f_{diff} a salt diffusion coefficient.

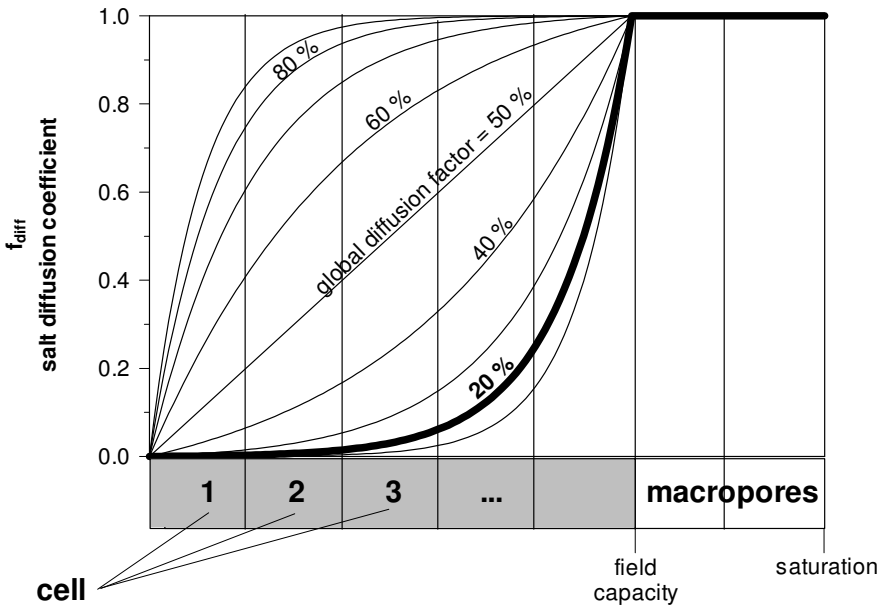


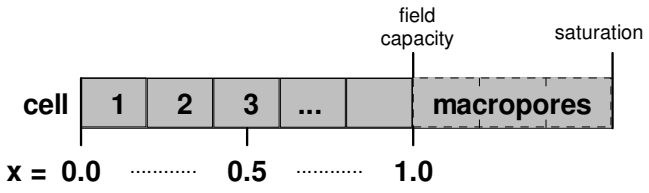
Figure 5.1d - The salt diffusion coefficient (f_{diff}) for the various cells and for various global diffusion factors

The salt diffusion between adjacent cells does not only depend on differences in their salt concentration but also on the swiftness with which salts can be rearranged between them (f_{diff}). Between cells having large pore diameters, salts can move quite easily since the forces acting on them are relatively small. Equilibrium between the salt content in those pores is reached quickly. Due to strong adsorption forces and low hydraulic conductivity's, salt diffusion will be rather limited in the small pores and it might take quite a while before equilibrium is reached between the salt concentrations in those cells. This is simulated in AquaCrop by adjusting the diffusion process with the ease salts can diffuse. The ease of salt

movement is expressed by the diffusion coefficient (f_{diff}). The coefficient varies between 1 for the macro pores (no limitation on salt diffusion) and 0 for the very smallest pores (salts can no longer diffuse between adjacent cells). Between cells representing macro pores the diffusion is entirely in response to salt concentration gradients ($f_{diff} = 1$). Between cells representing the smaller pores, salt diffusion is more limited ($f_{diff} < 1$).

The salt diffusion coefficient for the various cells is plotted in Figure 5.1d, for various global salt diffusion factors. The global diffusion factor is a program parameter (Fig. 5.1c) that describes the global capacity for salt diffusion and can be used to calibrate the model. Increasing or decreasing the global salt diffusion factor alters the ease for salt diffusion and increases or decreases the speed with which equilibrium is reached between the salt concentrations in the adjacent cells. The default setting for the salt diffusion factor is 20 %. In Table 5.1a the calculation procedure (Eq. 5.1d) for f_{diff} is presented.

Table 5.1a - Equation 5.1d: Calculation procedure for the salt diffusion coefficient (fdiff)

GDF (global diffusion factor)	< 50 %	> 50 %
x		
f_{diff}	$\frac{a\,b^{x}-a}{a\,b-a}$ (Eq.5.1d1)	$1-\frac{a\,b^{(1-x)}-a}{a\,b-a}$ (Eq.5.1d2)
a	$a=2\frac{GDF}{100}$ (Eq.5.1d3)	$a=2\left(1-\frac{GDF}{100}\right)$ (Eq.5.1d5)
b	$b=10^{10\,(0.5-GDF/100)}$ (Eq.5.1d4)	$b=10^{10\,(GDF/100-0.5)}$ (Eq.5.1d6)

5.1.4 Vertical salt movement in response to soil evaporation

Soil evaporation in Stage II (falling rate stage) will bring soil water and its dissolved salts from the upper soil layer to the evaporating surface layer (see Chapter 3, section 'Soil evaporation'). At the soil surface, water will evaporate while the salts remain at the soil surface. If the upper soil layer is sufficiently wet, the transport of soil water will be entirely in the liquid phase and the upward salt transport can be important. When the soil dries out, water movement will be gradually replaced by vapour diffusion, resulting in a decrease of upward salt transport.

To simulate upward salt transport in response to soil evaporation, AquaCrop considers not only the amount of water that is extracted out of the soil profile by evaporation, but also the wetness of the upper soil layer (Fig. 5.1e). The relative soil water content of the upper soil layer determines the fraction of the dissolved salts that moves with the evaporating water:

$$f_{salt} = \frac{SWC_{rel}}{10} 10^{SWC_{rel}} \qquad \text{(Eq. 5.1e)}$$

$$SWC_{rel} = \frac{\theta - \theta_{air\ dry}}{\theta_{sat} - \theta_{air\ dry}} \qquad \text{(Eq. 5.1f)}$$

where f_{salt} fraction of dissolved salts that moves with the evaporating water
SWC_{rel} relative soil water content of the upper soil layer with thickness $Z_{e,top}$
θ soil water content of the upper soil layer ($m^3.m^{-3}$)
θ_{sat} soil water content at saturation ($m^3.m^{-3}$) of the upper soil layer
$\theta_{air\ dry}$ soil water content when the upper layer is air dry ($m^3.m^{-3}$), which is taken as half of the soil water content at permanent wilting point ($\theta_{air\ dry} = \theta_{PWP}/2$)

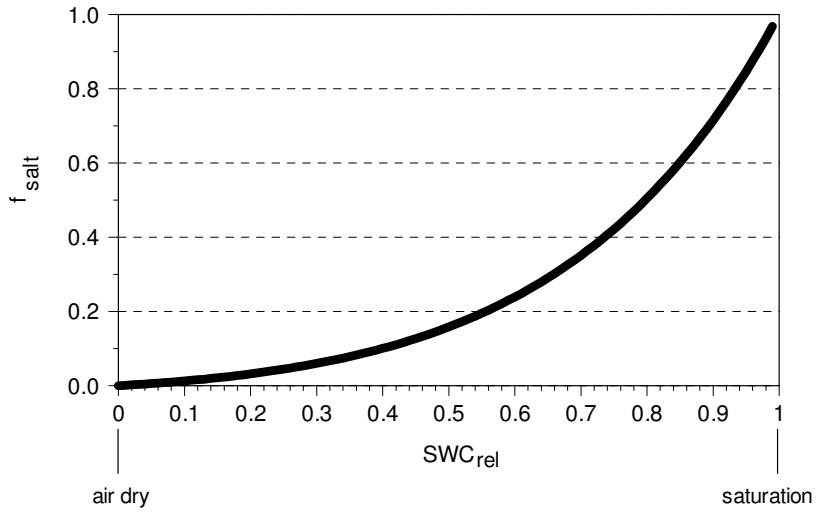


Figure 5.1e – Fraction of dissolved salts (f_{salt}) that moves upward with the evaporating water for various relative soil water contents (SWC_{rel}) of the upper soil layer.

When the upper soil layer is sufficiently wet, soil evaporation will move an important fraction of dissolved salts with the water that is moved by the process to the evaporating soil surface layer. When the layer dries out, the fraction of the dissolved salts that can be transported upward diminishes since water is no longer entirely moved by soil water flow but also by vapour diffusion. Vertical salt movement in response to soil evaporation is no longer considered when the soil water content of the upper soil layer becomes air dry (Fig. 5.1e).

At the start of Stage II of soil evaporation, the thickness of the upper layer ($Z_{e,top}$) is set at 0.15 m (see Chapter 3, Section 'Evaporation reduction coefficient'). When evaporation removes water from the upper layer $Z_{e,top}$ gradually expands to a maximum depth which is a program parameter. Its default value is 0.3 m and the range is 0.15 to 0.50m.

5.1.5 Vertical salt movement as a result of capillary rise

Salts might also accumulate in the root zone as a result of upward transport of saline water from a shallow groundwater table. The amount of salts that accumulate in the top soil depends on the magnitude of the capillary rise (see 6 of this not 'Capillary rise'), the salinity of the groundwater and the leaching by excessive rainfall or irrigation.

5.1.6 Soil salinity content

The salt content of a cell is given by:

$$Salt_{cell} = 0.64\ W_{cell}\ EC_{cell} \qquad \text{(Eq. 5.1g)}$$

where $Salt_{cell}$ is the salt content expressed in grams salts per m^2 soil surface, W_{cell} (Eq. 5.1b) its volume expressed in liter per m^2 (1 mm = 1 l/m^2), and 0.64 a global conversion factor used in AquaCrop to convert deciSiemens per meter in gram salts per liter (1 dS/m = 0.64 g/l).

The electrical conductivity of the soil water (EC_{sw}) and of the saturated soil paste extract (ECe) at a particular soil depth (soil compartment) is:

$$EC_{sw} = \frac{\sum_{j=1}^{n} Salt_{cell,j}}{0.64\,(1000\,\theta\,\Delta z)} \qquad \text{(Eq. 5.1h)}$$

$$ECe = \frac{\sum_{j=1}^{n} Salt_{cell,j}}{0.64\,(1000\,\theta_{sat}\,\Delta z)} \qquad \text{(Eq. 5.1i)}$$

where n is the number of salt cells of the soil compartment, θ the soil water content (m^3/m^3), θ_{sat} the soil water content (m^3/m^3) at saturation, and Δz (m) the thickness of the compartment.

The effect of soil salinity on biomass production is determined by the average ECe of the soil water in the compartments of the effective rooting depth (see 5.2 of this note 'Soil salinity stress and crop response').

5.1.7 Assessment of the simulation of the salt balance

The building up of soil salinity was simulated with AquaCrop (version 4.0) for various soil types, qualities of irrigation water and leaching fractions and compared with the theoretical model of Ayers and Westcot (1985). In this theoretical model the soil salinity expected in the root zone after several years of irrigation is given by:

$$ECe = CF\ EC_w \qquad \text{(Eq. 5.1j)}$$

where ECe is the average electrical conductivity of the saturation extract in the root zone, EC_w the electrical conductivity of the irrigation water, and CF the concentration fraction. The concentration factor, found by using a crop water use pattern of 40-30-20-10, varies with the leaching fraction (LF). For LF of 10, 20 and 30 %, CF is respectively 2.1, 1.3 and 1.0.

- **INPUT**

Climatic conditions:

The effect of the climate on crop development and salt balance was kept under control by considering a constant evaporative demand (ETo = 5 mm/day), optimal air temperature conditions avoiding temperature stress (Tmax = 28°C; Tmin = 12°C) and the absence of rainfall avoiding uncontrolled leaching of the soil profile.

Crop:

To eliminate soil evaporation a crop with a maximum canopy cover (CC_x) of 100% and no canopy senescence was considered during a crop cycle of 1 year. By considering a $Kc_{Tr,x}$ of 1 (without any ageing effects) crop transpiration was equal to ETo (5 mm/day). To mimic the conditions set in the theoretical model of Ayers and Westcot (1985), a maximum root extraction rate of 5.0 mm/day and a 40/30/20/10 percent of water uptake from the upper to lower quarter of the root zone were assumed. The rooting depth was kept constant (1.20 m) throughout the whole crop cycle. The effect of soil salinity on crop development and transpiration was not considered (Ks_{salt} = 1). Water stress was avoided by irrigating weekly.

Irrigation:

To avoid water stress and to build up salts in the root zone, irrigation was applied every 7 days. The quality of the irrigation water remained constant throughout the series of simulation runs. Different electrical conductivities of the irrigation water (ECw) were considered in the various series of runs: from 0.5 up to 3.5 dS/m. Irrigation was applied to cover the losses by crop transpiration and to create some percolation through and below the root zone of 1.20 m. The fraction of extra water applied on top of the crop water requirement of 35 mm (7 x 5 mm/day) carried a portion of the accumulated salts out of the root zone. Leaching fractions (LF) of 10, 20 and 30 % were considered. The leaching fraction (LF) refers to the ratio of the depth of water leached below the root zone to the depth of water applied at the surface.

Soil:

Simulations were run for 10 different soil types with a uniform soil profile. The soil physical characteristics (defaults of AquaCrop) are listed in Table 5.1b. Simulations for silty clay and clay soil types could not be conducted since a leaching of 10, 20 and 30 % could not be achieved due to the low saturated hydraulic conductivity (Ksat).

Table 5.1b – Default soil physical characteristics for various soil types, as available in AquaCrop, and considered in the simulations

Soil type	soil water content			Saturated hydraulic conductivity
	Saturation	Field Capacity	Permanent Wilting Point	
	vol %	vol %	vol %	mm/day
Sand	36	13	6	1500
Loamy sand	38	16	8	800
Sandy loam	41	22	10	500
Loam	46	31	15	250
Silt loam	46	33	13	150
Silt	43	33	9	50
Sandy clay loam	47	32	20	125
Clay loam	50	39	23	100
Silty clay loam	52	44	23	120
Sandy clay	50	39	27	75

Simulations:
The simulation consisted in continuously repeating the simulations over the crop cycle of 1 year, until the salt accumulation in the root zone reached an equilibrium concentration. At the start of the series of runs there were no salts in the soil profile (Electrical conductivity of the saturation extract (ECe) = 0 dS/m) and the soil water content was at Field Capacity. At the end of each run in a series, the values for the soil water content and soil salinity were kept from the previous run so that salts could concentrate during the successive runs (years). The number of runs in the series varied from 1 for the sandy soils with high Ksat and few salt cells to 20 and more for the clayey soil types with low Ksat and the maximum number (11) of salt cells.

▪ RESULTS

Salt contents at the equilibrium concentration in the soil profile are plotted in Figure 5.1f and 5.1g for various qualities of irrigation water (ECw) and leaching fractions (LF). In the figures the salt content is expressed as the electrical conductivity of the saturation extract (ECe) and refers to the average salt content in the 1.20 m rooting depth. Figure 5.1f is for soil types with Ksat > 150 mm/day (sand, loamy sand, sandy loam, loam and silty loam) and Figure 5.1g for soil types with a Ksat ≤ 125 mm/day (silt, sandy clay loam, clay loam, silty clay loam and sandy clay). The bold line in the figures refers to the ECe calculated with the theoretical model of Ayers and Westcot (1985) as obtained with Eq. 5.1j.

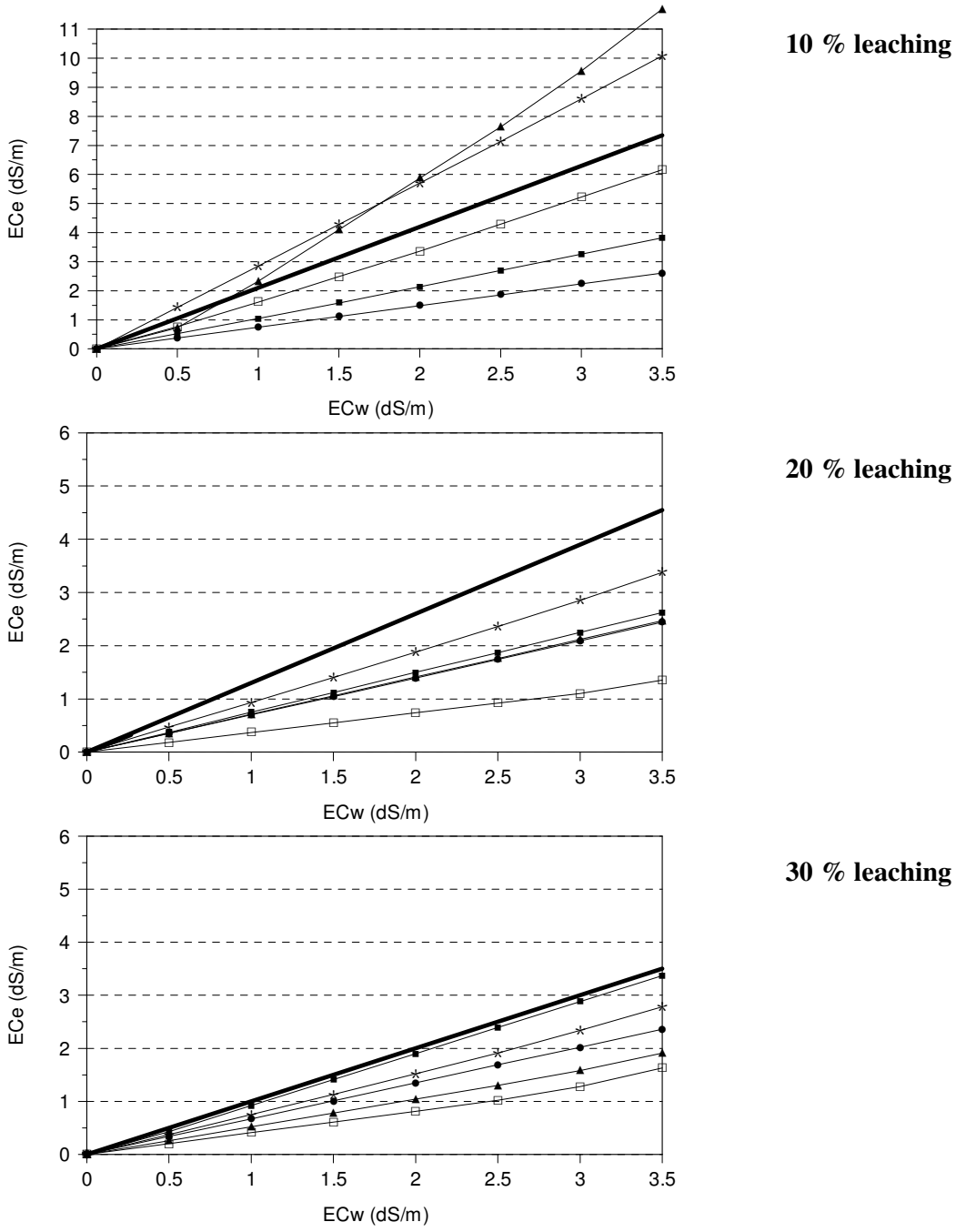


Figure 5.1f – Simulated (lines with symbols) and theoretical (bold line) electrical conductivity of the saturation extract (ECe) for different qualities of irrigation water (ECw) and 10, 20 and 30 % of leaching, **for soil types with a saturated hydraulic conductivity larger then 150 mm/day**: Sand (circle), Loamy sand (square), Sandy Loam (triangle), Loam (filled square), and silt loam (asterisk).

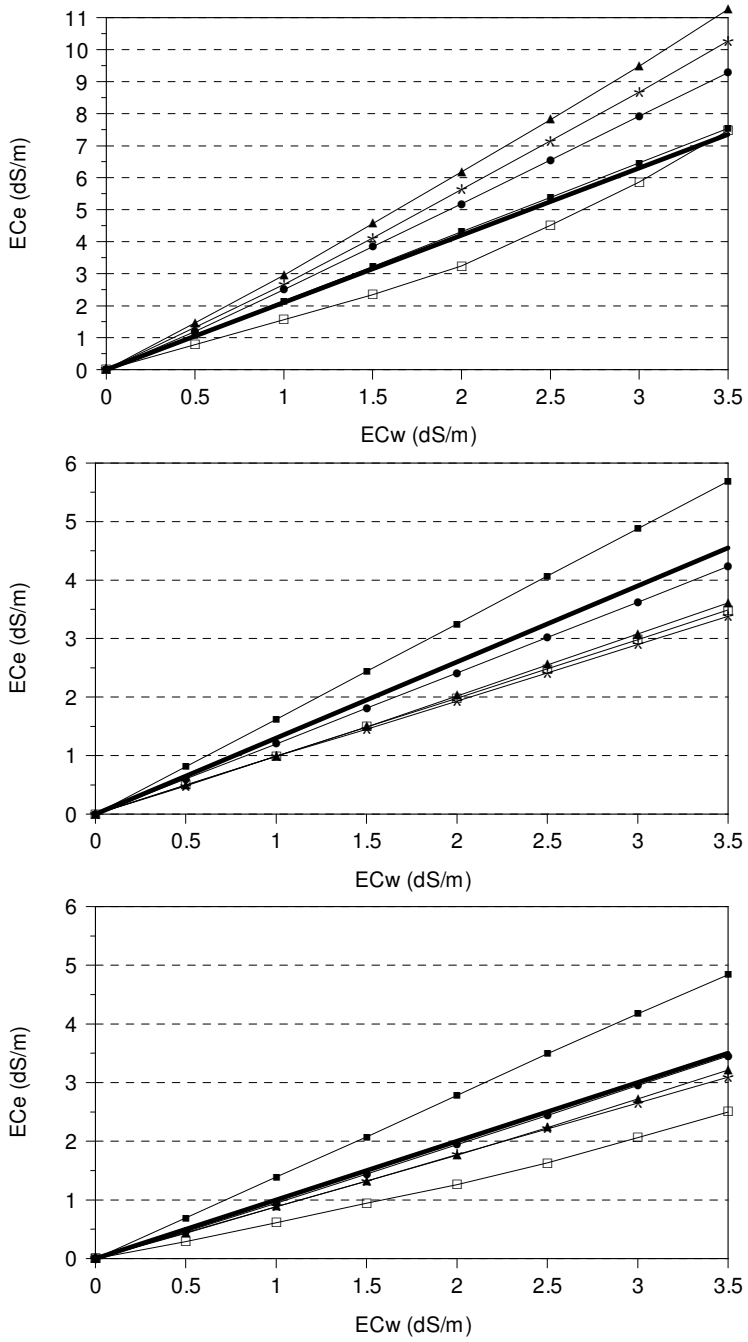


Figure 5.1g – Simulated (lines with symbols) and theoretical (bold line) electrical conductivity of the saturation extract (ECe) for different qualities of irrigation water (ECw) and 10, 20 and 30 % of leaching, **for soil types with a saturated hydraulic conductivity of 125 mm/day or less**: Silt (circle), Sandy clay loam (square), Clay Loam (triangle), Silty clay loam (filled square), and sandy clay (asterisk)

In figure 5.1h the soil salinity profile at equilibrium concentration for a 10 % leaching is plotted for the silty soil irrigated with water with an ECw of 2 dS/m. At equilibrium the amount of salts entering the soil profile by irrigation water is in equilibrium with the amount of salts leaving the 1.20 m root zone by drainage water. The average ECe in the root zone was 5.20 dS/m.

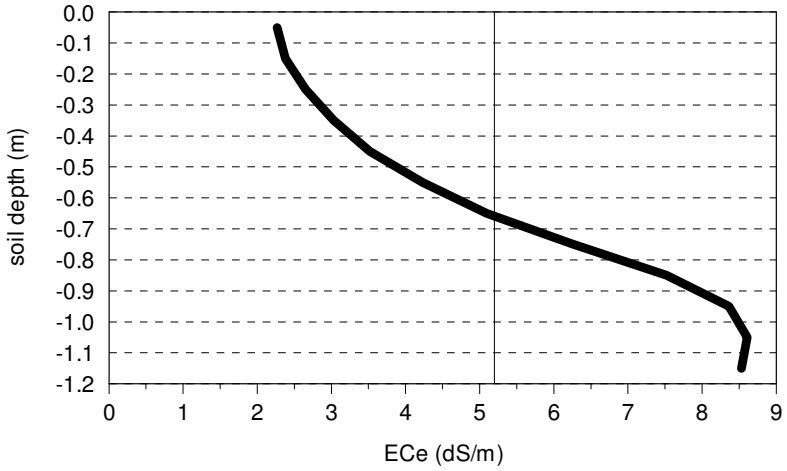


Figure 5.1h – Simulated soil salinity profile (bold line) and average soil salinity (thin vertical line) at equilibrium concentration in the 1.20 m root zone of a silty soil irrigated every 7 days with water of an electrical conductivity (ECw) of 2 dS/m and subjected to a 10 % leaching. Soil salinity is expressed in electrical conductivity of the saturation extract (ECe).

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5.2 Soil salinity stress and crop response

5.2.1 Soil salinity stress coefficient

Biomass production might be affected by soil salinity stress. To describe this process a soil salinity stress coefficient is considered (Table 5.2a).

Table 5.2a – Soil salinity stress coefficient and its effect on biomass production

Soil salinity stress coefficient	Direct effect	Target model parameter
Ks_{salt} Soil salinity stress coefficient	Reduction of biomass production	Canopy cover (CGC, CCx and canopy decline) and Crop transpiration (stomatal closure)

The average electrical conductivity of the saturation soil-paste extract (ECe) from the root zone is the indicator for soil salinity stress. At the lower threshold of soil salinity (ECe_n), Ks becomes smaller than 1 and the stress starts to affect biomass production. Ks becomes zero at the upper threshold for soil salinity (ECe_x) at which the soil salinity stress becomes so severe that biomass production ceases (Fig. 5.2a). The shape of the Ks curve can be linear, convex or logistic. Values for ECe_n and ECe_x for many agriculture crops are given by Ayers and Westcot (1985) in the Irrigation and Drainage Paper Nr. 29 and presented in Annex I.

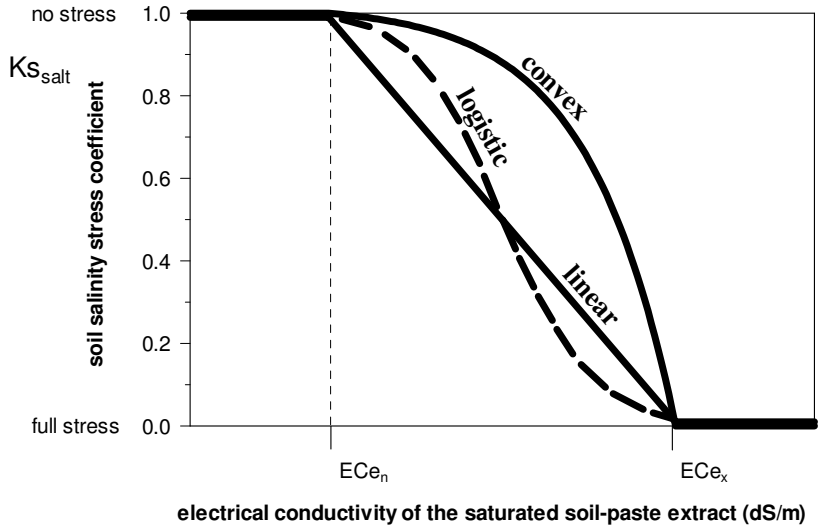


Figure 5.2a – Various shapes for the Ks_{salt} curve

5.2.2 Simulating the effect of soil salinity on biomass production

As indicated in the FAO Irrigation and Drainage Paper Nr. 29, the average seasonal ECe in the root zone determines the reduction in crop yield (relative to the potential yield). For ECe smaller than the upper threshold ($ECe < ECe_n$), crop yield is assumed not to be affected by soil salinity. For ECe equal to or larger than the lower threshold ($ECe > EC_x$), soil salinity is so severe, that crops can no longer be cultivated. For ECe between the thresholds, the shape of the Ks_{salt} curve (Fig. 5.2a) determines the relative biomass production (B_{rel}):

$$B_{rel} = 100\left(1 - Ks_{salt}\right) \qquad \text{(Eq. 5.2a)}$$

B_{rel} expresses the expected biomass production under salt stress with reference to the maximal biomass that can be produced in the given environment in the absence of any other stress.

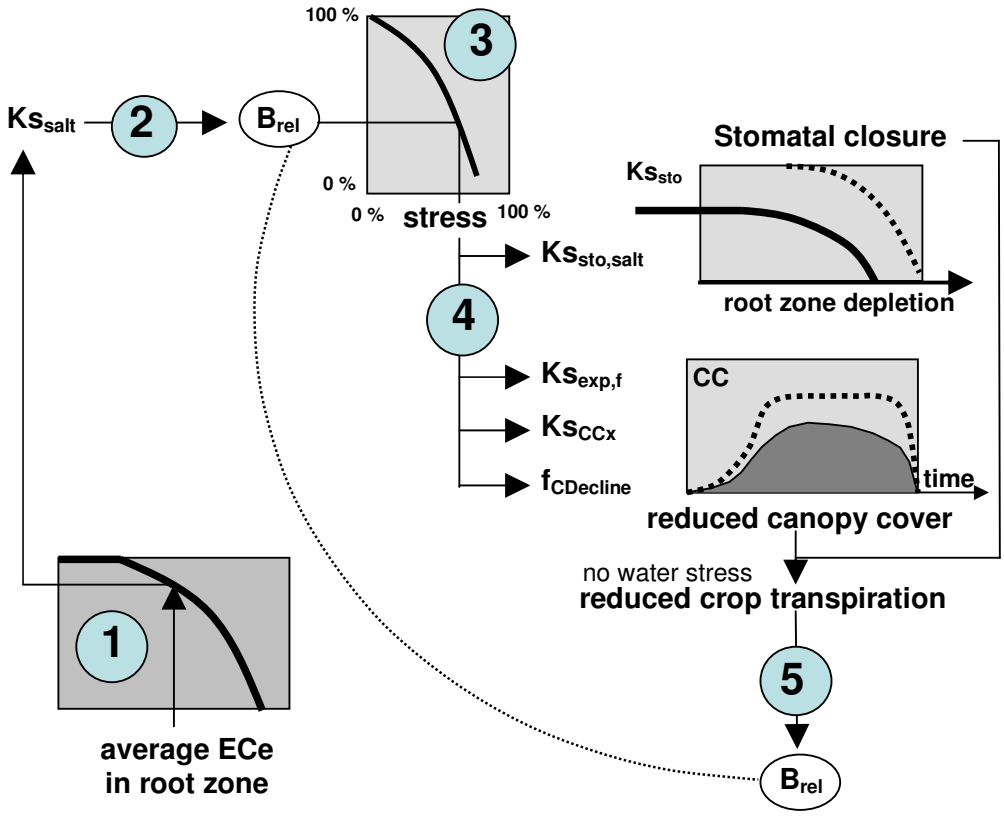


Figure 5.2b – The effect of soil salinity on biomass production in a well watered soil

By assuming that the effect of soil salinity is similar to the effect of soil fertility on canopy development, AquaCrop uses this approach to simulate the effect of soil salinity on CC. The relative biomass production is obtained by considering also the effect of stomatal closure on crop transpiration. The calculation procedure is schematically depicted in Figure 5.2b:

1. the average electrical conductivity of the saturation soil-paste extract (ECe) from the root zone determines the soil salinity stress (Ks_{salt}), as described in Fig. 5.2a;
2. the relative biomass (B_{rel}) that can be produced with the salinity stress (Ks_{salt}) is obtained by Eq. 5.2a;
3. the stress inducing stomatal closure ($Ks_{sto,salt}$) and affecting the canopy development is derived from the user calibrated relationship between relative biomass production and stress (Fig. 4.4);
4. the stress determines the value for (i) $Ks_{sto,salt}$ (resulting in stomatal closure and affecting crop transpiration, Tr), (ii) $Ks_{exp,f}$ (slowing down canopy development), (iii) Ks_{CCx}

(reducing the maximum canopy cover) and (iv) $f_{CDecline}$ (triggering canopy decline) resulting in reduced canopy cover and reduced crop transpiration;

5. as a result of the calibration (see 4 of this note) the resulting B_{rel} is identical to the expected B_{rel} (Eq. 5.2a) in the absence of soil water stress

Changes in salt content during the season require a continuous adjustment of the stress coefficients ($Ks_{sto,salt}$, $Ks_{exp,f}$, Ks_{CCx}, and $f_{CDecline}$). However, since time is required to build up salts in the root zone (or to leach them out of the root zone) the adjustment of the stress coefficients remains modest throughout the simulation run.

The smaller canopy cover and stomatal closure as a result of salinity stress, results in a reduced crop transpiration which affects the soil water balance. Canopy development and crop transpiration might be further affected if next to soil salinity stress, also water stress develops during the growing season (Fig. 5.2c).

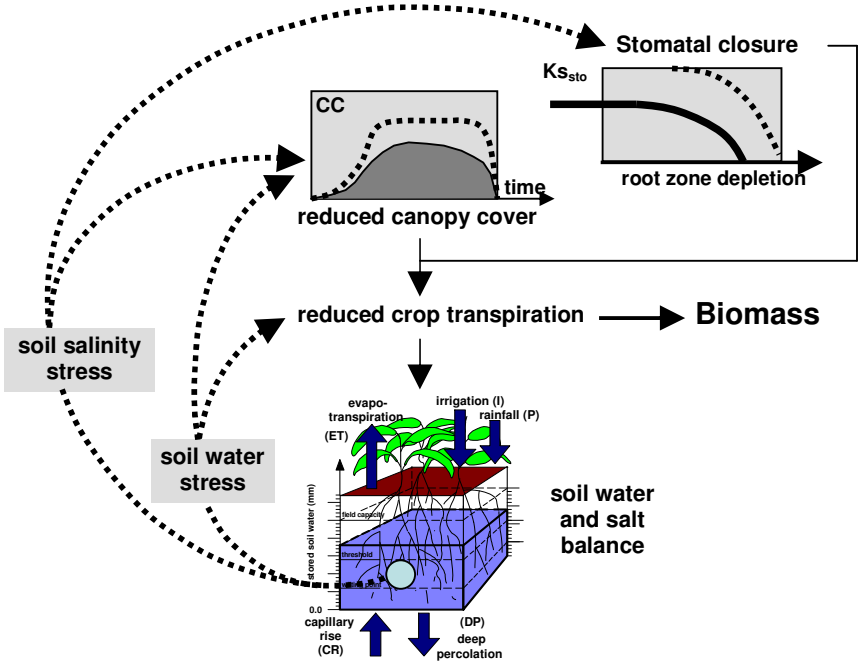


Figure 5.2c – The combined effect of soil salinity and soil water stress on the biomass production

If next to soil salinity stress also soil fertility stress affects canopy development, the resulting reduction in CC at a specific moment during the growing cycle is determined by the strongest stress at that moment. In AquaCrop the effect of soil fertility and soil salinity stress on CC are not added up.

5.2.3 The effect of soil salinity stress on thresholds for soil water depletion

The effect of soil salinity stress on stomatal closure is simulated by multiplying the soil water stress coefficient for stomatal closure (Ks_{sto}) with the soil salinity stress coefficient for stomatal closure ($Ks_{sto,salt}$):

$$Ks_{sto,adj} = Ks_{sto,salt}\ Ks_{sto} \qquad \text{(Eq. 5.2b)}$$

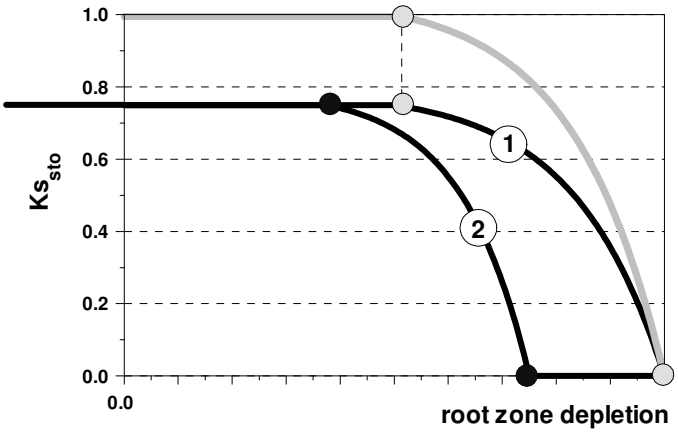


Fig. 5.2d – The soil water coefficient for stomatal closure (Ks_{sto}) without (gray line) and with (black line 1) the effect of soil salinity stress, and the shift of the thresholds (circles) by considering (black line 2) the effect of soil salinity stress on the thresholds.

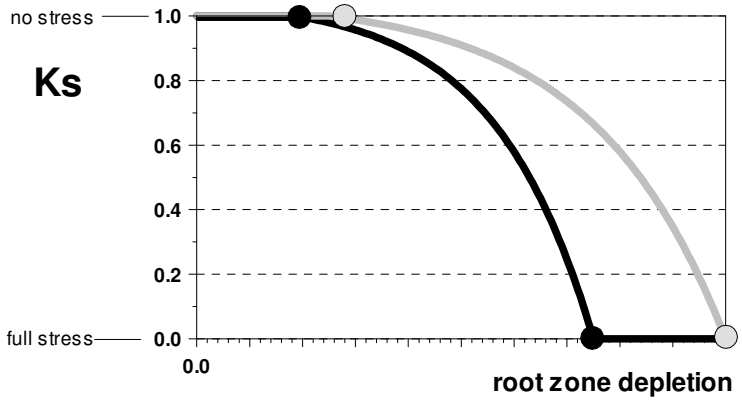


Figure 5.2e – Shift of the thresholds (circles) for root zone depletion and its effect on Ks_{exp} and Ks_{sen} for leaf expansion and canopy senescence (lines) with (black) and without (gray) the effect of soil salinity on the thresholds.

Due to osmotic forces, which lower the soil water potential, the salts in the root zone makes the water less available for the crop. The osmotic forces are likely to alter also the upper and lower thresholds for root zone depletion at which soil water stress (i) affects leaf expansion (Ks_{leaf}), (ii) induces stomatal closure (Ks_{sto}) and (iii) triggers canopy senescence (Ks_{sen}). This is simulated by multiplying the fractions (p_{upper} and p_{lower}) of TAW with $Ks_{sto,salt}$ (Fig. 5.2d and Fig. 5.2e). By means of the Program settings in the ***Crop characteristics*** menu, the user can switch "on" or "off" the additional effect of salinity stress on the thresholds. The effect is only considered for the simulation of canopy development, but has no effect on the adjustment of the Harvest Index (to avoid the double effect of soil salinity on crop yield).

5.3 User interface

5.3.1 Crop characteristics menu

The presence of salts in the root zone affects biomass production. The effect is described by the soil salinity stress coefficient (Ks_{salt}) which varies between 0 (full effect of soil salinity stress) and 1 (no effect).

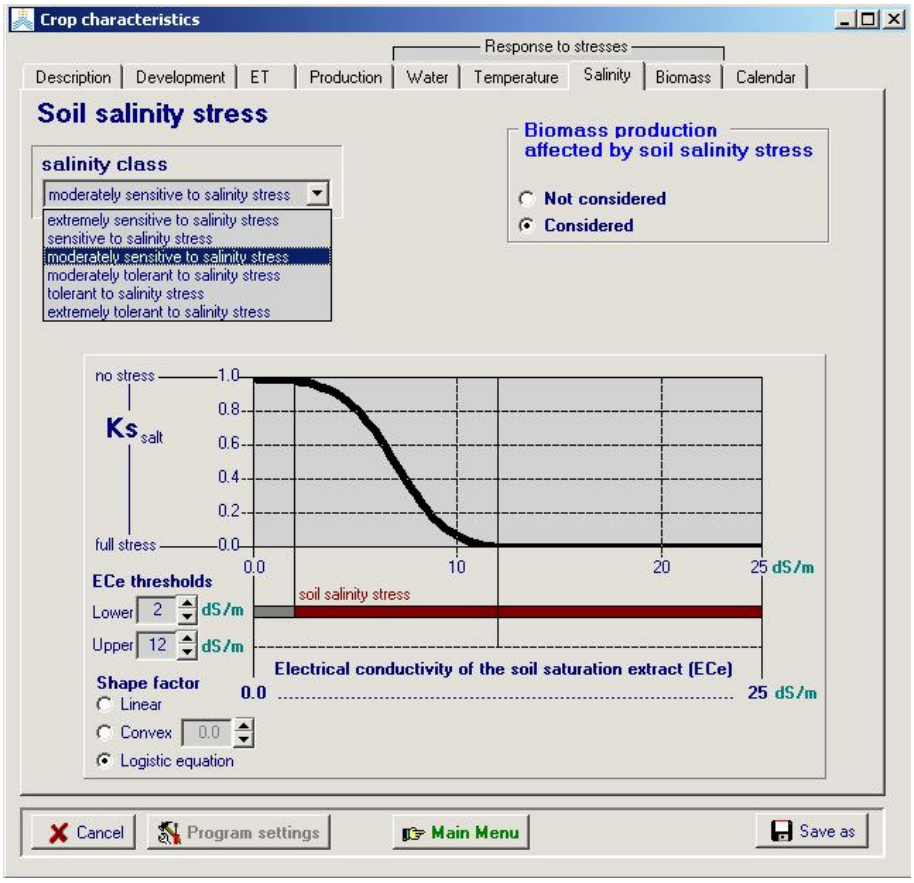


Figure 5.3a – Specification of the upper and lower thresholds and the shape of the Ks_{salt} curve for the effect of soil salinity stress on Biomass production in the ***Crop Characteristics*** menu.

Thresholds: The user specifies the effect of soil salinity stress by selecting a sensitivity class (Tab. 5.3a) or by specifying values for an upper and lower threshold for soil salinity in the root zone (Fig. 5.3a). The thresholds are crop specific (see Annex I) and are given by electrical conductivities of saturated soil-paste extracts (ECe) and expressed in deciSiemens per meter (dS/m). Distinction is made between:

- the lower threshold (ECe_n) at which soil salinity stress starts to affect crop production, and
- the upper threshold (ECe_x) at which soil salinity stress has reached its maximum effect and crop production is no longer possible.

Table 5.3a – Classes and corresponding default values for the lower (ECe_n) and upper (ECe_x) threshold of soil salinity stress

Class Sensitivity to salinity stress	Electrical conductivity of the saturated soil-paste extract (ECe) in dS/m	
	ECe_n	ECe_x
extremely sensitive to salinity stress	0	6
sensitive to salinity stress	1	8
moderately sensitive to salinity stress	2	12
moderately tolerant to salinity stress	5	18
tolerant to salinity stress	7	25
extremely tolerant to salinity stress	8	37

Shape of Ks curve: Between the upper and lower threshold of the saturated soil-paste extracts, the shape of the Ks_{salt} curve determines the magnitude of the effect of soil salinity stress on biomass production. The shape can be linear, convex or logistic (Fig. 5.2a). For the convex shape, the shape factor can range from +6 (strongly convex) to 0 (linear).

5.3.2 Specifying the salinity of the irrigation and groundwater

The water quality of the irrigation water can be specified in the (i) ***Irrigation management,*** and (ii) ***Off-season conditions*** menus or (iii) in the ***Simulation Run*** menu at run time. The quality of the groundwater table is specified in the ***Groundwater characteristics*** menu.

Since the quality of the irrigation water can alter during the year, it can be specified for each irrigation event (Fig. 5.3b). The quality is expressed by the electrical conductivity of the irrigation water (EC_w) in deciSiemens per meter (dS/m). When the quality of the irrigation water remains constant over the crop cycle the constant EC_w can be assigned for all irrigation events. Indicative values for EC_w for various classes of irrigation water are listed in Table 5.3b.

Table 5.3b – Indicative values for the quality classes of the irrigation water (EC_w)

Range of EC_w Electrical Conductivity (dS/m)	Class Quality of irrigation water
0.0 ... 0.2	excellent
0.3 ... 1.0	good
1.0 ... 2.0	moderate
2.1 ... 3.0	poor
> 3.0	very poor

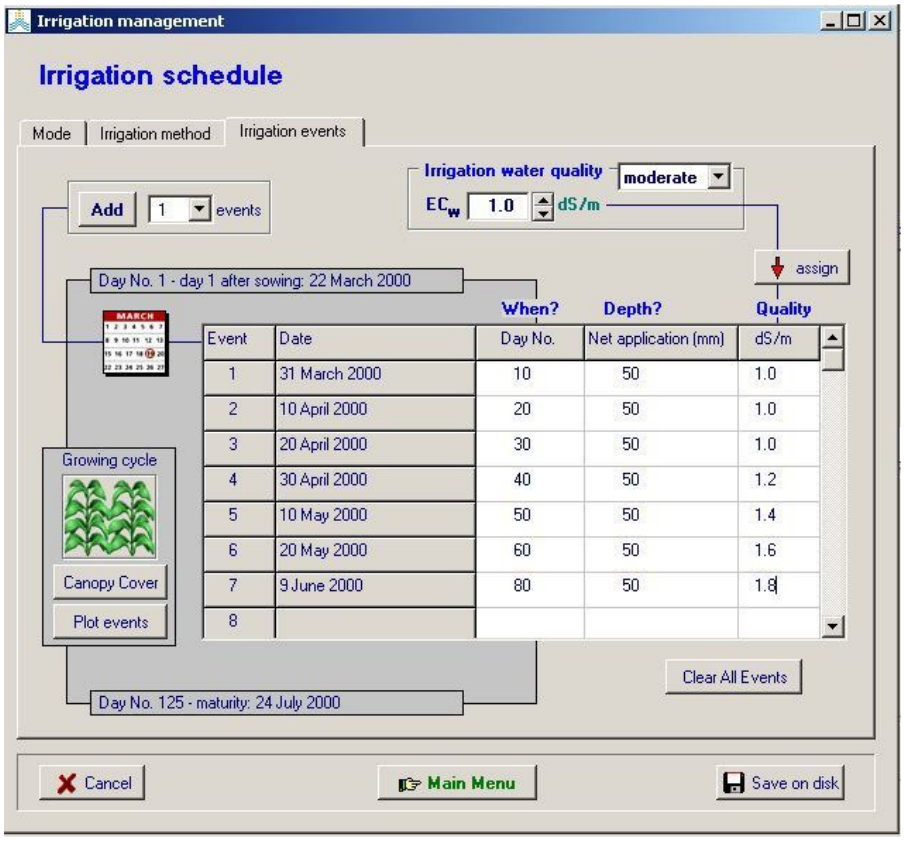


Figure 5.3b - Specification of the time, application depth and water quality for irrigation events in the ***Irrigation management*** menu.

The change in salinity of the groundwater throughout the year can be specified in the ***Groundwater characteristics*** menu (see 6 of this note 'Capillary rise').

5.3.3 Specifying the initial soil salinity (at start of the simulation period)

The soil salinity at the start of the simulation run can be adjusted by (i) specifying the Electrical Conductivity of the saturated soil-paste extract (ECe) at particular depths of the soil profile, (ii) specifying it for specific layers, or by (iii) setting the whole soil profile at a specific ECe (Fig. 5.3c).

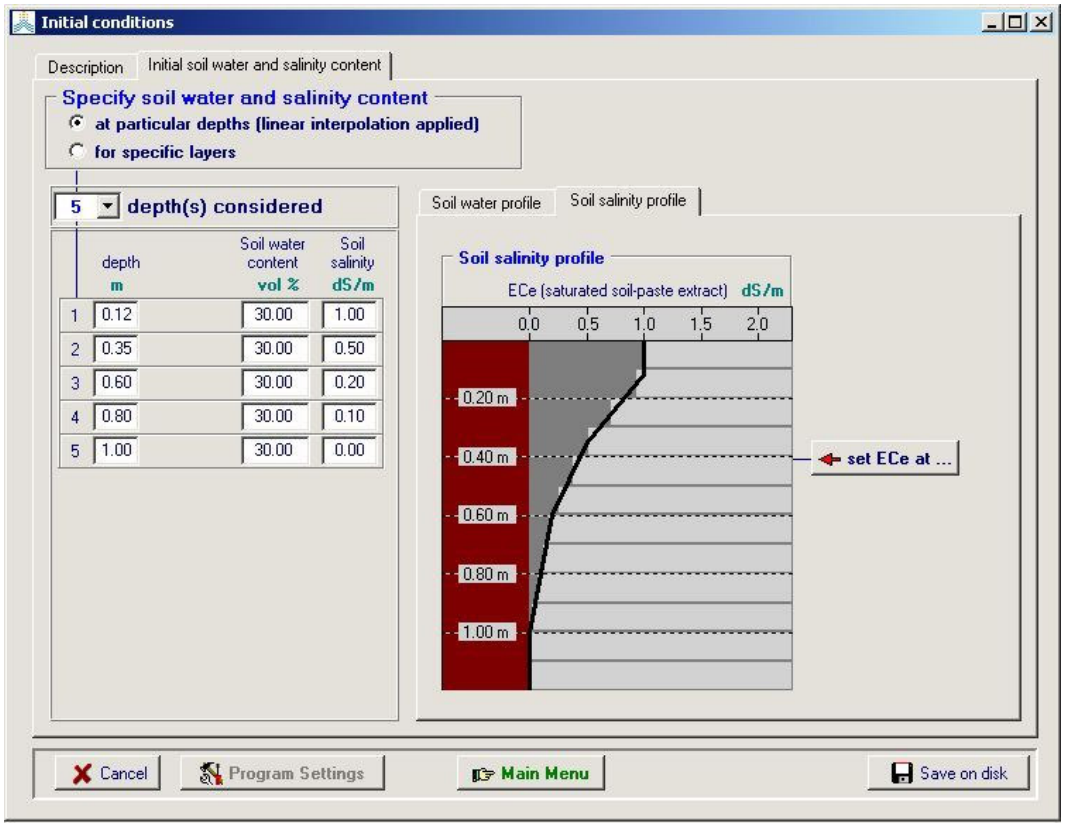


Figure 5.3c - Specification of the initial salinity in the soil profile in the ***Initial conditions*** menu

5.3.4 Simulation Run menu

Soil salinity tab sheet

In the soil salinity tab sheet of the ***Simulation run*** menu, the simulated soil salinity profile and the parameters of the salt balance in the soil profile and root zone are adjusted and displayed for each day of the simulation period (Fig. 5.3d).

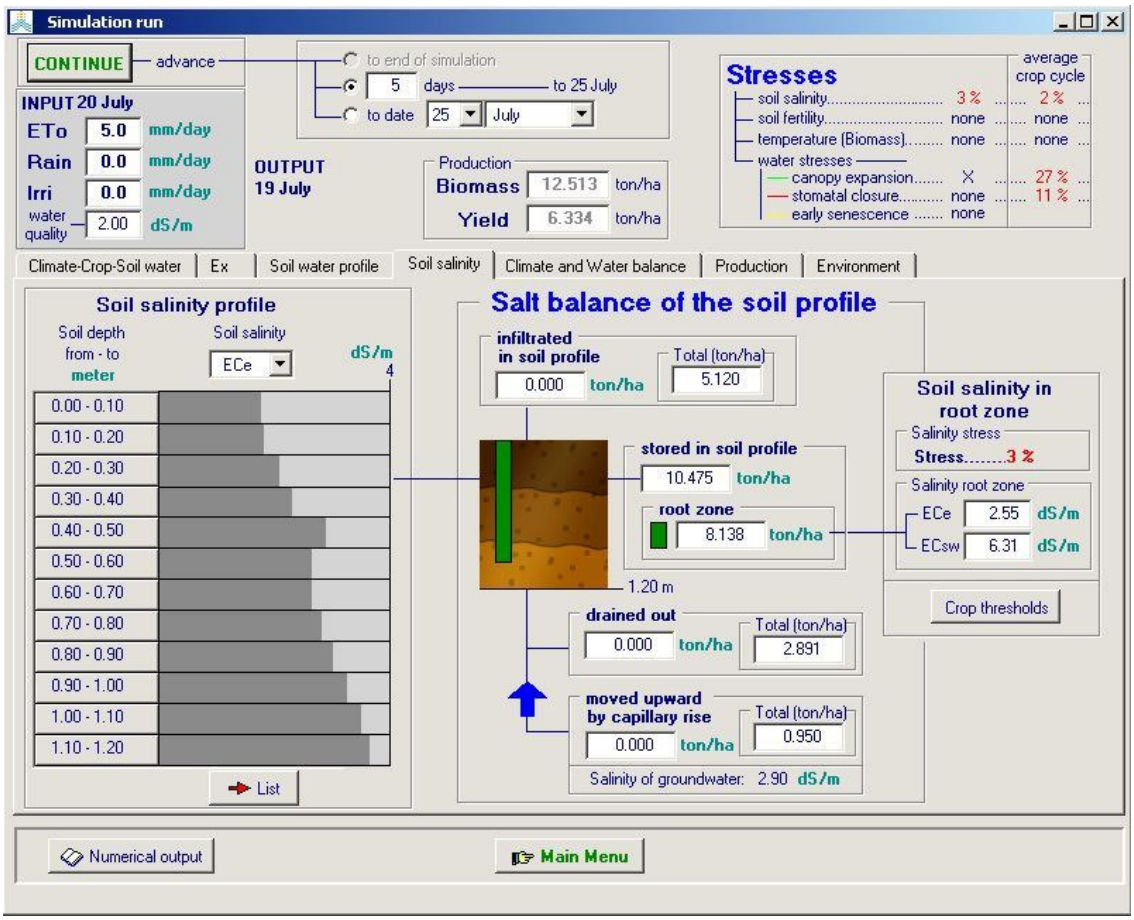


Figure 5.3d - Display of the soil salinity profile and the salt balance in the ***Simulation run*** menu

Tab sheet with selected parameter

In the second sheet of the ***Simulation run*** menu, the user can select particular parameters for further analysis (Fig. 5.3e). Several crop parameters and parameters of the soil water balance and soil salinity can be selected and the scale of the plot can be adjusted. The parameters which can be selected for soil salinity are:

- Salt infiltrated in the profile
- Salt infiltrated in the profile (cumulative)
- Salt drained out of the profile
- Salt drained out of the profile (cumulative)
- Salt moved upward from groundwater table
- Salt moved upward (cumulative)
- Salt stored in the profile
- Salt stored in the root zone
- EC of saturated soil-paste extract from root zone
- EC of soil water in root zone
- EC of groundwater table

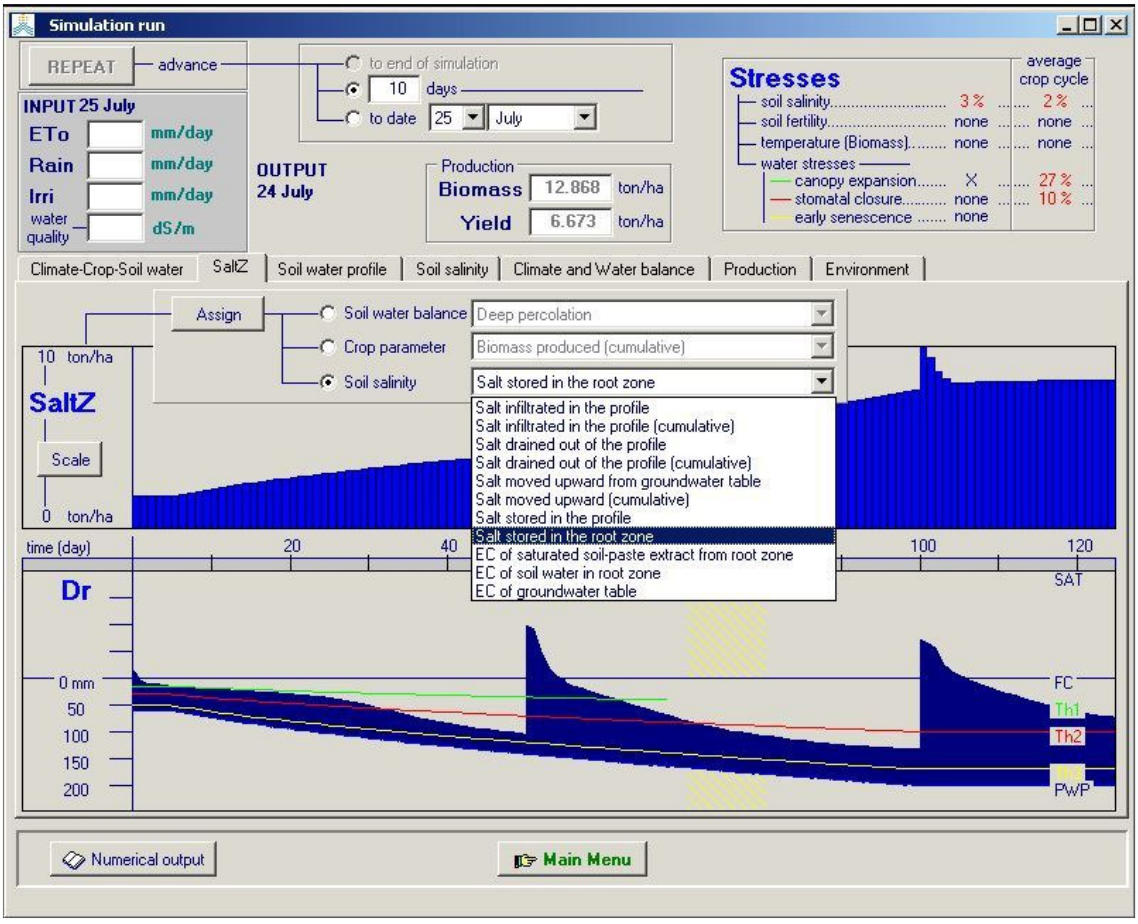


Figure 5.3e – Selection of a soil salinity parameter for display in the ***Simulation run*** menu

Display of Numerical output and output files

Simulation results are recorded in output files and the data can be displayed by clicking on the **<Numerical output>** command in the ***Simulation run*** menu (Fig. 5.3f). The data can be aggregated in 10-day, monthly or yearly data.

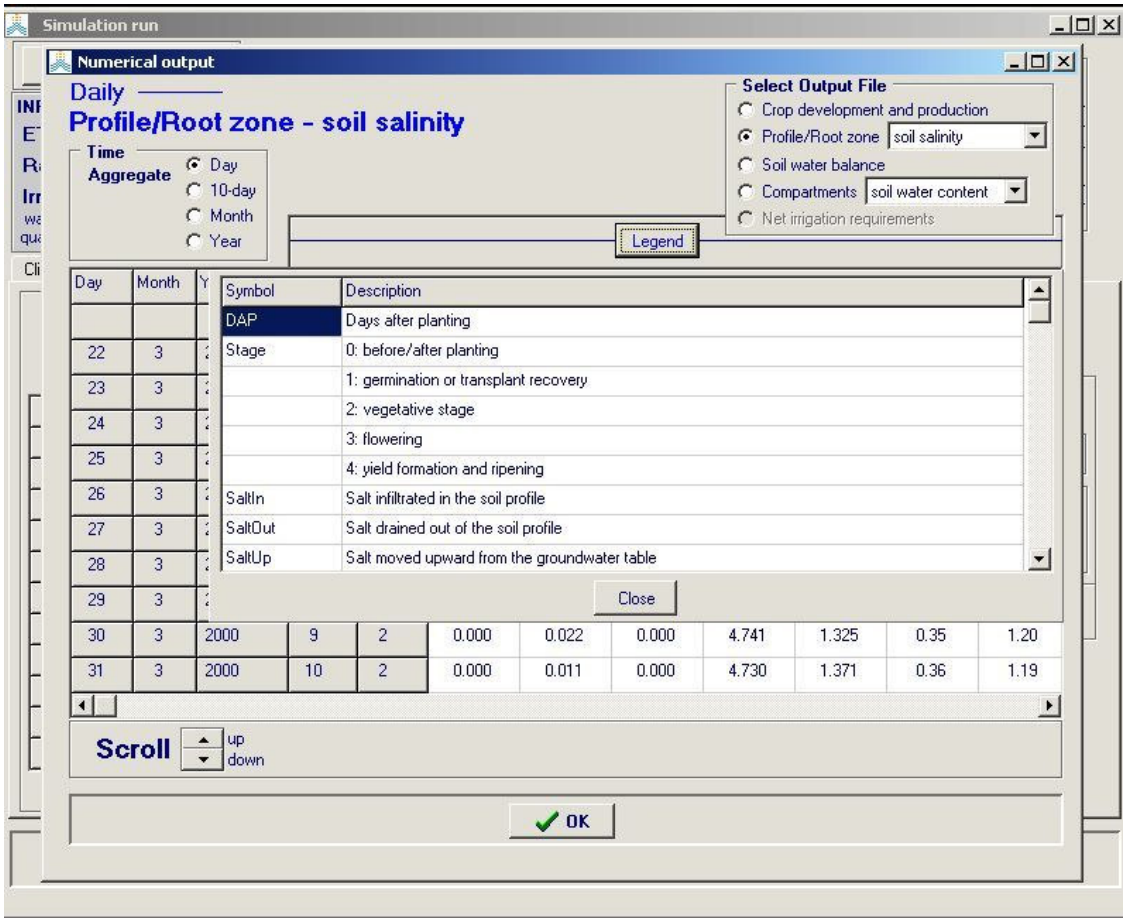


Figure 5.3f – Display of daily values of soil salinity parameters in the ***Numerical output*** menu.

On exit of the ***Simulation run*** menu, the option is available to save the output on disk. Distinction is made between files containing daily simulation results and seasonal results. The output of the daily results consists of 7 files containing key variables (Table 5.3c).

Table 5.3c – Output files with daily simulation results

File name	Content
-Crop.OUT	Crop development and production:
-Wabal.OUT	Parameters of the soil water balance
-Prof.OUT	Soil water content (profile and root zone)
-Salt.OUT	Salt balance (profile and root zone)
-CompWC.OUT	Soil water content (compartments)
-CompEC.OUT	Soil salinity (compartments)
-Inet.OUT	Net irrigation requirements

The output of the seasonal results can be stored as well (Table 5.3d).

Table 5.3d – Parameters saved as seasonal results in the seasonal Output file -Run.OUT

Nr	Symbol	Description	Unit
1	RunNr	Number simulation run	-
2	Day1	Start day of simulation run	-
3	Month1	Start month of simulation run	-
4	Year1	Start year of simulation run	-
5	Rain	Rainfall	mm
6	ETo	Reference evapotranspiration	mm
7	GD	Growing degrees	C.day
8	CO2	Atmospheric CO2 concentration	ppm
9	Irri	Water applied by irrigation OR Net irrigation requirement	mm
10	Infilt	Infiltrated water in soil profile	mm
11	Runoff	Water lost by surface runoff	mm
12	Drain	Water drained out of the soil profile	mm
13	Upflow	Water moved upward by capillary rise	mm
14	E	Soil evaporation	mm
15	E/Ex	Relative soil evaporation (100 E/Ex)	%
16	Tr	Crop transpiration	mm
17	Tr/Trx	Relative crop transpiration (100 Tr/Trx)	%
18	SaltIn	Salt infiltrated in the soil profile	ton/ha
19	SaltOut	Salt drained out of the soil profile	ton/ha
20	SaltUp	Salt moved upward by capillary rise from groundwater table	ton/ha
21	SaltProf	Stored salt in the soil profile	ton/ha
22	Cycle	Length of crop cycle: from germination to maturity (or early senescence)	days
23	SaltStr	Average soil salinity stress	%
24	FertStr	Average soil fertility stress	%
25	TempStr	Average temperature stress (affecting biomass)	%
26	ExpStr	Average leaf expansion stress	%
27	StoStr	Average stomatal stress	%
28	Biomass	Cumulative biomass produced	ton/ha
29	Brelative	Relative biomass (Reference: no water, no soil fertility, no soil salinity stress)	%
30	HI	Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress	%
31	Yield	Yield (HI x Biomass)	ton/ha
32	WPet	ET Water Productivity for yield part (kg yield produced per m3 water evapotranspired)	kg/m^3
33	DayN	End day of simulation run	-
34	MonthN	End month of simulation run	-
35	YearN	End year of simulation run	-

6. Capillary rise

6.1 Capillary rise for various depths of the groundwater table

The upward flow from a shallow groundwater table to the top soil can be described with the Darcy equation by considering the water retention curve (h-θ relationship) and the relationship between matric potential (h) and hydraulic conductivity (K). Since h-θ and K-h relationships are not available in AquaCrop, capillary rise is estimated by considering the soil type and its hydraulic characteristics.

The relationship between capillary rise and the depth of the groundwater table is given by the exponential equation:

$$CR = \exp\left(\frac{\ln(z) - b}{a}\right) \qquad \text{(Eq. 6.1a)}$$

where CR is the expected capillary rise (mm.day^{-1}), z the depth (m) of the water table below the soil surface and a and b parameters specific for the soil type and its hydraulic characteristics. Since the magnitude of capillary rise is strongly affected by the shape of the water retention curve and the K-h relationship, the a and b parameters of the equation varies with the textural class (Fig. 6.1a).

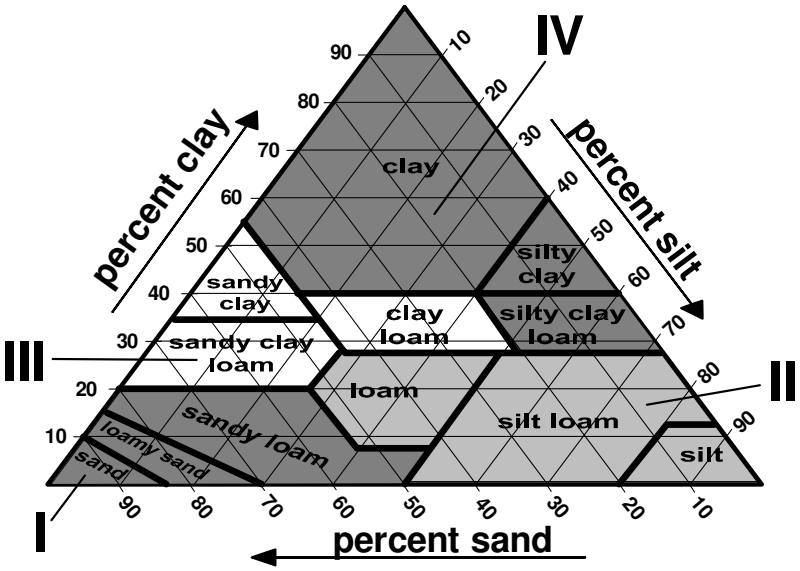


Figure 6.1a –Textural triangle with indication of the 12 different soil types and the 4 soil Classes considered for the determination of the a and b parameters of Eq. 6.1a.
I. Sandy soils (dark area), II. Loamy soils (grey area),
III. Sandy clayey soils (white area) and IV. Silty clayey soils (dark area).

The a and b parameters describing the capillary rise in AquaCrop were obtained in 4 successive steps:

1. Selection of typical water retention curves for the various textural classes. By considering similarities in h-θ relationships, the 12 distinguished classes were grouped into 4 Classes: I. Sandy soils, II. Loamy soils, III. Sandy clayey soils, and IV. Silty clayey soils (Fig. 6.1a). For each of the classes one representative water retention curve was selected;
2. Generation for each of the 4 classes a set of K-h relationships from the shape of the unique h-θ relationship (obtained in step 1) by considering the range of saturated hydraulic conductivities (K_{sat}) typical for each class (Tab. 6.1);
3. Simulation of the capillary rise that can be expected for each of the 4 soil classes at various depths (z) of the water table by considering the typical water retention curve (step 1) and the different generated K-h relationships (step 2). Simulations were carried out with the UPFLOW software (Raes and De Proost, 2003);
4. From the obtained CR-z plots (step 3), a and b soil parameters were derived by Janssens (2006) for each class (by considering the saturated hydraulic conductivity (K_{sat}) as the independent variable). The coefficients of determination for the a and b equations (Eq. 6.1b and 6.1c in Tab. 6.1) were always high ($R^2 > 0.96$).

The capillary rise from a shallow groundwater table (Eq. 6.1a) for the 4 soil classes and for various depths of the groundwater table are plotted in Figure 6.1b.

Table 6.1 – Equation 6.1b and 6.1c for the 4 soil Classes with indication of the considered range for the saturated hydraulic conductivity (K_{sat}) (Janssens, 2006).

Soil Class	**Range K_{sat} mm.day^{-1}**	**a** **Eq. 6.1b**	**b** **Eq. 6.1c**
I. Sandy soils sand, loamy sand, sandy loam	200 to 2000	$-0.3112 - 10^{-5} K_{sat}$	$-1.4936 + 0.2416 \ln(K_{sat})$
II. Loamy soils loam, silt loam, silt	100 to 750	$-0.4986 + 9 (10^{-5}) K_{sat}$	$-2.1320 + 0.4778 \ln(K_{sat})$
III. Sandy clayey soils sandy clay, sandy clay loam, clay loam	5 to 150	$-0.5677 - 4 (10^{-5}) K_{sat}$	$-3.7189 + 0.5922 \ln(K_{sat})$
IV. Silty clayey soils silty clay loam, silty clay, clay	1 to 150	$-0.6366 + 8 (10^{-4}) K_{sat}$	$-1.9165 + 0.7063 \ln(K_{sat})$

References

Janssens, P. 2006. Invloed van een ondiepe grondwatertafel op de planning van irrigaties voor intensieve groenteteelt. Master dissertation, Fac. Bio-ingenieurswetenschappen, K.U.Leuven University, Leuven, Belgium. 89 pp.

Raes, D., and De Proost, P. 2003. Model to assess water movement from a shallow water table to the root zone. Agricultural Water Management 62(2): 79-91.

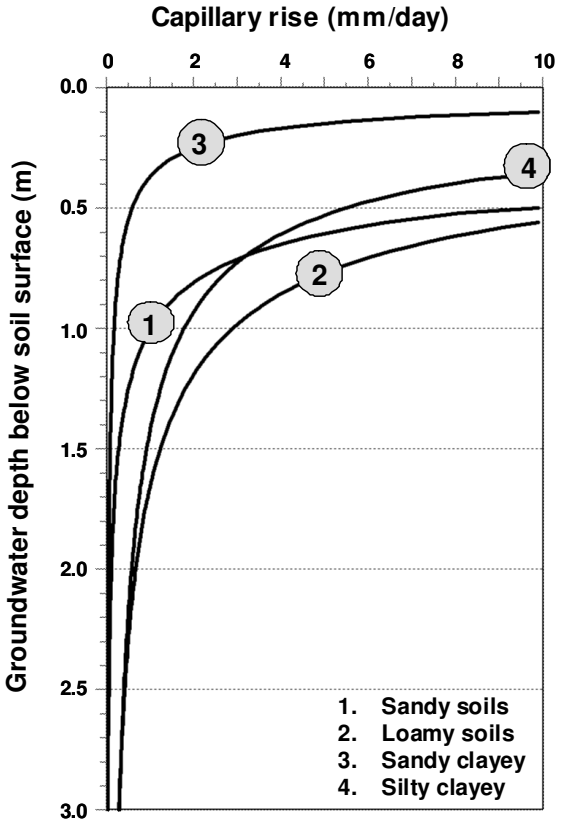


Figure 6.1b – Capillary rise to a bare soil surface, as obtained with Eq. 6.1a, for the 4 considered soil Classes and for various depths of a shallow groundwater table and by assuming a typical saturated hydraulic conductivity (Ksat) of 500 mm/day for Class I (Sandy soils), 250 mm/day for Class II (Loamy soils), 100 mm/day for Class III (Sandy clayey soils) and 25 mm/day for Class IV (Silty clayey soils).

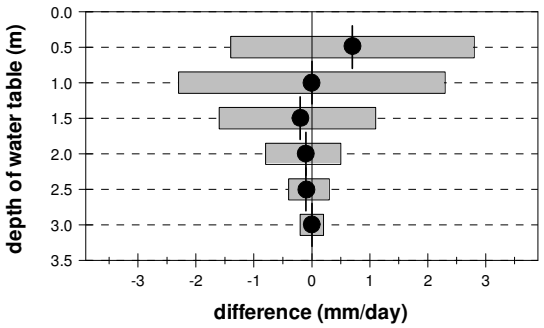
Box 6.1a - Evaluation of the equation for Capillary rise

To evaluate the simplified solution, the capillary rise as calculated with Eq. 6.1a was compared with the capillary rise obtained with UPFLOW (Raes and De Proost, 2003) for various soils. The calculation procedure of UPFLOW is based on the Darcy equation (Box 6.1b).

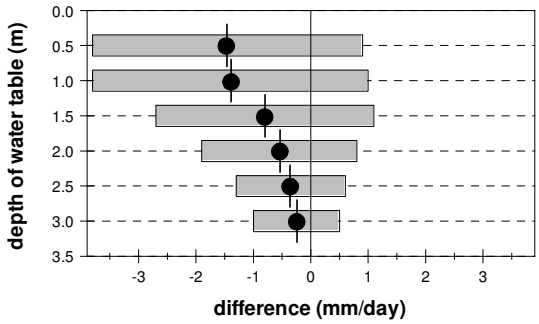
Soil characteristics for 67 soils were obtained from literature (Rijtema, 1969; Wösten et al. (1994), Raes et Deckers (1993), Meyer et al. (1997). 21 of the soils belonged to Class I, 21 soils to Class II, 15 soils to Class III, and 10 soils to Class IV. For UPFLOW (based on the Darcy Equation) the hydraulic characteristics (h-θ and K-h relationships) of the soil were required, while for Eq. 6.1a only the soil Class and K_{sat} had to be specified. For each of the 67 considered soils, the capillary rise was calculated by both methods for 6 depths of the water table: 3.0, 2.5, 2.0, 1.5, 1.0 and 0.5 meter below the top soil.

Box 6.1a - Evaluation of the equation for Capillary rise (Continue)

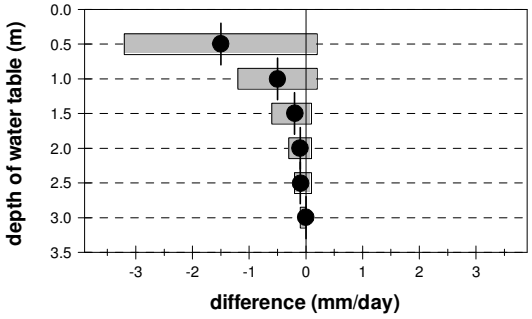
For each of the 4 Classes and 6 depths, the mean differences between the capillary rise estimated by both approaches and the standard deviations for the 6 depths are plotted



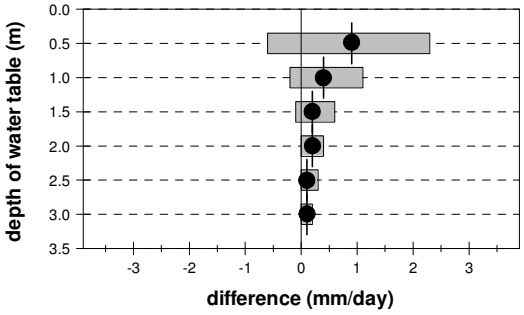
a. Class I. Sandy soils
(sand, loamy sand, sandy loam)



b. Class II. Loamy soils
(loam, silt loam, silt)



c. Class III. Sandy clayey soils
(sandy clay, sandy clay loam, clay loam)



d. **Class IV. Silty clayey soils**
(silty clay loam, silty clay, clay)

Fig. Box6.1a – Mean difference (circle) and standard deviation of the differences (bars) between capillary rise estimated with Eq.6.1a and Darcy Equation (Box 6.1b) for 67 soils belonging to Class I (a), II (b), III (c), and IV (d) for various depths of the groundwater table.

The evaluation reveals that:
- the mean difference between both methods is rather small;
- the deviation increases when the ground water table becomes shallower;
- given the high variability of characteristics of soil layers of one class, the amount of water that can be transported upwards as calculated with the Darcy equation can vary widely between the soil layers belonging to the class. Hence, the standard deviation is rather large in each of the classes. This highlights the need for calibration.

Meyer, P.D., Rockhold, M.L., and Gee G.W. 1997. Uncertainty analysis of Infiltration and Subsurface Flow and Transport for SDMP sites. Pacific Northwest National Laboratory. USA. 38 pp.

Raes, D. et Deckers, J. 1993. Les sols du Delta du fleuve Sénégal. Bulletin Technique Nr.8. SAED – centre de NDiaye, BP. 74, Saint-Louis, Sénégal. 84 pp.

Rijtema, P.E. 1969. Soil moisture forecasting. Nota ICW. Wageningen.28 pp.

Wösten, J.H.M., Veerman, .J., and Stolte, J. 1994. Waterretentie en doorlatendheidskarakteristieken van boven- en ondergronden in Nederland: de Staringreeks. Technisch Document 18. DLO-Staring Centrum, Wageningen, The Netherlands. 28 pp.

Box 6.1b. Calculation procedure in UPFLOW for steady upward flow

The steady upward flow from a shallow water table to the topsoil is estimated in UPFLOW (Raes and Deproost, 2003) by means of a calculation procedure presented by De Laat (1980; 1995). By assuming a constant flux from a shallow water table to the top soil, De Laat rewrote and integrated the Darcy equation as

$$z = -\int_0^h \frac{K(h)}{q + K(h)} dh \qquad \text{(Eq. 1)}$$

where z [m] is the vertical co-ordinate, q the constant upward flux [$m^3.m^{-2}.day^{-1}$] of water, h the soil matric potential per unit weight of water (head) [m], and K(h) the corresponding hydraulic conductivity [$m.day^{-1}$]. The reference level is chosen at the stationary phreatic surface at which level z and h are zero. The vertical co-ordinate and the flux are both taken positive upward. If the functional relation between K and h is known, the soil matric potential at specific points above the water table can be calculated for particular steady upward flows (q) by means of Eq. 1. The obtained relation between the height above the water table (z) and the matric head (h) is called a pressure profile. Given the relation between the matric head and the soil water content (θ) (i.e. the soil water characteristics curve) the pressure profiles are easily transformed in moisture profiles.

Given the K-h and θ-h relation for the various soil layers of the profile above the water table, UPFLOW calculates for various fluxes the corresponding pressure and soil water profiles. Water profiles whereby the soil water content in the topsoil drops below the specified water content in the top soil are rejected. To guarantee a steady state condition, the amount of water that is transported upward will have to be removed with the same rate from the topsoil by evapotranspiration. As such the upward flow can never exceed the specified average evapotranspiration demand. Given the above restrictions, the maximum upward flow q that can be expected under the specified environmental conditions is obtained.

De Laat, P.J.M. 1980. Model for unsaturated flow above a shallow water-table. Applied to a regional sub-surface flow problem. PUDOC, Doctoral thesis, Wageningen, The Netherlands. 126 pp.

De Laat, P.J.M. 1995. Design and operation of a subsurface irrigation scheme with MUST. In Pereira, L.S., B.J. van den Broek, P. Kabat and R.G. Allen (Editors). Crop-water-simulation models in practice. Wageningen Pers, The Netherlands: 123-140.

Raes, D., and De Proost, P. 2003. Model to assess water movement from a shallow water table to the root zone. Agricultural Water Management 62(2): 79-91.

6.2 Generation of the parameters for capillary rise

The soil profile in AquaCrop can be composed of up to five different horizons, each with their own physical characteristics. The soil data for the various soil horizons consist in the soil water content at saturation (θ_{Sat}), field capacity (θ_{FC}), and permanent wilting point (θ_{PWP}), and the value for the hydraulic conductivity at soil saturation (Ksat).

To generate default values for the a and b soil parameters (Eq. 6.1a), AquaCrop determines:

- in a first step the class of the soil type for each of the soil layers. The classification is obtained by comparing the volumetric water content at saturation, field capacity and permanent wilting point of each soil layer with the expected ranges of those soil water contents in the 4 classes (Tab. 6.2);
- in the next step, the a and b soil parameters for each soil layer with Eq. 6.1b and 6.1c (Tab. 6.1) by considering (i) the soil class and (ii) the specified saturated hydraulic conductivity (Ksat).

Table 6.2 – Ranges considered for the soil water content at saturation, field capacity and permanent wilting point for the 4 soil classes

Soil class	Soil water content (vol %)		
	Saturation	**Field Capacity**	**Permanent Wilting Point**
I. Sandy soils	32 – 51	9 – 28	4 – 15
II. Loamy soils	42 – 55	23 – 42	6 – 20
III. Sandy clayey soils	40 – 53	25 – 45	16 – 34
IV. Silty clayey soils	49 – 58	40 – 58	20 - 42

In the ***Soil profile characteristic*** menu, the soil class and the default values are displayed (Fig. 6.2). If required the user can calibrate the a and b soil parameters by considering the simulated capillary rise for various depths of the groundwater table (see 6.5.2 of this note 'The soil profile characteristics menu').

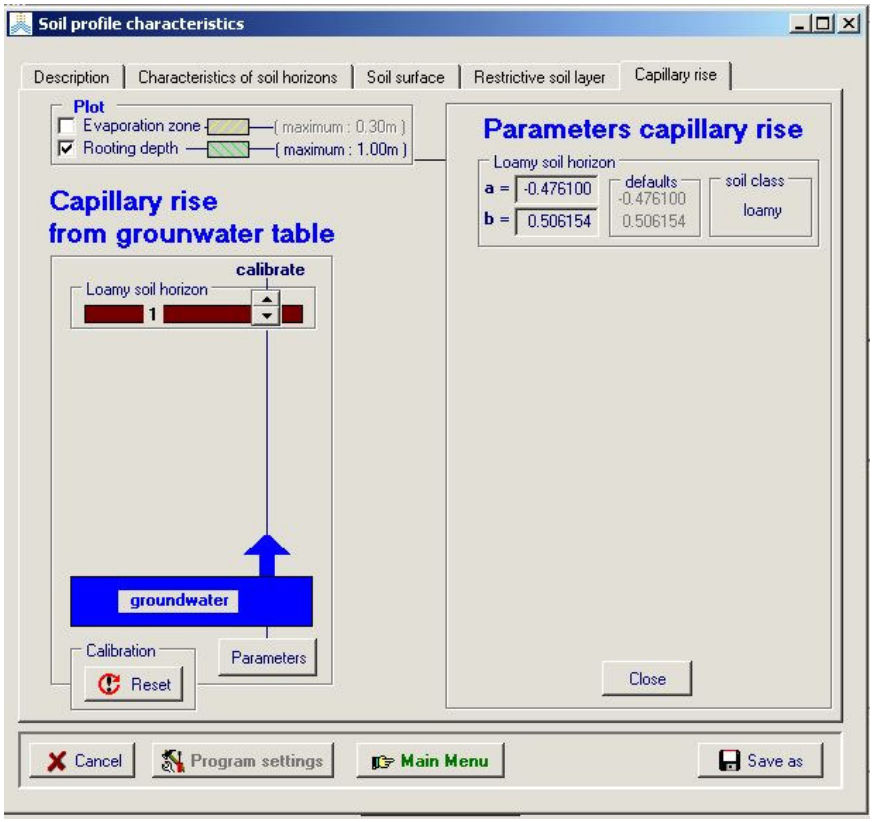


Figure 6.2 – Display of the a and b parameters, their default values, and the soil class of a soil horizon of the soil profile in the ***Soil profile characteristics*** menu.

6.3 Equilibrium at field capacity

After the drainage of a thoroughly wetted soil profile, the soil water content will remain at Field Capacity (FC) in the absence of any soil water extraction. In the presence of a shallow groundwater table, the soil water content in the soil profile is in equilibrium with the groundwater table and varies with soil depth (Fig. 6.3).

To simulate drainage and capillary rise correctly, AquaCrop needs to know this equilibrium state (called adjusted Field Capacity). In AquaCrop a parabolic function is used to describe the adjustment of FC in the presence of the groundwater table:

$$\theta_{FC\,adj,i} = \theta_{FC} + \Delta\theta_{FC,i} \qquad \text{(Eq. 6.3a)}$$

$$\text{with } \Delta\theta_{FC,i} = \left[\frac{(\theta_{Sat} - \theta_{FC})}{x^2}\right] (x - z_i)^2 \qquad \text{for } z_i <= x \qquad \text{(Eq. 6.3b)}$$

where θ_{FC} soil water content at FC in the absence of a groundwater table ($m^3\ m^{-3}$)
$\Delta\theta_{FC,i}$ increase in FC at height z_i above the groundwater table ($m^3\ m^{-3}$)
$\theta_{FCadj,i}$ adjusted FC at height z_i above the groundwater table ($m^3\ m^{-3}$)
θ_{sat} soil water content at saturation ($m^3\ m^{-3}$)
z_i height above the groundwater table (m)
x height above the groundwater table where FC is no longer adjusted

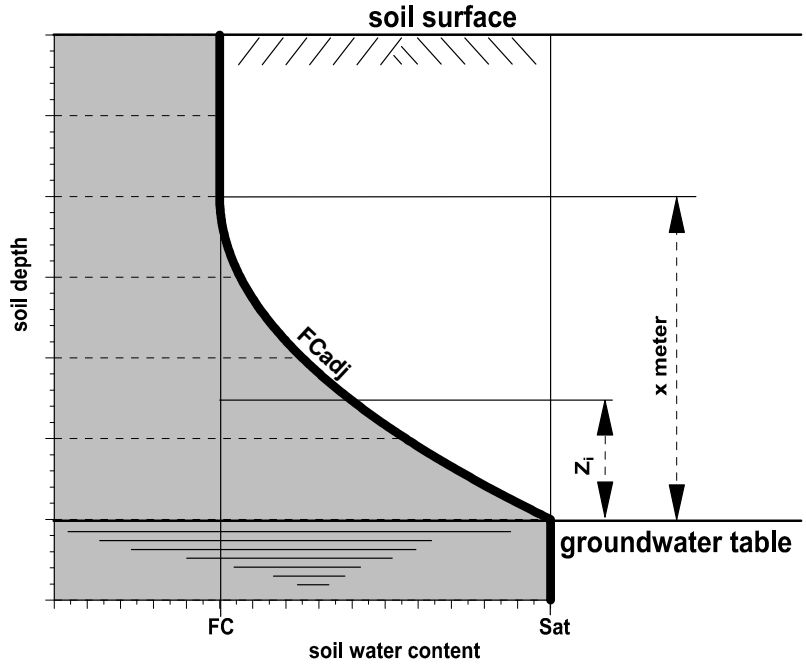


Figure 6.3 – Soil water profile in equilibrium with the groundwater table

At a height of x meter or more above the groundwater table, the adjustment of Field Capacity is neglected. At the groundwater table, $\theta_{FCadj,i}$ is equal to θ_{sat}, and at a height of x meter or more above the groundwater table (where $z_i \geq x$), $\theta_{FCadj,i}$ is equal to θ_{FC} (Fig. 6.3).

The value for x can be derived from the soil matrix potential at Field Capacity (FC) which varies between -10 kPa (for the more sandy soils) to -20 kPa (for the more loamy and clayey soils) when expressed as energy per unit volume. This corresponds with a head (energy per unit weight) of about – 1 m water (pF 2.0) up to – 2 m (pF 2.3). By considering indicative values for the soil water content at FC of 10 vol% for the more sandy and 30 vol % for the more loamy soils, the height (meter) where the effect of the groundwater table on FC can be neglected is given by:

$$x = \frac{10^{2+0.3\left(\frac{\theta_{FC}-10}{30-10}\right)}}{100} \qquad \text{(Eq. 6.3c)}$$

where θ_{FC} the soil water content at FC (vol %) varying between 10 and 30 vol% (Tab. 6.3).

Table 6.3 – The soil water content at Field Capacity (θ_{FC}) and the height (x) above which the effect of the groundwater table on FC can be neglected (Eq. 6.3c).

θ_{FC} (vol%)	x (meter)
$\theta_{FC} \leq 10$ vol%	1.00
15	1.19
20	1.41
25	1.68
$\theta_{FC} \geq 30$ vol%	2.00

6.4 Calculation procedure

6.4.1 Concept

The calculation starts at the bottom compartment (n) of the soil profile, and moves step by step upwards to the upper lying compartments (i+1, i, i-1, ..) till the top compartment (1) is reached (Fig 6.4a). The calculation procedure consists of the following steps:

1. Calculation of the maximum amount of water that can be transported upward by capillary rise to the node (center) of the compartment ($CR_{max,i}$) by considering the depth of the groundwater table below the center of the soil compartment (z_i) and the characteristics of the soil layer (Eq. 6.1a);
2. Storage of water in that compartment till θ_i is equal to $\theta_{FCadj,i}$ or all the $CR_{max,i}$ has been stored. The amount of water stored in compartment i is:

$$\text{IF } \theta_i \le \theta_{FCadj,i} \quad \text{THEN } W_{stored,i} = 1000\left(\theta_{FCadj,i} - \theta_i\right)\Delta z_i \le f_{CR,i}\, CR_{max,i} \qquad \text{(Eq. 6.4a)}$$

$$\text{ELSE } W_{stored,i} = 0 \qquad \text{(Eq. 6.4b)}$$

where Δz_i is the thickness of the compartment (m), $f_{CR,i}$ the capillary rise factor (see 6.4.2), and $W_{stored,i}$ the stored amount of water (mm) in the compartment. The amount of water still to store is obtained by subtraction the stored amount of water from $CR_{max,i}$

$$W_{remain} = CR_{max,i} - W_{stored,i} \qquad \text{(Eq. 6.4c)}$$

where W_{remain} is the amount of water still to store (mm). If the soil water content (θ_i) of the compartment was initially at $\theta_{FCadj,i}$ no water could have been stored and W_{remain} is equal to $CR_{max,i}$. If the stored water ($W_{stored,i}$) is equal to $CR_{max,i}$, the calculation stops since W_{remain} becomes zero;

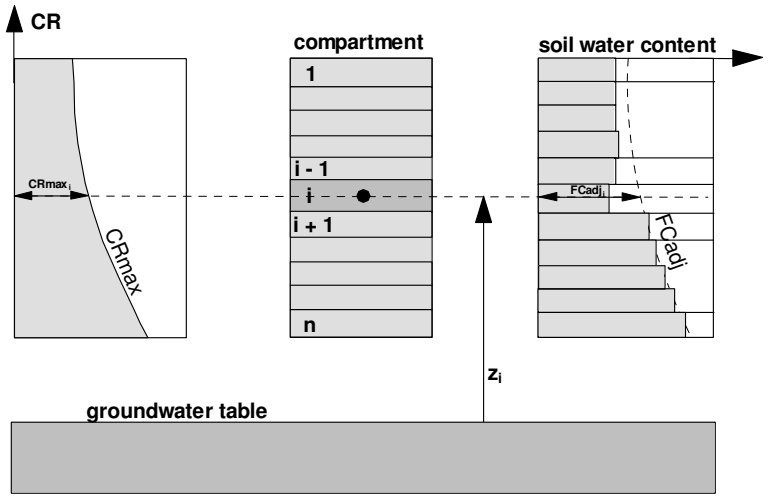


Figure 6.4a – The maximum amount of water that can be transported upward by capillary rise ($CR_{max,i}$) and the adjusted field capacity ($FC_{adj,i}$) for the node of compartment i, at a height of z_i meter above the groundwater table

3. As long as W_{remain} is not zero, the calculation continues by moving to the next upper lying compartment (i-1). The calculations restart with step 1, i.e. with the calculation of CR_{max} for that compartment ($CR_{max,i-1}$). The calculation will continue with the minimum of $CR_{max,i-1}$ and W_{remain}. This control takes care of (i) water already stored in the underlying compartments and (ii) possible changes of layers in the soil profile when moving upward (whereby the restricted capillary capacity of an underlying soil layer, limits the upward flow to the upper lying soil layers).

The calculation stops if all the water has been stored (W_{remain} becomes 0) or the soil surface is reached (i = 1). The total amount of water that has been moved upward by capillary rise to the soil profile is given by the sum of the water stored in each of the compartments:

$$CR = \sum_{i=1}^{n} W_{stored,i} \qquad \text{(Eq. 6.4d)}$$

6.4.2 Adjustment for soil water content

The water movement in the soil is determined by (i) a driving force (i.e. the water potential gradient) and (ii) the capacity of the soil to conduct the water (i.e. the hydraulic conductivity):

- In the absence of a water potential gradient the soil water content (θ) in the profile is at θ_{FCadj} (Fig. 6.3). Water moves downward (drainage) if $\theta > \theta_{FCadj}$ and upwards (capillary rise) when $\theta < \theta_{FCadj}$. The larger the difference between θ and θ_{FCadj}, the stronger the water potential gradient, and the stronger the driving force for water movement.
- When most of the soil pores are filled with water as in a wet soil, the capacity of the soil to conduct the water and hence the hydraulic conductivity are large. In a soaked soil all pores are able to conduct the water and the hydraulic conductivity is at its maximum (Ksat, the saturated hydraulic conductivity). If the soil is dry, only the small pores contain water and the hydraulic conductivity is very low. In a dry soil, water can only move if the potential gradient is huge.

Upward flow affected by the potential gradient (driving force)

To move water upward from a groundwater table a water potential gradient is required. The strength of the gradient is expressed in AquaCrop by the relative wetness:

$$relative\ wetness = \frac{\theta_i - \theta_{PWP}}{\theta_{FCadj,i} - \theta_{PWP}} \qquad \text{(Eq. 6.4e)}$$

where θ_i is the soil water content at a height z_i above the groundwater table, and θ_{PWP} and $\theta_{FCadj,i}$ the soil water content at the Permanent Wilting Point and the adjusted Field Capacity respectively.

The restrictions for upward water movement as a result of a low potential gradient is estimated by considering a power function of the relative wetness and is expressed by a capillary rise factor ($f_{CR,i}$):

$$f_{CR,i} = 1 - \left(\frac{(\theta_i - \theta_{PWP})}{(\theta_{FCadj,i} - \theta_{PWP})} \right)^x \qquad \text{(Eq. 6.4f)}$$

The capillary rise factor, $f_{CR,i}$, varies with the soil water content (θ_i) and ranges between 1 and 0 (Fig. 6.4b). The capillary rise factor considers on the one hand the driving force for upward water movement and on the other hand the hydraulic conductivity.

If the top soil is dry, the potential gradient is strong and the driving force for water movement is strong as well ($f_{CR} = 1$). The wetter the soil profile, the smaller the potential gradient and the smaller the upward water movement ($f_{CR} < 1$). If the soil water content at a given height above the groundwater table is equal to $\theta_{FCadj,i}$, upward water movement is fully inhibited due to the absence of any water potential gradient.

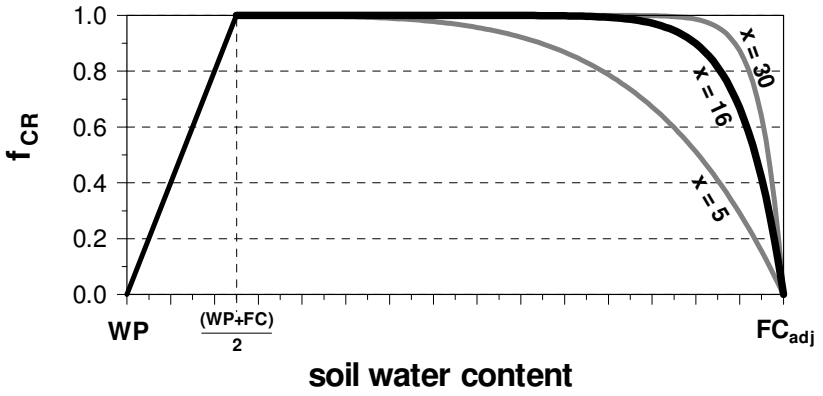


Figure 6.4b – The capillary rise factor (Eq. 6.4f) for different soil water content above the groundwater table and values for the power x.

The power (x) in Equation 6.4f is a program parameter and set at 16 for testing. The parameter can vary between 5 and 30. With the program parameter the user can adjust the simulated capillary rise. Increasing the required soil water content gradient (by reducing x) will limit upward flow from the groundwater table, while reducing the required soil water content gradient (by increasing x) will facilitate the capillary rise to the soil profile.

The capillary rise factor affected by the hydraulic conductivity

Although the soil water potential gradient becomes very high when the top soil is very dry, upward movement of water is restricted due to the extreme low hydraulic conductivity in a dry soil. If the soil water content drops below the threshold halfway between Field Capacity and Permanent Wilting Point, f_{CR} decreases linear from 1 (at the threshold) to zero when Permanent Wilting Point is reached (Fig. 6.4b).

6.4.3 Capillary rise versus drainage

The calculation of upward movement from a groundwater table, which starts at the bottom compartment (see 6.4.1 of this note 'Concept), will stop when a compartment i is reached which soil water content is above $\theta_{FCadj,i}$. At this soil water content the compartment is draining and water cannot be stored ($f_{CR,i} = 0$). More important, as a result of the downward movement of water, water can no longer move further upwards to the upper lying compartments.

If the total soil profile is draining ($\theta_n > \theta_{FCadj,n}$), the calculation process does not start at all. As long as water moves out of the bottom compartment, capillary rise to the soil profile is inhibited. After a thorough drainage, the upward movement of water can not restart immediately since all over the soil profile, θ_i is equal to $\theta_{FCadj,i}$ and $f_{CR,i}$ is zero (Eq. 6.4f). Capillary rise is restored when sufficient water is extracted out of the soil profile by crop transpiration and/or soil evaporation and $f_{CR,i}$ becomes larger than 0 (Fig. 6.4b).

6.4.4 Root zone expansion

Roots of crops sensitive to water logging can not develop below the groundwater table. Hence, the maximum rooting depth (Z_x) is restricted to the depth of the groundwater table. If later in the season the water table drops, the root zone will expand till Z_x is reached.

If during the season the water table enters in the root zone, the roots under the groundwater table will become inactive and might die off. If later in the season the water table drops, it is assumed that the part of the root zone that was flooded becomes active again and that the root zone expands till Z_x is reached.

6.4.5 Deficient aeration conditions and reduced crop transpiration

Transpiration is hampered when the soil water content in the root zone results in deficient soil aeration. If the water content in the root zone is above the anaerobiosis point the root zone becomes water logged and transpiration is limited. This is likely to be the case if the groundwater table is very shallow and the soil water content in the root zone is close to saturation (Fig. 6.3).

The sensitivity of the crop to water logging is specified by the soil water content (anaerobiosis point) at which the aeration of the root zone will be deficient for the crop and starts to affect crop transpiration (see Reference Manual section 3.10 Crop transpiration). To simulate the resistance of crops to short periods of waterlogging, the full effect will only be reached after a specified number of days.

6.4.6 Preliminary evaluation of the calculation procedure

The contribution of capillary rise from a shallow water table (0.2 to 2.8m below the soil surface) to the soil water balance of the top soil, as simulated by AquaCrop, was evaluated for 38 fields in northern Belgium. In the period from 1999 to 2005, the soil water content in the root zone (Wr) was determined by gravimetric sampling during the growing season. The evaluation consisted in comparing observed with simulated Wr. Three types of simulations were run with AquaCrop: (1) without considering capillary rise, (2) with capillary rise using the default parameters for the soil type and (3) with capillary rise using calibrated a and b soil

parameters for Eq. 6.1a. As an example, the observed and simulated Wr for a field in Sint-Katelijne-Waver is plotted in Fig. 6.4c. The relationship between the steady state capillary rise and the depth of the groundwater table as given by UPFLOW (Darcy equation) was used to calibrate the soil parameters. Therefore the measured saturated hydraulic conductivity (K_{sat}) and soil water retention curve obtained from measurements on undisturbed soil samples for each location were specified as input in UPFLOW.

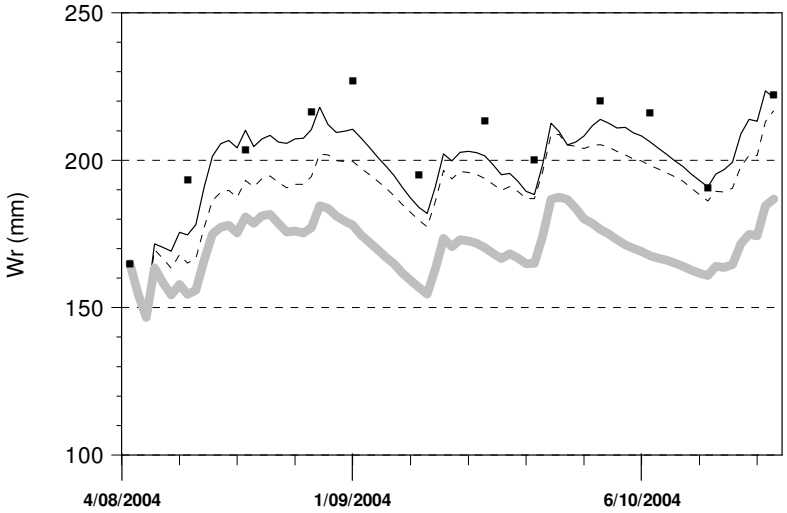


Figure 6.4c – Measured (squares) and simulated soil water content in the root zone (0.6m) of Brussels sprouts between 4 August and 20 October 2004 without considering capillary rise (light grey thick line), with capillary rise using the default parameters (black line) and using calibrated parameters (dotted line). The crop was cultivated on a silty loam soil (with a loamy sand top soil of 0.30m) in Sint-Katelijne-Waver (Belgium). The water table fluctuated between 0.70 and 1.13 m below the soil surface during the simulation period.

In general, the estimation of Wr considerably improved when the contribution of capillary rise was considered. Only for 5 fields out of 38, AquaCrop strongly overestimated the effect of capillary rise. Good results were obtained by using the default soil parameters provided in AquaCrop (Eq. 6.1b and 6.1c). On average, the use of the calibrated a and b soil parameters only slightly improved the estimation of Wr. The preliminary evaluation seems to indicate that the default parameters are sufficient to quantify capillary rise. The goodness-of-fit statistics are presented in Table 6.4.

Table 6.4 – Assessment of the simulated water content in the root zone in 38 fields in Northern Belgium by the average root mean square error (RMSE), normalized root mean square error (NRMSE), Nash-Sutcliffe efficiency coefficient (EF) and Willmott's d.

Simulation process	RMSE [mm]	NRMSE [%]	EF	d
No capillary rise considered	21.8	16.7	-2.80	0.65
Capillary rise with default parameters	15.6	12.6	-0.98	0.75
Capillary rise with calibrated parameters	14.8	11.6	-0.93	0.75

6.5 User interface

6.5.1 *Main menu*

In AquaCrop Version 4.0 the **Soil** is described by (Fig. 6.5a):

- a ***Soil profile*** (as in previous AquaCrop versions), and
- the characteristics of the ***Groundwater*** table (if any).

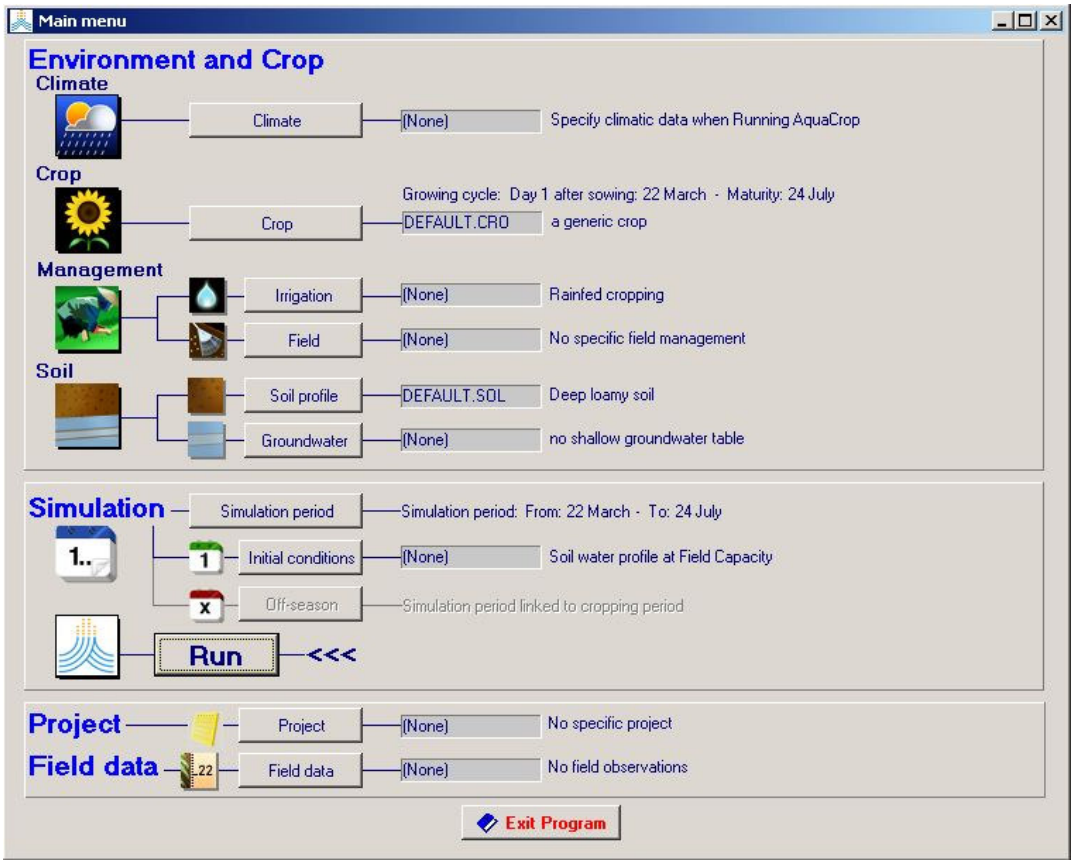


Figure 6.5a - The ***Main menu*** of AquaCrop version 4.0

The groundwater is an additional feature which further characterizes the environment. Like the other components of the Crop environment (Climate, Irrigation and Field Management), it has its own

- set of menus to describe the characteristics of the groundwater table, and
- data base from where groundwater files can be selected, and created files are stored.

6.5.2 The *Soil profile characteristics* menu

The selected (i) characteristics of the various soil horizons and (ii) of the soil surface layer, (iii) the occurrence of a restrictive soil layer that might block the root zone expansion, and (iv) the maximum possible capillary rise are displayed in the various tab sheets of the ***Display of soil profile characteristics*** menu and updated in the ***Soil profile characteristics*** menu.

In the 'Capillary rise' tab sheet the user can study the maximum possible upward flow to the top soil for various depths of the groundwater table (Fig. 6.5b). If the water potential gradient in the soil profile is not strong enough, the capillary rise will be smaller than indicated (see 6.4 of this note 'Calculation procedure'). The maximum possible capillary rise is calculated with Eq. 6.5a.. The default a and b parameters, describing the capillary rise for each soil horizon, are obtained by considering the class of the soil type and the saturated hydraulic conductivity as described in section 6.2 (Generation of the parameters for capillary rise).

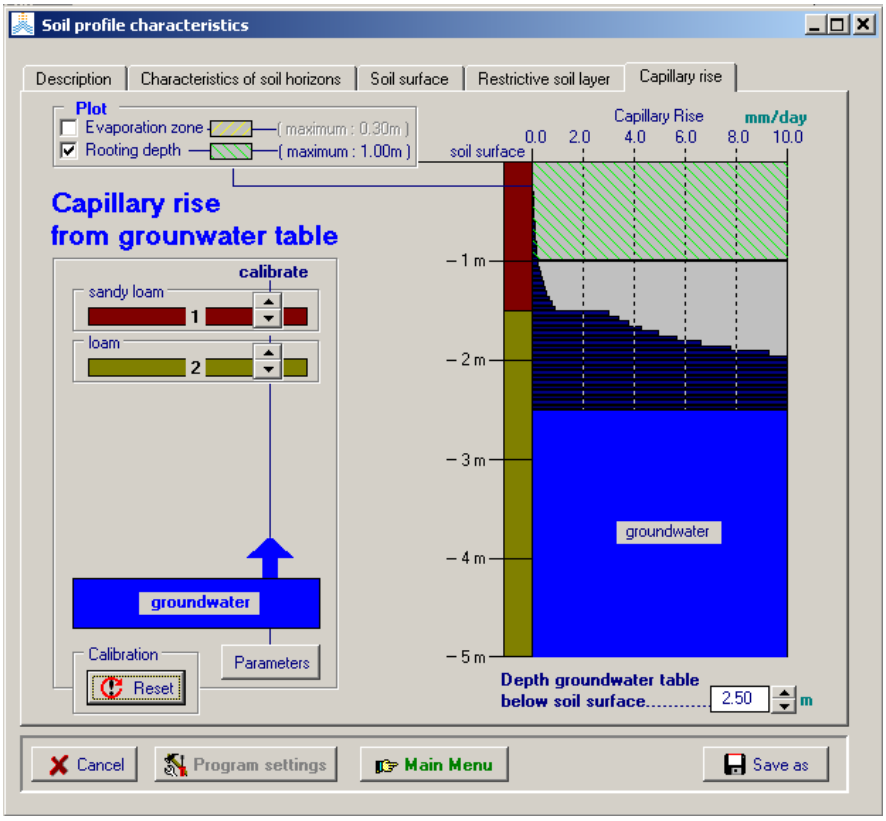


Figure 6.5b - The Capillary rise tab sheet in the ***Soil profile characteristics*** menu

With the spin buttons the user can calibrate the a and b parameters for each soil horizon and match the observed maximum possible upward flow with the simulated and plotted capillary rise. By selecting the **<Parameters>** button, the calibrated and defaults values for the a and b parameters are displayed (Fig. 6.2). By hitting on the **<Reset>** button, the user undoes the calibration and the a and b parameters are reset at their default values.

6.5.3 The *Groundwater characteristics* menu

The selected characteristics of the groundwater can be displayed in the ***Display of groundwater characteristics*** menu and updated in the ***Groundwater characteristics*** menu. The user can choose between the presence or the absence of water table. The considered characteristics of the groundwater table are its depth below the soil surface and its salinity.

- **Constant depth and salinity**

The characteristics can remain constant during the season. The characteristics are specified in the Groundwater table tab sheet (Fig. 6.5c) and graphically displayed in the Plot tab sheet.

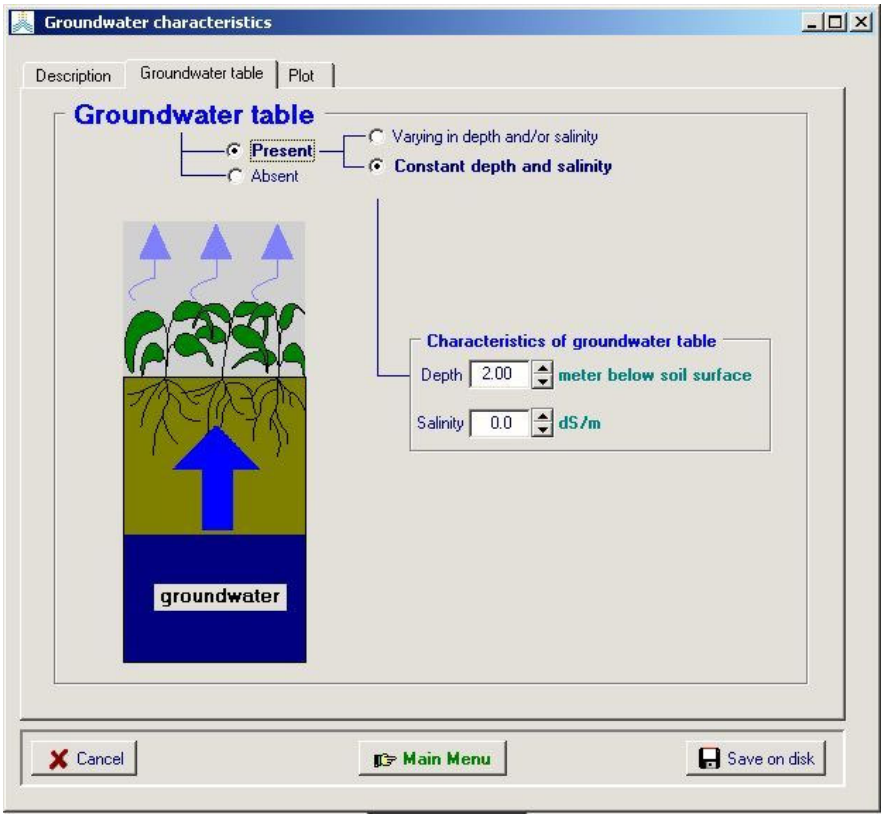


Figure 6.5c – Specifying the constant characteristics of a groundwater table in the Groundwater table tab sheet of the ***Groundwater characteristics*** menu.

- **Characteristics vary throughout the year(s)**

The characteristics can vary throughout the year. The characteristics are specified in the Groundwater table tab sheet (Fig. 6.5d and 6.5f) and graphically displayed in the Plot tab sheet (Fig. 6.5e and 6.5g). The characteristics of the groundwater table for days between specified day numbers will be obtained at run time by means of linear interpolation.

<u>Characteristics are not linked to a specific year</u>

If the characteristics are not linked to a specific year, linear interpolation also applies between the characteristics specified on the last and first day number (Fig. 6.5d and 6.5e).

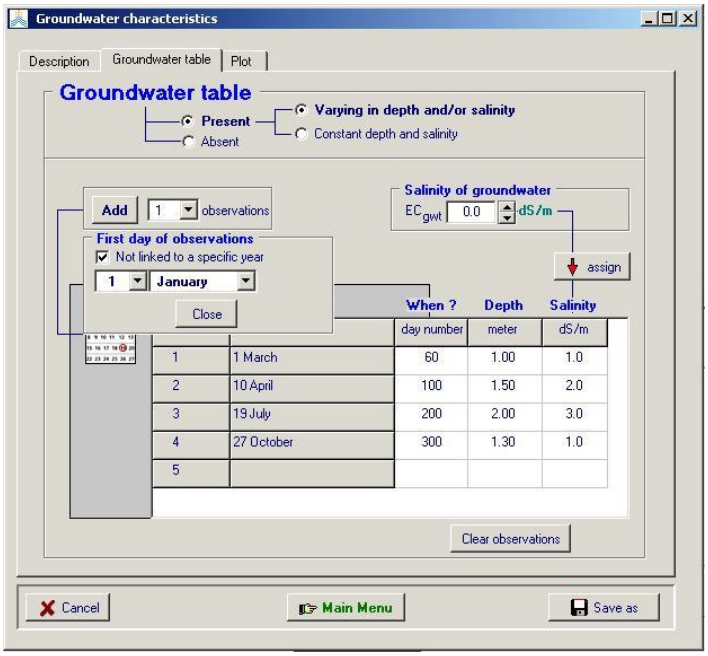


Figure 6.5d – Specifying the variable characteristics of a groundwater table in the Groundwater table tab sheet of the ***Groundwater characteristics*** menu.

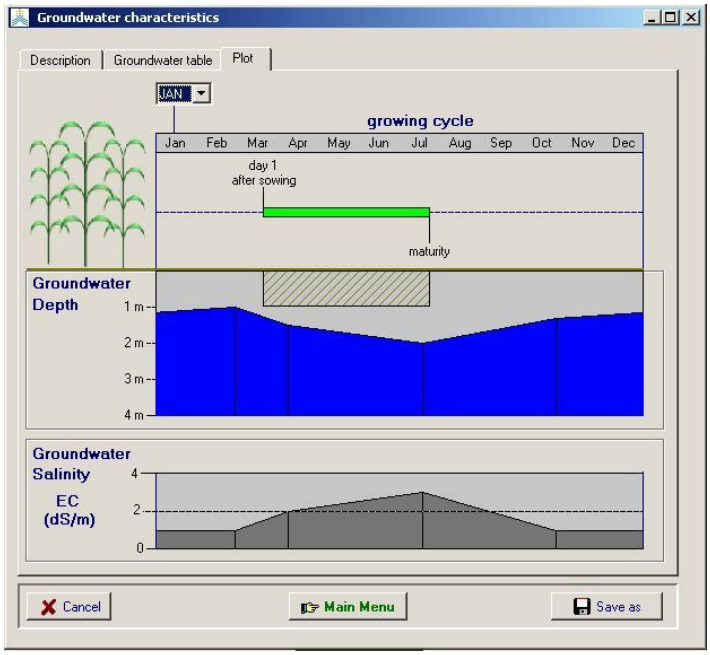


Figure 6.5e – Graphical display of the variable characteristics of a groundwater table in the Plot tab sheet of the ***Groundwater characteristics*** menu

Characteristics are linked to specific year(s)

If the characteristics are linked to specific year(s), linear interpolation is only applied between the characteristics specified on the day numbers (Fig. 6.5f and 6.5g). The characteristics for days before the first specified day number are identical to the characteristics specified on the first day number. The characteristics specified on the last day number remain valid for all successive days.

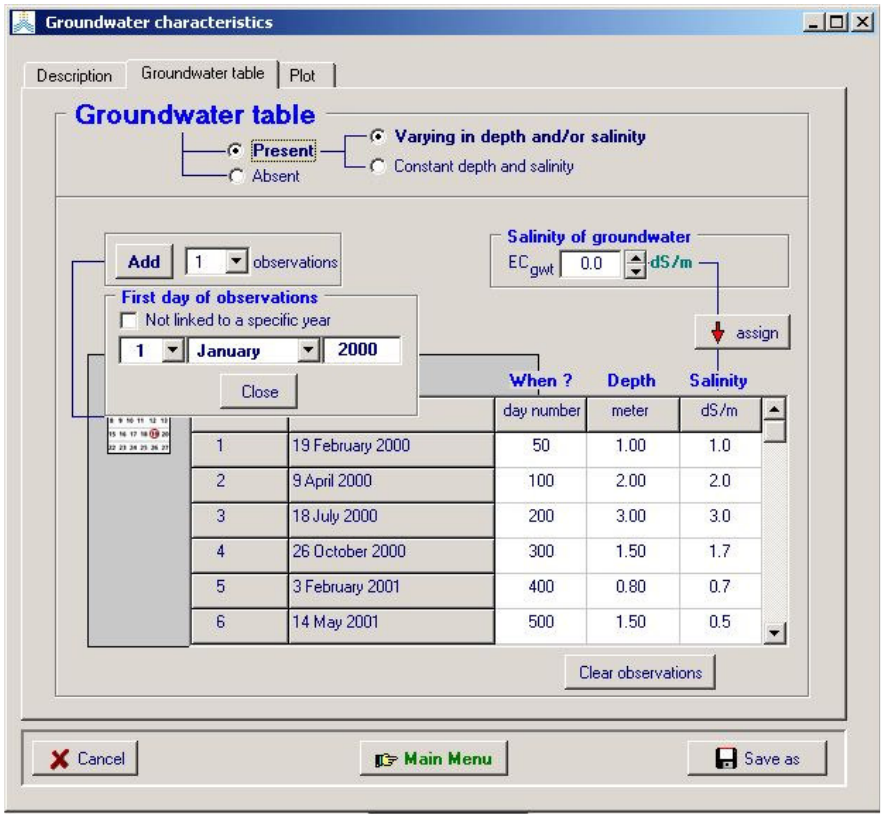


Figure 6.5f – Specifying the variable characteristics of a groundwater table linked to a specific year in the ***Groundwater characteristics*** menu.

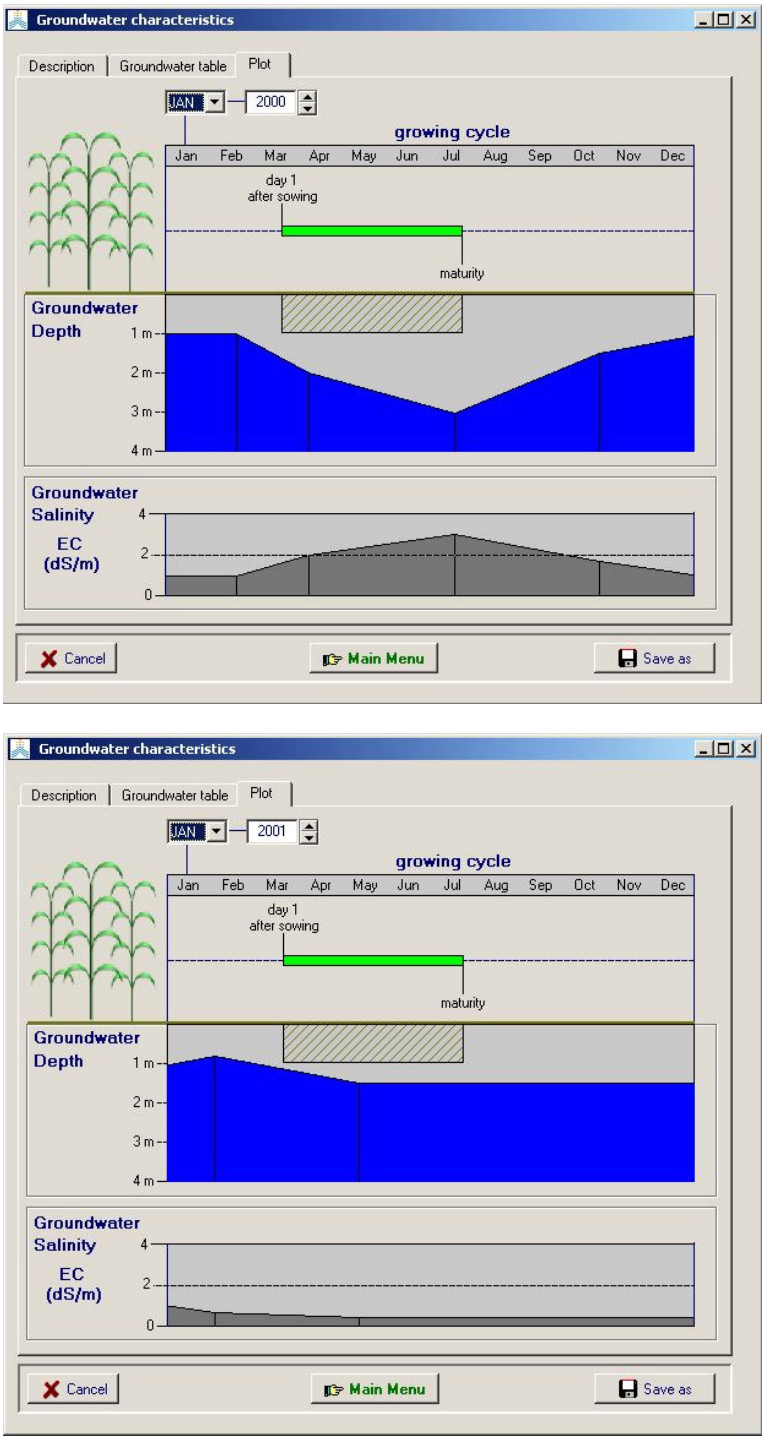


Figure 6.5g – Graphical display of the variable characteristics of a groundwater table linked to specific years (2000 and 2001) in the ***Groundwater characteristics*** menu.

6.5.4 The *Simulation run* menu

In the ***Simulation run*** menu the effect of the shallow groundwater table on the soil water and soil salinity balance of the soil profile can be studied in the 'Soil salinity' (Fig. 5.3d) and 'Climate and Water balance' (Fig. 6.5h) tab sheets.

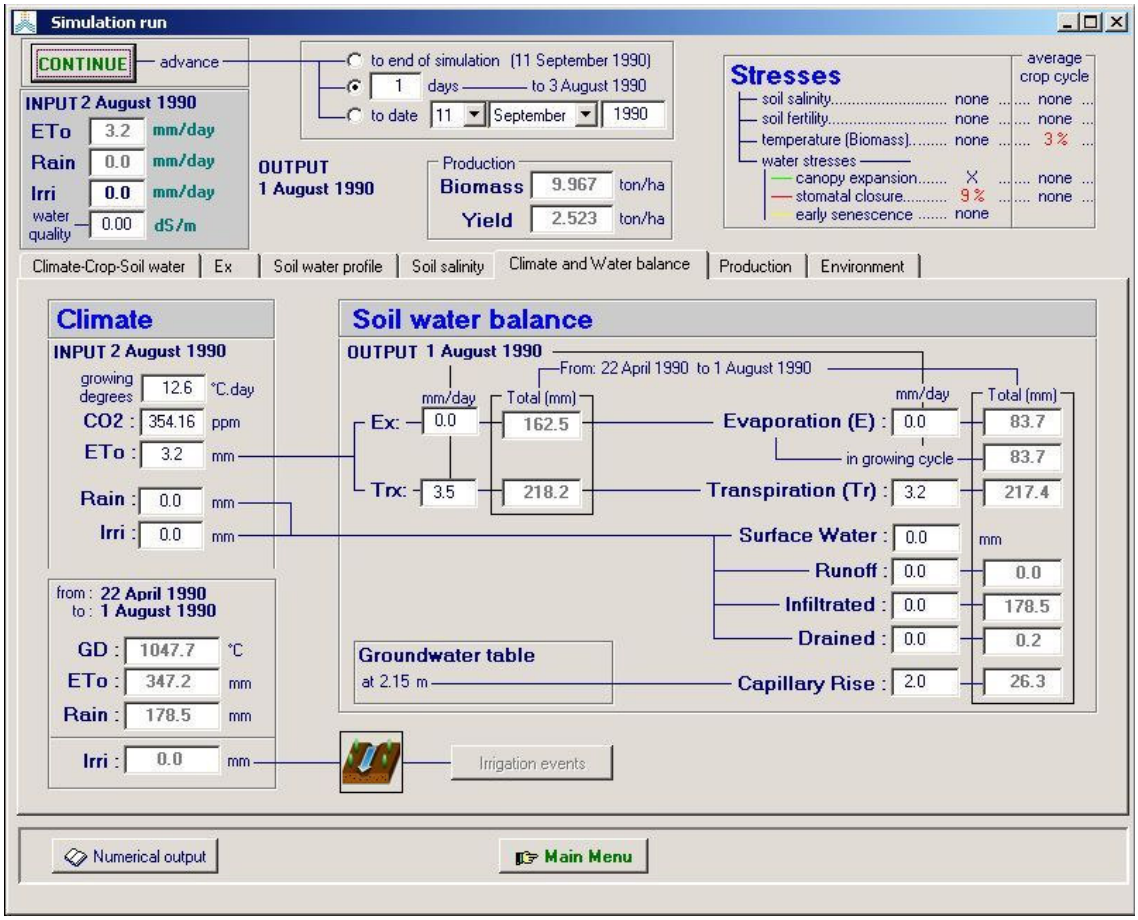


Figure 6.5h – The Climate and Water balance tab sheet in the ***Simulation run*** menu

The depth and salinity of the groundwater table, the simulated capillary rise (Fig. 6.5i) and corresponding upward salt transport to the soil profile can be plotted throughout the simulation period in the second tab-sheet (plot of a parameter).

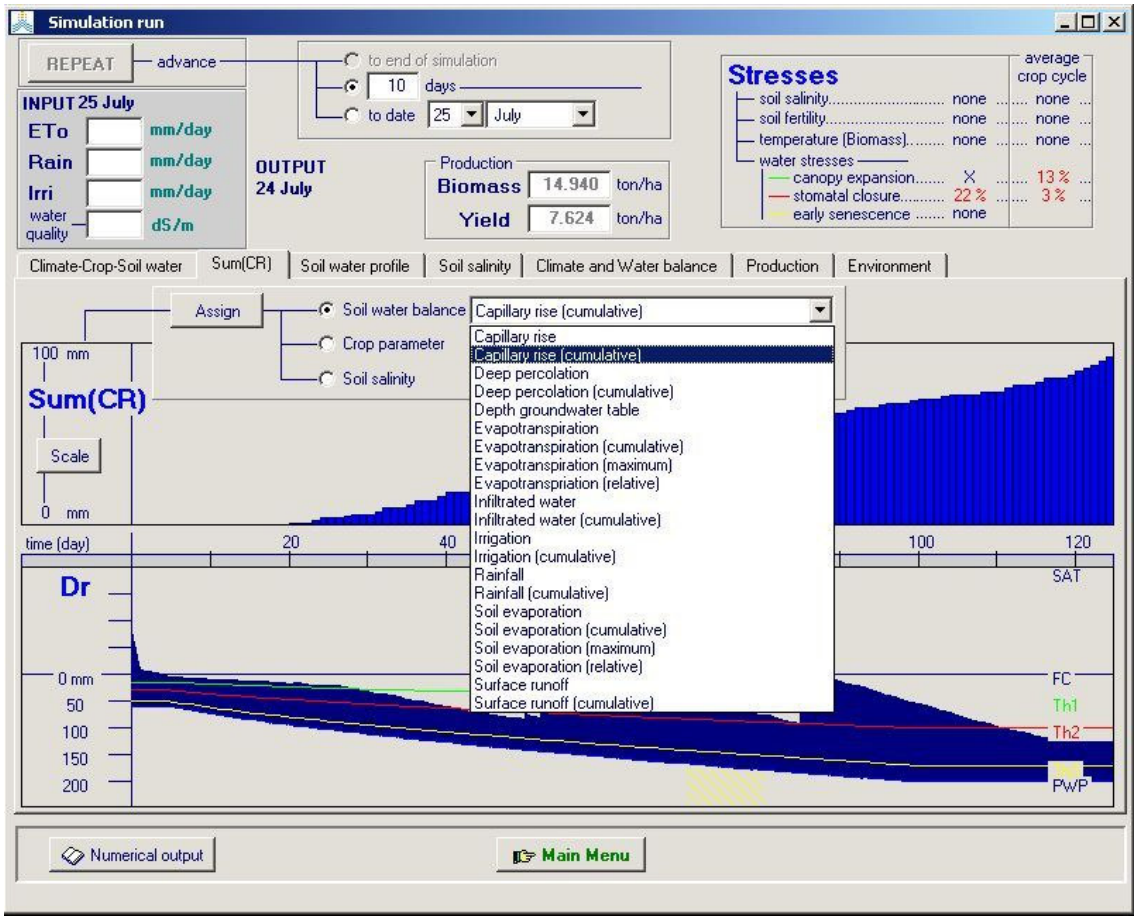


Figure 6.5i – Plot of the cumulative Capillary rise in the ***Simulation run*** menu

7. Update for water logging

When the root zone is water logged, deficient soil aeration will hamper crop transpiration. In previous versions of AquaCrop the soil water content in each of the soil compartment was assessed to determine the restriction of the water extraction at that depth. With the introduction of capillary rise, resulting in large soil water contents in the soil profile in the presence of a shallow groundwater table, the calculation procedure was insufficient too restrict crop transpiration in water logged soils.

In AquaCrop 4.0, the aeration stress in the total root zone determines the water stress coefficient Ks_{aer} and hence the reduction in crop transpiration.

8. Field data

8.1 Access to field data menus and data base

Next to (i) the crop selection and the description of the environment (Environment and Crop panel), (ii) the selection of the simulation period, and the initial and off-season conditions (Simulation Panel), and (iii) the selection or description of projects, the user can enter field data in the AquaCrop Version 4 (Fig. 8.1).

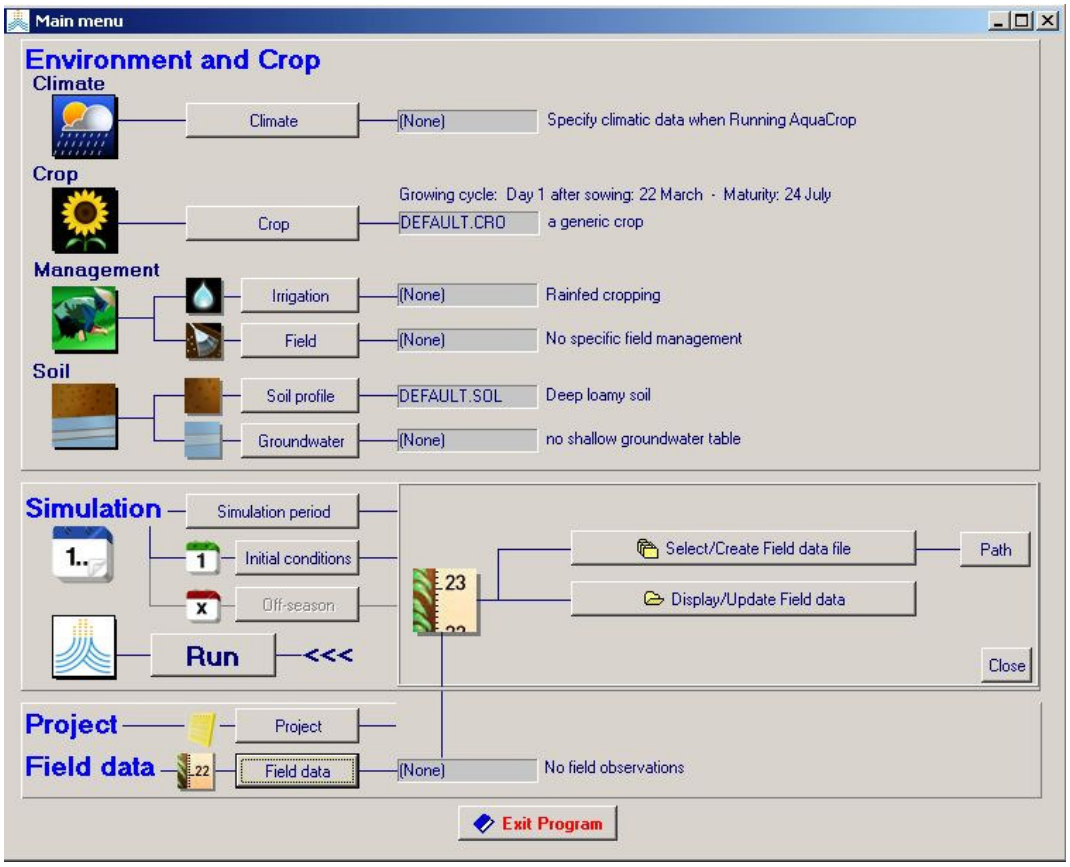


Figure 8.1 – The **<Select/Create Field data file>** and the **<Display/Update Field data>** command in the ***Main menu***.

By means of the **<Select/Create data file>** command in the ***Main menu*** the user has access to the data base where the data files are stored or can create new data files (Fig. 8.1). The default data base is the OBS subdirectory of the AquaCrop folder. With the **<Path>** command the user can specify other directories.

From the ***Main menu*** the user can display the observed field data in the ***Display of field data*** menu. This is done by clicking on the file name or the corresponding icon in the ***Main menu***. By selecting the **<Display/Update Field data>** command, the field observations can be displayed, specified or updated in the ***Field data*** menu.

8.2 Specifying field data

In the ***Field data*** menu, the user specifies the observed field data which can consists of observed green canopy cover (CC), dry above ground biomass (B) and/or soil water content (SWC) collected at a number of specific days (Fig. 8.2). The mean value together with its standard deviation can be specified if various observations were made during the sampling at a specific day. The soil water content is the total water content in a well defined zone (e.g. root zone). Therefore the soil depth, for which soil water contents were calculated, has to be specified.

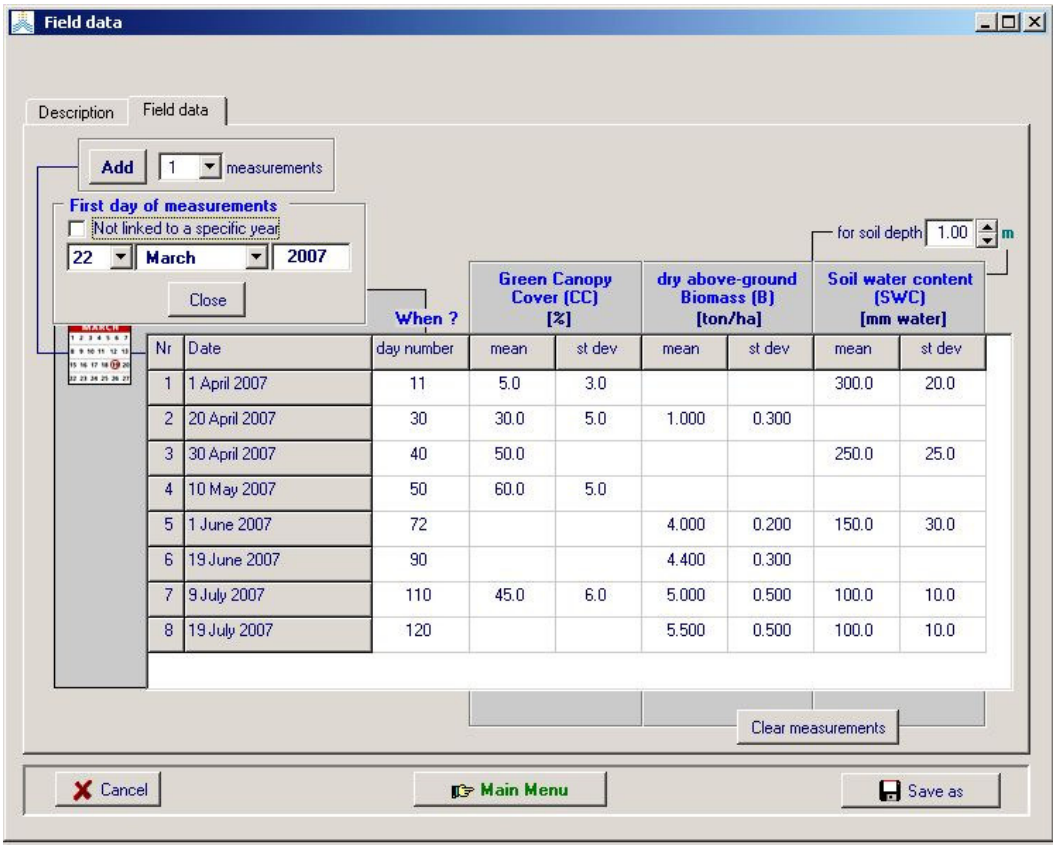


Figure 8.2 – Specifying observations at particular days in the ***Field data*** menu.

8.3 Evaluation of simulation results

When running a simulation, users can evaluation the simulation results with the help of the field data stored in an observation file. The user gets access to the ***Evaluation of simulation results*** menu by clicking on the **<Observations>** command in the command panel of the ***Simulation run*** menu (Fig. 8.3a).

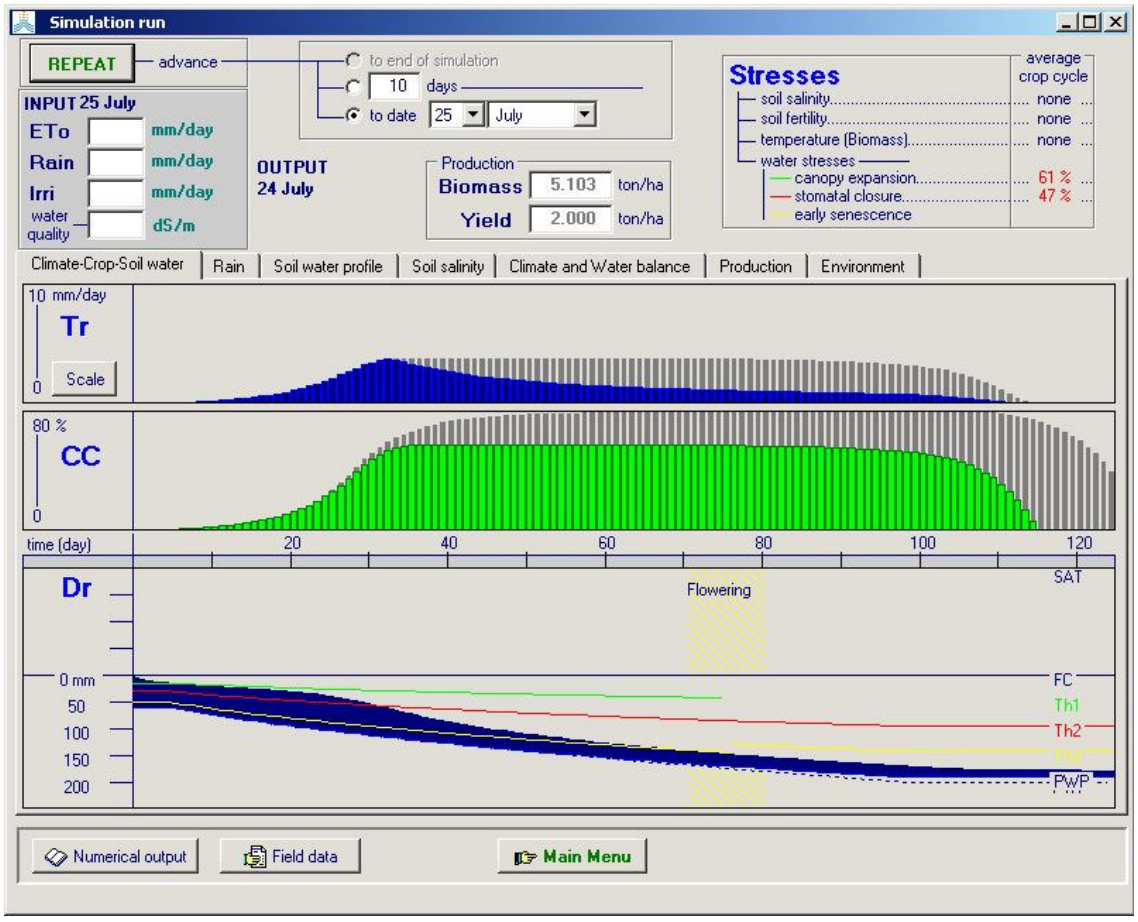


Figure 8.3a – The ***Simulation run*** menu with the **<Observations>** command in the command panel.

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. 8.3b);
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. 8.3c).

The assessment can be saved on disk for later use.

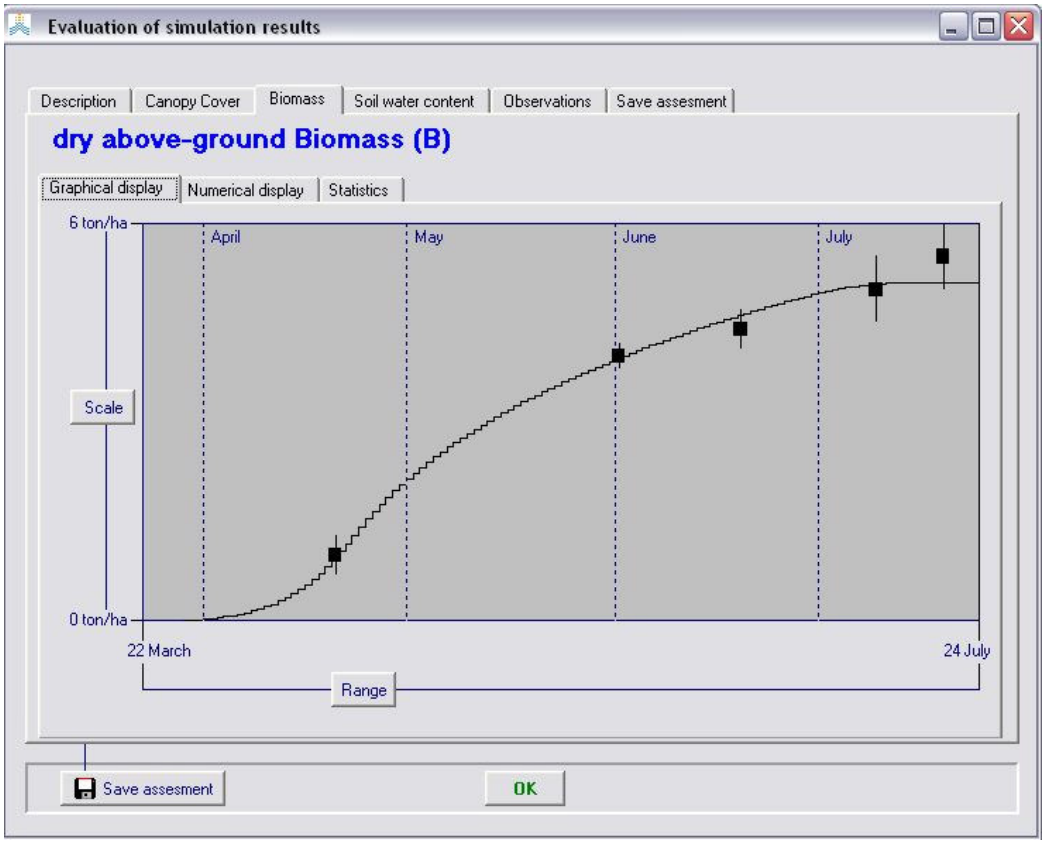


Figure 8.3b – Simulated (line) and observed (dots) dry above-ground Biomass with their standard deviations (vertical lines) in the ***Evaluation of simulation results*** menu.

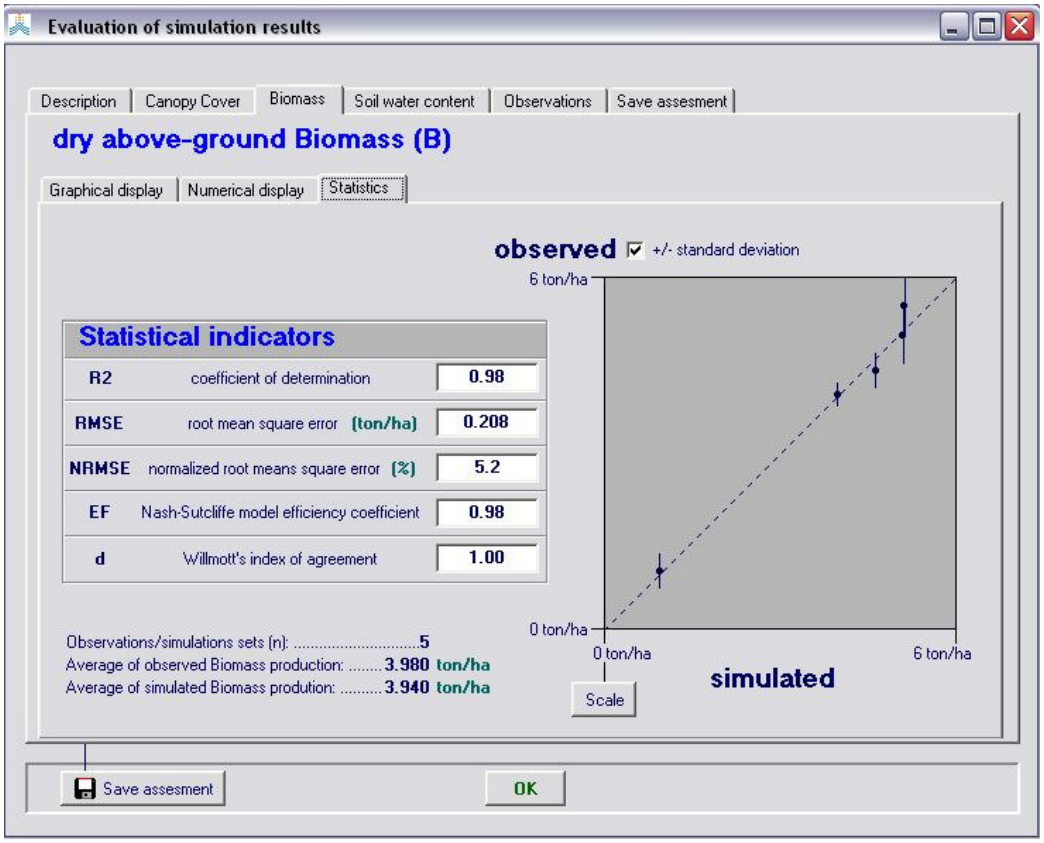


Figure 8.3c – Statistical indicators for the assessment of the simulated dry above-ground Biomass in the ***Evaluation of simulation results*** menu.

8.4 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 8.4a to 8.4e, O_i and P_i are the observations and predictions respectively, $\overline{O}$ and $\overline{P}$ their averages and n the number of observations.

8.4.1 Coefficient of determination (R^2)

The coefficient of determination r^2 is defined as the squared value of the Pearson correlation coefficient. r^2 signifies the proportion of the variance in measured data explained by the model, or can also be interpreted as the squared ratio between covariance and the multiplied standard deviations of the observations and predictions. It ranges from 0 to 1, with values close to 1 indicating a good agreement, and typically values greater than 0.5 are considered acceptable in watershed simulations (Moriasi et al., 2007).

$$r^2 = \left[\frac{\sum (O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum (O_i - \overline{O})^2 \sum (P_i - \overline{P})^2}} \right]^2 \qquad (8.4a)$$

A major drawback of 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.

8.4.2 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.

$$RMSE = \sqrt{\frac{\sum (P_i - O_i)^2}{n}} \qquad (8.4b)$$

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.

8.4.3 Normalized Root Mean Square Error (NRMSE)

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 variable ($\overline{O}$). The normalized RMSE (NRMSE) is expressed as a percentage and gives an indication of the relative difference between model and observations.

$$NRMSE = \frac{1}{\overline{O}} \sqrt{\frac{\sum (P_i - O_i)^2}{n}} 100 \qquad (8.4c)$$

A simulation can be considered excellent if NRMSE is smaller than 10%, good if between 10 and 20%, fair if between 20 and 30% and poor if larger than 30%.

8.4.4 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.

$$EF = 1 - \frac{\sum (P_i - O_i)^2}{\sum (O_i - \overline{O})^2} \qquad (8.4d)$$

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 r^2, EF is not very sensitive to systematic over- or underestimations by the model (Krause et al., 2005).

8.4.5 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.

$$d = 1 - \frac{\sum (P_i - O_i)^2}{\sum \left(|P_i - \overline{O}| + |O_i - \overline{O}| \right)^2} \qquad (8.4e)$$

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).

8.4.6 References

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

Annex I.
Indicative values for soil salinity tolerance for some agriculture crops

References

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Table I-1. Salt tolerance[1] of common agriculture crops with indication of the lower (ECe_n) and upper (ECe_x) thresholds[2] for salinity stress, and the slope of reduction in crop yield with increasing salinity beyond ECe_n

Agriculture crop	ECe_n	ECe_x	Yield decline
	dS/m	dS/m	%/(dS/m)
Extremely sensitive crops			
Apricot	1.6	5.8	24.0
Blackberry	1.5	6.0	22.0
Boysenberry	1.5	6.0	22.0
Peaches	1.7	6.5	21.0
Beans	1.0	6.3	19.0
Almonds	1.5	6.8	19.0
Sensitive crops			
Plum, prune	1.5	7.1	18.0
Strawberries	1.3	7.3	17.0
Onions	1.2	7.5	16.0
Citrus (Grapefruit)	1.8	8.1	16.0
Citrus (Orange)	1.7	8.0	16.0
Carrots	1.0	8.1	14.0
Peas	1.5	8.6	14.0
Rice	3.0	11.3	12.0
Moderately sensitive crops			
Groundnut (Peanut)	3.2	6.6	29.0
Trefoil, big	2.3	7.6	19.0
Squash (scallop)	3.2	9.5	16.0
Peppers	1.6	9.3	13.0
Pumpkin, winter squash	1.2	8.9	13.0
Lettuce	1.5	9.8	12.0
Potato	1.7	10.0	12.0
Flax	1.7	10.0	12.0
Maize	1.7	10.0	12.0
Maize, sweet corn	1.7	10.0	12.0
Clover (alsike, ladino, red)	1.5	9.8	12.0
Cabbage	1.4	10.1	11.9
Spinach	2.6	12.2	11.9

[1] The ranking is based on the ECe of the upper and lower threshold (Gullentops, C. 2010 – Introducing soil salinity in AquaCrop. Master research, Interuniversity programme in water Resources Engineering (IUPWARE), Belgium).

[2] ECe means average root zone salinity as measured by electrical conductivity of the saturation extract of the soil. ECe_n is the lower thresholds at which crop growth starts to be affected and ECe_x is the upper threshold at which crop growth ceases.

Cowpea (forage)	2.5	11.6	11.0
Vetch, common	3.0	12.1	11.0
Radishes	1.6	12.0	10.3
Cucumber	1.8	12.8	10.0
Sweet potato	2.0	12.0	10.0
Brussels sprouts	1.8	12.1	9.7
Celery	2.2	14.1	9.6
Broadbean (fababean)	1.6	12.0	9.6
Foxtail	1.5	11.9	9.6
Grapes	1.5	12.0	9.6
Broccoli	2.8	13.7	9.2
Tomato	1.7	12.8	9.0
Turnip	0.9	12.0	9.0
Lovegrass	2.0	13.9	8.4
Maize (forage)	1.8	15.3	7.4
Alfalfa	2.0	15.7	7.3
Sesbania	2.3	16.6	7.0
Sphaerophysa	2.2	16.5	7.0
Cauliflower	1.8	17.9	6.2
Orchardgrass	1.5	17.6	6.2
Sugar cane	1.7	18.6	5.9
Clover, Berseem	1.5	19.0	5.7
Moderately tolerant crops			
Soybeans	5.0	10.0	20.0
Sorghum	6.8	13.1	16.0
Cowpea	4.9	13.2	12.0
Squash, Zucchini	4.7	14.7	10.0
Trefoil, narrowleaf birdsfoot	5.0	15.0	10.0
Beets, red	4.0	15.1	9.0
Hardinggrass	4.6	17.8	7.6
Rye-grass (perennial)	5.6	18.8	7.6
Wheat (Triticum aestivum)	6.0	20.1	7.1
Barley (forage)	6.0	20.1	7.1
Wildrye, beardless	2.7	19.4	6.0
Fescue	3.9	21.4	5.8
Sudangrass	2.8	26.1	4.3
Wheatgrass, standard crested	3.5	28.5	4.0
Tolerant crops			
Wheatgrass, fairway crested	7.5	22.0	6.9
Bermuda	6.9	22.5	6.4
Sugar beet	7.0	24.0	5.9

Cotton	7.7	26.9	5.2
Barley	8.0	28.0	5.0
Extremely tolerant crops			
Wheat, durum (Triticum turgidum)	5.8	28.0	4.7
Wheatgrass, tall	7.5	31.3	4.2
Date Palms	4.0	31.8	3.6
Wheat, semidwarf (T. aestivum)	8.6	41.9	3.0
Asparagus	4.1	54.1	2.0