## Topic 3 – Crop Modelling and AquaCrop

Intention of crop modelling and AquaCrop course was to be familiar with modelling concepts starting from their fundamentals to their practical application.
In the first part of the course, given in the introductory part, theoretical concepts of modelling are provided: what is a model, why we use models, how models are classified. Model development process was also analysed, from model choice to model calibration and validation.
In the second part of the course, AquaCrop model was presented. The model was selected based its characteristics: simplicity, robustness, availability (free downloadable from FAO website) and huge users community. In this second part, the model theory was explained in detail and the model was installed by students on their own laptop. Practical training was carried out on database management, input creation (meteo, soil, and crop files), model run, and output analysis.
AquaCrop manuals (FAO website) were distributed to student along with teaching material and basic meteorological and crop data for modelling exercise.
At the end of the course all students were able to install and run AquaCrop on their own.

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# AquaCrop the FAO crop-model to simulate yield response to water

A. Dalla Marta, F. Natali, S. Orlandini,

Department of Agrifood Production and Environmental Sciences
University of Firenze, Italy

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## Literature

© FAO, 2011. AquaCrop Reference Manual. Chapters 1-2-3.
http://www.fao.org/nr/water/aquacrop.html

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## AquaCrop

AquaCrop is a crop water productivity model developed by the Land and Water Division of FAO

It simulates yield response to water of herbaceous crops, and is particularly suited to address conditions where water is a key limiting factor in crop production

AquaCrop attempts to balance accuracy, simplicity, and robustness. It uses a relatively small number of explicit and mostly-intuitive parameters and input variables requiring simple methods for their determination.

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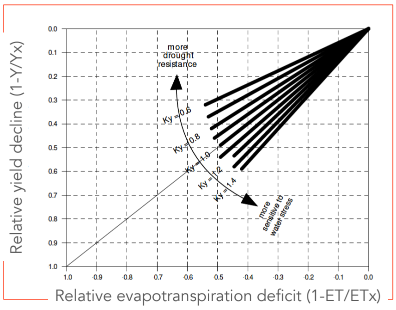
Yield response to water describes the relation between crop yield and water stress

(1-Y/Yx) = Ky(1-ET/Etx)

Yx = max yield
Y = actual yield

ETx= max evapotranspiration
ET = actual evapotranspiration

Ky = yield response factor

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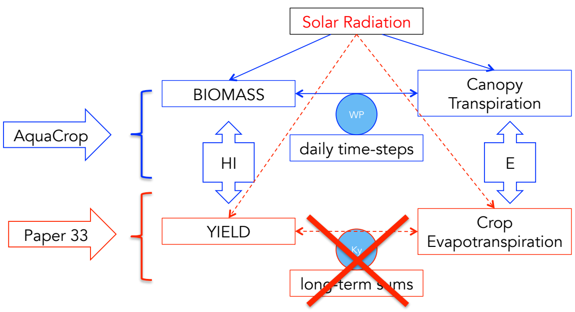
## AquaCrop

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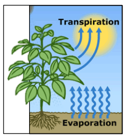
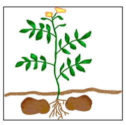
## AquaCrop approach



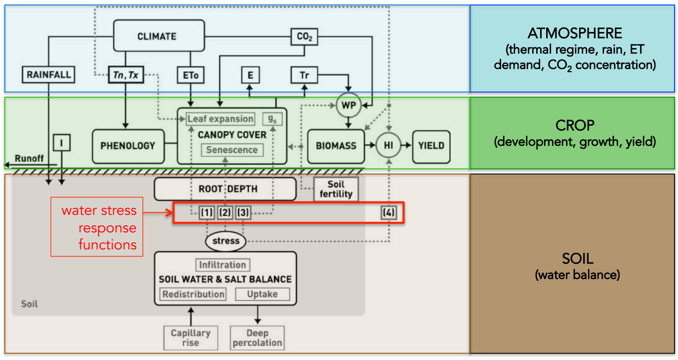

ET = E + Tr → Avoids the confounding effect of the non-productive use of water (soil evaporation)



Y = HI (B) → Avoids the confounding effects of water stress on biomass and harvest index

(1-Y/Yx) = Ky (1-ET/ETx) → B = WP × Σ Tr

WP: kg of biomass per $m^2$ and per mm of cumulated water transpired




AquaCrop model components

direct links
feedbacks



AquaCrop is essentially a crop water balance model. What distinguish AquaCrop from other crop models is:

- Focus on water
- Use of canopy cover instead of LAI
- Use of WP values normalized for atmospheric evaporative demand and CO2 concentration
- Low number of parameters
- Simplicity of input data

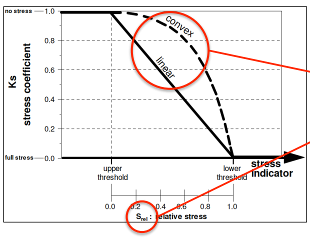


## Stress response functions

STRSS FACTORS: water, air temperature, soil fertility, soil salinity

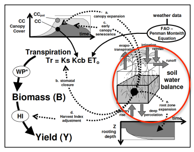
Effects of stress are described by stress coefficients Ks, a modifier of its target model parameter.

- Above the upper threshold of a stress indicator, the stress is non-existent (Ks = 1)
- Below the lower threshold of a stress indicator, the effect is maximum (Ks = 0)




Magnitude of the effect on the process between threshold





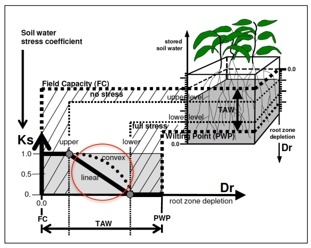

### 1 – Soil water balance

Considering input and output water fluxes the amount of water retained in the root zone and the root zone depletion are calculated

The effect of water stress is described by stress coefficients Ks

Ks = 1 no stress → upper threshold of root zone depletion

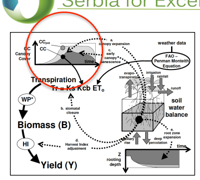
Ks = 0 max stress → below threshold of root zone depletion




Processes affected:

- *green canopy expansion*
- *transpiration*
- *senescence*
- *harvest index*
- *root deepening*

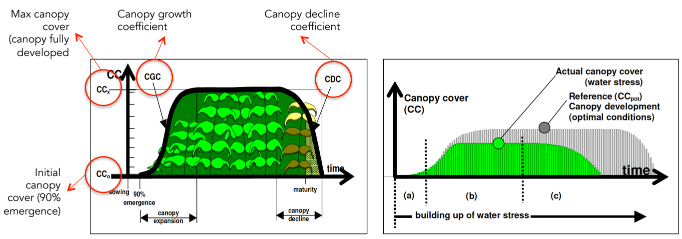




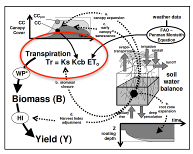

### 2 – Green canopy development (CC)

CC express foliage development, is the fraction of soil surface covered by the green canopy.

Effect of water stress = CGC x $Ks_{exp,w}$



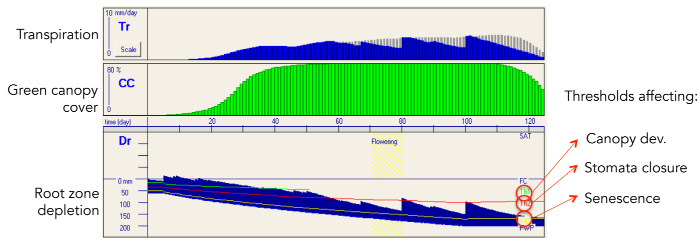



### 3 – Crop transpiration (Tr)

Tr is calculated by multiplying the evaporating power of the atmosphere with crop coefficient (Kcb) and by considering water stress (Ks):

Tr = Ks ($Kcb_x$ x CC*) ET0



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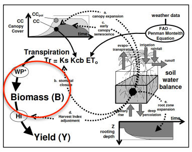
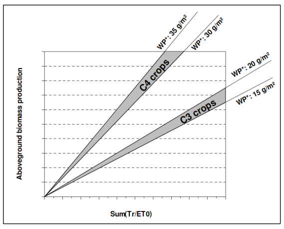


## 4 – Above ground biomass (B)

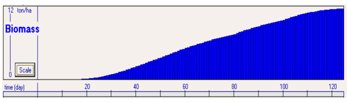
WP expresses the above ground dry matter produced per unit of land per unit of water transpired.

B production can be hampered by low TEMPERATURE stress

$B = Ks_b \, WP^* \, \Sigma(Tr_i/ET0_i)$




Relation between above ground biomass and total water transpired for C3 and C4




Simulated biomass production for canopy development and crop Tr

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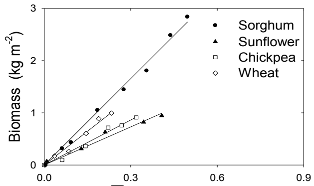
## Water Productivity

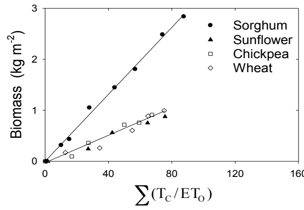
$$WP = \frac{Biomass}{\sum T_C}$$

(g m$^{-2}$ mm$^{-1}$)

$$WP^* = \left[\frac{Biomass}{\sum\left(\frac{T_C}{ET_O}\right)}\right]_{CO_2\,(2000)}$$

(g m$^{-2}$)

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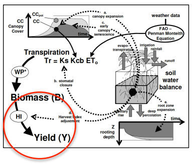


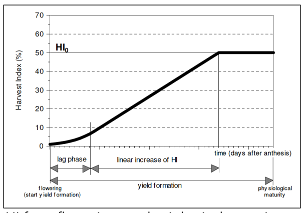
## 5 – Partitioning of biomass (B) into yield (Y)

From flowering (or tuber initiation) the HI gradually increases to reach reference value $HI_0$ at maturity

$Y = f_{HI} \, HI_0 \, B$

$f_{HI}$ is a multiplier that considers stresses (w, t) that adjust HI. The adjustment depends on timing and extent of stress

The effect of stress on HI can be positive or negative!




HI from flowering to physiological maturity

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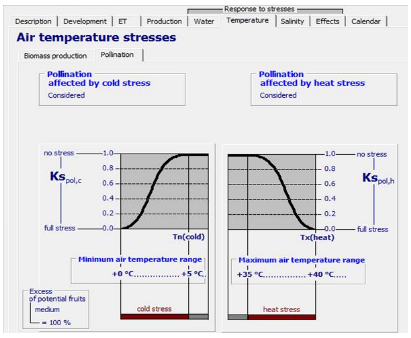
## Production stresses




- Many variables are defined for crop stress during different growth stages
  - Soil Water
  - Temperature
  - Soil salinity
  - Fertility

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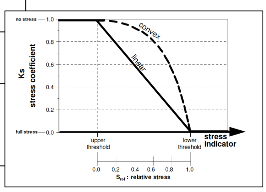
## SOIL WATER STRESS

| Soil water stress coefficient | Direct effect | Target model parameter |
|---|---|---|
| $Ks_{aer}$ Water logging (aeration stress) | Reduces Tr | $Tr_x$ |
| $Ks_{exp,w}$ Canopy expansion | Reduces canopy expansion and might positively affect HI | CGC and HI |
| $Ks_{pol,w}$ Pollination | Affects flowering and might negatively affect HI | $HI_0$ |
| $Ks_{sen}$ Canopy senescence | Reduces green canopy cover and so affects Tr | CC |
| $Ks_{sto}$ Stomatal closure | Reduces Tr and root zone expansion and might negatively affect HI | $Tr_x$ and HI |

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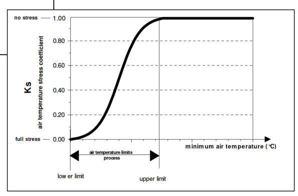
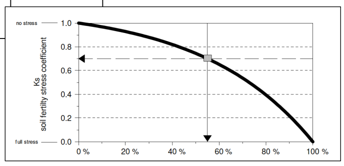
## TEMPERATURE STRESS

| Air temperature stress coefficient | Direct effect | Target model parameter |
|---|---|---|
| $Ks_b$ Cold stress coefficient for biomass production | Reduces biomass production | WP* |
| $Ks_{pol,c}$ Cold stress coefficient for pollination | Affects flowering and might negatively affect HI | $HI_0$ |
| $Ks_{pol,h}$ Heat stress coefficient for pollination | Affects flowering and might negatively affect HI | $HI_0$ |



## SOIL FERTILITY STRESS

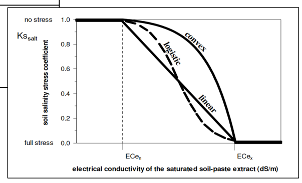
| Soil fertility stress coefficient | Direct effect | Target model parameter |
|---|---|---|
| $Ks_{CCx}$ Maximum canopy cover | Reduces canopy cover | $CC_x$ |
| $Ks_{exp,f}$ Canopy expansion | Reduces canopy expansion | CGC |
| $Ks_{WP}$ Water productivity | Reduces biomass production | WP* |
| $Ks_{CDecline}$ Decline coefficient of canopy cover | Decline of the canopy cover once the maximum canopy cover is reached | $CC_x$ |



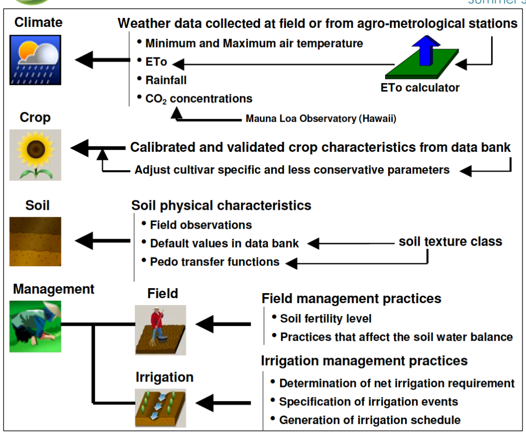



## SOIL SALINITY STRESS

| Soil salinity stress coefficient | Direct effect | Target model parameter |
|---|---|---|
| $Ks_{salt}$ Soil salinity stress coefficient | Reduces biomass production | Tr |
| $Ks_{CCx}$ Maximum canopy cover | Reduces canopy cover | $CC_x$ |
| $Ks_{exp,f}$ Canopy expansion | Reduces canopy expansion | CGC |
| $Ks_{sto,sal}$ Stomatal closure | Reduces crop Tr | $Ks_{sto}$ |
| $Ks_{CDecline}$ Decline coefficient of canopy cover | Decline of the canopy cover once the maximum canopy cover is reached | $CC_x$ |



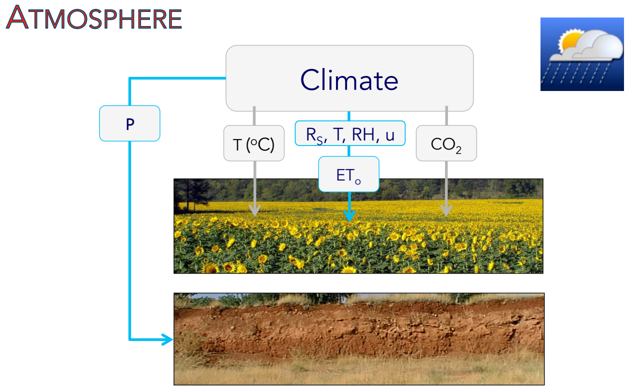


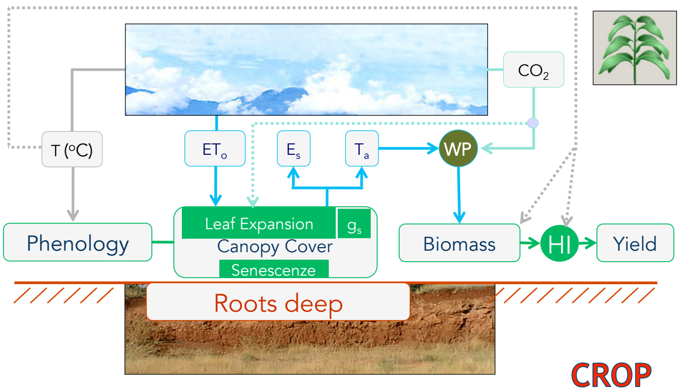

INPUT REQUIREMENT



## ATMOSPHERE



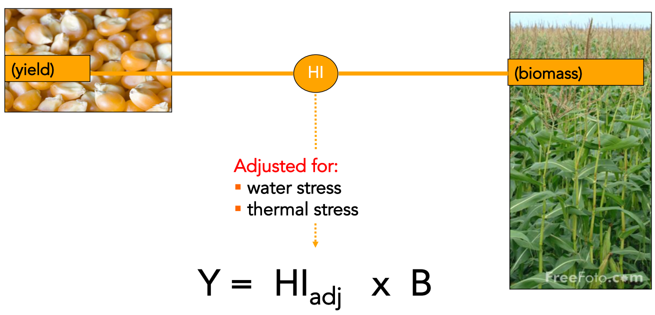



CROP

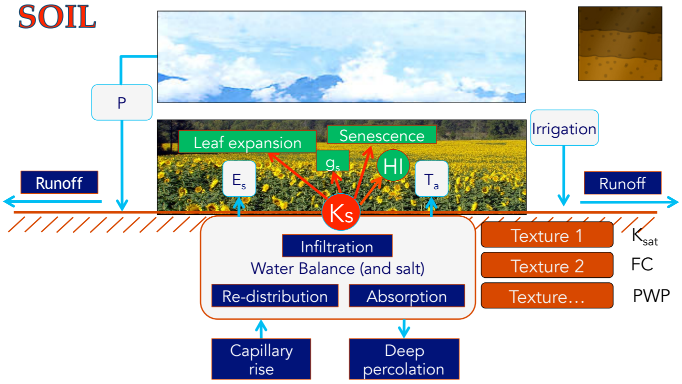


## YIELD



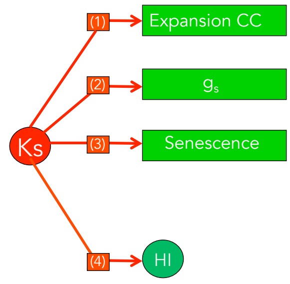

$$Y = HI_{adj} \times B$$

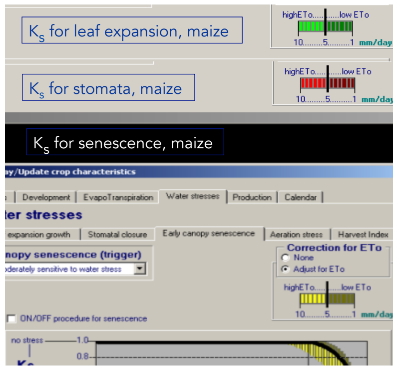
# SOIL



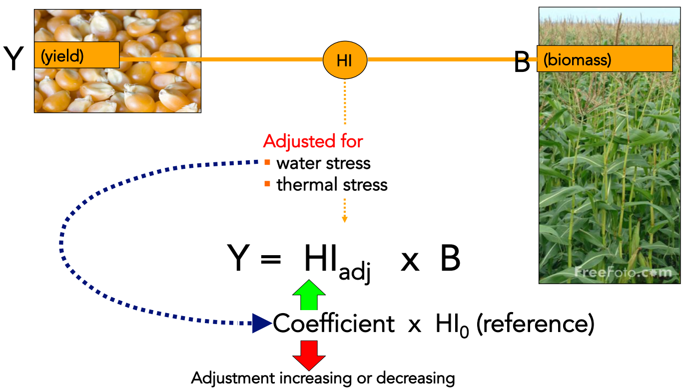



*+ thermal stress*
*& root asphyxia*








# Management


FIELD MANAGEMENT

- Soil fertility level(non-limiting; moderate; poor)
- Practices that affect soil water balance (mulching, etc.)


IRRIGATION MANAGEMENT

- Determination of net irrigation requirement
- Specification of irrigation events
- Generation of irrigation schedule



# AquaCrop – Purpose of the tool

- Predicting crop production under different water-management conditions (including rain fed conditions and supplementary, deficit and full irrigation) under present and future climate change conditions

- Investigating different management strategies, under present and future climate change conditions. Biomass and yield predictions are possible under global warming and elevated $CO_2$, making the model suitable for climate change studies

- Optimising cropping planning and management and developing irrigation strategies under water deficit conditions



# Output

Per run 7 type of output files

- Seasonal output (summary)
- Daily electrical conductivity
- Daily Soil Water Content at various soil depths
- Daily crop development and production
- Water content in soil profile and root zone
- Salt balance for soil profile and soil salinity in root zone
- Daily soil Water balance

# Chapter 1
# FAO cropwater productivity model to simulate yield response to water

# AquaCrop

*Version 3.1plus*

**Reference Manual**
**January 2011**

Developed by

**Dirk RAES, Pasquale STEDUTO, Theodore C. HSIAO, and Elias FERERES**

**with special support by Gabriella IZZI and Lee K. HENG**
**with contributions of the AquaCrop Network**

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**Acknowledgments**
**List of principal symbols**

**Chapter 1. FAO cropwater productivity model to simulate yield response to water**

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**II. Indicative values for lengths of crop development stages**



# Chapter 1
# FAO cropwater productivity model to simulate yield response to water

## 1.1 From the Ky approach to the AquaCrop model

Yield response to water describes the relationship between crop yield and water stress as a result from insufficient supply of water by rainfall or irrigation during the growing period. In the FAO Irrigation & Drainage Paper n. 33 (Doorenbos and Kassam, 1979) an empirical production function is used to asses the yield response to water:

$$\left(1-\frac{Y}{Y_x}\right)=K_y\left(1-\frac{ET}{ET_x}\right) \qquad \text{(Eq.1.1a)}$$

where $Y_x$ and Y are the maximum and actual yield, $(1\text{-}Y/Y_x)$ the relative yield decline, $ET_x$ and ET the maximum and actual evapotranspiration, $(1\text{-}ET/ET_x)$ the relative water stress, and $K_y$ the proportionality factor between relative yield decline and relative reduction in evapotranspiration (Fig. 1.1a).

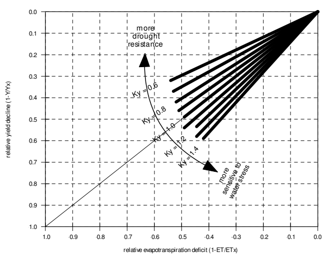


**Figure 1.1a**
**Relationship between relative yield decline (1-Y/Ym) and relative evapotranspiration deficit (1-ET/ETc) for the total growing period for various yield response factor (Ky)**



AquaCrop (Steduto et al., 2007; Raes et al., 2007; Hsiao et al., 2007) evolves from the Ky approach by separating

(i) the actual evapotranspiration (ET) into soil evaporation (E) and crop transpiration (Tr):

$$ET = E + Tr \qquad \text{(Eq. 1.1b)}$$

The separation of ET into soil evaporation and crop transpiration avoids the confounding effect of the non-productive consumptive use of water (soil evaporation). This is important especially when ground cover is incomplete early in the season or as the result of sparse planting.

(ii) and (ii) the final yield (Y) into biomass (B) and harvest index (HI):

$$Y = HI\ (B) \qquad \text{(Eq. 1.1c)}$$

The separation of yield into biomass and harvest index allows the partitioning of the corresponding functional relations as response to environmental conditions. These responses are in fact fundamentally different and their separation avoids the confounding effects of water stress on B and on HI.

The changes described leads to the following equation at the core of the *AquaCrop* growth engine:

$$B = WP \cdot \Sigma Tr \qquad \text{(Eq. 1.1d)}$$

where Tr is the crop transpiration (in mm) and WP is the water productivity parameter (kg of biomass per $m^2$ and per mm of cumulated water transpired over the time period in which the biomass is produced). This step-up from Eq. (1.1a) to Eq. (1.1d) has a fundamental implication for the robustness of the model due to the conservative behavior of WP (Steduto et al., 2007). It is worth noticing, though, that both equations have water as driving force for growth.

To be functional, Eq. 1.1d was inserted in a complete set of additional model components, including: *the soil*, with its water balance; *the crop*, with its development, growth and yield processes; and *the atmosphere*, with its thermal regime, rainfall, evaporative demand and carbon dioxide concentration. Additionally, some *management* aspects are explicitly considered (e.g., irrigation, fertilization, etc.), as they will affect the soil water balance, crop development and therefore final yield. AquaCrop can also simulate crop growth under climate change scenarios (global warming and elevated carbon dioxide concentration) while pests, diseases, and weeds are not yet considered. The functional relationships between the different model components are depicted in Fig. 1.1b and described in section 1.2.

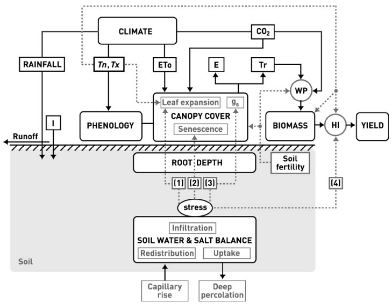


**Figure 1.1b**
**Chart of *AquaCrop* indicating the main components of the soil–plant–atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production, and final yield. [I, irrigation; $T_n$, minimum airtemperature; $T_x$, maximum air temperature; $ET_o$, reference evapotranspiration; E, soil evaporation; Tr, canopy transpiration; gs, stomatal conductance; WP, water productivity; HI, harvest index; $CO_2$, atmospheric carbon dioxide concentration; (1), (2), (3), (4), water stress response functions for leaf expansion, senescence, stomatal conductance and harvest index, respectively]. Continuous lines indicate direct links between variables and processes. Dashed lines indicate feedbacks. See section 1.2 for a more extensive description**



Particular features that distinguishes AquaCrop from other crop models are:

- its focus on water;
- the use of canopy cover instead of leaf area index;
- the use of water productivity (WP) values normalized for atmospheric evaporative demand and $CO_2$ concentration that confer the model an extended extrapolation capacity to diverse locations, seasons, and climate, including future climate scenarios;
- the relatively low number of parameters;
- input data which requires only explicit and mostly intuitive parameters and variables;
- a well developed user interface;
- its considerable balance between accuracy, simplicity, and robustness;
- its applicability to be used in diverse agricultural systems that exists world wide.

Although the model is relatively simple, it emphasizes the fundamental processes involved in crop productivity and in the responses to water deficits, both from a physiological and an agronomic perspective.

It is important to realize that several crop models are already available in literature to simulate yield response to water. They are used mostly by scientists, graduate students, and advanced users in highly commercial farming. However, it is also important to recognize that these models present substantial complexity and are rarely used by the majority of FAO target users, such as extension personnel, water user associations, consulting engineers, irrigation and farm managers, planners and economists. Furthermore, these models require an extended number of variables and input parameters not easily available for the diverse range of crops and sites around the world. Some of these variables are much more familiar to scientists than to end users (e.g., leaf area index –LAI– or leaf water potential –$\psi_l$–). Lastly, the insufficient transparency and simplicity of model structure for the end user were considered strong constraints for their adoption.



## 1.2 AquaCrop operation

### 1.2.1 Calculation scheme

A general calculation scheme of AquaCrop is depicted in Figure 1.2a. With a daily time step the model simulates successively the following processes:

1. Soil water balance. The amount of water stored in the root zone is simulated by accounting for the incoming and outgoing water fluxes at its boundaries. The root zone depletion determines the magnitude of a set of water stress coefficients (Ks) affecting: (a) green canopy (CC) expansion, (b) stomatal conductance and hence transpiration (Tr) per unit CC, (c) canopy senescence and decline, (d) the harvest index (HI) and (e) the root system deepening rate;

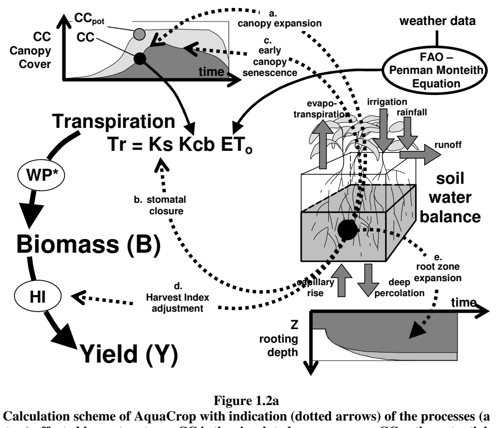


**Figure 1.2a**
**Calculation scheme of AquaCrop with indication (dotted arrows) of the processes (a to e) affected by water stress. CC is the simulated canopy cover, $CC_{pot}$ the potential canopy cover, Ks the water stress coefficient, Kcb the crop coefficient, ETo the reference evapotranspiration, WP* the normalized crop water productivity, and HI the Harvest Index**



2. Crop development. In the simulation of crop development, the canopy expansion is separated from the expansion of the root zone. The interdependence between shoot and root is indirect via water stress. AquaCrop uses canopy cover to describe crop development. The canopy is a crucial feature of AquaCrop. Through its expansion, ageing, conductance and senescence, it determines the amount of water transpired (Tr), which in turns determines the amount of biomass produced (B) and the final yield (Y). If water stress occurs, the simulated CC will be less than the potential canopy cover ($CC_{pot}$) for no stress conditions and the maximum rooting depth might not be reached (dark shaded areas in Fig. 1.2a);
3. Crop transpiration (Tr). Crop transpiration is obtained by multiplying the evaporating power of the atmosphere ($ET_o$) with a crop coefficient. The crop coefficient (Kcb) is proportional to CC and hence continuously adjusted. The evaporating power is expressed by the reference grass evapotranspiration ($ET_o$) as determined by the FAO Penman-Monteith equation. If water stress induces stomatal closure, the water stress coefficient for stomatal conductance (Ks) reduces transpiration accordingly. Green canopy cover and duration represent the source for transpiration, stomatal conductance represents transpiration intensity;
4. Above ground biomass (B). The cumulative amount of water transpired (Tr) translates into a proportional amount of biomass produced through the biomass water productivity (Eq. 1.1c). In AquaCrop the water productivity normalized for atmospheric demand and air $CO_2$ concentrations (WP*) is used. It expresses the strong relationship between photosynthetic $CO_2$ assimilation or biomass production and transpiration independently of the climatic conditions. Beyond the partitioning of biomass into yield (Step 5), there is no partitioning of above-ground biomass among various organs. This choice avoids dealing with the complexity and uncertainties associated with the partitioning processes, which remain among the least understood and most difficult to model;
5. Partitioning of biomass into yield (Y). Given the simulated above ground biomass (B), crop yield is obtained with the help of the Harvest Index (Eq. 1.1c). In response to water and/or temperature stresses, HI is continuously adjusted during yield formation.

### 1.2.2 Step 1 – simulation of the soil water balance

In a schematic way, the root zone can be considered as a reservoir (Fig. 1.2b). By keeping track of the incoming (rainfall, irrigation and capillary rise) and outgoing (runoff, evapotranspiration and deep percolation) water fluxes at the boundaries of the root zone, the amount of water retained in the root zone, and the root zone depletion can be calculated at any moment of the season by means of a soil water balance.

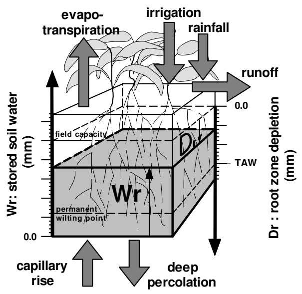


**Figure 1.2b**
**The root zone as a reservoir with indication of the fluxes at its boundaries affecting the water stored in the root zone (Wr) and the root zone depletion (Dr)**

To accurately describe surface run-off, water infiltration and retention, water and salt movement, and to separate soil evaporation from crop transpiration, AquaCrop divides both the soil profile and time axis into small fractions. The simulations run with a daily time step (Δt) and the soil profile is divided into 12 compartments (Δz), which size is adjusted to cover the entire root zone.

The effect of water stress is described by stress coefficients (Ks). Above an upper threshold of root zone depletion, water stress is non-existent (Ks is 1) and the process is not affected. Soil water stress starts to affect a particular process when the stored soil water in the root zone drops below an upper threshold level (Fig. 1.2c). Below the lower threshold, the effect is maximum (Ks is 0) and the process is completely halted. Between the thresholds the shape of the Ks curve determines the magnitude of the effect of soil



water stress on the process. Since the effect of water stress might differ along the processes, each process has its own Ks coefficient and threshold values.

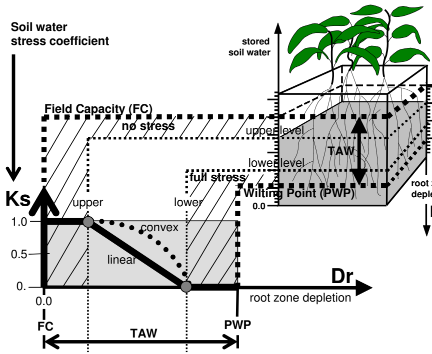


**Figure 1.2c**
**The water stress coefficient (Ks) for various degrees of root zone depletion (Dr). TAW is the Total Available soil Water in the root zone which is the difference between the water content at Field Capacity and Permanent Wilting Point**



### 1.2.3 Step 2 – simulation of green canopy development (CC)

In stead of leaf area index (LAI) AquaCrop uses green canopy cover (CC) to express foliage development. CC is the fraction of the soil surface covered by green canopy cover. Canopy development under optimal conditions is described by only a few crop parameters which are retrieved from the crop file at the start of the simulation:

- initial canopy cover at 90 % emergence ($CC_o$);
- maximum canopy cover when the canopy is fully developed ($CC_x$);
- canopy growth coefficient (CGC), used to describe the canopy expansion between cop emergence and full development;
- canopy decline coefficient (CDC), used to describe the declining phase due to leaf senescence as the crop approaches maturity.

In figure 1.2d, the variation of green canopy cover throughout a crop cycle under non-stress conditions is represented.

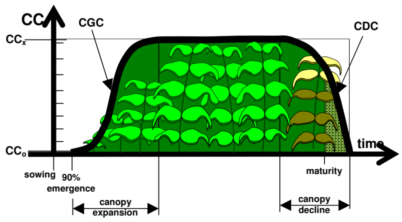


**Figure 1.2d**
**Variation of the green canopy cover (CC) throughout the crop cycle under non-stress conditions. $CC_o$ and $CC_x$ are the initial and maximum green canopy cover, respectively; CGC is the green canopy growth coefficient; CDC is the green canopy decline coefficient**

The effect of water stress on canopy expansion is simulated by multiplying the Canopy Growth Coefficient (CGC) with the water stress coefficient for canopy expansion ($Ks_{exp,w}$). As root zone depletion increases and drops below the upper threshold, the stress coefficient becomes smaller than 1 and the canopy expansion starts to be reduced (Fig. 1.2c). When the lower threshold of root zone depletion is reached, $Ks_{exp,w}$ is zero, and the process is completely halted. As a result, $CC_x$ might not be reached or much later in the season than described in Fig. 1.2d for non-stressed conditions.

Early canopy senescence is triggered when water stress becomes severe. As a consequence the upper threshold of root zone depletion for senescence is much lower in Fig. 1.2c and close to permanent wilting point. The degree of senescence is described by the value of the water stress coefficient for early canopy senescence ($Ks_{sen}$) which



modifies the canopy decline coefficient (CDC). Due to the induced early canopy senescence, the crop life might become much shorter than for non-stressed conditions. The simulation of the green canopy cover (CC) during the building up of water stress during the crop cycle is presented in Figure 1.2e.

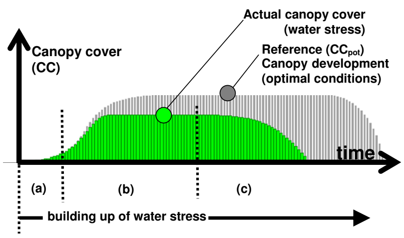


**Figure 1.2e**
**Simulation of the green canopy cover (CC) when water stress builds during the crop cycle with reference to the canopy development for non stressed conditions ($CC_{pot}$). With indication of periods (a) no effect of water stress on canopy development; (b) water stress affecting leaf expansion; (c) water stress triggering early canopy decline**

Other stresses considered by Aquacrop affecting CC are:

- air temperature stress. The effect of air temperature on canopy development is simulated by running AquaCrop in growing degree days (GDD). For the purpose of GDD calculations, a base temperature (below which crop development does not progress) and an upper temperature (above which the crop development no longer increases) are required;
- soil salinity stress. Since soil salinity reduces the availability of the water in the root zone reservoir, the presence of dissolved salts increase the effect of soil water stress. This is simulated in AquaCrop by moving the thresholds in Fig. 1.2c closer to Field Capacity;
- Mineral nutrient stress. AquaCrop does not simulate nutrient cycles and balance but provides a set of soil fertility stress coefficients (Ks), to simulate the effect of soil fertility on the growing capacity of the crop and the maximum canopy cover ($CC_x$) that can be reached at mid season. A distinction is made between a soil fertility coefficient for leaf expansion ($Ks_{exp,f}$) which reduces CGC and a soil fertility coefficient for maximum canopy cover ($Ks_{CCx}$) which reduces $CC_x$. Next to the effect on leaf expansion and maximum canopy cover, AquaCrop simulates a steady decline of the canopy cover once $CC_x$ is reached (Fig. 1.2f). The average daily decline is given by a decline factor ($f_{CDecline}$).

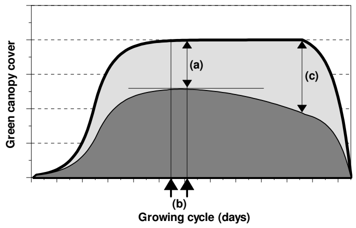


**Figure 1.2f**
**Green canopy cover (CC) for unlimited (light shaded area) and limited (dark shaded area) soil fertility with indication of the processes resulting in (a) a less dense canopy cover, (b) a slower canopy development, and (c) a steady decline of CC once the maximum canopy cover is reached**

### 1.2.4 Step 3 – simulation of crop transpiration (Tr)

Crop transpiration (Tr) is calculated by multiplying the evaporating power of the atmosphere with the crop coefficient (Kcb) and by considering water stresses (Ks):

$$Tr = Ks\,(Kcb_x\; CC^*)\,ETo \qquad \text{(Eq. 1.2a)}$$

where the evaporating power ($ET_o$) is expressed by the reference grass evapotranspiration as determined by the FAO Penman-Monteith equation. The crop transpiration coefficient (Kcb) is proportional to the fractional canopy cover (CC) and as such continuously adjusted to the simulated canopy development. The proportional factor ($Kcb_x$) integrates all the effects of characteristics that distinguish the crop transpiration from the grass reference surface. As the crop develops, $Kcb_x$ is adjusted for ageing and senescence effects. In Eq. 1.2a, CC is replaced by $CC^*$ to account for interrow microadvection which make extra energy available for crop transpiration. When canopy cover is not complete the contribution is substantial (Fig. 1.2g).

Either a shortage or an excess of water in the root zone might reduce crop transpiration. This is simulated by considering water stress coefficients (Ks). When water shortage in the root zone provokes stomatal closure a stress coefficient for stomatal closure ($Ks_{sto}$) is considered. When the excess of water results in anaerobic conditions, the effect of stress on transpiration is expressed by the coefficient for water logging ($Ks_{aer}$). According to the general rule in AquaCrop, the water stress coefficients range between 1, when water



stress is non-existent and 0, when the stress is at its full strength and crop transpiration is completely halted. The simulation of crop transpiration affected by water stress during the crop cycle is presented in Figure 1.2h.

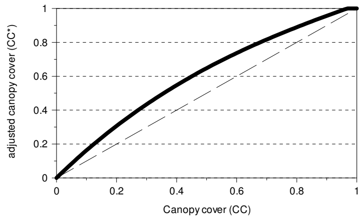


**Figure 1.2g**
**Canopy cover ($CC^*$) adjusted for micro-advective effects (bold line) for various fractions of green canopy cover (CC)**

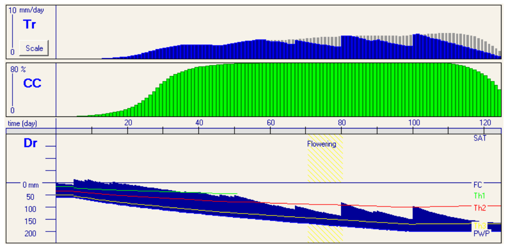


**Figure 1.2h**
**Simulated root zone depletion (Dr), green canopy cover (CC) and crop transpiration (Tr) throughout the crop cycle with indication of the soil water thresholds affecting canopy development (Th1), inducing stomata closure (Th2), and triggering early canopy senescence (Th3)**



### 1.2.5 Step 4 – simulation of the above-ground biomass (B)

The crop water productivity (WP) expresses the aboveground dry matter (g or kg) produced per unit land area ($m^2$ or ha) per unit of water transpired (mm). Many experiments have shown that the relationship between biomass produced and water consumed by a given species is highly linear for a given climatic condition (Eq. 1.1d).

To correct for the effect of the climatic conditions, AquaCrop uses the normalized water productivity ($WP^*$) for the simulation of aboveground biomass. The goal of the normalization is to make WP applicable to diverse location and seasons, including future climate scenarios. The normalization consists in a normalizing for:

- the atmospheric $CO_2$ concentration. The normalization for $CO_2$ consists in considering the crop water productivity for an atmospheric $CO_2$ concentration of 369.41 ppm (parts per million by volume). The reference value of 369.41 is the average atmospheric $CO_2$ concentration for the year 2000 measured at Mauna Loa Observatory in Hawaii (USA);
- the evaporative demand of the atmosphere. The normalization for climate is obtained by dividing the daily amount of water transpired (Tr) with the reference evapotranspiration ($ET_o$) for that day:

After normalization, recent findings indicate that crops can be grouped in classes having a similar $WP^*$, which are depicted in Fig. 1.2i. Distinction can be made between C4 crops with a $WP^*$ of about 30 to 35 g/$m^2$ (or 0.30 to 0.35 ton per ha) and C3 crops with a $WP^*$ of about 15 to 20 g/$m^2$ (or 0.15 to 0.20 ton per ha).

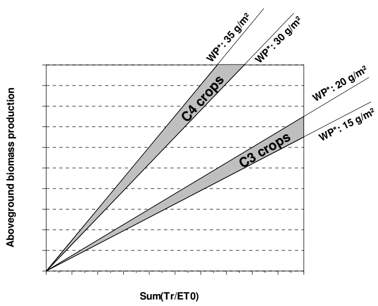


**Figure 1.2h**
**The relationship between the aboveground biomass and the total amount of water transpired for C3 and C4 crops after normalization for $CO_2$ and $ET_o$**



The aboveground biomass production for every day of the crop cycle is obtained by multiplying the WP* with the ratio of crop transpiration to the reference evapotranspiration for that day ($Tr/ET_o$). The production of biomass might be hampered when the air temperature is too cool irrespectively of the transpiration rate and ETo on that day. This is simulated in AquaCrop by considering a temperature stress coefficient ($Ks_b$):

$$B = Ks_b\; WP^* \sum_i \frac{Tr_i}{ETo_i} \qquad \text{(Eq. 1.2b)}$$

If the growing degrees generated in a day drops below an upper threshold, full conversion of transpiration to biomass production can no longer be achieved and $Ks_b$ becomes smaller than 1 and might even reach zero when it becomes too cold to generate any growing degrees. The simulated biomass production throughout the crop cycle for the canopy development and crop transpiration in Fig. 1.2h is presented in Figure 1.2j.

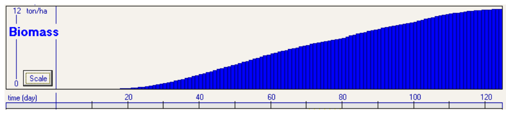


**Figure 1.2j**
**Simulated biomass production throughout the crop cycle for the canopy development and crop transpiration presented in Fig. 1.2g**

During the simulation, the normalized $WP^*$ might be adjusted to consider:

- atmospheric $CO_2$ concentration different from its 369.41 ppm reference value (i.e. the concentration for the year 2000 at Mauna Loa Observatory in Hawaii). This is simulated by multiplying WP* with a correction factor. The correction factor is larger than 1 for $CO_2$ concentrations above 369.41 ppm, and smaller than 1 for $CO_2$ concentrations below the reference value;
- the type of products that are synthesized during yield formation. If they are rich in lipids or proteins, considerable more energy per unit dry weight is required then for the synthesis of carbohydrates. As a consequence, the water productivity during yield formation needs to be reduced. This is simulated by multiplying WP* with a reduction coefficient for the products synthesized;
- limited soil fertility. Since soil fertility stress might decrease the crop water productivity, the effect of stress is simulated with the help of the soil fertility stress coefficient for crop water productivity ($Ks_{WP}$) which varies between 1 and 0. As long as soil fertility does not affect the process, $Ks_{WP}$ is 1 and WP* is not adjusted.

### 1.2.6 Step 5 – partitioning of biomass (B) into yield (Y)

Starting from flowering or tuber initiation the Harvest Index (HI) gradually increases to reach its reference value ($HI_o$) at physiological maturity (Fig. 1.2k). A too short grain/fruit filling stage or tuber formation stage as a result of early canopy senescence might result in inadequate photosynthesis and a reduction of the reference Harvest Index. For leafy vegetable crops HI builds up right after germination and reaches quickly $HI_o$.

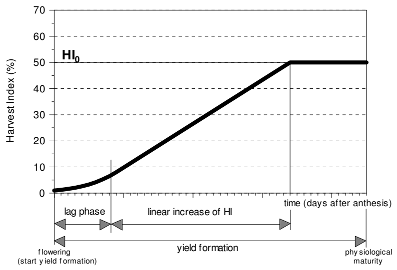


**Figure 1.2k**
**Building up of Harvest Index from flowering till physiological maturity for fruit and grain producing crops**

Yield (Y) is obtained by multiplying the above ground biomass (B) with the adjusted reference Harvest Index:

$$Y = f_{HI}\ HI_o\ B \qquad \text{(Eq. 1.2c)}$$

where $f_{HI}$ is a multiplier which considers the stresses that adjust the Harvest Index from its reference value. The adjustment of the Harvest Index to water deficits and air temperature depends on the timing and extent of stress during the crop cycle. The effect of stress on the Harvest Index can be positive or negative. Distinction is made between stresses before the start of the yield formation, during flowering which might affect pollination, and during yield formation.



## 1.3 Input requirement

AquaCrop uses a relative small number of explicit parameters and largely intuitive input variables, either widely used or requiring simple methods for their determination. Input consists of weather data, crop and soil characteristics, and management practices that define the environment in which the crop will develop (Fig. 1.3). The inputs are stored in climate, crop, soil and management files and can be easily adjusted through the user interface.

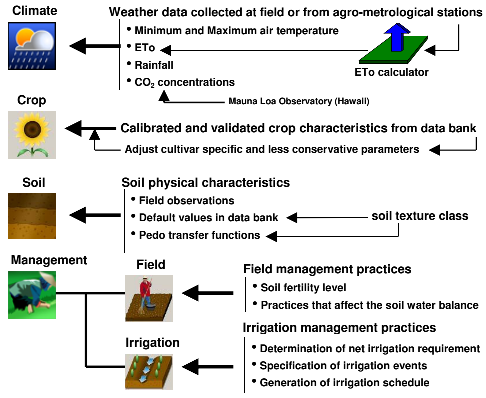


**Figure 1.3**
**Input data defining the environment in which the crop will develop.**

### 1.3.1 Weather data

For each day of the simulation period, AquaCrop requires minimum ($T_n$) and maximum ($T_x$) air temperature, reference evapotranspiration ($ET_o$) as a measure of the evaporative demand of the atmosphere, and rainfall. Additional the mean annual $CO_2$ concentration has to be known. Temperature affects crop development (phenology), and when limiting, growth and biomass accumulation. Rainfall and $ET_o$ are determinants for the water balance of the root zone and air $CO_2$ concentration affects crop water productivity.



$ET_o$ is derived from weather station data by means of the FAO Penman-Monteith equation (as defined in the Irrigation and Drainage Paper N° 56). An ETo calculator is available for that purpose. The calculator, which is public domain software, can be downloaded from the FAO website. The climatic data can be given in a wide variety of units, and procedures are available in the calculator to estimate missing climatic data.

The daily, 10-daily or monthly air temperature, $ET_o$ and rainfall data for the specific environment are stored in climate files from where the program retrieves data at run time. In the absence of daily weather data, the program invokes built-in approximation procedures to derive daily temperature, $ET_o$ and rainfall from the 10-daily or monthly means. For rainfall, with its extremely heterogeneous distribution over time, the use of 10-daily or monthly total rainfall data might reduce the accuracy of the simulations.

Additionally, an historical time series of mean annual atmospheric $CO_2$ concentrations measured at Mauna Loa Observatory in Hawaii, as well as the expected concentrations for the near future are provided in AquaCrop. The data is used to adjust the WP* to the $CO_2$ concentration of the year for which the simulation is running. The user can enter other future year's $CO_2$ for prospective analysis of climate change.

### 1.3.2 Crop characteristics

Although grounded on basic and complex biophysical processes, AquaCrop uses a relative small number of crop parameters describing the crop characteristics. FAO has calibrated crop parameters for major agriculture crops, and provides them as default values in the model. When selecting a crop its crop parameters are downloaded. Distinction is made between conservative, cultivar specific and less conservative parameters:

- The conservative crop parameters do not change materially with time, management practices, or geographical location. They were calibrated with data of the crop grown under favourable and non-limiting conditions and remain applicable for stress conditions via their modulation by stress response functions. As such the conservative parameters require no adjustment to the local conditions and can be used as such in the simulations;
- The cultivar specific crop parameters might require an adjustment when selecting a cultivar different from the one considered for crop calibration. Less-conservative crop parameters are affected by field management, conditions in the soil profile, or the weather (especially when simulating in calendar day mode). These parameters might require an adjustment after downloading to account for the local variety and or local environmental conditions.

When a crop is not available in the data bank, a crop file can be created by specifying only the type of crop (fruit or grain producing crops; root and tuber crops; leafy vegetables, or forage crops) and the length of its growth cycle. On the basis of this information AquaCrop provides defaults or sample values for all required parameters. In the absence of more specific information these values can be used. Through the user interface the defaults can be adjusted.



### 1.3.3 Soil characteristics

The soil profile can be composed of up to five different horizons of variable depth, each with their own physical characteristics. The considered hydraulic characteristics are the hydraulic conductivity at saturation ($K_{sat}$) and the soil water content at saturation ($\theta_{sat}$), field capacity ($\theta_{FC}$), and at permanent wilting point ($\theta_{PWP}$). The user can make use of the indicative values provided by AquaCrop for various soil texture classes, or import locally determined or derived data from soil texture with the help of pedo-transfer functions. If a layer blocks the root zone expansion, its depth in the soil profile has to be specified as well.

### 1.3.4 Management practices

Management practices are divided into two categories: field management and irrigation management practices:

- Under field management practices are choices of soil fertility levels, and practices that affect the soil water balance such as mulching to reduce soil evaporation, soil bunds to store water on the field, and tillage practices such as soil ridging or contours reducing run-off of rain water. The fertility levels range from non-limiting to poor, with effects on WP, on the rate of canopy growth, on the maximum canopy cover, and on senescence;
- Under irrigation management the user chooses whether the crop is rainfed or irrigated. If irrigated, the user can select the application method (sprinkler, drip, or surface), the fraction of surface wetted, and specify for each irrigation event, the irrigation water quality, the timing and the applied irrigation amount. There are also options to asses the net irrigation requirement and to generate irrigation schedules based on specified time and depth criteria. Since the criteria might change during the season, the program provides the means to test deficit irrigation strategies by applying chosen amounts of water at various stages of crop development.

## 1.4 Applications

AquaCrop can be used as a planning tool or to assist in management decisions for both irrigated and rainfed agriculture. The model is particular useful:

- to develop irrigation strategies under water deficit conditions;
- to study the effect on crop yield of location, soil type, sowing date, …;
- to study the effect on crop yield of various land management techniques;
- to compare the attainable against actual yields in a field, farm, or a region, to identify the constraints limiting crop production and water productivity (benchmarking tool);
- to predict climate change impacts on crop production
- for scenario simulations and for planning purposes for use by economists, water administrators and managers.

## References


Allen, R.G., L.S. Pereira, D. Raes and M. Smith 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Paper n. 56. FAO, Rome, Italy, 300 pp.

Doorenbos, J. and A.H. Kassam 1979. Yield response to water. Irrigation and Drainage Paper n. 33. FAO, Rome, Italy, 193 pp.

Hsiao, T.C., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., and Fereres, E. 2009. AquaCrop-The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. Agronomy Journal, 101(3): 448-459

Raes, D., Steduto, P., Hsiao, T.C., and Fereres, E. 2009. AquaCrop-The FAO crop model to simulate yield response to water: II. Main algorithms and software description. Agronomy Journal, 101(3): 438-447

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

Steduto, P., Hsiao, T.C., Raes, D. and Fereres, E. 2009. AquaCrop-The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agronomy Journal, 101(3): 426-437




# Chapter 2
# Users guide

AQUACROP

# AquaCrop
***Version 4.0***

**Reference Manual**
**June 2012**

**Dirk RAES, Pasquale STEDUTO, Theodore C. HSIAO, and Elias FERERES**
**with contributions of the AquaCrop Network**

**FAO, Land and Water Division**
**Rome, Italy**

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**Acknowledgments**

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**Chapter 3. Calculation procedures**

**Chapter 4. Calibration guidance**

**Annexes**

**I. Crop parameters**

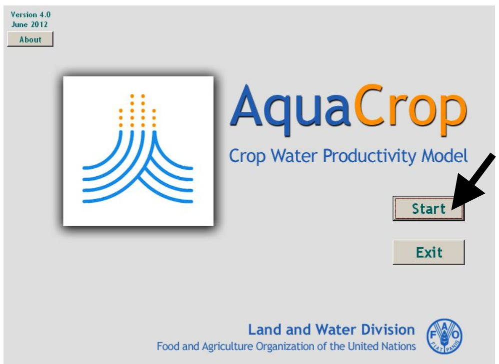
**II. Indicative values for lengths of crop development stages**

**III. Indicative values for soil salinity tolerance for some agriculture crops**




# Chapter 2.
# Users guide

## Running AquaCrop



## 2.1 The AquaCrop environment

AquaCrop is a menu-driven program with a well developed user interface. Windows (called menus) are the interface between the user and the program. Multiple graphs and schematic displays in the menus help the user to discern the consequences of input changes and to analyze the simulation results.

From the ***Main menu*** the user has access to a whole set of menus where input data is displayed and can be updated. Input consists of weather data, crop, irrigation and field management, soil and groundwater characteristics that define the environment in which the crop will develop. Also the sowing or planting day, the simulation period and conditions at the start of the simulation period are input. If the simulation period does not fully coincide with the growing cycle of the crop, off-season conditions valid outside the growing period can be specified as well as input.

Before running a simulation, the user specifies in the ***Main menu*** the sowing date, the simulation period and the appropriate environmental, initial and off-season conditions. Input can be retrieved from input files. In the absence of input files, default settings are assumed (see 2.3 Default settings at start). The user can also select a project file containing all the required information for that run, and a field data file with measurements to assess simulation results.

When running a simulation the user can in the ***Simulation run*** menu track changes in soil water and salt content, and the corresponding changes in crop development, soil evaporation and transpiration rate, biomass production, yield development and water productivity. Simulation results are stored in output files and the data can be retrieved in spread sheet programs for further processing and analysis.

Program settings allow the user switching off calculation procedures, or altering default settings in AquaCrop. With the **<Reset>** command in the ***Program Settings*** menus, settings can be reset to their default.



## 2.2 Main menu

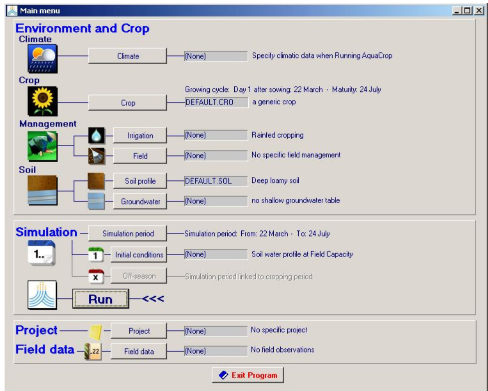



**Figure 2.2**
**Main menu of AquaCrop**

The ***Main Menu*** consists of 3 panels where the names and descriptions of the selected input files are displayed (Figure 2.2):

**A. Environment panel:** where the user:

(1) selects or creates Climate (Temperature, ETo, Rain, $CO_2$), Crop, Management (Irrigation and Field), Soil profile and Groundwater files and updates the corresponding data;
(2) specifies the start of the growing cycle;

**B. Simulation panel:** where the user:

(3) specifies: (i) the simulation period, (ii) the initial conditions for a simulation run, and (iii) the off-season conditions when the simulation period exceeds the growing period;
(4) runs a simulation for the specified environment, period and conditions.

**C. Project and Field data panel:** where projects and field data files can be selected, created or updated.



## 2.3 Default settings at start

### 2.3.1 Selected input

When AquaCrop is launched it selects a default crop and soil file. No other files (files are '(None)') are selected. In the absence of climate, irrigation management, field management, groundwater, initial and off-season conditions files, the default settings are assumed (Tab. 2.3).

**Table 2.3. Default settings assumed at the start of AquaCrop or after undoing the selection of a project**

| Environment | File | Remarks |
|---|---|---|
| Climate | (None) | A default minimum and maximum air temperature (see Climate), an ETo of 5 mm/day, no rainfall and an average atmospheric $CO_2$ concentration of 369.47 ppm are assumed throughout the growing cycle. When running a simulation without a climate file, the user has still the option to specify other than the default ETo and rainfall data. This climatic data can be specified for each day of the simulation period in the Input panel of the ***Simulation run*** menu |
| Crop | Default | Generic crop data |
| Irrigation management | (None) | Rainfed cropping is assumed. When running a simulation in this mode, irrigation can still be scheduled. The quality of the irrigation water and the irrigation application amount can be specified for each day of the simulation period in the Input panel of the ***Simulation run*** menu |
| Field management | (None) | No specific field management conditions are considered. It is assumed that soil fertility is unlimited, and that field surface practices does not affect soil evaporation or surface run-off |
| Soil | Default | Deep loamy soil |
| Groundwater | (None) | Absence of a shallow groundwater table |
| **Simulation** | **File** | **Remarks** |
| Period | | The simulation period covers the growing cycle completely |
| Initial conditions | (None) | At the start of the simulation it is assumed that in the soil profile (i) the soil water content is at field capacity and (ii) salts are absent |
| Off-season conditions | (None) | No specific field management conditions are considered outside the growing period. When running a simulation there are no irrigation events and mulches does not cover the field surface in the off-season |
| **Project/ Field data** | **File** | **Remarks** |
| Project | (None) | |
| Field data | (None) | |



The default input can be altered by selecting input files (see 2.4), by updating the default settings in the corresponding menus or by altering the characteristics retrieved from the input files (see 2.5), or by creating input files (see 2.6).

### 2.3.2 Program settings

## 2.4 Selecting input files and undoing the selection

By means of the **<Select/Create>** commands in the ***Main menu*** the user has access to data bases where the input files are stored (Fig. 2.4). The default data base is the DATA subdirectory of the AquaCrop folder. With the **<Path>** command the user can specify other directories.

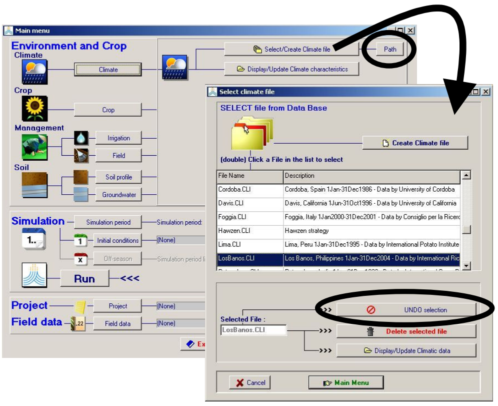



**Figure 2.4**
**Access to the *Select climate file* menu where input files can be selected from the data base and where the selection can be undone with the <UNDO selection> command**

### 2.4.1 Selecting a file

By clicking on the **<Select>** command in the ***Main menu***, a list of the relevant input files available in the selected directory is displayed in one of the ***Select file*** menus (Fig. 2.4). An input file is selected by clicking on its name in the list.

### 2.4.2 Undo the selection

When a climate, irrigation, field management, groundwater, initial conditions, off-season conditions, field data, or a project file has been selected, an option is available to undo the selection and to return to the default settings (see 2.3). This is achieved by clicking on the **<UNDO selection>** command in the ***Select file*** menu (Fig. 2.4).



## 2.5 Displaying and updating input characteristics

### 2.5.1 Displaying input data

From the ***Main menu*** the user has access to a whole set of menus where input data are displayed (Fig. 2.5a). This is done by clicking on the file name or the corresponding icon in the ***Main menu***.

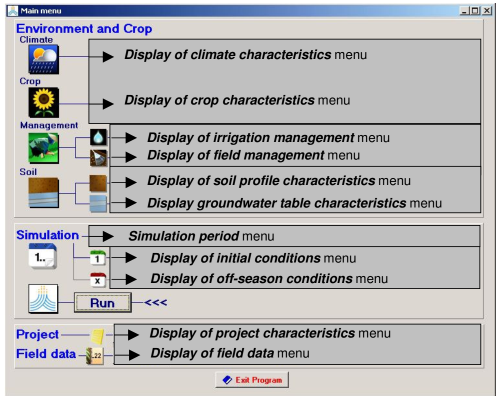



**Figure 2.5a**
**By clicking on the Icons (or file names) in the *Main menu* the specified input data is displayed in a set of *Display* menus**



### 2.5.2 Updating input data

From the ***Main menu*** the user has access to a set of menus where input data can be updated (Fig. 2.5b). This is done by first opening the access to the data base (click on the appropriate command in the ***Main menu***) and by subsequently selecting the **<Display/Update characteristics>** command. In the menus the data can be updated and saved as default settings or in input files when returning to the ***Main menu*** (see 2.7 to exit and close a menu).

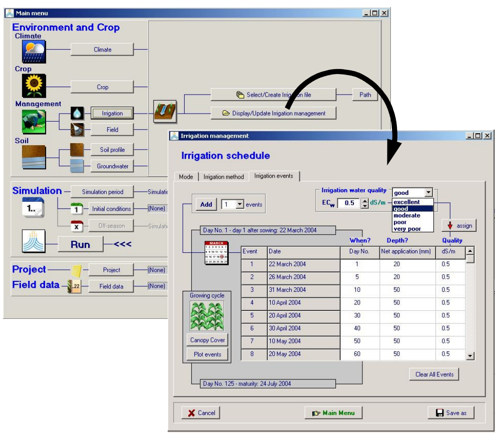



**Figure 2.5b**
**Access to the *Irrigation management* menu where the displayed input data can be updated**

In the Menu reference of this Chapter the Display/Update menus are described (sections 2.8 to 2.20).



## 2.6 Creating input files

### 2.6.1 The save on disk command

After updating the characteristics in one of the menus (see 2.5.2), an input file (if not yet available) is created by selecting the **<Save on disk>** command (Figure 2.6a).

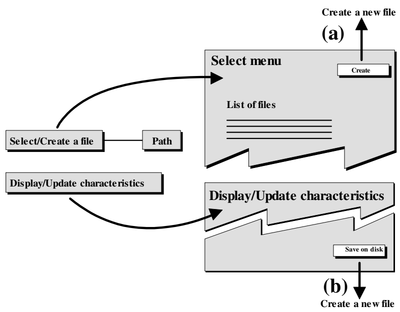



**Figure 2.6a**
**Options available to create input files by means of the user interface**

### 2.6.2 The save as command

If the displayed data in the characteristic menu was retrieved from an input file (Fig. 2.5b), a copy of the file will be created by clicking on the **<Save as>** command. This option allows the user to create various copies of a dataset which may differ only in one particular setting. This might be useful for the analysis of one or another effect on crop development or water productivity.

### 2.6.3 Create file

***Create file*** menus are available to create input files for new climate, crop, irrigation management, soil profile, groundwater, field data or project data. The ***Create file*** menus becomes available by selecting the **<Create file>** command in the ***Select file*** menu (Fig. 2.6a).

- **Create climate file**

Creating a climate file consists in selecting or creating a Temperature file, ETo file, Rain file and $CO_2$ file (Fig. 2.6b)

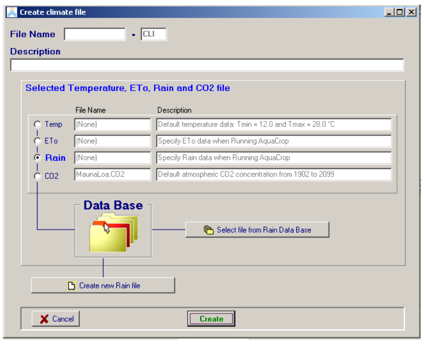



**Figure 2.6b**
***Create climate file* menu**

- **Create ETo, Rain or Temperature file**

When creating an ETo, Rain or Temperature file, the user has to specify the type of data (daily, 10-daily or monthly data), the time range and the data. Existing climatic data can be also pasted in an ETo, Rain, or Temperature file as long as the structure of the file is respected (see 2.21.2 Temperature, ETo and Rainfall files).



- **Create crop file**

When creating a crop file, the user selects the type of crop (Fruit/Grain producing crops, Leafy vegetable crops, Roots and tubers, or Forage crops) and specifies a few parameters (Fig. 2.6c). With the help of this information AquaCrop generates the complete set of required crop parameters. The parameters are displayed and the values can be adjusted in the ***Crop characteristics*** menu (see 2.9).

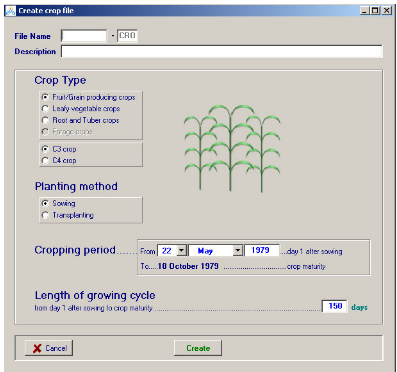



**Figure 2.6c**
***Create crop file* menu**

- **Create irrigation file**

When creating an irrigation file, the type of file has first to be selected:
1. Net irrigation water requirement;
2. Irrigation schedule; or
3. Generation of irrigation schedule.

Subsequently the user specifies the required information:
1. the allowable depletion when determining the net irrigation requirement;
2. the time, application depth and the irrigation water quality of the successive irrigation events; or
3. the irrigation water quality, and the time and depth criteria to generate irrigation events.



- **Create soil profile file**

When creating a soil profile file, the user has to specify only a few characteristics (Fig. 2.6d). With the help of this information AquaCrop generates the complete set of soil profile parameters. The parameters are displayed and the values can be adjusted in the ***Soil profile characteristics*** menu (see 2.13).

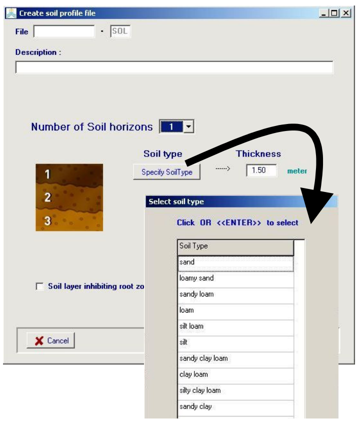



**Figure 2.6d**
***Create soil profile file* menu**

- **Create groundwater file**

When creating a groundwater file, the type of file has first to be selected:
1. Constant depth and water quality; or
2. Variable depth or water quality.

Subsequently the user specifies the depth and quality of the groundwater table for various moments (if variable) in the season in the ***Groundwater characteristics*** menu (see 2.14)



- **Create project file**

When creating a project file, the type of file has first to be selected (Fig. 2.18b):
1. Single simulation run;
2. Successive years (multiple runs); or
3. Crop rotation (multiple runs).

Subsequently the user specifies the climate file, crop(s) file, irrigation and field management file, soil file, and selects the sowing or planting date(s), the simulation period and the corresponding initial and off-season conditions (see 2.18.2 Selecting and creating a project). The characteristics can be updated in the ***Project Characteristics*** menu (see 2.18.3 Updating project characteristics).

- **Create field data file**

When creating a field data file, the user specifies the experimental determined green canopy cover (CC), and/or the dry above-ground biomass (B), and/or the soil water content (SWC) observed in the field at particular dates in the ***Field Data*** menu (see 2.19).

## 2.7 To exit and close a menu

Commands to exit a menu are available in the control panel at the bottom of each menu (Fig. 2.7). On exit, the window will be closed and the control is returned to the ***Main menu***. The exit mode is determined by the selected command. The following options to exit a menu are generally available:

- **<Cancel>** All changes made to the input displayed in the menu are disregarded when returning to the ***Main menu***;
- **<Return to Main menu>** Before returning to the ***Main menu***, the program checks if data was changed or settings were altered in the menu. The changes will be saved if the user confirms to save the changes;
- **<Save on disk>** When data was not retrieved from an input file but consists of an update of the default settings, the user can select this option to save the data on disk before returning to the ***Main menu***;
- **<Save as>** When data was retrieved from an input file, the user can select this option to save the data in a different file from which it was retrieved before returning to the ***Main menu***.

By clicking on the "X" symbol at the upper right corner of a menu, the window is closed as well. This option is however not recommended since the exit mode cannot be specified.

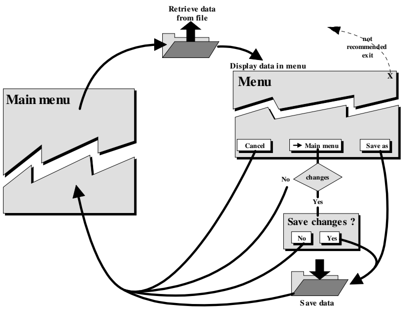



**Figure 2.7**
**Options to exit and close a menu**



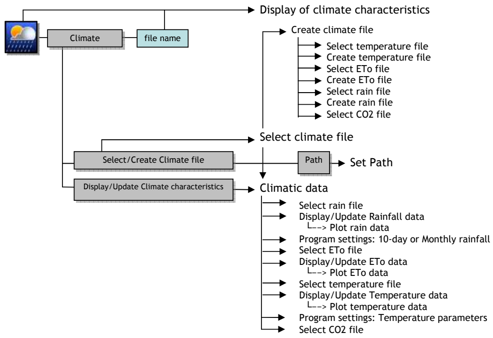
# Menu reference

## Hierarchical structure of the menus

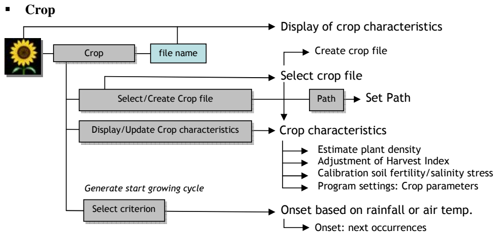
## Main Menu

### Environment panel

- **Climate**




- **Crop**

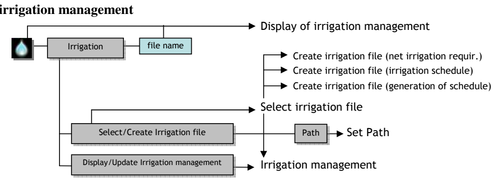




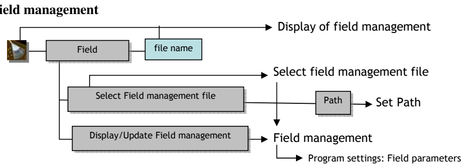

### Environment panel (continued)

- **Management**

**- irrigation management**




**- field management**

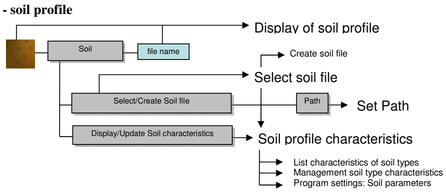




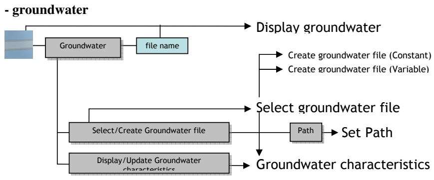

### Environment panel (continued)

- **Soil**

**- soil profile**

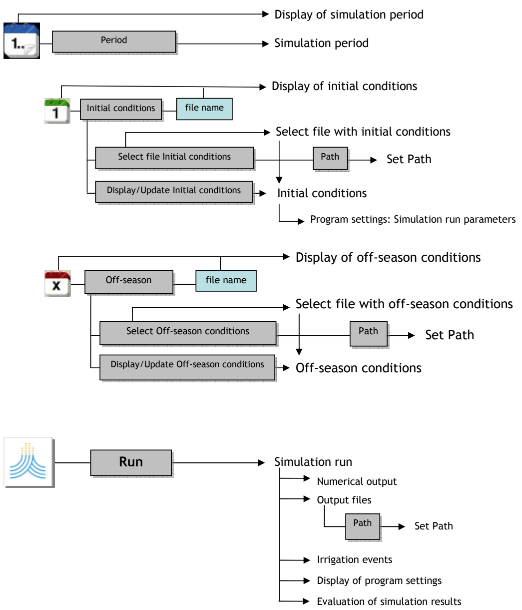



**- groundwater**



## Main menu

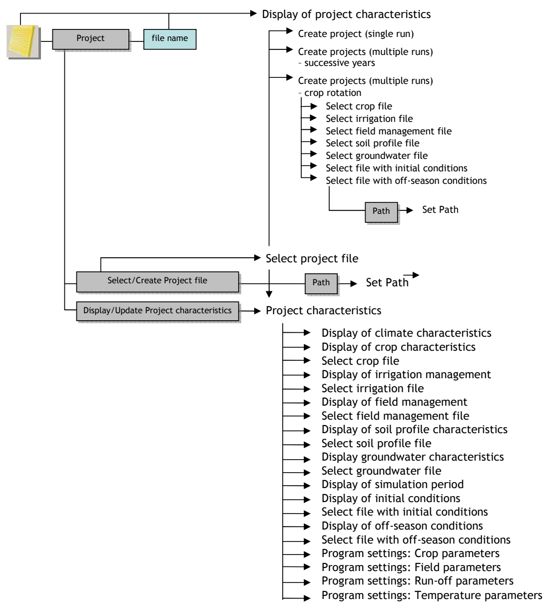
### Simulation panel



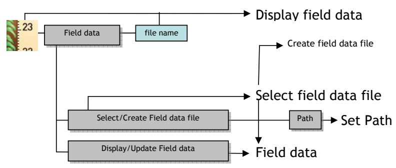



## Main Menu

### Project/Field data panel








## 2.8 Climatic data

For each day of the simulation period, AquaCrop requires minimum and maximum air temperature, reference evapotranspiration ($ET_o$), rainfall and the mean annual atmospheric $CO_2$ concentration. The climatic data are retrieved from files containing daily, 10-daily or monthly data. The selected climatic data can be displayed in the ***Display of climate characteristics*** menu and updated in the ***Climatic data*** menu (Fig. 2.8).


**Figure 2.8**
***Climatic data* menu**

### 2.8.1 Minimum and maximum air temperature

Temperature data are used to calculate growing degree day, which determines crop development and phenology (see 2.9.2), and also for making adjustment in biomass production during damaging cold periods (see 2.9.8). In the absence of daily data, the input may also consists of 10-day or monthly data and the program uses an interpolation procedure to obtain daily temperature from the 10-day or monthly means.

The daily minimum air temperature ($T_n$) and the daily maximum air temperature ($T_x$) are, respectively the minimum and maximum air temperature observed during the 24-hour period, beginning at midnight. $T_n$ and $T_x$ for 10-day's or months are the average of the daily values.

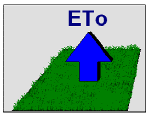
### 2.8.2 Reference evapotranspiration (ETo)

The reference evapotranspiration, denoted as ETo, is used in AquaCrop as a measure of evaporative demand of the atmosphere. It is the evapotranspiration rate from a reference surface, not short of water. A large uniform grass (or alfalfa) field is considered worldwide as the reference surface. The reference crop completely covers the soil, is kept short, well watered and is actively growing under optimal agronomic conditions.

ETo can be derived from weather station data by means of the FAO Penman-Monteith equation, and an ETo calculator is available for that purpose (Box 2.8). In the calculator, the data from a weather station can be specified in a wide variety of units, meteorological data can be imported, procedures are available to estimate missing climatic data and the calculated ETo can be exported to AquaCrop.

**Box 2.8.**
**The ETo Calculator (Land and water Digital Media Service N° 36, FAO, 2009).**

The ETo Calculator is public domain software, and an installation disk (1.5 Mb) and a software copy of the Reference Manual can be obtained from:




Land and Water Development Division
FAO, Viale delle Terme di Caracalla
00100 Rome, Italy
e-mail: Land-and-Water@fao.org
Fax: (+39) 06 570 56275

web page: http://www.fao.org/nr/water/ETo.html

In the absence of daily data, the input may also consists of 10-day or monthly data and the program uses an interpolation procedure to obtain daily $ET_o$ from the 10-day or monthly means.

### 2.8.3 Rainfall

The rainfall is the amount of water collected in rain gauges installed on the field or recorded at a nearby weather station. For rainfall, with its extremely heterogeneous distribution over time, the use of long-term mean data is not recommended. In case no daily rainfall data is available, 10-day and monthly data can be used as input.



### 2.8.4 Mean annual atmospheric $CO_2$

AquaCrop considers 369.47 parts per million by volume as the reference. It is the average atmospheric CO2 concentration for the year 2000 measured at Mauna Loa Observatory in Hawaii. Other CO2 concentrations will alter canopy expansion and crop water productivity (Chapter 3). AquaCrop uses as default the data from the MaunaLoa.CO2 (stored in the SIMUL subdirectory) which contains the mean annual atmospheric CO2 concentration measured at Mauna Loa Observatory since 1958. For earlier years data obtained from firn and ice samples close to the coast of Antarctica[1] are used, and for future estimates an increase of 2.0 ppm is assumed (following Pieter Hans (NOAA) - personal communication, December 2007). Other CO2 files, containing data from alternative sources, can be selected in AquaCrop. When creating CO2 files it is important to respect the file structure (see 2.19.3).

### 2.8.5 Program settings

From the ***Climatic data*** menu the user has access to the program settings listed in Table 2.8. Distinction is made in program settings for 10-day or monthly rainfall, and for Temperature parameters.

**Table 2.8**
**Program settings for temperature parameters and for procedures when simulating with 10-day or monthly rainfall data**

| Symbol | Program parameter | Default |
|---|---|---|
| | ***Temperature parameters*** | |
| | ▪ Method to estimate growing degree days (see Chapter 3) | Method 3 |
| | ▪ Default minimum ($T_n$) and maximum ($T_x$) air temperature in the absence of a temperature file | $T_n$ = 12 °C<br>$T_x$ = 28 °C |
| | ***10-day or monthly rainfall*** | |
| | Procedures to estimate effective rainfall, surface runoff and soil evaporation when rainfall data consists of 10-day or monthly totals (see Chapter 3) | |
| | ▪ Effective rainfall: calculation procedure | USDA-SCS |
| | ▪ Effective rainfall: percentage (fraction of rainfall) | 70 |
| | ▪ Surface runoff: showers per 10-day | 2 |
| | ▪ Soil evaporation: root number | 5 |

[1] David Etheridge et al. (1996), J. Geophys. Research vol. 101, 4115-4128



## 2.9 Crop characteristics

The crop characteristics required by the program can be displayed in the ***Display of crop characteristics*** menu and updated in the ***Crop characteristics*** menu (Fig 2.9a). The number and type of crop parameters vary slightly with the crop types selected when creating a new crop in AquaCrop (see 2.6.3). Distinction is made between

– fruit/grain producing crops (with a yield formation period, starting at flowering, during which the Harvest Index builds up);
– leafy vegetable crops (where flowering information is not considered and the Harvest Index builds up starting from germination);
– root and tuber crops (with a yield formation period, starting at tuber formation or root enlargement, during which the Harvest Index builds up);
– forage crops (crops undergoing cutting more than once a year possibly causing some of the crop characteristics to be altered after a cutting).


**Figure 2.9a**
**First page of the *Crop characteristics* menu showing the two options for the display mode**



The crop characteristics are grouped in 9 different folders (tab sheets):

– **Description**
  - File description
  - Type of edit fields (cells)
  - Protected file (if applicable)

– **Development**
  - Initial canopy cover
  - Canopy development
  - Flowering and yield formation
  - Root deepening
  - Temperatures

– **ET**
  - Coefficients
  - Water extraction pattern

– **Production**
  - Crop water productivity
  - Harvest Index

– **Water stress**
  - Canopy expansion
  - Stomatal closure
  - Early canopy senescence
  - Aeration stress
  - Harvest Index
    - Before flowering
    - During flowering
    - During yield formation
    - Overview

– **Temperature stress**
  - Biomass production
  - Pollination

– **Salinity stress**

– **Biomass - stress**
  - Canopy
  - Water productivity
  - Transpiration
  - Biomass
  - Biomass – stress relationship
  - Ks curves
  - Crop parameters

7 Folders (tab sheets) displaying crop characteristics

– **Calendar**

### 2.9.1 Description

- **Display modes of crop parameters**

Two types of display mode of crop parameters can be selected (Fig. 2.9a):

- ***Limited set:*** Crop parameters describing mainly phenology and life cycle length are displayed. They are

| | |
|---|---|
| Planting | |
| Type of planting method (direct sowing or transplanting) | |
| Canopy size of the transplanted seedling (method of planting: transplanting) | |
| Phenology (cultivar specific) | |
| Time to flowering or the start of yield formation | |
| Length of the flowering stage | |
| Time to start of canopy senescence | |
| Time to maturity (i.e. the length of crop cycle) | |
| Time to reach full canopy (only if crop cycle is expressed in calendar days) | |
| Management dependent | |
| Plant density | |
| Time to emergence | |
| Maximum canopy cover (depends on plant density and cultivar) | |
| Soil dependent | |
| Maximum rooting depth | |
| Time to reach maximum rooting depth | |
| **Soil and management dependent** | |
| Response to soil fertility and/or soil salinity stress | |

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 (Table 2.9a).

- **Type of edit fields (cells)**

Crop parameters are displayed in edit-fields (cells). The color of the edit fields varies depending on the type of parameters. The conservative parameters (displayed in silver cells) are crop specific but do not change materially with time, management practices, geographic location or climate. They are also assumed not to change with cultivars unless shown otherwise. They were calibrated with data of the crop grown under favorable and non-limiting conditions but remain applicable for stress conditions via their modulation by stress response functions. The other parameters (displayed in white cells) are cultivar specific or less conservative and affected by the climate, field management or conditions in the soil profile. The crop parameters are listed in Table 2.9a.

- **Protected files**

Crop files which come with the AquaCrop software contain crop parameters that are calibrated and validated by FAO. Although the user can alter the crop parameters in the



***Crop characteristics*** menu, the adjustments cannot be saved in the protected file. Select the **<Save as>** command to save the updated crop parameters in a new crop file.

**Table 2.9a.**
**List of the crop parameters and their type**

## 1. Crop Phenology

| Symbol | Description | Type (1), (2), (3), (4) |
|---|---|---|
| **1.1 Threshold air temperatures for growing degree days** | | |
| $T_{base}$ | Base temperature (°C) | Conservative (1) |
| $T_{upper}$ | Upper temperature (°C) | Conservative (1) |
| **1.2 Development of green canopy cover** | | |
| $cc_o$ | Canopy size of the average seedling at 90% emergence, or canopy size of the transplanted seedling (cm$^2$) | Conservative (2) Management (3) |
| | Number of plants per hectare | Management (3) |
| | Time from sowing to emergence (days or GD days) or recovery time (for transplanted seedlings) | Management (3) |
| CGC | Canopy growth coefficient (fraction per day or per growing degree day) | Conservative (1) |
| $CC_x$ | Maximum canopy cover (fraction soil cover) | Management (3) |
| | Time from sowing to start senescence (days or GD days) | Cultivar (4) |
| CDC | Canopy decline coefficient (fraction per day or per growing degree day) | Conservative (1) |
| | Time from sowing to maturity, i.e. length of crop cycle (days or GD days) | Cultivar (4) |
| **1.3 Flowering or start of yield formation** | | |
| | Time from sowing to flowering or to the start of yield formation (days or GD days) | Cultivar (4) |
| | Length of the flowering stage (days or GD days) | Cultivar (4) |
| | Crop determinacy linked/unlinked with flowering | Conservative (1) |
| **1.4 Development of root zone** | | |
| $Z_n$ | Minimum effective rooting depth (m) | Management (3) |
| $Z_x$ | Maximum effective rooting depth (m) | Management (3) |
| | Shape factor describing root zone expansion | Conservative (1) |

(1) Conservative generally applicable
(2) Conservative for a given specie but can or may be cultivar specific
(3) Dependent on environment and/or management
(4) Cultivar specific



**Table 2.9a. continued.**

## 2. Crop transpiration

| Symbol | Description | Type (1), (2), (3), (4) |
|---|---|---|
| $Kc_{Tr?x}$ | Crop coefficient when canopy is complete but prior to senescence | Conservative (1) |
| 100 $f_{age}$ | Decline of crop coefficient (% of $CC_x$ per day) as a result of ageing, nitrogen deficiency, etc. | Conservative (1) |
| $S_{x,top}$ | Maximum root water extraction (m$^3$ m$^{-3}$ day$^{-1}$) in top quarter of root zone | Conservative (1) |
| $S_{x,bot}$ | Maximum root water extraction (m$^3$ m$^{-3}$ day$^{-1}$) in bottom quarter of root zone | Conservative (1) |
| | Effect of canopy cover in reducing soil evaporation in late season stage (% reduction in soil evaporation) | Conservative (1) |

## 3. Biomass production and yield formation

| Symbol | Description | Type |
|---|---|---|
| **3.1 Crop water productivity** | | |
| WP* | Water productivity normalized for ETo and $CO_2$ (gram/m$^2$) | Conservative (1) |
| $f_{yield}$ | Reduction coefficient describing the effect of the products synthesized during yield formation on the normalized water productivity | Conservative (1) |
| | Crop performance under elevated atmospheric $CO_2$ concentration (%) | Management (3) Cultivar (4) |
| **3.2 Harvest Index** | | |
| $HI_o$ | Reference harvest index (%) | Cultivar (4) |
| | Excess of potential fruits (%) | Conservative (2) |
| | Possible increase (%) of HI due to water stress before flowering | Conservative (1) |
| | Coefficient describing positive impact of restricted vegetative growth during yield formation on HI | Conservative (1) |
| | Coefficient describing negative impact of stomatal closure during yield formation on HI | Conservative (1) |
| | Allowable maximum increase (%) of specified HI | Conservative (1) |

(1) Conservative generally applicable
(2) Conservative for a given specie but can or may be cultivar specific
(3) Dependent on environment and/or management
(4) Cultivar specific



**Table 2.9a. continued.**

## 4. Stresses

| Symbol | Description | Type (1), (2), (3), (4) |
|---|---|---|
| **4.1 Soil water stresses** | | |
| $p_{exp,lower}$ | Soil water depletion threshold for canopy expansion - Upper threshold | Conservative (1) |
| $p_{exp,upper}$ | Soil water depletion threshold for canopy expansion - Lower threshold | Conservative (1) |
| | Shape factor for Water stress coefficient for canopy expansion | Conservative (1) |
| $p_{sto}$ | Soil water depletion threshold for stomatal control – Upper threshold | Conservative (1) |
| | Shape factor for Water stress coefficient for stomatal control | Conservative (1) |
| $p_{sen}$ | Soil water depletion threshold for canopy senescence – Upper threshold | Conservative (1) |
| | Shape factor for Water stress coefficient for canopy senescence | Conservative (1) |
| | Sum(ETo) during stress period to be exceeded before senescence is triggered | Conservative (1) |
| $p_{pol}$ | Soil water depletion threshold for failure of pollination – Upper threshold | Conservative (1) |
| | Vol% at anaerobiotic point (with reference to saturation) | Cultivar (4) Environment (3) |
| **4.2 Soil fertility/salinity stress** | | |
| | Stress at calibration (%) | (calibration) |
| | Shape factor for the stress coefficient for canopy expansion | Management (3) |
| | Shape factor for the stress coefficient for Maximum Canopy Cover | Management (3) |
| | Shape factor for the stress coefficient for Crop Water Productivity | Management (3) |
| | Shape factor for the response of Decline of Canopy Cover to stress | Management (3) |
| | Shape factor for the stress coefficient for stomatal closure | Management (3) |
| **4.3 Air temperature stress** | | |
| | Minimum air temperature below which pollination starts to fail (cold stress) (°C) | Conservative (1) |
| | Maximum air temperature above which pollination starts to fail (heat stress) (°C) | Conservative (1) |
| | Minimum growing degrees required for full biomass production (°C - day) | Conservative (1) |

(1) Conservative generally applicable
(2) Conservative for a given specie but can or may be cultivar specific
(3) Dependent on environment and/or management
(4) Cultivar specific

**Table 2.9a. continued.**

| Symbol | Description | Type [(1), (2), (3), (4)] |
|---|---|---|
| **4.4 Soil salinity stress** | | |
| $ECe_n$ | Electrical conductivity of the saturated soil-paste extract: lower threshold (at which soil salinity stress starts to occur) | Conservative [(1)] |
| $ECe_x$ | Electrical conductivity of the saturated soil-paste extract: upper threshold (at which soil salinity stress has reached its maximum effect) | Conservative [(1)] |
| | Shape factor for Soil salinity stress coefficient | Conservative [(1)] |

(1) Conservative generally applicable
(2) Conservative for a given specie but can or may be cultivar specific
(3) Dependent on environment and/or management
(4) Cultivar specific



### 2.9.2 Development

In figure 2.9b1 the crop development for non-limiting conditions is plotted for fruit/grain producing crops. Instead of LAI, AquaCrop uses green canopy cover (CC) which is the fraction of soil surface covered by the green canopy. Crop development can be specified in growing degree days (GDD) or calendar days. Crop development parameters are grouped in 5 folders:

- Initial canopy cover (initial canopy cover at 90% emergence);
- Canopy development (canopy expansion and decline);
- Flowering and Yield formation (or Root/Tuber formation);
- Root deepening;
- Temperatures (required for the calculation of growing degree days).

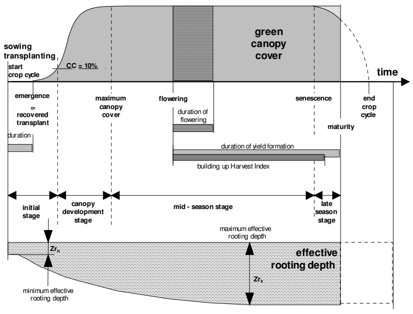



**Figure 2.9b1**
**Schematic representation of crop development for fruit/grain producing crops**



▪ **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 will have to confirm or adjust the proposed default size, when altering the method of planting (Fig. 2.9b2).

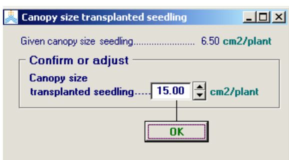



**Figure 2.9b2**
**Confirming the canopy size of the transplanted seedling when altering the planting method from direct sowing to transplanting in the *Canopy size seedling* menu**

**Specifying the initial canopy cover ($CC_o$)**

$CC_o$ can be specified by:

- specifying the plant density in the ***Crop characteristics*** menu;
- specifying the sowing rate or plant spacing. This option becomes available by clicking on the **<estimate>** command in the ***Crop characteristics*** menu. The plant density in the ***Estimate plant density*** menu is calculated from the specified sowing rate and approximate germination rate, or from the specified row and plant spacing (Fig. 2.9b3);
- selecting one of the classes ranging from very small to very high cover (Tab. 2.9b1);
- specifying directly the percentage in the ***Crop characteristic*** menu, which might be required for transplanted seedlings.



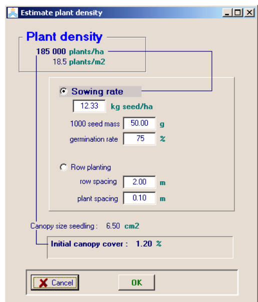



**Figure 2.9b3**
**Estimation of plant density from sowing rate or plant density in the *Estimate plant density* menu**

**Table 2.9b1**
**Classes, corresponding default values, and ranges for the initial canopy cover ($CC_o$)**

| Class | Default value | Range |
|---|---|---|
| Very small cover | 0.10 % | 0.10 … 0.12 % |
| Small canopy cover | 0.20 % | 0.13 … 0.30 % |
| Good canopy cover | 0.40 % | 0.31 … 0.50 % |
| High canopy cover | 0.70 % | 0.51 … 0.70 % |
| Very high cover (mostly for transplants) | 1.50 % | 0.71 … 10.00 % |

- **Canopy development**

Canopy expansion for no stress condition is described by two equations (see Chapter 3 – section 3.3.2 Canopy development) requiring information on (i) initial canopy cover ($CC_o$), (ii) maximum canopy cover ($CC_x$) for that plant density under optimal conditions, and (iii) canopy growth coefficient (CGC). Once senescence starts, CC declines. To simulate the canopy decline the starting time of senescence and a canopy decline coefficient (CDC) are required. The crop parameters governing canopy expansion and decline are displayed in the canopy development sheet of the ***Crop characteristics*** menu (Fig. 2.9b4).

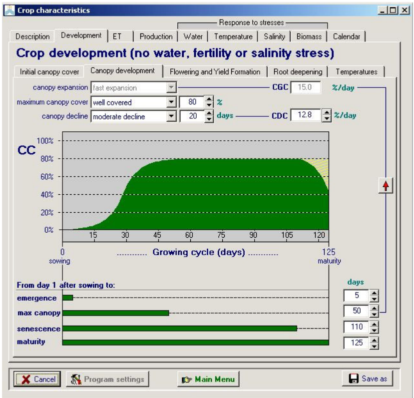



**Figure 2.9b4**
**Specification of canopy development in the *Crop characteristics* menu**



***Time to emergence*:** It is the time required from sowing to reach 90% emergence. Because field preparation, soil temperature and water content vary with each case, the time to emergence is user specific.

***Canopy Growth Coefficient (CGC) and the corresponding time to reach maximum canopy*:** CGC is a conservative crop parameter. AquaCrop provides alternative procedures to specify CGC or the corresponding time required to reach $CC_x$:
- If the red arrow is downwards (Fig. 2.9b4) the time to reach maximum canopy cover is derived from the specified canopy growth coefficient;
- If the red arrow is upwards the canopy growth coefficient is derived from the specified time to reach maximum canopy cover;
- The canopy growth coefficient can also be specified by selecting one of the classes ranging from very slow to very fast expansion (Tab. 2.9b2).

**Table 2.9b2**
**Classes, corresponding default values, and ranges for the Canopy Growth Coefficient (CGC) for no stress conditions**

| Class | Default value | Range |
|---|---|---|
| Very slow expansion | 3 %/day | 2.0 ... 4.0 %/day |
| Slow expansion | 6 %/day | 4.1 ... 8.0 %/day |
| Moderate expansion | 10 %/day | 8.1 ... 12.0 %/day |
| Fast expansion | 15 %/day | 12.1 ... 16.0 %/day |
| Very fast expansion | 18 %/day | 16.1 ... 40.0 %/day |

***Maximum canopy cover ($CC_x$)*:** Maximum canopy cover is dependent on plant density, CC per seedling at 90% emergence, and CGC. The user selects one of the classes which range from 'thinly covered' to 'entirely covered' (Tab. 2.9b3). AquaCrop displays the corresponding ground cover at maximum canopy. $CC_x$ can also be specified by entering directly the percentage.

**Table 2.9b3**
**Classes, corresponding default values, and ranges for the expected maximum canopy cover ($CC_x$) for no stress conditions**

| Class | Default value | Range |
|---|---|---|
| Very thinly covered | 40 % | 11 … 64 % |
| Fairly covered | 70 % | 65 … 79 % |
| Well covered | 90 % | 80 … 89 % |
| Almost entirely covered | 95 % | 90 … 98 % |
| Entirely covered | 99 % | 99 … 100 % |



***Senescence starting time*:** The time at which canopy senescence starts for optimal conditions. The senescence starting time depends on phenology and is cultivar specific.

***Canopy Decline Coefficient (CDC)*:** By selecting one of the classes for canopy decline ranging from very slow to very fast decline (Tab. 2.9b4), the canopy decline coefficient (CDC) is derived from the number of days required to achieve full senescence. The canopy decline coefficient can also be specified directly. The canopy decline coefficient is assumed to be conservative.

**Table 2.9b4**
**Classes, corresponding default values, and ranges for canopy decline expressed in days to achieve full senescence**

| Class | Default value | Range |
|---|---|---|
| Very slow decline | 5 weeks | more than 31 days |
| Slow decline | 4 weeks | 25 ... 31 days |
| Moderate decline | 3 weeks | 18 ... 24 days |
| Fast decline | 2 weeks | 13 ... 17 days |
| Very fast decline | 10 days | less than 13 days |

***Time to maturity*:** The user specifies the time at which maturity is reached. Although the crop can be harvested later it is assumed that the crop production no longer changes.



- **Flowering and yield formation (fruit/grain producing crops)**

The crop parameters to be specified are (i) the time of start of flowering, (ii) duration of flowering, (iii) the time required to build up the Harvest Index (HI), and (iv) if determinancy linked with flowering (Fig. 2.9b5). These parameters are mainly cultivar specific.

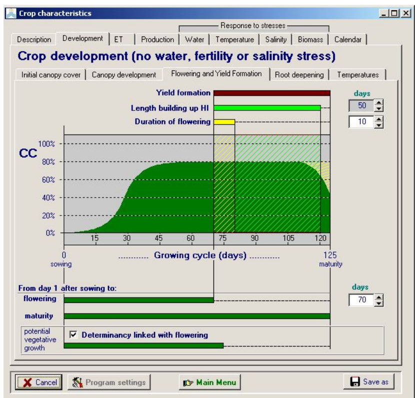



**Figure 2.9b5**
**Specification of flowering and time required to build up the Harvest Index for fruit/grain producing crops in the *Crop characteristic* menu for a crop where determinancy is linked with flowering**

If the **<Determinancy linked with flowering>** check button is checked (Fig. 2.9b5), the crop is determinant, and the canopy cover is assumed to have the potential growth (if CC < $CC_x$) up to peak flowering (set at half of the duration of flowering) but not thereafter. If due to the selection of the time of flowering, $CC_x$ can not be reached at peak flowering, AquaCrop adjust in the ***Crop characteristics*** menu the duration of flowering until the conditions can be fulfilled.

If the determinancy button is not checked (Fig. 2.9b6) the canopy development can stretch till canopy senescence. The corresponding period for potential vegetative growth is displayed.

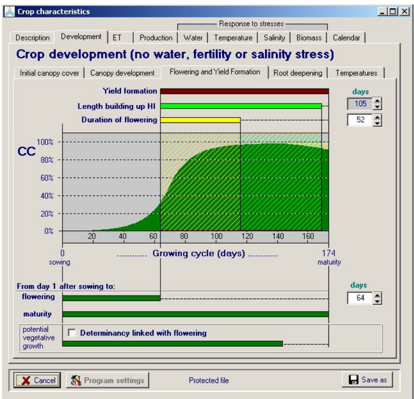



**Figure 2.9b6**
**Specification of flowering and time required to build up the Harvest Index for fruit/grain producing crops in the *Crop characteristic* menu for a crop where determinancy is not linked with flowering, such as cotton.**

The time required for the Harvest Index (HI) to increase from 0 (at flowering) to its reference values ($HI_o$) under optimal conditions is the duration for building up HI. The Harvest Index should be able to reach its reference value at or shortly before maturity.



- **Root/Tuber formation (root/tuber crops)**

The crop parameters to be specified are (i) the start of tuber formation or root enlargement, and (ii) the time required to build up the Harvest Index (HI) (Fig. 2.9b7). These parameters are mainly cultivar specific.

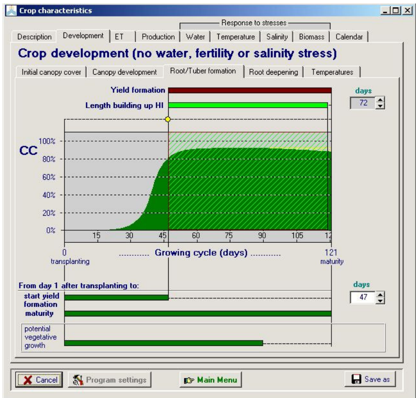



**Figure 2.9b7**
**Specification of the start of yield formation and the time required to build up the Harvest Index for root/tuber crops in the *Crop characteristic* menu**

Root/Tuber crops are assumed to be indeterminant. Hence the canopy development can stretch till canopy senescence. The corresponding period for potential vegetative growth is displayed in the menu.

The time required for the Harvest Index (HI) to increase from 0 (at the start of tuber formation or root enlargement) to its reference values ($HI_o$) under optimal conditions is the duration for building up HI. The Harvest Index should be able to reach its reference value at or shortly before maturity.



- **Root deepening**

The crop parameters to be specified are (i) the maximum effective rooting depth and (ii) the time reached, (iii) the minimum effective rooting depth and (iv) a shape factor for the rooting depth (Z) time curve (Fig. 2.9b8). These parameters are user specific as root development is strongly impacted by local soil conditions and the life cycle length of the crop.

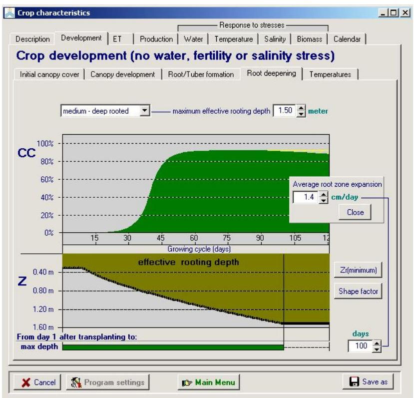



**Figure 2.9b8**
**Specification of root deepening in the *Crop characteristic* menu**



The ***minimum effective rooting depth*** refers to the depth from which the germinating seedling can extract water. For simulation purposes a depth of 0.20 to 0.30 m is generally considered.

The ***maximum effective rooting depth*** can be specified by selecting one of the classes which range from 'shallow rooted crops' to 'very deep-rooted crops' (Tab. 2.9b5). The shallow rooted crops category is only applicable to rice and crops with very short life cycle such as radish. AquaCrop displays the corresponding maximum effective rooting depth. The rooting depth can also be specified by entering directly the numeric value in meter. As a general rough guide for field crops in general, the roots deepening rate is about 2 cm per day when the environment is optimal for growth, the soil is not cold and soil layers that limits growth are absent.

**Table 2.9b5**
**Classes, corresponding default values, and ranges for maximum effective rooting depth of the fully developed crop under optimal conditions**

| Class | Default value | Range |
|---|---|---|
| Shallow rooted crops | 0.35 m | 0.10 … 0.39 |
| Shallow – medium rooted | 0.60 m | 0.40 … 0.99 |
| Medium – deep rooted | 1.00 m | 1.00 … 1.99 |
| Deep rooted crops | 1.35 m | 2.00 … 2.99 |
| Very deep rooted crops (perennial) | 2.00 m | 3.00 … 10.0 |

By varying the ***shape factor*** of the Z versus time curve, the expansion rate of the root zone can be altered between planting and the time when the maximum rooting depth is reached.

The effective rooting depth might not reach its maximum value if an impermeable soil layer blocks root development or when the exploitable soil depth is smaller than the maximum rooting depth. The root deepening rate is described by the shape factor, but once the effective rooting depth reaches the restrictive soil layer, the expansion is halted (Fig. 2.9b9).

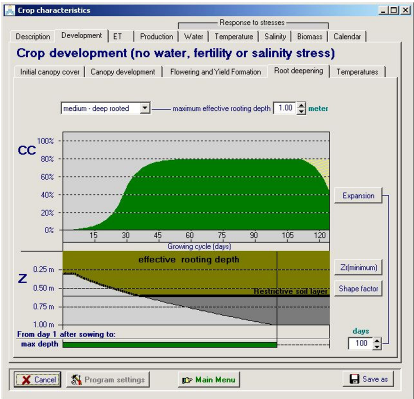



**Figure 2.9b9**
**Effect of a restrictive soil layer on root development**



- **Temperatures for growing degree days (GDD)**

Crop development can be specified in calendar days or growing degree days (GDD). For the purpose of GDD calculations a base temperature (below which crop development does not progress) and an upper temperature (above which the crop development no longer increases) are required (see Chapter 3 – section 3.2 Growing degree days). These temperatures are conservative for a given specie but may be cultivar specific for lines bred in drastically different environments. The base and upper temperatures are specified in the Temperatures folder (Fig.2.9b10).

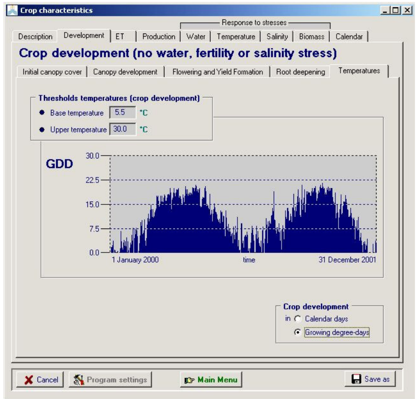



**Figure 2.9b10**
**Specification of the base and upper temperature threshold in the *Crop characteristics* menu**



## 2.9.3 Evapotranspiration

- **Coefficients**

The soil water evaporation coefficient (Ke) and the crop transpiration coefficient ($Kc_{Tr}$) are plotted from sowing to maturity (Fig. 2.9c1).

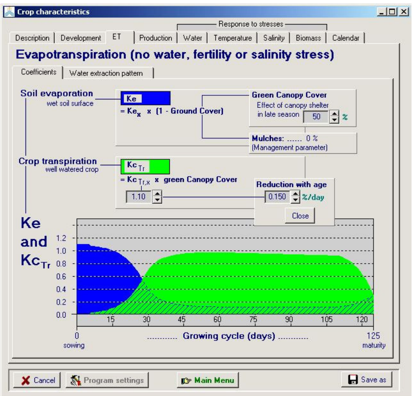



**Figure 2.9c1**
**Response of the soil evaporation (Ke) and the crop transpiration ($Kc_{Tr}$) coefficients to canopy development and decline during the growing cycle for non limiting conditions**

Evaporation from a fully wet soil surface is inversely proportional to the effective canopy cover. The proportional factor is the soil evaporation coefficient for fully wet and unshaded soil surface ($Ke_x$) which is a program parameter (see 2.9.11 Program settings) with a default value of 1.1. When canopy cover declines (senesces) late in the season as dictated by phenology, or as induced by water, nutrient or salinity stress, soil evaporation remains somewhat reduced by the sheltering effect of the yellow or dead canopy cover. The effect of canopy shelter is parameterized based on whether the senescening canopy retains more or less of its dead leaves.



Crop transpiration from a well water soil is proportional to the effective canopy cover. The proportional factor is the coefficient for maximum transpiration ($Kc_{Tr,x}$). It is the crop coefficient when canopy cover is complete (CC = 1) and without stresses. $Kc_{Tr,x}$ is conservative and approximately equivalent to the basal crop coefficient at mid-season of FAO Irrigation and Drainage Paper 56 but only for cases of full CC. After the time required to reach the maximum canopy cover ($CC_x$) under optimal conditions and before senescence, the canopy ages slowly and undergoes a progressive though small reduction in transpiration and photosynthetic capacity. This is simulated by reducing $Kc_{Tr,x}$ by a constant and very slight fraction per day (Fig. 2.9c1).

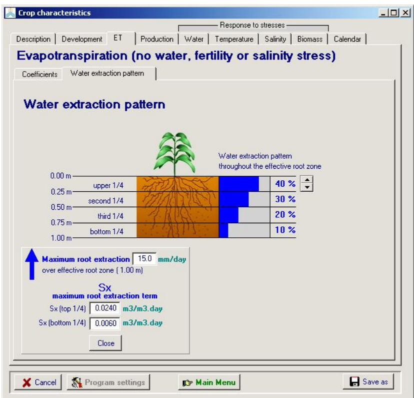



**Figure 2.9c2**
**Derived maximum extraction terms ($S_x$) at the top and bottom of the root zone after the specification of the water extraction pattern and the maximum root extraction**

- **Water extraction pattern**

The root water extraction from the soil profile is governed by the actual soil water content and the maximum amount of water ($S_x$) that can be extracted by the roots per unit of bulk volume of soil, per unit of time ($m^3$ water per $m^3$ soil per day). $S_x$ at the top of the soil profile is generally different from $S_x$ at the bottom of the root zone. By specifying the maximum root extraction of a well developed crop (a default value of 15 mm/day for root zones deeper than 0.5 m is considered), and the water extraction pattern throughout the root zone, $S_x$ values are derived in AquaCrop for different depths in the root zone (Fig. 2.9c2).

If a soil layer blocks the root zone expansion, the maximum root extraction term at the bottom of the root zone increases when the roots continue to develop. This simulates the concentration of roots above the restrictive soil layer. When a restrictive layer in the soil profile is present, the adjustment of the extraction terms can be displayed in AquaCrop (Fig. 2.9c3).

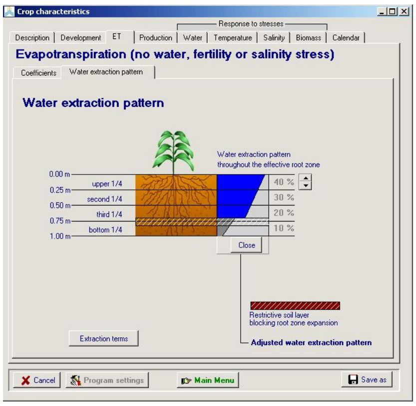



**Figure 2.9c3**
**Adjustment of the water extraction pattern**
**in the presence of a restrictive soil layer blocking root zone expansion**



### 2.9.4 Production

- **Crop water productivity normalized for climate and $CO_2$ (WP*)**

To simulate biomass and yield, the water productivity normalized for climate and air $CO_2$ concentration (WP*) is required. WP* is a conservative parameter. For use with crop species without calibrated WP*, general ranges are provided by AquaCrop for C3 and C4 species. If the harvestable organ is rich in oil and/or proteins, WP* after the beginning of flowering must be reduced over the yield formation period, by multiplying it by an adjustment factor entered by the user (Fig. 2.9d1).

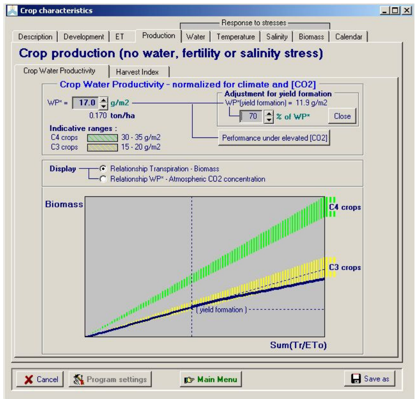



**Figure 2.9d1**
**The water productivity normalized for climate and atmospheric $CO_2$ and its adjustment if the harvestable organs are rich in oil and/or proteins**



- **Performance under elevated atmospheric $CO_2$ concentration**

$WP^*$ 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 at the year 2000). The adjustment is obtained by multiplying $WP^*$ with a correction coefficient as discussed in Chapter 3 (Section 3.11 Above ground biomass). The theoretical adjustment 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 yet not able to take care of the elevated $CO_2$ concentration. The performance of the crop under elevated atmospheric $CO_2$ concentration can be adjusted by the user by altering its sink strength in accordance with the expected soil fertility management and the cultivar (Fig. 2.9d2).

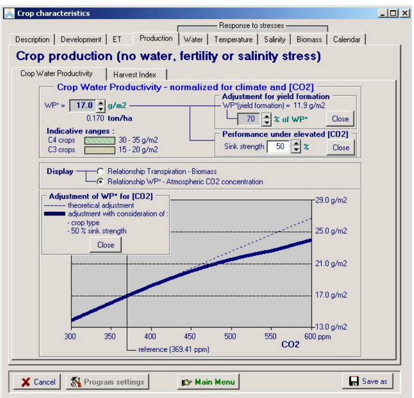



**Figure 2.9d2**
**The water productivity adjusted to atmospheric $CO_2$ concentration**
**by considering crop type and crop sink strength**



- **Reference Harvest Index ($HI_o$)**

The reference Harvest Index ($HI_o$) is the representative HI reported in the literature for the chosen crop species under non-stress conditions. $HI_o$ is conservative to a fair extent but can be cultivar specific.

***Fruit or grain producing crops***

Beginning at the start of flowering HI increases linearly after a lag phase until physiological maturity is reached (Fig. 2.9d3). The value reached at maturity under non-stress conditions is taken as $HI_o$ for that species.

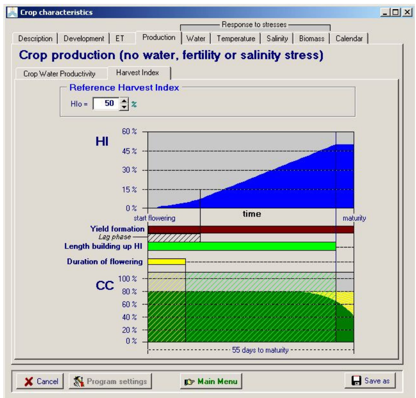



**Figure 2.9d3**
**Specification of the reference harvest index ($HI_o$)**
**and the display of the building up of the Harvest Index from flowering to physiological maturity for a fruit or grain producing crop**

***Root and tubers***
Beginning at tuber formation or root enlargement HI increases until physiological maturity (Fig. 2.9d4). The building up of the Harvest Index is described by a logistic function. The value reached at maturity under non-stress conditions is taken as $HI_o$ for that species.

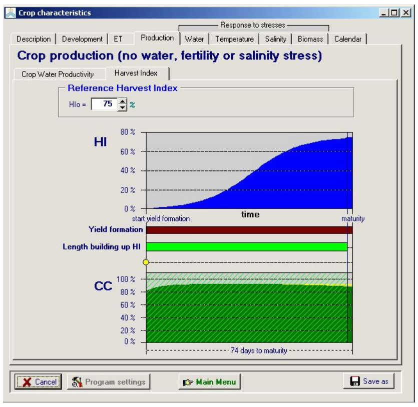



**Figure 2.9d4**
**Specification of the reference harvest index ($HI_o$)**
**and the display of the building up of the Harvest Index from the tuber formation or root enlargement to physiological maturity for roots and tubers**



***Leafy vegetable crops***
Beginning at germination, HI increases with a logistic equation till the reference harvest indeed (HIo) is reached (Fig. 2.9d5). For leafy vegetable crops, the time to reach $HI_o$ is expressed as a percentage of the growing cycle.

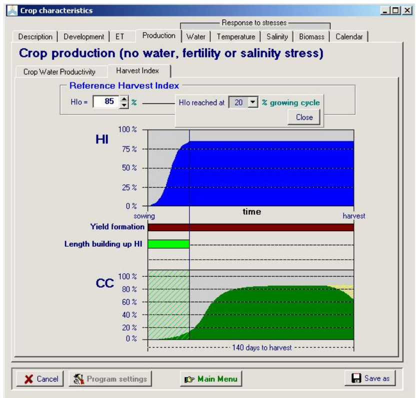



**Figure 2.9d5**
**Specification of the reference harvest index ($HI_o$) and the time to reach $HI_o$ for leafy vegetable crops**



### 2.9.5 Water stress

- **Canopy expansion, stomatal conductance and early canopy senescence**

Effects of water stress on canopy expansion, stomatal conductance, and early canopy senescence are described by water stress coefficients Ks. Above an upper threshold of soil water content, water stress is not considered and Ks is 1. Below a lower threshold, the stress is at its full effect and Ks is 0 (Fig. 2.9e1). The user can specify in the corresponding menus threshold values and curve shape, or can select a category graded for relative resistance to water stress.

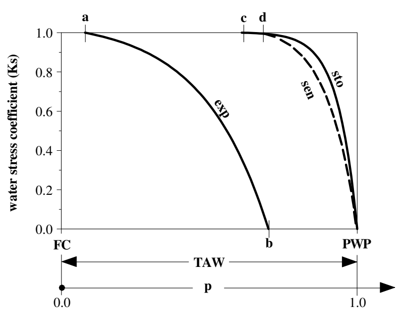



**Figure 2.9e1**
**Examples of the variation of the water stress coefficient for leaf expansion (exp), stomatal conductance (sto) and canopy senescence (sen) for various soil water depletions**

***Thresholds:*** The thresholds are expressed as a fraction (p) of the Total Available soil Water (TAW). TAW is the amount of water a soil can hold between field capacity (FC) and permanent wilting point (PWP). For leaf and hence canopy growth, the lower threshold is above PWP ($p < 1$), where as for stomata and senescence the lower threshold is fixed at PWP ($p = 1$).

***Shape of Ks curve:*** Between the upper and lower thresholds the shape of the Ks curve determines the magnitude of the effect of soil water stress on the process. The shape can be linear or convex (Fig. 2.9e2). Tests so far suggest that the thresholds and shapes of



these curves may be conservative, at least to a fair degree. The shape factor can range from +6 (strongly convex) to 0 (linear).

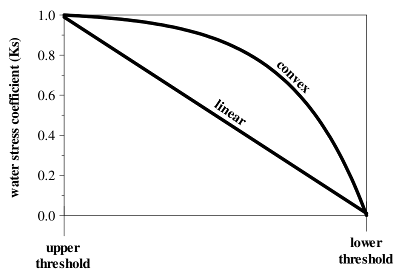



**Figure 2.9e2**
**Convex and linear shapes of the Ks curve**

***Adjustment by $ET_o$:*** Generally leaf and plant water status are partially dependent on transpiration rate, being lower for higher rate of transpiration. AquaCrop simulate this effect indirectly by adjusting the Ks curve according to $ET_o$. The specified soil water depletion factors (p) are for a reference evaporative demand of $ET_o$ = 5 mm/day, and the p is adjusted at run time for different levels of $ET_o$. The shaded bands in the corresponding displays (Fig. 2.9e3), on the two sides of the curved line indicate the range of the evaporative demand adjustments as dictated by ETo. The adjustment is not considered if the correction for ETo is switched off.

***Canopy expansion:*** Leaf growth by area expansion (expansive growth) and therefore canopy development are the highest in sensitivity to water stress among all the plant processes described by the model. The user specifies the effect of water stress on leaf expansion growth by selecting a sensitivity class (Tab. 2.9e1, Fig. 2.9e3) or by specifying values for an upper and lower soil water depletion thresholds (p):

- p(upper): The fraction of the Total Available soil Water (TAW) that can be depleted from the root zone before leaf expansion starts to be limited;
- p(lower): when this fraction of TAW is depleted from the root zone, there is no longer any leaf expansion growth (reduction of 100 %).

**Table 2.9e1**
**Classes and corresponding default values for the soil water depletion fractions for canopy expansion**

| Class<br>Sensitivity to water stress | Soil water depletion fraction for canopy expansion ($p_{exp}$) | |
|---|---|---|
| | p(upper) | p(lower) |
| extremely sensitive to water stress | 0.00 | 0.35 |
| sensitive to water stress | 0.10 | 0.45 |
| moderately sensitive to water stress | 0.20 | 0.55 |
| moderately tolerant to water stress | 0.25 | 0.60 |
| tolerant to water stress | 0.30 | 0.65 |
| extremely tolerant to water stress | 0.35 | 0.70 |

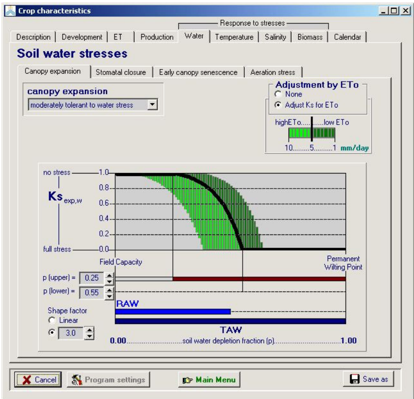



**Figure 2.9e3**
**Specification of the upper and lower thresholds and the shape of the Ks curve for the effect of water stress on canopy expansion ($Ks_{exp,w}$)**



***Stomatal closure:*** Stomata have been shown to be much less sensitive to water stress in comparison to leaf expansive growth. The user specifies the effect of water stress on crop transpiration by selecting a sensitivity class (Table 2.9e2) or by specifying a value for the upper soil water depletion thresholds (p):

- p(upper): which determines the Readily Available soil Water (RAW). RAW is the maximum amount of water that a crop can extract from its root zone without inducing stomatal closure and reduction in crop transpiration;
- p(lower): which is fixed at 1.0 (i.e. TAW is completely depleted). When the fraction p(lower) is depleted from the root zone, the soil water content is at permanent wilting point and crop transpiration becomes zero.

**Table 2.9e2**
**Classes and corresponding default values for the upper threshold of soil water depletion for stomatal closure**

| Class<br>Sensitivity to water stress | Upper threshold of soil water depletion for stomatal closure ($p_{sto}$) | |
|---|---|---|
| | Default value | Range |
| extremely sensitive to water stress | 0.25 | 0.10 … 0.29 |
| sensitive to water stress | 0.45 | 0.30 … 0.49 |
| moderately sensitive to water stress | 0.55 | 0.50 … 0.59 |
| moderately tolerant to water stress | 0.65 | 0.60 … 0.67 |
| tolerant to water stress | 0.70 | 0.68 … 0.72 |
| extremely tolerant to water stress | 0.75 | 0.73 … 0.90 |

***Early canopy senescence:*** Under moderate to severe water stress conditions, leaf and canopy senescence is triggered, thereby reducing the transpiring foliage area. The user specifies the effect of water stress on canopy senescence by selecting a ***sensitivity class*** (Tab. 2.9e3) or by specifying a value for the upper soil water depletion thresholds (p):

- p(upper): The fraction of the Total Available soil Water (TAW) that can be depleted from the root zone before canopy senescence is triggered;
- p(lower): which is fixed at 1.0 (TAW is completely depleted). When the fraction p(lower) is depleted from the root zone, the soil water content is at wilting point and canopy senescence is at full speed.

Early canopy senescence is likely to be depended on the nitrogen nutrition of the crop. When nitrogen is more limiting the crop is expected to be more sensitive.



**Table 2.9e3**
**Classes and corresponding default values for the upper threshold of soil water depletion for canopy senescence**

| Class<br>Sensitivity to water stress | Upper threshold of soil water depletion for canopy senescence ($p_{sen}$) | |
|---|---|---|
| | Default value | Range |
| extremely sensitive to water stress | 0.35 | 0.00 ... 0.39 |
| sensitive to water stress | 0.45 | 0.40 ... 0.49 |
| moderately sensitive to water stress | 0.55 | 0.50 ... 0.59 |
| moderately tolerant to water stress | 0.65 | 0.60 ... 0.69 |
| tolerant to water stress | 0.75 | 0.70 ... 0.75 |
| extremely tolerant to water stress | 0.80 | 0.76 ... 0.98 |

- **Effect of soil salinity stress on the thresholds for soil water depletion**

If soil salinity affects crop development, the thresholds for leaf expansion, stomatal conductance and early canopy senescence might shift upwards due to a decrease in soil water potential. By means of the Program settings the user can switch on or off the effect of soil salinity on the thresholds (Fig. 2.9e4).

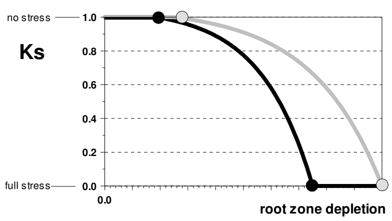



**Figure 2.9e4 –** Shift of the thresholds (circles) for root zone depletion and its effect on Ks (lines) with (black) and without (gray) the effect of soil salinity on the thresholds.



**Aeration stress**

Water logging causes stress that affects crop development and growth, except for the case of aquatic species such as rice. When the soil water content in the root zone rises above the anaerobiosis point (Figure 2.9e5), the aeration of the root zone will be deficient, resulting in a decrease of crop transpiration.

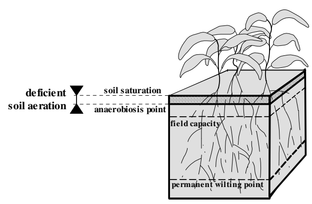



**Figure 2.9e5**
**Zone (dark area) of restricted soil water extraction as a result of deficient soil aeration**

The aeration stress is specified by a Ks coefficient. At soil saturation (upper threshold) the stress is at its full effect and Ks is 0. Below a lower threshold of soil water content, water stress is not considered and Ks is 1. The lower threshold is the soil water content below saturation at which poor aeration no longer limits transpiration. Between the upper and lower thresholds the shape of the Ks curve is linear (Fig. 2.9e6). The user specifies the sensitivity of the crop to water logging by selecting an aeration stress class (Tab. 2.9e4) or by specifying the anaerobiosis point (volume percent below soil saturation).

**Table 2.9e4**
**Classes, corresponding default values, and ranges for aeration stress**

| Class | anaerobiosis point (volume % below saturation) | |
|---|---|---|
| | default | range |
| not stressed when water logged | 0 | 0 |
| very tolerant to water logging | - 2 vol% | 1 … 3 |
| moderately tolerant to water logging | - 5 vol% | 4 … 6 |
| sensitive to water logging | - 10 vol% | 8 … 12 |
| very sensitive to water logging | - 15 vol% | 13 … 15 |

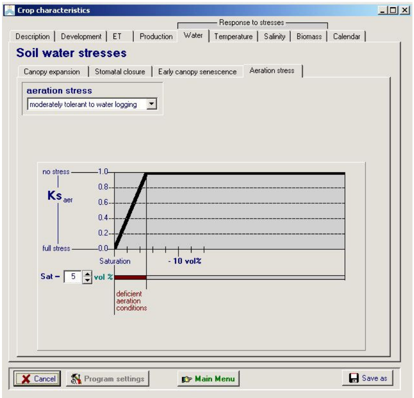



**Figure 2.9e6**
**Specification of the soil water content below saturation at which poor aeration no longer limits transpiration**



- **Harvest Index**

Water stress may alter HI, either positively or negatively, in several ways, depending on timing, severity and duration of the stress.

***Before flowering:*** Pre-anthesis water stress limiting vegetative growth may have positive effects on the Harvest Index. The user specifies the maximum increase that should be considered (Fig. 2.9e7) or select a class graded for the effect of pre-anthesis water stress (Tab. 2.9e5).

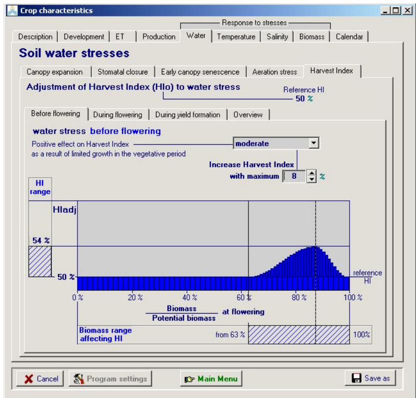



**Figure 2.9e7**
**Positive effect on Harvest Index of pre-anthesis water stress affecting biomass production**

**Table 2.9e5**
**Classes graded for the maximum positive effect of pre-anthesis stress on HI**

| Class | percent increase of HI |
|---|---|
| None | 0 % |
| Small | 4 % |
| Moderate | 8 % |
| Strong | 12 % |
| Very strong | 16 % |



***During flowering:*** When stress is ***very severe*** and inhibits pollination directly, the effect on HI is negative for a given class of excessive potential fruits, and its magnitude is set by a water stress coefficient (Ks). The threshold for the failure of pollination, expressed as a fraction (p) of TAW, is lower (stronger stress level) than the threshold for the effect for stomatal closure and triggering of senescence. The water stress coefficient $Ks_{pol}$ decreases linear from 1 to 0 between the upper threshold ($p_{pol}$) and lower threshold (permanent wilting point). The user specifies the soil water depletion (p) at the threshold or selects a class graded for relative resistance to drought (Fig. 2.9e8, Tab 2.9e6).

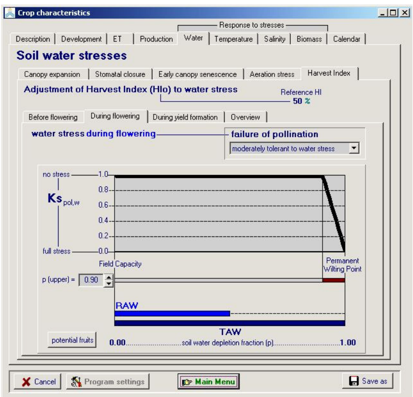



**Figure 2.9e8**
**Specification of the upper thresholds**
**for the effect of water stress on failure of pollination**

***During yield formation:*** The effect of water stress during yield formation can be positive or negative depending on the severity of the stress:

- One adjustment is for the competition between vegetative and reproductive growth after flowering begins, linked to Ks for leaf growth and with positive stress effect on HI. The magnitude of this effect as a function of Ks is set by a coefficient "a", increasing as "a" diminishes (Tab. 2.9e7);



- When stress is severe enough to cause substantial stomata closure and reduction in photosynthesis, the effect on HI is assumed to be negative and linked to Ks for stomata. The magnitude of this effect is set by coefficient "b", with the negative effect on HI being accentuated as "b" decreases (Tab. 2.9e8).

**Table 2.9e6**
**Classes, corresponding defaults values, and ranges for the soil water depletion factor (p) for failure of pollination**

| Class<br>Sensitivity to water stress | Soil water depletion fraction (p)<br>for failure of pollination | |
|---|---|---|
| | Default value | Range |
| extremely sensitive to water stress | 0.76 | 0.75 ... 0.77 |
| sensitive to water stress | 0.80 | 0.78 ... 0.82 |
| moderately sensitive to water stress | 0.85 | 0.83 ... 0.86 |
| moderately tolerant to water stress | 0.88 | 0.87 ... 0.90 |
| tolerant to water stress | 0.92 | 0.91 ... 0.93 |
| extremely tolerant to water stress | 0.95 | 0.94 ... 0.99 |

**Table 2.9e7**
**Classes, corresponding defaults values, and ranges for the "a" coefficient (positive stress effect on HI)**

| Class<br>Sensitivity to water stress | "a" coefficient | |
|---|---|---|
| | Default value | Range |
| None | - | - |
| small | 4 | 3 ... 40 |
| moderate | 2 | 1.5 ... 2.9 |
| strong | 1 | 0.75 ... 1.40 |
| very strong | 0.7 | 0.50 ... 0.70 |

**Table 2.9e8**
**Classes, corresponding defaults values, and ranges for the "b" coefficient (negative stress effect on HI)**

| Class<br>Sensitivity to water stress | "b" coefficient | |
|---|---|---|
| | Default value | Range |
| none | - | - |
| small | 10 | 7.1 ... 20 |
| moderate | 5 | 4.1 ...7.0 |
| strong | 3 | 1.6 ... 4.0 |
| very strong | 1 | 1.0 ... 1.5 |

In addition to the Ks value, the user specifies the extent of excessive potential fruits (Fig. 2.9e9). When conditions are favorable, crops pollinate many more flowers and set more fruits than needed for maximum yield. The excessive young fruits are aborted as the older fruits grow. The extent of reduction in HI caused by extreme temperature or severe water stress occurring during pollination time depends partly on the extent of this excess in potential reproductive bodies. The excess is specified by selecting one of the classes ranging from very small to large (Tab. 2.9e9).

**Table 2.9e9**
**Classes and corresponding default values for excess of potential fruits**

| Excess of potential fruits | Excess of fruits |
|---|---|
| Very small | 20 |
| small | 50 |
| medium | 100 |
| large | 200 |
| very large | 300 |

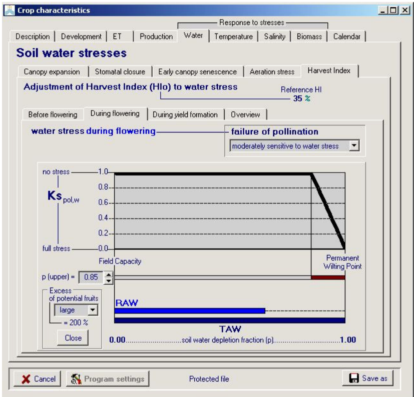


**Figure 2.9e9**
**Specification of the extent of excessive potential fruits**



The combined effect of water stress during yield formation is displayed in the corresponding tab sheet (Fig. 2.9e10).

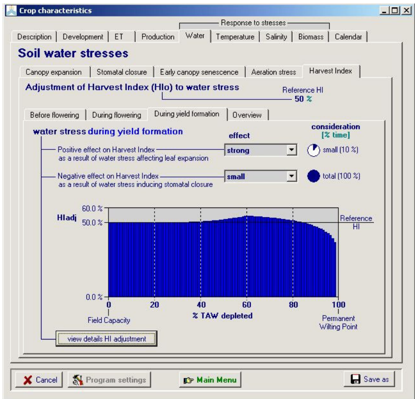


**Figure 2.9e10**
**Effect on Harvest Index of post-anthesis water stress**
**for various degrees of root zone depletion (% TAW depleted)**

By selecting the **<view details HI adjustment>** command, the user can study the individual and combined effect on the Harvest Index of water stress during yield formation in the ***Adjustment of Harvest Index*** menu (Fig 2.9e11 and 2.9e12). The individual and combined effect on HI can be displayed for various root zone depletions and evaporative demands.



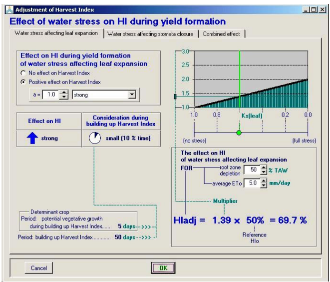


**Figure 2.9e11**

**Positive effect on Harvest Index of water stress during the period of potential vegetative growth for the selected:**

**(i) "a" coefficient,**

**(ii) root zone depletion,**

**(iii) evaporative demand**

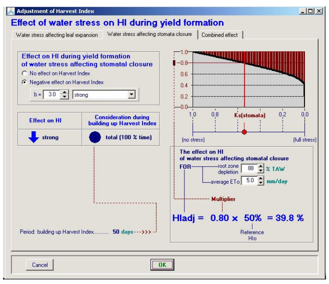


**Figure 2.9e12**

**Negative effect on Harvest Index of water stress during the building up of the Harvest Index for the selected:**

**(i) "b" coefficient,**

**(ii) root zone depletion,**

**(iii) evaporative demand**



***Overview:*** After combining the various effects on HI on water stress, the adjusted Harvest Index should remain smaller than a preset maximum. In the folder presenting the overview of water stress effects on Harvest Index, the user can adjust the maximum allowable increase (Fig. 2.9e13).

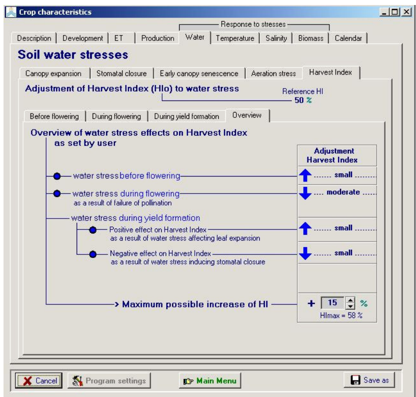


**Figure 2.9e13**
**Combined effect of water stress on harvest index**

### 2.9.6 Temperature stress

In AquaCrop temperature stress affecting biomass production and pollination is considered. The effects are described by temperature stress coefficients (Ks) which varies between 0 (full effect of temperature stress) and 1 (no effect).

- **Biomass production**

Low temperatures can cause stress that affects crop development and growth. AquaCrop considers the impact of low temperature in two ways. One is by using GDD as the clock, accounting for effects on phenology and canopy expansion and decline rate. In addition, it is necessary to account for the more direct effect of cold stress on biomass production. The latter is specified by a Ks coefficient, which varies between 1 and 0 between an upper threshold and a lower threshold defined in terms of growing degrees per day (Fig. 2.9f1). The lower threshold is fixed at 0 °C-day. Between the upper and lower threshold the shape of the Ks curve is logistic.

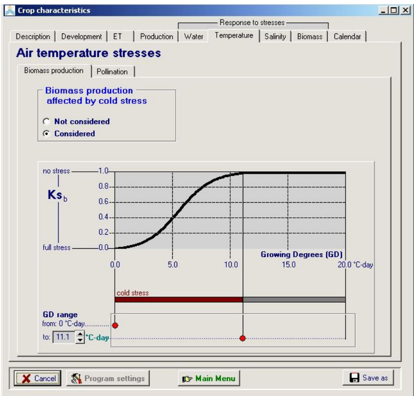



**Figure 2.9f1**
**Specification of the threshold for temperature stress on biomass production**



- **Pollination**

Cold and heat stress might affect pollination. The temperature stress is specified by a Ks coefficient, which varies from 0 to 1 between threshold temperatures. For the cold stress Ks is 0 at the lower threshold and 1 at the upper temperature threshold. For the heat stress Ks is 1 at the upper threshold and 0 at the lower threshold temperature (Fig. 2.9f2). Between the upper and lower thresholds the shapes of the Ks curves are logistic.

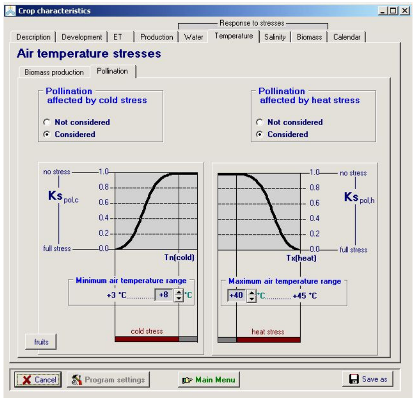



**Figure 2.9f2**
**Specification of the thresholds for cold and heat stress on pollination**

Only the upper threshold for the minimum air temperature ($T_{n,cold}$) and the lower threshold for the maximum air temperature ($T_{x,heat}$) at which pollination starts to fail are crop parameters. $T_{n,cold}$ can range from 0 to +15 °C and $T_{x,heat}$ from +30 to +45 °C. In AquaCrop it is assumed that full stress is reached (Ks = 0) at 5 °C below (cold stress) or above (heat stress) the specified threshold air temperature.



### 2.9.7 Soil fertility stress

Although the crop response to soil fertility stress is based on fundamental concepts, it is at present described by a qualitative assessment. Mineral nutrient stress, particularly the lack of nitrogen, can (i) reduce canopy expansion, resulting in a slower canopy development and (ii) the maximum canopy cover that can be reached ($CC_x$), resulting in a a less dense canopy. In addition, under long-term stress, (iii) CC normally undergoes steady decline once the adjusted $CC_x$ is reached at mid season. Further-on (iv) soil fertility stress reduces the water productivity (WP*).

- **Display of the effects of soil fertility stress**

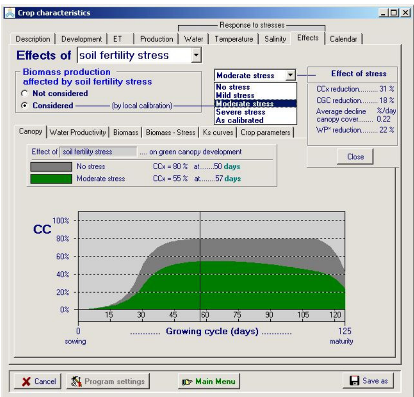



**Figure 2.9g**
**The effect of moderate soil fertility stress on canopy development**

If the crop response is calibrated for soil fertility stress, the user can see the effect of various stress levels in the ***Crop characteristics*** menu: No stress, mild stress, moderate stress, and severe stress (Fig. 2.9g).



- **Simulation of the effect of soil fertility stress**

To simulate the effect of soil fertility stress the user has to specify one of the categories of the soil fertility stress in the ***Field management*** menu (see 2.12 Field management).

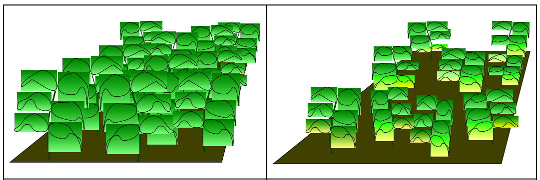
- **Calibration of the crop response**

Calibration of the crop response to soil fertility stress is done in the ***Crop characteristic*** menu (See 2.9.8 Calibration for soil fertility stress).

### 2.9.8 Calibration for soil fertility stress

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.

- **Reference and Stressed field**



| Reference field | Stressed field |
|---|---|
| - well watered field<br>- no soil fertility stress | - well watered field<br>- soil fertility stress |
| **Observations:** $B_{ref}$ and $CC_{ref}$ | **Observations:** $B_{stress}$ and $CC_{stress}$ |

**Figure 2.9h1 –** The calibration of crop response to soil fertility 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 stress. The field with no stress is regarded as the 'Reference field', while the field with limited soil fertility 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 (Fig. 2.9h1). 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.



- **Crop response to soil fertility stress**

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). The effect of the soil fertility stress on CC consists:
  - reduced canopy expansion resulting in a slower canopy development
  - reduced maximum canopy cover that can be reached ($CC_x$) resulting in a a less dense canopy
  - steady decline of CC once the adjusted $CC_x$ is reached at mid season.
- the biomass water productivity (WP*).

In Table 2.9h the stress coefficients (Ks) and decline coefficient (f) used for the simulation of the crop response to soil fertility stress are listed.

**Table 2.9h –** Stress coefficients for simulating crop response to soil fertility 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*) |



- **The effect of stress on biomass is not considered (not calibrated)**

<u>The calibration process</u>

Protected crop files (provided by FAO), do not consider the effect of soil fertility stress on biomass, and need to be calibrated before the effect can be simulated (Fig. 2.9h2).

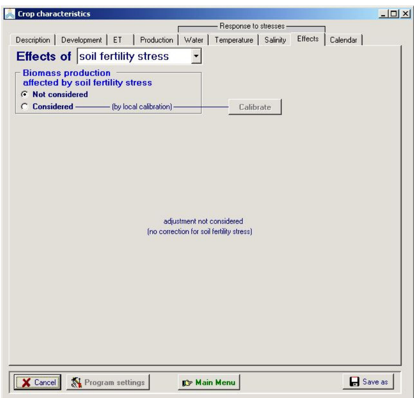



**Figure 2.9h2 –** Display in the ***Crop characteristics*** menu of a crop for which the effect of soil fertility stress on biomass is not considered

By selecting 'Considered' on the tab sheet in the ***Crop characteristics*** menu (Fig. 2.9h2), AquaCrop will display the ***Calibration soil fertility stress*** menu in which the calibration can be started (Fig. 2.9h3).



In the 'Field observations' tab sheet of the ***Calibration soil fertility stress*** menu (Fig. 2.9h3), the user specifies (with reference to Fig. 2.9h1) the observations as surveyed in the Stressed field:

1. the observed relative Biomass production, by selecting a class (varying from 'near optimal' to 'very poor') or by specifying the observed relative biomass (100 $B_{stress}/B_{ref}$);
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 ($CCx_{stress}$);
3. the observed Canopy decline in the season once CCx is reached, by selecting a class (varying from 'small' to 'strong').

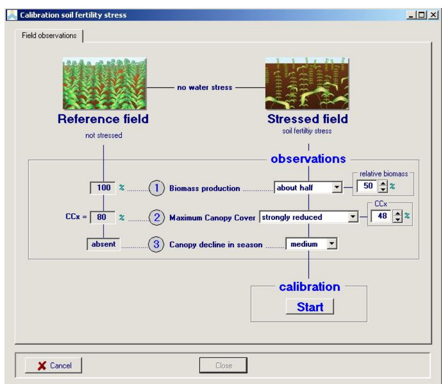



**Figure 2.9h3 –** Specification of field observations from the 'Stressed field' in the ***Calibration soil fertility stress*** menu

By clicking on the **<Start>** button in the 'Field observations' tab sheet of the ***Calibration soil fertility stress*** menu (Fig. 2.9h3), AquaCrop selects values for the stress coefficients ($Ks_{exp,f}$, $Ks_{CCx}$, $Ks_{WP}$, $f_{CDecline}$) and alters as such the simulated green canopy cover (CC), and biomass water production (WP*) for the Stressed field.

By trying different values for the various stress coefficients, and by respecting the specified observations (Fig. 2.9h3), AquaCrop calculates for each set of stress coefficients, the corresponding $CC_{stress}$ and Biomass production ($B_{stress}$) until the simulated relative biomass production is equal to the observed relative production in the Stressed field. The results are displayed in the 'Crop response to soil fertility stress' tab sheet (Fig. 2.9h4).

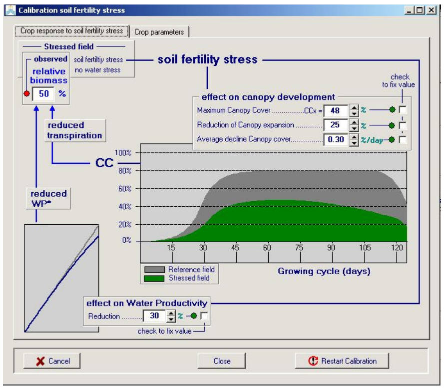



**Figure 2.9h4 –** The simulated relative biomass (similar as observed on the stressed field) obtained by considering the effect of soil fertility stress on (i) canopy development (maximum canopy cover, canopy expansion and canopy decline) and (ii) biomass Water Productivity (WP*), as displayed in the tab sheet 'Crop response to soil fertility stress' of the ***Calibration soil fertility stress*** menu.

In the 'Crop parameters' tab sheet of the ***Calibration soil fertility stress*** menu, the reduction in Canopy development and biomass Water Productivity (WP*) are displayed. The corresponding simulated relative Biomass production, the 4 Ks-curves and the Crop parameters (adjusted to the stress) can be consulted as well in their respectively tab-sheet (Fig. 2.9h5).



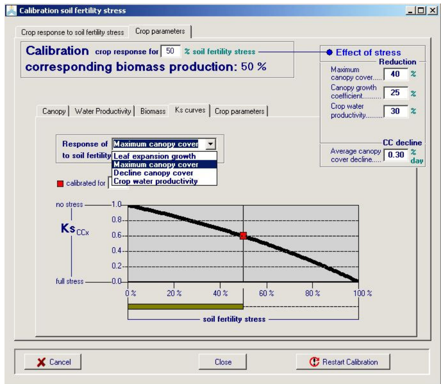



**Figure 2.9h5 –** The Ks curve for Maximum canopy cover as displayed in the tab-sheet 'Ks-curves' of the ***Calibration soil fertility stress*** menu

The calibration determines the shape of the 3 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 (not affecting biomass production), the stress is 0 % and the 3 soil fertility stress coefficients (Ks) are 1, and the decline coefficient ($f_{CDecline}$) is zero;
2. When the soil fertility 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 defined as:

$$stress = 100\left(1 - B_{rel}\right) \qquad \text{(Eq. 2.9)}$$

where $B_{rel}$ is the ratio between the observed biomass in the stressed and reference field ($B_{rel} = B_{stress}/B_{ref}$). By considering the effect on its target parameter (CCx, CGC, WP*, 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 % ($B_{stress}$ = 0.5 $B_{ref}$) and CCx by 40 % ($CCx_{stress}$ = 0.6 $CCx_{ref}$), $Ks_{CCx}$ is 0.6 at the soil fertility/salinity stress of 50 % (Fig. 2.9h5).

Once a curve is calibrated, the Ks corresponding to other soil fertility/salinity stresses can be obtained from the curves. With reference to Fig. 2.9h5, CCx will be reduced by 20 % ($Ks_{CCx}$ = 0.80 or CCx = 0.8 $CCx_{ref}$) for a soil fertility stress of 27 %, and by 60 % ($Ks_{CCx}$ = 0.40 or CCx = 0.4 $CCx_{ref}$) for a stress of 69 %.

**<u>Fine tuning</u>**

The user can fine tune the calibration by altering in the ***Calibration soil fertility stress*** menu (Fig. 2.9h4): (i) the maximum canopy cover (CCx), (ii) the reduction of canopy expansion, (iii) the average decline of the Canopy cover, or (iv) the reduction in biomass water productivity (WP*). Changing one of the above reductions will alter the reductions of the other parameters since AquaCrop always looks for the equilibrium between the simulated and observed relative biomass production in the Stressed field. By clicking on one or more of the 4 check boxes, the user can fix the value of one or more parameters (Fig. 2.9h4).

By clicking on the **<Restart calibration>** button key in the command panel of the ***Calibration soil fertility stress*** menu, the user returns to the 'Field observation' tab sheet (Fig. 2.9h3).

- **The effect of stress on biomass is considered (calibrated)**

**<u>Relationship between Biomass and soil fertility stress</u>**

For crop files where the effect of soil fertility stress on biomass is considered, AquaCrop displays in the ***Crop characteristics*** menu the effect on canopy development, biomass water productivity, and biomass production for several stress levels (mild up to severe stress). In the menu the relationship between Biomass and soil fertility stress is displayed as well (Fig. 2.9h6). The relationships are obtained by:

(i) considering for various soil fertility stress levels the individual effect on CCx, CGC, canopy decline, and WP*, as described in each of the Ks curves (Fig. 2.9h5); and

(ii) calculating by considering the stress coefficients, the corresponding canopy development, and reduction in relative biomass production by assuming no water stress. The effect of the each considered soil fertility stress level on CCx, on CGC, on canopy decline, and on WP* are described in the individual calibrated Ks and reduction curves (Fig. 2.9h5). Since the shapes of the Ks curve are not identical, and the effect of stress on WP* increases when the canopy cover increases, the B-stress relationship is not linear (Fig. 2.9h6).



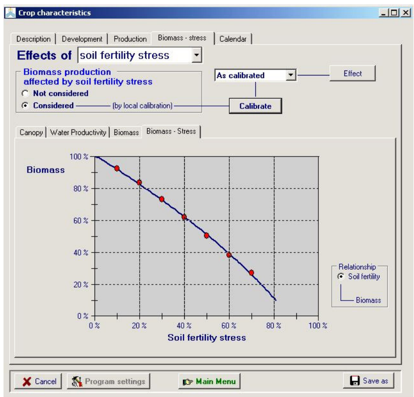



**Figure 2.9h6 –** Display of the relationship between Biomass and soil fertility stress in the 'Biomass-Stress' tab-sheet of the ***Crop characteristics*** menu.

**<u>Fine tuning</u>**

For crop files where the effect of soil fertility 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 stress*** menu (Fig. 2.9h4 and 2.9h5).

By clicking on the **<Restart calibration>** button key in the control panel of the ***Calibration soil fertility stress*** menu, the user returns to the 'Field observation' tab sheet (Fig. 2.9h3).

### 2.9.9 Soil salinity stress

- **Ks curve**

Biomass production might be affected by soil salinity stress. To describe this process a soil salinity stress coefficient ($Ks_{salt}$) is considered which varies between 0 (full effect of soil salinity stress) and 1 (no effect). The average electrical conductivity of the saturation soil-paste extract (ECe) from the root zone is the indicator for soil salinity stress.

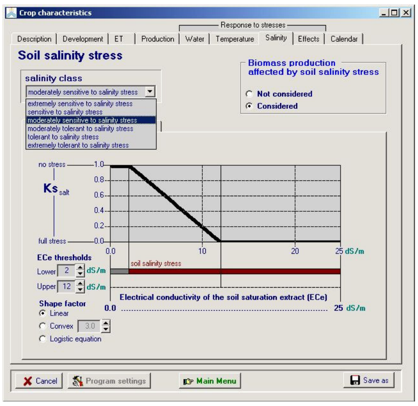



**Figure 2.9i1**
**Specification of the upper and lower thresholds and the shape of the $Ks_{salt}$ curve for the effect of soil salinity stress on biomass production**

***Thresholds:*** The user specifies the effect of soil salinity stress by selecting a sensitivity class or by specifying values for an upper and lower threshold for soil salinity in the root zone (Tab. 2.9i; Fig. 2.9i1). The thresholds are crop specific (see Annex III) 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 biomass production, and



- the upper threshold ($ECe_x$) at which soil salinity stress has reached its maximum effect and the stress becomes so severe that biomass production ceases.

**Table 2.9i**
**Classes and corresponding default values for the lower ($ECe_n$) and upper ($ECe_x$) threshold of soil salinity stress**

| Class<br>Sensitivity to water 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 curve determines the magnitude of the effect of soil salinity stress on the biomass production. The shape can be linear, convex or logistic (Fig. 2.9i2). For the convex shapes, the shape factor can range from +6 (strongly convex) to 0 (linear).

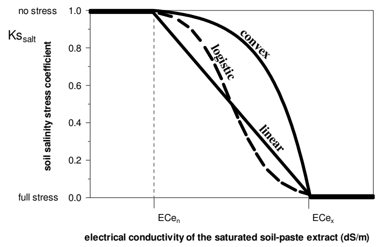



**Figure 2.9i2**
**Linear, convex and logistic shapes of the Ks curve**



- **Display of the effects of soil salinity stress**

Soil salinity stress can reduce canopy expansion and the maximum canopy cover that can be reached ($CC_x$). In addition, under long-term stress CC normally undergoes steady decline once the adjusted $CC_x$ is reached at mid season. Further-on soil salinity stress induces stomatal closure.

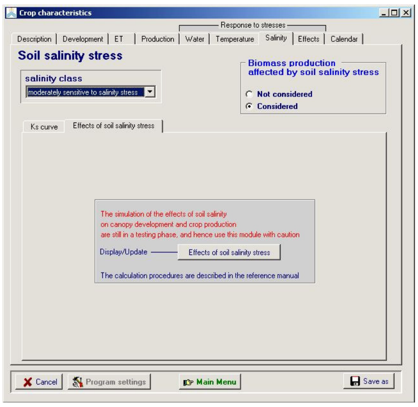



**Figure 2.9i3**
**Information concerning the effect of soil salinity stress**

As mentioned in the 'effects of soil salinity stress' tab sheet (Fig. 2.9i3), the simulation of the effects of soil salinity on canopy development and crop production are still in a testing phase. By clicking on the **<Effects of soil salinity stress>** button, the effects of soil salinity are displayed (Fig. 2.10j1). In this tab sheet the user can see the effect of various stress levels (if the crop response is calibrated for soil salinity stress), and/or calibrate the crop response for the stress.

- **Calibration of the crop response**

Calibration of the crop response to soil salinity stress is done in the ***Crop characteristic*** menu (See 2.9.10 Calibration for soil salinity stress).

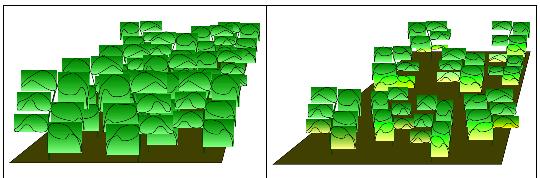


### 2.9.10 Calibration for soil salinity stress

- **Crop response to soil salinity stress**

Soil salinity stress reduces biomass production (B). The electrical conductivity of the saturated soil-paste extract (ECe) from the root zone determines the value of the soil salinity stress coefficient, $Ks_{salt}$ (Fig. 2.9i1). As explained in Chapter 3 (3.15 Simulation of the effect of soil salinity stress), $Ks_{salt}$ expresses the degree of soil salinity stress and hence determines the total reduction in biomass production. The reduction in biomass production is the result of stomatal closure and a poor canopy development (slow canopy expansion, poor canopy cover and canopy decline during the crop cycle). Although the total reduction in biomass (given by $Ks_{salt}$) and the causes for its reduction are known, the individual effect of salinity stress on each of the processes is not yet sufficient documented for the simulation in AquaCrop.

In absence of extensive testing, the reduction in biomass production due to soil salinity stress is described in a similar way as the effect of soil fertility stress on B. The calibration for soil salinity stress is hence identical as the calibration for soil fertility stress (2.9.8 Calibration for soil fertility stress), and requires the access to observed green Canopy Cover (CC) and biomass production (B) in two well watered fields: one with and the other without soil salinity stress. The field with no stress is regarded as the 'Reference field', while the field with 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 soil salinity stress (Fig. 2.9j1).



| **Reference field** | **Stressed field** |
|---|---|
| - well watered field<br>- no soil salinity stress | - well watered field<br>- soil salinity stress |
| **Observations:** $B_{ref}$ and $CC_{ref}$ | **Observations:** $B_{stress}$ and $CC_{stress}$ |

**Figure 2.9j1 –** The calibration of crop response to 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 observed reduction in biomass is the result of an integration of effects of the stress on several processes. As explained in section 2.9.8 (Calibration for soil fertility stress) the soil fertility stress affects green canopy development (CC) and hence indirectly crop transpiration (Tr), and the biomass water productivity (WP*). The soil salinity stress affects in a similar way the green canopy development (CC) and hence indirectly crop transpiration (Tr), but it also affects crop transpiration directly by inducing stomatal closure. In Table 2.9j the stress coefficients (Ks) and decline coefficient (f) used for the simulation of the crop response to soil salinity stress are listed.

**Table 2.9j –** Stress coefficients for simulating crop response to soil 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 salinity stress** | | |
| $Ks_{sto,salt}$ | Stress coefficient for stomatal closure | Crop transpiration (Tr) |

In absence of extensive testing, the effects of soil fertility stress and soil salinity stress on canopy development are assumed to be identical. Hence $Ks_{exp,f}$, $Ks_{CCx}$ and $f_{CDecline}$ are used for simulating the effect of both soil fertility and soil salinity stress.



- **The effect of stress on biomass is not yet considered**

**The calibration process**
By selecting 'Considered' on the 'Effects' tab sheet in the ***Crop characteristics*** menu (Fig. 2.9j2), AquaCrop will display the ***Calibration soil salinity stress*** menu in which the calibration can be started (Fig. 2.9j3).

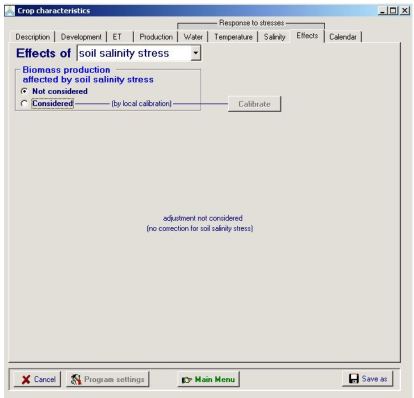



**Figure 2.9j2 –** Display in the ***Crop characteristics*** menu of a crop for which the effect of soil salinity stress on biomass is not considered

In the 'Field observations' tab sheet of the ***Calibration soil salinity stress*** menu (Fig. 2.9j3), the user specifies (with reference to Fig. 2.9j1) the observations as surveyed in the Stressed field:

1. the observed relative Biomass production, by selecting a class (varying from 'near optimal' to 'very poor') or by specifying the observed relative biomass ($100\ B_{stress}/B_{ref}$);



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 ($CCx_{stress}$);
3. the observed Canopy decline in the season once CCx is reached, by selecting a class (varying from 'small' to 'strong').

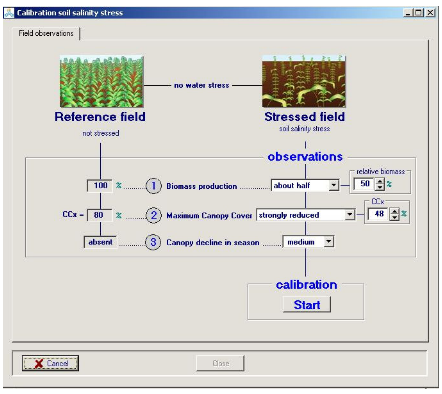



**Figure 2.9j3 –** Specification of field observations from the 'Stressed field' in the ***Calibration soil salinity stress*** menu

By clicking on the **<Start>** button in the 'Field observations' tab sheet of the ***Calibration soil salinity stress*** menu (Fig. 2.9j3), AquaCrop selects values for the stress coefficients ($Ks_{exp,f}$, $Ks_{CCx}$, $Ks_{sto,salt}$, $f_{CDecline}$) and alters as such the simulated green canopy cover (CC) and crop transpiration (Tr) for the Stressed field.

By trying different values for the various stress coefficients, and by respecting the specified observations (Fig. 2.9j3), AquaCrop calculates for each set of stress coefficients, the corresponding $CC_{stress}$, crop transpiration (Tr) and Biomass production ($B_{stress}$) until the simulated relative biomass production is equal to the observed relative production in the Stressed field.



The results are displayed in the tab sheet 'Crop response to soil salinity stress' (Fig. 2.9j4). 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. 2.9h4) while soil salinity stress induces stomatal closure (Fig. 2.9j4).

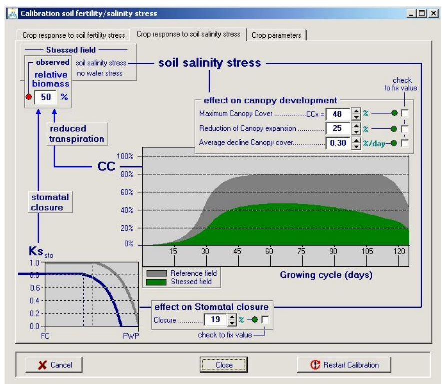



**Figure 2.9j4 –** The simulated relative biomass (similar as observed in the stressed field) obtained by considering the effect of soil salinity stress on (i) canopy development (CCx, CGC and canopy decline) and (ii) stomatal closure ($Ks_{sto}$), as displayed in the tab sheet 'Crop response to soil salinity stress' of the ***Calibration soil salinity stress*** menu.

In the 'Crop parameters' tab sheet of the ***Calibration soil salinity stress*** menu, the reduction in Canopy development and in crop Transpiration are displayed. The corresponding simulated relative Biomass production, the 4 Ks-curves and the Crop parameters (adjusted to the stress) can be consulted as well in their respectively tab-sheet.

The calibration determines the shape of the 3 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 soil salinity not affecting biomass production, the stress is 0 % and the 3 soil salinity stress coefficients (Ks) are 1, and the decline coefficient ($f_{CDecline}$) is zero;
2. When the 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 defined as:

$$stress = 100\,(1 - B_{rel}) \qquad \text{(Eq. 2.9)}$$

where $B_{rel}$ is the ratio between the observed biomass in the stressed and reference field ($B_{rel} = B_{stress}/B_{ref}$). By considering the effect on its target parameter (CCx, CGC, Tr, and canopy decline), the corresponding values for Ks and f are obtained for the defined stress level.

Once a curve is calibrated, the Ks corresponding to other soil salinity stresses can be obtained from the curves.

**Fine tuning**
The user can fine tune the calibration by altering in the ***Calibration soil salinity stress*** menu (Fig. 2.9j4): (i) the maximum canopy cover (CCx), (ii) the reduction of canopy expansion, (iii) the average decline of the Canopy cover, or (iv) the effect on stomatal closure. Changing one of the above reductions will alter the reductions of the other parameters since AquaCrop always looks for the equilibrium between the simulated and observed relative biomass production in the Stressed field. By clicking on one or more of the 4 check boxes, the user can fix the value of one or more parameters (Fig. 2.9j4).

By clicking on the **<Restart calibration>** button key, the user returns to the 'Field observation' tab sheet (Fig. 2.9j3).

- **The effect of stress on biomass is considered**

**Relationship between Biomass and soil salinity stress**
For crop files where the effect of soil salinity stress on biomass is considered, AquaCrop displays in the ***Crop characteristics*** menu the effect on canopy development, crop transpiration, and biomass production for several stress levels (mild up to severe stress). In the menu the relationship between Biomass and soil salinity stress is displayed as well (Fig. 2.9j5). The relationships are obtained by (i) considering for various stress levels the individual effect on CCx, CGC, canopy decline, and crop transpiration (Tr), 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, on CGC, on canopy decline, and on Tr are described in the individual calibrated Ks and reduction curves. Since the shapes of the Ks curve are not identical, the B-stress relationship is not linear and differ also between soil fertility and soil salinity stress (Fig. 2.9j5).



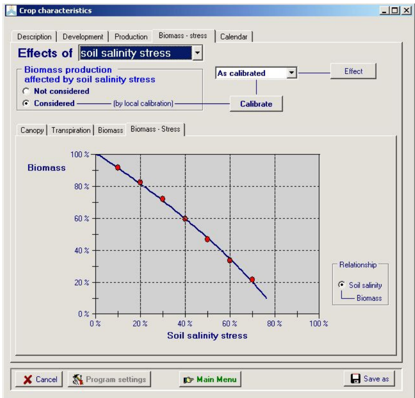



**Figure 2.9j5 –** Display of the relationship between Biomass and soil salinity stress in the Biomass-Stress tab-sheet of the ***Crop characteristics*** menu.

**Fine tuning**
For crop files where the effect of soil 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 salinity stress*** menu (Fig. 2.9j4).

By clicking on the **<Restart calibration>** button key in the control panel of the ***Calibration soil salinity stress*** menu, the user returns to the 'Field observation' tab sheet (Fig. 2.9j3).



### 2.9.11 Calendar
An overview of the calendar of the growing period is displayed in the Calendar folder of the ***Crop characteristics*** menu (Fig. 2.9k).

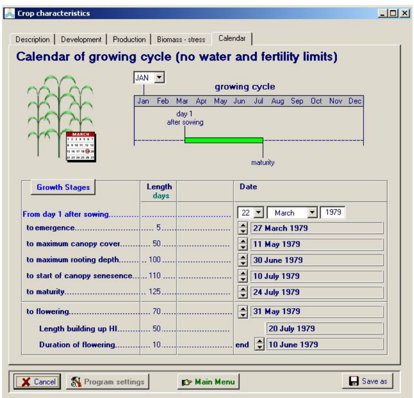



**Figure 2.9k**
**Crop calendar with indication of the FAO-56 growth stages**

In the calendar the length of crop growth stages can also be displayed. The stages refer to the definitions used in earlier FAO publications (Irrigation and Drainage Papers Nr. 24, 33 and 56) and are:
- The **initial stage** starts at sowing and stops when canopy cover is 10% (CC = 0.10);
- The **canopy development stage** starts when the canopy cover is larger then 10 % and stops when 98% of the maximum canopy cover is reached (CC = 0.98 $CC_x$).
- The **mid season stage** starts when the canopy covers reaches 0.98 $CC_x$ and stops when canopy senescence begins. The end of the stage is given by the time to reach canopy senescence.
- The **late season stage** starts when the days to senescence are reached and stops at the moment crop maturity is reached, and the crop is ready to be harvested.

In Annex II (Tab. II-1) indicative values for lengths of crop development stages for various planting period and climate regions for common agriculture crops are presented.



### 2.9.12 Program settings

From the ***Crop characteristics*** menu the user has access to the program settings listed in Table 2.9l. The effect of the settings on soil evaporation, crop transpiration, canopy expansion and decline, and soil water stress are explained in the relevant sections of Chapter 3 (Calculation procedures).

**Table 2.9l**
**Program settings affecting soil evaporation, crop transpiration, crop development, production and the effect of water and salinity stresses**

| Symbol | Program parameter | Default |
|---|---|---|
| | ***Soil evaporation*** | |
| $f_K$ | ▪ Evaporation decline factor for stage II | 4 |
| $Ke_x$ | ▪ Soil evaporation coefficient for fully wet and non-shaded soil surface | 1.10 |
| | ***Harvest Index*** | |
| - | ▪ Threshold for green canopy cover below which HI can no longer increase due to inadequate photosynthesis (% cover) | 5 % |
| | ***Germination*** | |
| - | ▪ Minimal soil water content required for germination at sowing depth (% TAW) | 20 % |
| | ***Root zone*** | |
| $Z_o$ | ▪ Starting depth of the root zone expansion curve (% of minimum effective rooting depth) | 70 % |
| - | ▪ Shape factor for the curve describing the effect of water stress (relative transpiration) on root zone expansion | -6 |
| | ***Senescence*** | |
| - | ▪ Shape factor (exponent a) for an adjustment factor of $Kcb_x$, considering the drop in photosynthetic activity of dying crop | 1 |
| β | ▪ Decrease of p(sen) once canopy senescence is triggered (% of p(sen)) | 12 % |
| | ***Stresses*** | |
| - | ▪ Aeration stress: Number of days after which deficient aeration is fully effective | 3 days |
| $f_{adj}$ | ▪ Water stress: Adjustment factor for the ETo correction of the soil water depletion (p) (fraction of default FAO-adjustment) | 1.0 |
| - | ▪ Soil salinity stress: Thresholds for water stress for stomatal closure | affected by soil salinity |

## 2.10 Start of the growing cycle

The start of the growing cycle is specified in the ***Main menu*** (Fig. 2.10a) by
- specifying the date, or
- generating an onset based on rainfall or air temperature.

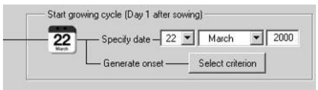



**Figure 2.10a**
**Panel in *Main menu* where the start of the growing cycle is specified**

### 2.10.1 Specified date

The user specifies the first day of the observed or planned start of the growing cycle (i.e. the first day after sowing or planting). If the selected climatic data is linked to a specific year, the start of the growing period is also linked to that year. If the climatic data consists of several years, the start of the growing period occurs in the first year of the climatic data set. The year can be adjusted in the panel.

### 2.10.2 Generated onset

- **Onset generated based on rainfall**

In rainfed cropping, sowing or planting is typically determined by rainfall events. By clicking on the **<Select criterion>** commanding the ***Main menu***, the ***Onset based on rainfall*** menu is displayed (Fig. 2.10b). By selecting one or another criterion, the start of the growing cycle is determined by appraising the rainfall data specified in the selected Rain data file. By specifying the first and last day in a 'Search window', only rainfall within the specified window is evaluated. The following criteria can be selected to determine the onset of the growing cycle:
- ***cumulative rainfall*** since the start of the search period is equal to or exceeds the preset value;
- observed ***rainfall during a number of successive days*** is equal to or exceeds the preset value;
- ***10-day rainfall*** is equal to or exceeds the preset value;
- ***10-day rainfall exceeds*** the preset ***fraction of the 10-day ETo***.

The last two options are particular useful if only 10-day or monthly rainfall is available.



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. When the start of the rainy season is not certain at the first occurrence of the selected criterion, selecting one of the displayed next occurrences or specifying a more stringent criterion might avoid early canopy senescence and a complete crop failure after germination.

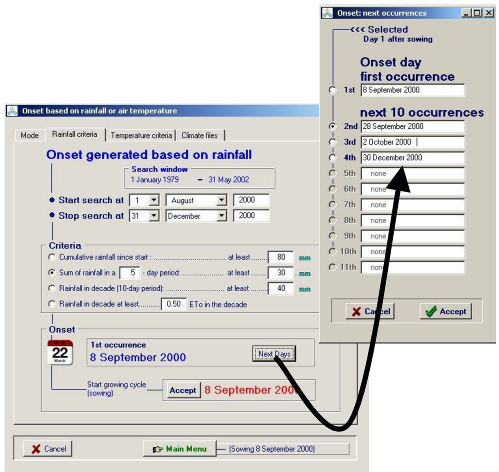



**Figure 2.10b**
***Onset based on rainfall* menu where the onset of the growing period is determined by the exceedance of 25 mm of rainfall in a period of 5 successive days, counting from 1 August 2000 (start of the search window)**



- **Onset generated 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 (Fig. 2.10c).

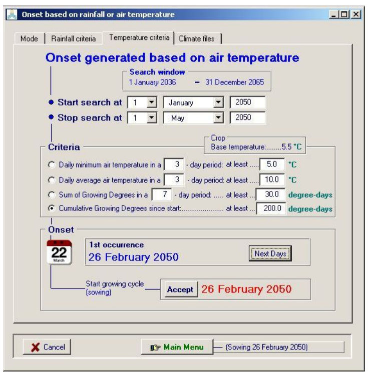



**Figure 2.10c –** Selection of a temperature criterium
in the ***Onset based on rainfall or air temperature*** menu

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.

## 2.11 Irrigation management

The selected irrigation management can be displayed in the ***Display of irrigation management*** menu and updated in the ***Irrigation management*** menu (Fig. 2.11a). Various irrigation modes can be considered in AquaCrop. One opts for (i) rainfed cropping (no irrigation in season), (ii) the determination of Net irrigation water requirement, (iii) an irrigation schedule by specifying the events or (iv) the generation of an irrigation schedule by specifying a time and depth criterion.


**Figure 2.11a**
**The selection of the mode in the *Irrigation management* menu**

### 2.11.1 No irrigation (rainfed cropping)

When selecting this option, no irrigations will be generated when running a simulation.

### 2.11.2 Determination of net irrigation water requirement

When selecting this option, AquaCrop will calculate during the simulation run the amount of water required to avoid crop water stress. When the root zone depletion exceeds a given threshold value (50% of RAW is the default), a small amount of irrigation water will be stored in the soil profile to keep the root zone depletion just above



the specified threshold. The threshold for the allowable root zone depletion can be adjusted.

The total amount of irrigation water required to keep the water content in the soil profile above the threshold is the net irrigation water requirement for the period. The net requirement does not consider extra water that has to be applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field.

### 2.11.3 Irrigation schedule (specified events)

The user specifies the date, application depth and water quality for each irrigation event (Fig. 2.11b). The irrigation depth refers to the net irrigation amount. Extra water applied to the field to account for conveyance losses or the uneven distribution of irrigation water on the field should not be added.

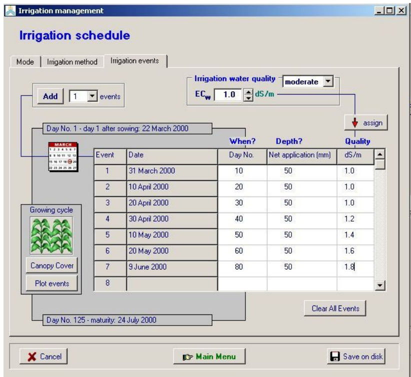



**Figure 2.11b**
**Specification of the time, application depth and water quality for irrigation events**



### 2.11.4 Generation of irrigation schedules

At run time irrigations can be generated by specifying a time and a depth criterion. The time criterion specifies 'When' an irrigation has to be applied while the depth criterion determines 'How much' water has to be applied. After the selection of the criteria the values linked with the time, depth criteria and water quality have to be specified (Fig. 2.11c). The values specified at a specific day of the cropping period will be valid till the date where another value is specified or to the end of the cropping period when no values at later dates are specified. As such one can adjust the values to crop development or the time in the season. In Figure 2.11d the generated irrigation schedules as defined in Figure 2.11c is presented.

The time and depth criteria with their corresponding parameters that need to be specified are listed in Tables 2.11a and 2.11b.

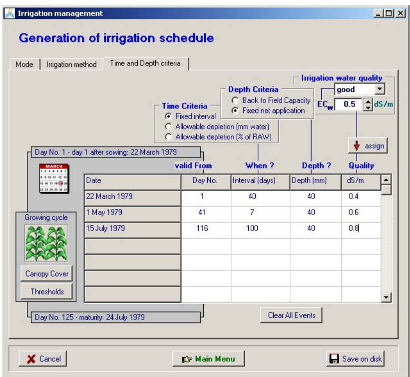



**Figure 2.11c**
**Specifying an irrigation schedule**
**where the fixed irrigation interval (time criterion) varies over the season,**
**while the fixed irrigation application depth (depth criterion) remains constant,**
**and the irrigation water quality deteriorates**



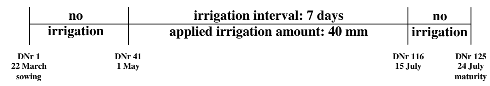



**Figure 2.11d**
**Generated irrigation schedules as defined in Figure 2.11c.**

**Table 2.11a**
**Time criteria with corresponding parameter**

| Criterion | Parameter |
|---|---|
| Fixed interval (days) | Interval between irrigations (for example 10 days) |
| Allowable depletion (mm water) | Amount of water that can be depleted from the root zone (the reference is soil water content at field capacity) before an irrigation has to be applied (for example 30 mm) |
| Allowable depletion (% of RAW) | Percentage of RAW that can be depleted before irrigation water has to be applied (for example 100 %) |

**Table 2.11b**
**Depth criteria with corresponding parameter**

| Criterion | Parameter |
|---|---|
| Back to Field Capacity (+/- extra mm water) | Extra water on top of the amount of irrigation water required to bring the root zone back to Field Capacity. The specified value can be zero, positive or negative:<br>▪ zero : the applied irrigation will bring the soil water content in the root zone at Field Capacity (reached at the end of the day);<br>▪ positive: an over irrigation is planned for example for leaching purposes (for example + 20 mm);<br>▪ negative: an under irrigation is planned for example to profit from expected rainfall (for example – 10 mm) |
| Fixed application depth (mm water) | Net irrigation application depth |

### 2.11.5 Irrigation method

Many types of irrigation systems wet only a fraction of the soil surface. Since only part of the soil surface is wetted, less water evaporates from the soil surface after an irrigation event. By selecting an irrigation method, an indicative value for the fraction of soil surface wetted is assigned (Tab. 2.11c). The user can alter the value if more specific information is available from field observations.

**Table 2.11c**
**Indicative values for the fraction of soil surface wetted for various irrigation methods**

| Irrigation method | Soil surface wetted (%) |
|---|---|
| Sprinkler irrigation | 100 |
| Basin irrigation | 100 |
| Border irrigation | 100 |
| Furrow irrigation (every furrow), narrow bed | 60 – 100 |
| Furrow irrigation (every furrow), wide bed | 40 – 60 |
| Furrow irrigation (alternated furrows) | 30 – 50 |
| Trickle/Drip - Micro irrigation | 15 – 40 |
| Subsurface drip irrigation | 0 |

### 2.11.6 Irrigation water quality

Since the quality of the irrigation water can alter during the season, it has to be specified for each irrigation event (see 2.11b and 2.11c). 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 2.11d.

**Table 2.11d**
**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 |



## 2.12 Field management

The selected field management can be displayed in the ***Display of field management*** menu and updated in the ***Field management*** menu (Fig. 2.12a). Options of soil fertility levels and practices that affect the soil water balance are specified in this menu.


**Figure 2.12a.**
***Field management* menu**

### 2.12.1 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 stresses. The crop response on soil fertility will be different if additionally stresses occur during the season.

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. 2.12b).

**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 % |

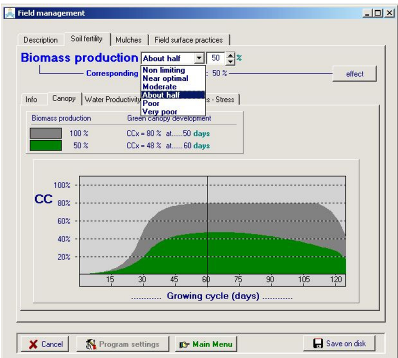



**Figure 2.12b**
**Display of the crop response**
**for the selected biomass production in the *Field management* menu**



The biomass – stress relationship (Fig. 2.12c), calibrated in the ***Crop characteristic*** menu, determines the corresponding soil fertility stress and as such the values for the stress coefficients ($Ks_{exp,f}$, $Ks_{WP}$, $Ks_{CCx}$, $f_{CDecline}$).

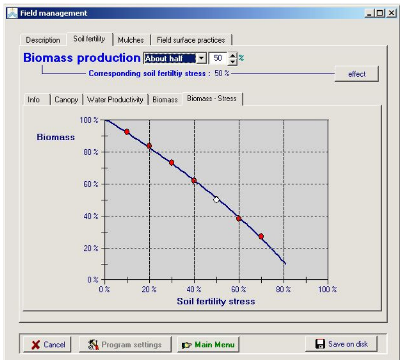



**Figure 2.12c**
**Display of the calibrated Biomass - stress relationship**
**in the *Field management* menu**

### 2.12.2 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 losses 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. 2.12d).

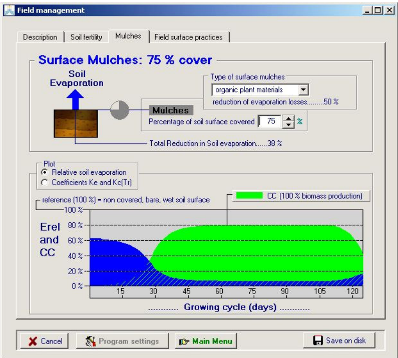



**Figure 2.12d**
**Display of the effect of mulches on soil evaporation**



### 2.12.3 Field surface practices

Field surface practices and soil bunds might prevent that part of intense rainfall or excessive irrigation will be lost as surface runoff:

- If ploughing or tillage practices, such as soil ridging or contours, eliminate run-off of rain water, the user can switch off the run-off procedure. However runoff will still occur if rain or irrigation events exceed the infiltration rate of the top soil layer. Only if the excess of rain or irrigation water can be stored on the field between soil bunds the surface runoff will be completely inhibited.
- Soil bunds are built to store water on the field (as is the case in rice paddy fields). When bunds are present, the user specifies the height of the bunds (Fig. 2.12e).

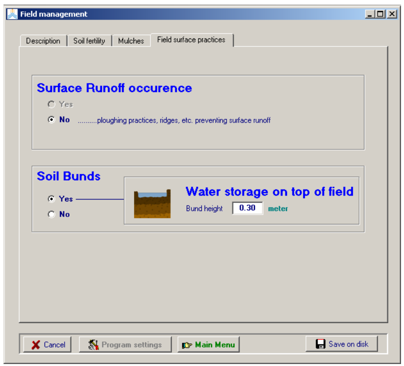



**Figure 2.12e**
**Selection of soil bunds as field management**



### 2.12.4 Program settings

From the ***Field management*** menu the user has access to the program setting of field parameters listed in Table 2.12b.

**Table 2.12b**
**Program settings affecting soil evaporation**

| Symbol | Program parameter | Default |
|---|---|---|
| | ▪ Soil depth from which evaporation can extract water out of the top of the soil profile | 30 cm |



## 2.13 Soil profile characteristics

The selected characteristics of the various soil horizons and of the soil surface layer, the presence of a restrictive soil layer that might block the root zone expansion, and the maximum possible capillary rise are displayed in the ***Display of soil profile characteristics*** menu and updated in the ***Soil profile characteristics*** menu (Fig. 2.13a).

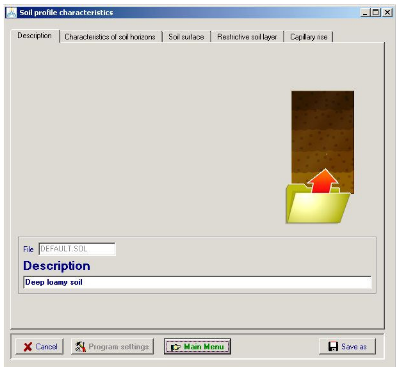



**Figure 2.13a**
***Soil profile characteristics* menu**

### 2.13.1 Soil horizons and their physical characteristics

The soil profile can be composed of up to five different horizons, each with their own physical characteristics. The soil data consist of the various soil horizons, their volumetric water content at saturation, field capacity, and permanent wilting point, and their hydraulic conductivity at soil saturation.

- **Soil water content at saturation, field capacity and permanent wilting point**
    - **Saturation**. When the total pore volume is filled with water, the soil water content is at saturation. Such conditions are rather uncommon in the root zone due to entrapped air and vertical drainage. Saturated conditions generally only exist when the groundwater table is in or near the root zone.

- **Field Capacity** is the quantity of water that a well-drained soil would hold against the gravitational forces. It is the upper limit for the plant extractable water. Although the soil matric potential at field capacity varies with the soil type and environmental conditions, the water content at a matric potential of –10 kPa (pF 2.0) up to – 33 kPa (pF 2.5 or 1/3 bar) is often considered as field capacity.
- **Permanent Wilting Point** is the soil water content at which plants stop extracting water and will permanently wilt. It is the lower limit of the plant extractable water. Although permanent wilting point may somewhat vary for different crops, plant age and root distribution it is generally accepted that the soil water content at a matric potential of –1.5 MPa (pF 4.2) is a representative value for the permanent wilting point.

- **Saturated hydraulic conductivity ($K_{sat}$).** The hydraulic conductivity expresses the property of the soil to conduct water through a soil. When the soil is saturated all pores are filled with water and the value for the hydraulic conductivity is at its maximum. The saturated hydraulic conductivity or permeability defines the rate for the soil layer to transmit water through the saturated soil under the influence of gravity.
- **Total Available soil Water (TAW) and drainage coefficient (tau).** From the specified hydraulic characteristics, AquaCrop determines for each soil horizon the total amount of soil water (TAW) that is available for crop transpiration and the drainage coefficient (tau). TAW is the amount of water held in the soil between field capacity and permanent wilting point. The dimensionless drainage coefficient is used for the simulation of the downward water movement in the soil profile (Chapter 3).

### 2.13.2 Indicative values for soil physical characteristics

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

The user can make use of indicative values provided by AquaCrop for various soil textural classes (Tab. 2.13a), or import locally determined or derived data from soil texture with the help of pedo-transfer functions (Box 2.13). The values presented in Table 2.13a or derived with the help of pedo-transfer functions are only indicative values. They are not intended to replace measurements.

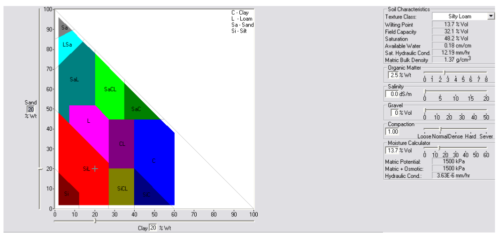
By selecting the **<Update list of soil type characteristics>** command in the ***Soil Profile characteristics*** menu, the indicative values for the soil hydraulic characteristics can be updated and soil types can be added or removed from the list. The characteristics are stored in the file 'SOILS.DIR' of the AquaCrop directory.



**Table 2.13a**
**Default soil physical characteristics for various soil types (listed in Soils.DIR)**

| 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 |
| Silty clay | 54 | 50 | 32 | 15 |
| Clay | 55 | 54 | 39 | 2 |

**Box 2.13**
**Soil water characteristics derived from pedo-transfer functions available in the Hydraulic Properties Calculator**



Calculator developed by the USDA Agricultural Research Service in cooperation with the Washington State University (Keith E. Saxton: ksaxton@wsu.edu) available at Internet: http://http//hydrolab.arsusda.gov/soilwater/Index.htm



### 2.13.3 Characteristics of the soil surface layer

When specifying soil data for the top horizon, default values for the Curve Number (Tab. 2.13b) and the Readily Evaporable Water are derived and displayed (Fig. 2.13b).

- The Curve Number (CN) is required for the simulation of the surface runoff (see Chapter 3) and its value refers to the value for antecedent moisture class II (AMC II).
- The Readily Evaporable Water (REW) expresses the amount of water that can be evaporated from the soil surface layer in the energy limiting stage (see Chapter 3).

The user can specify other than the displayed default values for CN and REW if specific information about the soil surface is available.

**Table 2.13b**
**Default CN values for various saturated hydraulic conductivities of the top horizon**

| Saturated hydraulic conductivity ($K_{sat}$) mm/day | CN default value for AMC II |
|---|---|
| > 250 | 65 |
| 250 – 50 | 75 |
| 50 – 10 | 80 |
| < 10 | 85 |

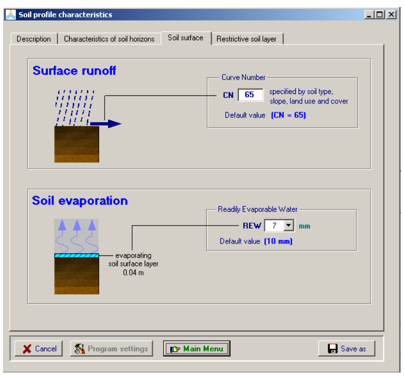



**Figure 2.13b**
**Characteristics of the soil surface layer**



### 2.13.4 Restrictive soil layer

If an impermeable soil layer blocks root development, the user specifies its depth (Fig. 2.13c). The root zone expansion is halted once the restrictive soil layer is reached (see 2.9.2 Development and 2.9.3 Evapotranspiration). If also water movement is hampered depends on the specified characteristics of the soil horizons below the restrictive layer (section 2.13.1)

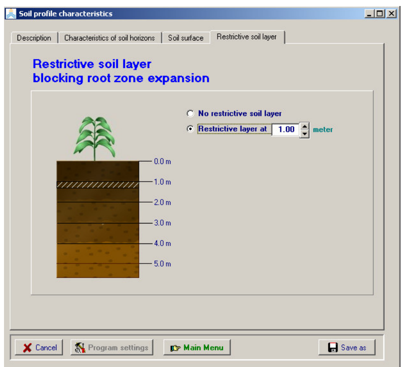



**Figure 2.13c**
**Restriction soil layer blocking root zone expansion**

### 2.13.5 Capillary rise

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. 2.13d). If the water potential gradient in the soil profile is not strong enough, the capillary rise will be smaller than indicated (see Chapter 3).

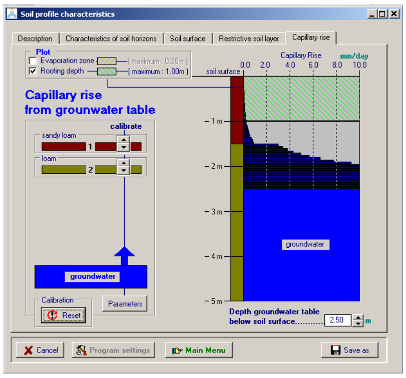



**Figure 2.13d -** The Capillary rise tab sheet in the ***Soil profile characteristics*** menu

The maximum possible capillary rise is calculated with an exponential equation (Chapter 3). 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. 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. By hitting on the **<Reset>** button, the user undoes the calibration and the a and b parameters are reset at their default values.



### 2.13.6 Program settings

From the ***Soil profile characteristics*** menu the user has access to the program settings affecting the simulation of surface runoff, soil salinity and capillary rise (Tab. 2.13c).

**Table 2.13c**
**Program settings affecting surface runoff and soil salinity**

| Symbol | Program parameter | Default |
|---|---|---|
| | **Surface runoff** | |
| | ▪ Adjustment of the CN value to the relative wetness of the topsoil (The CN values for the three different antecedent moisture classes (AMC) are displayed) | Yes |
| | ▪ Default thickness of the topsoil that will be considered for the determination of its wetness (required for the determination of AMC) | 30 cm |
| | **Soil salinity** | |
| | ▪ Salt diffusion factor (expressing the capacity of salt diffusion in the soil matrix | 20 % |
| | ▪ Salt solubility | 20 g/liter |
| | **Capillary rise** | |
| | ▪ Shape factor for effect of soil water content gradient on capillary rise | 16 |



## 2.14 Groundwater characteristics

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.

### 2.14.1 Constant depth and salinity

If the characteristics remain constant during the season the user specifies the deptjh and salinity of the groundwater table (Fig. 2.14a). The characteristics are graphically displayed in the Plot tab sheet.

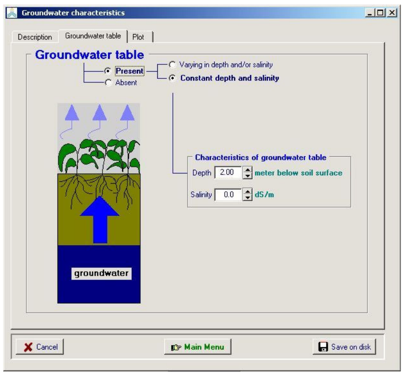



**Figure 2.14a –** Specifying the constant characteristics of a groundwater table in the Groundwater table tab sheet of the ***Groundwater characteristics*** menu.



### 2.14.2 Characteristics vary throughout the year(s)

The characteristics can vary throughout the year. The characteristics are specified in the Groundwater table tab sheet (Fig. 2.14b and 2.14d) and graphically displayed in the Plot tab sheet (Fig. 2.14c and 2.14e). The characteristics of the groundwater table for days between specified day numbers will be obtained at run time by means of linear interpolation.

- **Characteristics are not linked to a specific year**

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. 2.14b and 2.14c).

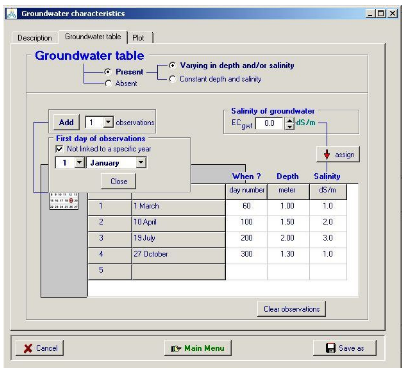



**Figure 2.14b –** Specifying the variable characteristics of a groundwater table not linked to a specific year in the ***Groundwater characteristics*** menu.

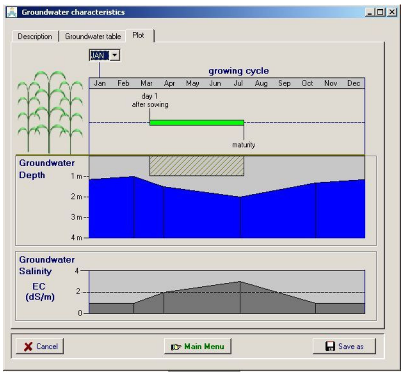



**Figure 2.14c –** Graphical display of the variable characteristics of a groundwater table not linked to a specific year in the ***Groundwater characteristics*** menu.



- **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. 2.14d and 2.14e). 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.

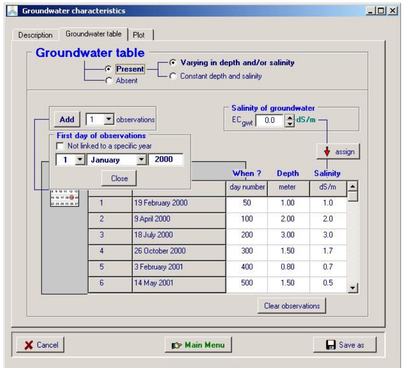



**Figure 2.14d –** Specifying the variable characteristics of a groundwater table linked to a specific year in the ***Groundwater characteristics*** menu.



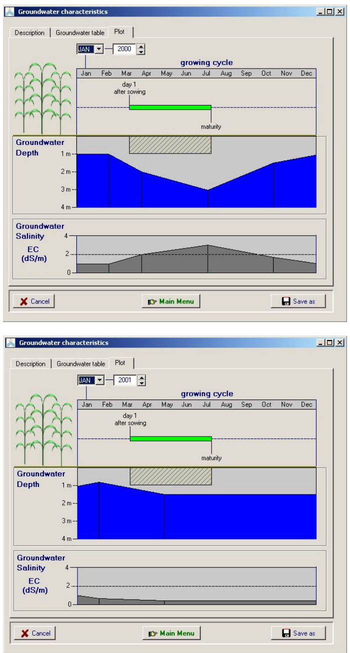



**Figure 2.14e –** Graphical display of the variable characteristics of a groundwater table linked to specific years (2000 and 2001) in the ***Groundwater characteristics*** menu.



## 2.15 Simulation period

The selected simulation period for a simulation run can be displayed in the ***Display of simulation period*** menu and adjusted in the ***Simulation period*** menu (Fig. 2.15). The length of the growing cycle and range of available climatic data is given as a reference in the menu.

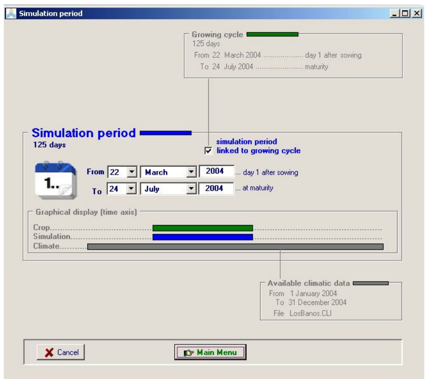



**Figure 2.15**
**Specification of the simulation period in the *Simulation period* menu**

The user adjusts the range of the simulation period by specifying the first and last day, month and eventually year. The simulation period can be shorter, longer or linked with the growing cycle as long as the period does not exceed the range of climatic data. If no climate file is selected, the user can select any simulation period but will have to specify the climatic data at run time.

The graph in the menu displays on a time axis (i) the length of the cropping period (Crop), (ii) the selected simulation period (Simulation), and (iii) the length of the period for which climatic data is available (Data).

## 2.16 Initial conditions

The information used by AquaCrop at the start of each simulation run can be displayed in the ***Display of initial conditions*** menu and adjusted in the ***Initial conditions*** menu (Fig. 2.16a).

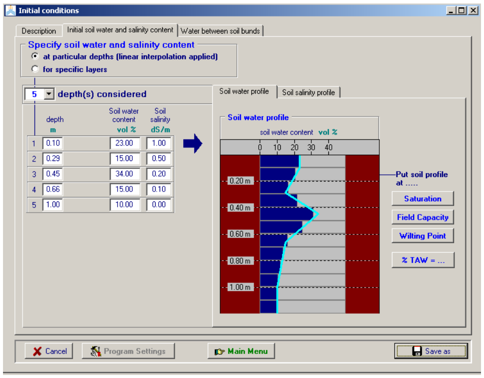



**Figure 2.16a**
**Specification of the initial soil water content in the *Initial conditions* menu**

### 2.16.1 Initial soil water content

The soil water content at the start of the simulation run can be adjusted by (i) specifying the soil water content at particular depths of the soil profile, (ii) specifying it for specific layers, or by (iii) setting the whole soil profile at Saturation, Field Capacity, Wilting Point, or at specific percentage of TAW (Total Available soil Water).

The initial soil water conditions are strongly determined by the climatic conditions (ETo and Rain) and irrigation applications in the period before the simulation period. If the simulation period starts at the end of a very rainy season, the soil water content of the soil profile might be close to field capacity. If the simulation starts in the hot dry season, the topsoil might be wet by pre-irrigation but the subsoil will be dry and the water content close to wilting point.



### 2.16.2 Initial soil salinity

The soil salinity at the start of the simulation run can be adjusted by 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.2.16b).

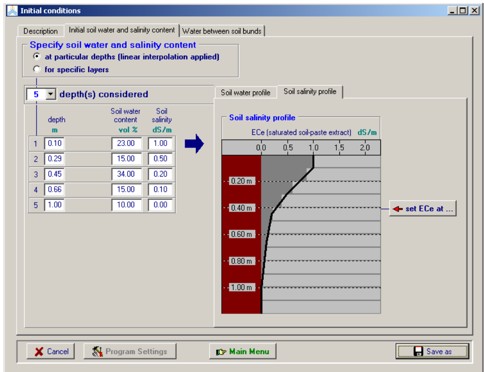



**Figure 2.16b**
**Specification of the initial salinity in the soil profile in the *Initial conditions* menu**



### 2.16.3 Water between soil bunds

If the field is surrounded by soil bunds (see 2.12 Field management) the depth of the water layer on top of the soil surface and its water quality at the start of the simulation run can be specified (Fig. 2.16c).

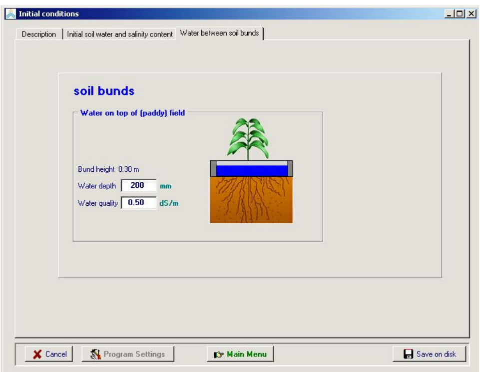



**Figure 2.16c**
**Specification of the depth and quality between soil bunds at the start of the simulation period in the *Initial conditions* menu**



### 2.16.4 Program settings

In program settings the user can adjust the number and size of the soil compartments and alter the setting assumed at the start of the simulation run.

- **Soil compartments**

To describe accurately the retention and movement of water and salts in the soil profile throughout the growing season, AquaCrop divides the soil profile into small fractions (see Soil water balance in Chapter 3). The soil profile is divided into soil compartments (12 by default) with thickness $\Delta z$ (0.10 m by default). However, after the crop selection AquaCrop will adjust the size of the compartments to cover the entire root zone if the maximum rooting depth exceeds 1.20 meter. For deep root zones, $\Delta z$ is not constant but increases exponentially with depth, so that infiltration, soil evaporation and crop transpiration from the top soil layers can be described with sufficient detail. The hydraulic characteristics of each compartment are that of the soil horizon to which it belongs. In program settings the user has the option to overwrite the AquaCrop settings by adjusting the number and thickness of the soil compartments.

- **Setting at the start of the simulation run**

When starting a new simulation run, the soil water content and soil salinity conditions in the soil profile are by default reset to the specified initial conditions (see 2.16.1 and 2.16.2). This is correct when successive simulation runs are not linked in time or apply to different fields. With the 'Keep' option the soil water content and soil salinity at the end of a simulation run becomes the soil water content and/or soil salinity at the start of the next run. This assumes that the various runs refer all to one particular field and are successive in time (one crop after another is cultivated in the same field). It is obvious that in such cases the user can no longer alter the soil type.

## 2.17 Off season conditions

If the simulation period (see 2.15 Simulation period) is not fully linked with the growing cycle but starts before the planting or sowing of the crop or finishes after the moment of maturity, the management conditions outside the growing cycle needs to be considered. The information used by AquaCrop in the off-season (such as the presence of mulches, the occurrence of irrigation events and the quality of the irrigation water outside the growing cycle) can be displayed in the ***Display of off-season conditions*** menu and adjusted in the ***Off-season conditions*** menu (Fig. 2.17a and 2.17b).

### 2.17.1 Mulches in the off-season

The soil cover (mulches) of the fallow land before and/or after the growing cycle and the type of surface mulches can be specified (Fig. 2.17a). The soil cover will reduce the evaporation losses from the non-cropped land.

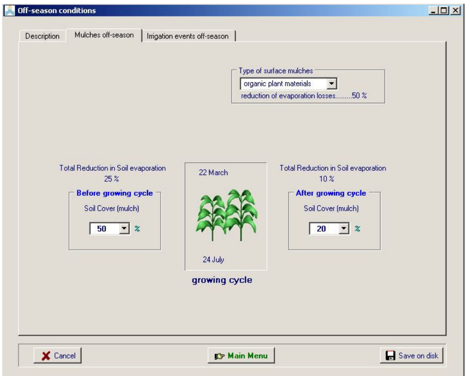


**Figure 2.17a**
**Specification of mulches in the *Off-season conditions* menu**



### 2.17.2 Irrigation events in the off-season

Irrigation events can be scheduled before and after the growing cycle (Fig. 2.17b). This allows the users to simulate a pre-irrigation before the sowing or planting of the crop or to schedule irrigations out of the crop season to leach accumulated salts out of the root zone. The quality of the irrigation water, which may differ from the quality in the season, is specified by selecting an irrigation water quality class (Tab. 2.17) or by specifying a value for the electrical conductivity of the irrigation water.

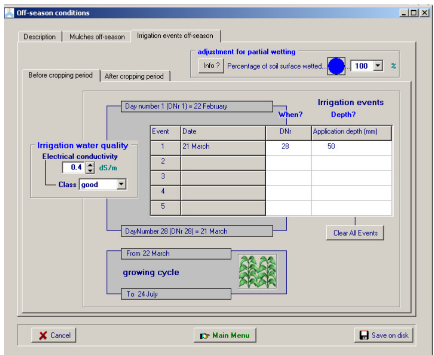


**Figure 2.17b**
**Specification of a pre-irrigation in the *Off-season conditions* menu**

**Table 2.17**
**Classes and corresponding default values for the quality of the irrigation water.**

| Class<br>Quality of irrigation water | Electrical Conductivity (dS/m)<br>Default value | <br>Range |
|---|---|---|
| excellent | 0 | 0.0 ... 0.2 |
| good | 0.4 | 0.3 ... 1.0 |
| moderate | 1.0 | 1.1 ... 2.0 |
| poor | 1.7 | 2.1 ... 3.0 |
| very poor | 2.5 | > 3.0 |



## 2.18 Project characteristics

When running a simulation, initial conditions applicable at the start of the simulation period and environmental conditions relevant during the simulation period are considered. If the simulation period does not fully coincide with the growing cycle of the crop, off-season conditions valid outside the growing period will be considered as well. Before running a simulation, the user can specify in the Main menu the sowing date, the simulation period and the appropriate environmental, initial and off-season conditions (Project file is 'None'). The user can also load a project file containing all the required information for that run.

Once a project file is selected, its characteristics can be displayed in the ***Display of project characteristics*** menu and adjusted in the ***Project characteristic*** menu. Once the project file is selected, the **<Select/Create>** and the **<Display/Update>** commands for climate, crop, irrigation, field, soil profile, groundwater, initial and off-season conditions are no longer available in the ***Main Menu*** (Fig. 2.18a). By clicking on the **<UNDO selection>** command, one return to the default settings considered at the start of AquaCrop (see 2.3 Default settings at start).

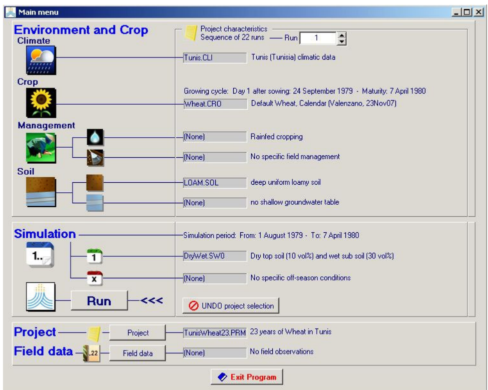


**Figure 2.18a**
***Main menu* once a project file is selected.**



### 2.18.1 Single run and multiple run projects

Distinction is made between projects containing the required information for a single simulation run (with 'PRO' as the filename extension) or projects consisting of a set of successive runs, the so called multiple run projects (with 'PRM' as the filename extension).

With a multiple run project the user can asses the effect of weather conditions (rainfall, evaporative demand and air temperature) on crop development and production by running a particular simulation for a number of successive years. A multiple run project can also be used to simulate a crop rotation (successive crops).

A project file contains:

- the period(s) of the growing cycle (from day 1 after sowing/transplanting to crop maturity);
- the simulation period(s): the first and last day of the simulation period need not to coincide with the growing cycle;
- the file names (with their directory) containing the characteristics of the selected environment (climate, crop, irrigation management, field management, soil profile, and groundwater file);
- the file names (with their directory) containing the initial and off-season conditions; and
- the specific program settings for the run(s).

If no file names are specified the default conditions are considered (see 2.3 Default settings at start).

### 2.18.2 Selecting and creating a project

- **Selecting a project**

Since the single and multiple run projects have different file extensions, the list of project files displayed in the ***Select project file*** menu depends on the selected type of projects (Fig. 2.18b).

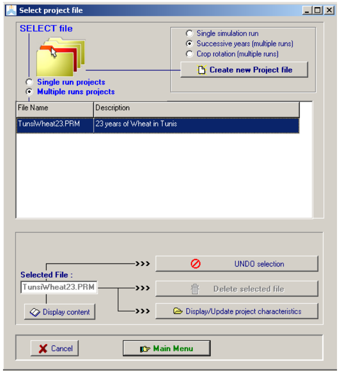



**Figure 2.18b**
**The *Select project file* menu where the user can select a project file from one of the displayed lists of projects (single run or multiple runs projects) and can indicate which type of project needs to be created (Single simulation run; Successive years (multiple runs); Crop rotation (Multiple runs)**

- **Creating a project**

When creating a new project file, the user specifies the type of file:
- Single simulation run;
- Successive years (multiple runs); or
- Crop rotation (multiple runs).



***Create project (single run)***
The user selects:
- the climate file;
- the crop file, and specifies
  - day 1 after sowing/planting, or
  - select a criterion (see 2.10.2 Generate onset) to generate an onset day (only available if a climate file is selected);
- the irrigation file;
- the field management file;
- the soil profile file;
- the groundwater file;
- the simulation period;
- the file with initial conditions; and
- the file with off-season conditions (only available if the simulation period is not linked with the growing cycle).

The selected crop growing cycle and simulation period are displayed by selecting the **<Calendar>** command.
If no file is selected default conditions are considered (see 2.3 Default settings at start).

***Create project (multiple runs) - successive years***
The user selects:
- the climate file;
- the crop file, and specifies
  - day 1 after sowing/planting, or
  - select a criterion (see 2.10.2 Generate onset) to generate an onset day (only available if a climate file is selected); and
  - the year at which the series of successive years start;
- the common irrigation file;
- the common field management file;
- the soil profile file;
- the common groundwater file;
- the simulation period by specifying:
  - day 1 of the initial run;
  - the simulation period for the next runs (only available if a climate file is selected);
- the file with initial conditions;
- the initial conditions for next runs (only available if a climate file is selected);
- the common file with off-season conditions (only available if the simulation period is not linked with the growing cycle); and
- the number of years.

The determined crop growing cycles and simulation periods for the successive years are displayed by selecting the **<Calendar>** command (Fig. 2.18c).

If no file is selected default conditions are considered (see 2.3 Default settings at start).

If the selected irrigation management, field management, and/or file with off-season conditions are not common between the successive years, the selection can be adjusted in the **Project characteristics** menu (see 2.18.3).



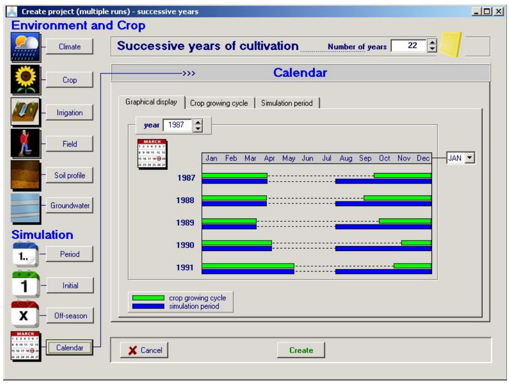



**Figure 2.18c**
**The calendar in the *Create project (multiple runs) – successive years* menu, indicating the determined crop growing cycles and simulation periods for the successive years**

***Create project (multiple runs) – crop rotation***
The user selects:
- the climate file;
- the number of crops, and specifies for each of the crops:
  - the crop file; and
  - day 1 after sowing/planting (Fig. 2.18d);
- the common irrigation file;
- the common field management file;
- the soil profile file;
- the common groundwater file;
- the simulation period by specifying:
  - day 1 of the initial run; and
  - the simulation period for the next runs (only available if a climate file is selected);
- the file with initial conditions;
- the initial conditions for next runs (only available if a climate file is selected); and



- the common file with off-season conditions (only available if the simulation period is not linked with the growing cycle).

The determined crop growing cycles and simulation periods for each of the crops of the rotation are displayed by selecting the **<Calendar>** command.

If no file is selected default conditions are considered (see 2.3 Default settings at start).

If the selected irrigation management, field management, groundwater and/or file with off-season conditions are not common in the crop rotation, the selection can be adjusted in the **Project characteristics** menu (see 2.18.3).

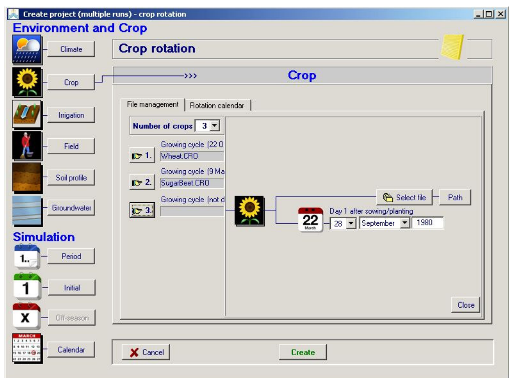



**Figure 2.18d**
**Crop file management in the *Create project (multiple runs) – crop rotation* menu**

### 2.18.3 Updating project characteristics

In the ***Project characteristics*** menu (Fig. 2.18e), the user can:

- select other crop file(s), irrigation file(s), field management file(s), another soil profile file, groundwater file(s), file(s) with initial conditions, and file(s) with off-season conditions.
  With the exception of the climate file, the soil profile file and the crop file (if successive years are considered), the files need not to be common between the simulation runs of a multiple runs project;
- alter the start of the growing cycle;
- alter the start and the end of the simulation period; and
- update the program settings.

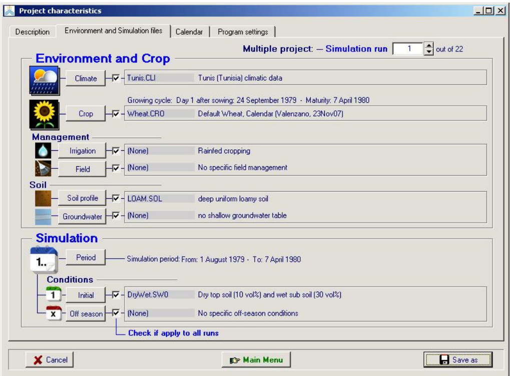



**Figure 2.18e**
**The *Project characteristics* menu**



## 2.19 Field data

### 2.19.1 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 ***Main menu*** of AquaCrop.

By means of the **<Select/Create Observation 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. 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 data can be displayed, specified or updated in the ***Field data*** menu.

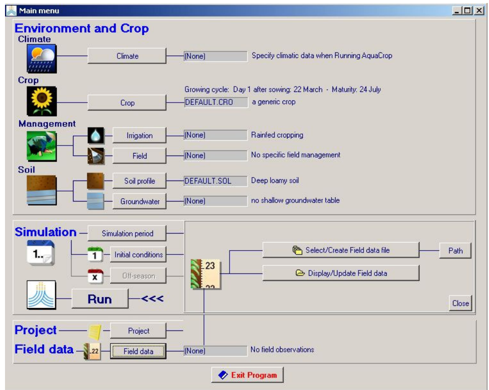



**Figure 2.19a** - The **<Select/Create Field data file>** and the **<Display/Update Field data>** command in the ***Main menu***.



### 2.19.2 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. 2.19b). 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.

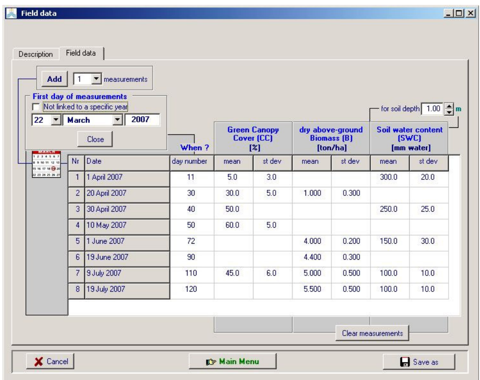



**Figure 2.19b** – Specifying observations at particular days in the ***Field data*** menu.



## 2.20 Simulation run

### 2.20.1 Display of simulation results

Simulation results are plotted in the ***Simulation run*** menu in a number of graphs which are updated at the end of each daily time step (Fig. 2.20a, b, c, d and e). From such plots the user can follow throughout the simulation run the effects of water, temperature, fertility and salinity stress on crop development and production, and switch between several displays, each of a different set of outputs, presented in different folders. The capacity of simulating in short time steps and switching between several folders is particularly useful if one wants to study the effect of a particular event on a specific parameter.

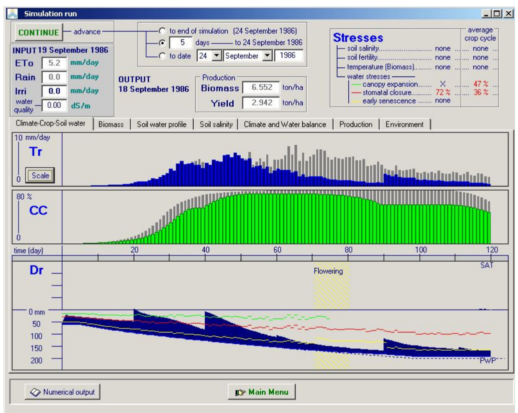



**Figure 2.20a**
**Graphical displays of Climate-Crop-Soil water output in the *Simulation run* menu**

- **Climate-Crop-Soil water sheet**

The Climate-Crop-Soil water sheet (Fig. 2.20a) contains graphs with plots of (i) the soil water depletion of the root zone (Dr), (ii) the corresponding development of the green canopy cover (CC), and (iii) the transpiration (Tr), plotted as functions of time.

The absence of rain and irrigation during long periods might led to a drop in root zone water content below the threshold (green line) affecting canopy expansion. This will result in a slower canopy development than expected. In the canopy cover graph (CC) the canopy cover without water stress is plotted in light gray in the back portion of the figure as a reference. More severe water stress will result in stomata closure (red line), resulting in reduced crop transpiration. In the transpiration graph (Tr), the maximum crop transpiration that can be reached when the crop is well watered is plotted in light gray in the back as a reference. Severe water stress might even trigger early canopy senescence when the root zone depletion exceeds the threshold for senescence (yellow line).

- **Sheet with selected parameter**

In the second sheet of the ***Simulation run*** menu, the user can select particular parameters for further analysis (Tab. 2.20a). Several crop parameters and parameters of the soil water and soil salinity balance can be selected and the scale for the plot can be adjusted (Fig. 2.20b).

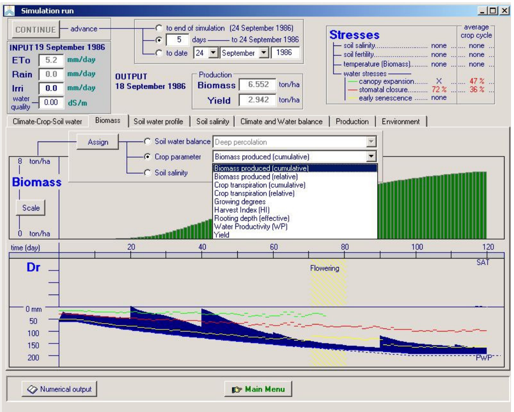


**Figure 2.20b**
**Selection of a parameter for display in the *Simulation run* menu**



**Table 2.20a**
**Parameters of the soil water balance, crop parameters, and parameters concerning soil salinity that can be selected for display in the Simulation run menu**

| Symbol | Description | Units |
|---|---|---|
| **Parameters of the soil water balance** | | |
| Drain | Deep percolation | mm |
| Sum(Drain) | Deep percolation (cumulative) | mm |
| ET | Evapotranspiration | mm |
| Sum(ET) | Evapotranspiration (cumulative) | mm |
| ETx | Evapotranspiration (maximum) | mm |
| ET/ETx | Evapotranspiration (relative) | % |
| Inf | Infiltrated water | mm |
| Sum(Inf) | Infiltrated water (cumulative) | mm |
| Irri | Irrigation | mm |
| Sum(Irri) | Irrigation (cumulative) | mm |
| Rain | Rainfall | mm |
| Sum(Rain) | Rainfall (cumulative) | mm |
| Evap | Soil evaporation | mm |
| Sum(E) | Soil evaporation (cumulative) | mm |
| Ex | Soil evaporation (maximum) | mm |
| E/Ex | Soil evaporation (relative) | % |
| Runoff | Surface runoff | mm |
| Sum(RO) | Surface runoff (cumulative) | mm |
| **Crop parameters** | | |
| Biomass | Biomass produced (cumulative) | ton/ha |
| B(rel) | Biomass produced (relative) | % |
| Sum(Tr) | Crop transpiration (cumulative) | mm |
| Tr/Trx | Crop transpiration (relative) | % |
| GDD | Growing degrees | °C-day |
| HI | Harvest Index (HI) | % |
| Z | Effective rooting depth | m |
| WP | Water Productivity (WP) | $g/m^2$ |
| Yield | Yield | ton/ha |
| **Parameters concerning soil salinity** | | |
| SaltIn | Salt infiltrated in the profile | ton/ha |
| Sum(Sin) | Salt infiltrated in the profile (cumulative) | ton/ha |
| SaltOut | Salt drained out of the profile | ton/ha |
| Sum(Sout) | Salt drained out of the profile (cumulative) | ton/ha |
| SaltUp | Salt moved upward from groundwater table | ton/ha |
| Sum(Sup) | Salt moved upward (cumulative) | ton/ha |
| SaltTot | Salt stored in the profile | ton/ha |
| SaltZ | Salt stored in the root zone | ton/ha |
| ECe | EC of saturated soil-paste extract from root zone | dS/m |
| ECsw | EC of soil water in root zone | dS/m |
| ECgw | EC of groundwater table | dS/m |



- **Soil water profile sheet**

In the soil water profile sheet of the ***Simulation run*** menu, the simulated water content in the various compartments of the soil profile is adjusted for every day of the simulation period.

- **Soil salinity sheet**

In the soil salinity 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 for every day of the simulation period (Fig. 2.20c).

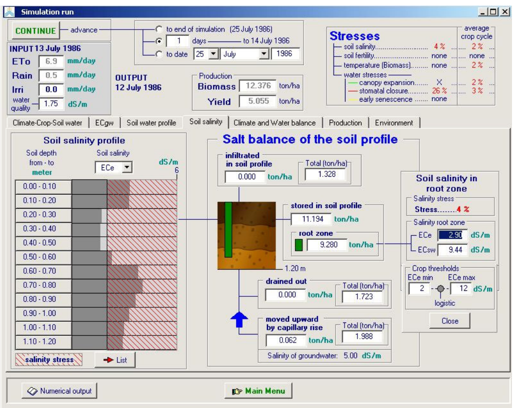


**Figure 2.20c**
**Display of the soil salinity profile and the salt balance in the *Simulation run* menu**



- **Climate and Water balance sheet**

In the Climate and Water balance sheet of the ***Simulation run*** menu, values are given for soil evaporation, crop transpiration, surface runoff, infiltrated water, drainage, and capillary rise. The irrigation events are displayed in the ***Irrigation Events*** menu (Fig. 2.20d).

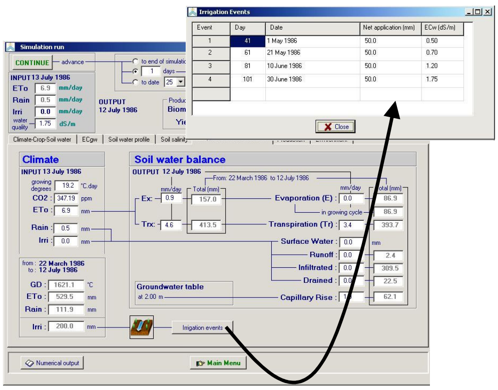


**Figure 2.20d**
**Display of the parameters of the climate and soil water balance in the *Simulation run* menu and the irrigation events in the *Irrigation Events* menu**

- **Production sheet**

In the Production sheet of the ***Simulation run*** menu, information is given on the ante and post-anthesis impact of water stress on the adjustment of HI (Fig 2.20e). The simulated amount of biomass produced and the biomass that could have been produced in the absence of water, soil fertility and salinity stress are displayed as well. Information is also given on the ET water productivity (yield per unit of evapotranspired water).

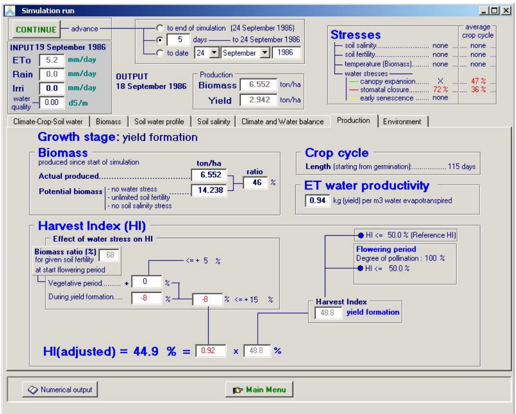


**Figure 2.20e**
**Information on biomass production, ET water productivity, and the ante and post-anthesis impact of water stress on the adjustment of HI in the *Simulation run* menu**



- **Totals Run sheet**

In the Totals Run sheet of the ***Simulation run*** menu, information is given on totals of a selected number of parameters (Tab. 2.20b) at the end of each simulation run (Fig. 2.20f).

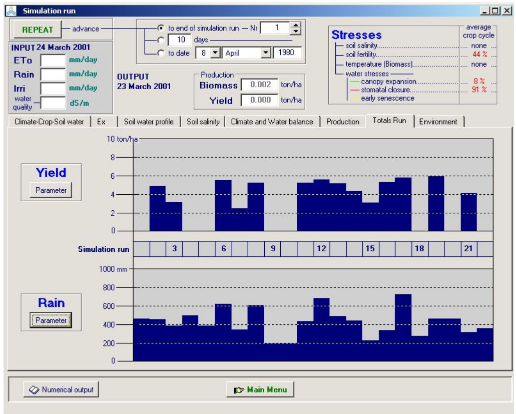


**Figure 2.20f**
**Information on the simulated yield and total rainfall (during the simulation period) for the successive years of a multiple run project in the *Simulation run* menu**



**Table 2.20b**
**Parameters that can be selected for display in the *Simulation run* menu**

| Symbol | Description | Units |
|---|---|---|
| Rain | Rainfall | mm |
| ETo | ETo | mm |
| GD | GD | °C |
| CO2 | CO2 | ppm |
| Irri | Irrigation | mm |
| Inf | Infiltrated water | mm |
| RO | Runoff | mm |
| Drain | Deep percolation | mm |
| CR | Capillary rise | mm |
| Evap | Soil evaporation | mm |
| E/Ex | Soil evaporation (relative) | % |
| Tr | Crop transpiration | mm |
| Tr/Trx | Crop transpiration (relative) | % |
| SaltIN | Salt infiltrated in the soil profile | ton/ha |
| SaltOUT | Salt drained out of the soil profile | ton/ha |
| SaltUP | Salt moved upward by capillary rise | ton/ha |
| SaltProf | Salt stored salt the soil profile | ton/ha |
| Ccyle | Length of crop cycle | day |
| SaltStr | Average salinity stress | % |
| FertStr | Average soil fertility stress | % |
| TempStr | Average temperature stress (biomass) | % |
| ExpStr | Average leaf expansion stress | % |
| StStr | Average stomatal stress | % |
| Biomass | Biomass | ton/ha |
| Brelative | Relative Biomass (Ref: optimal conditions) | % |
| HI | Harvest Index | - |
| Yield | Yield | ton/ha |
| WPet(Y) | ET water productivity (for yield) | kg/m$^3$ |



- **Simulated environment sheet**

In the Simulated environment sheet of the ***Simulation run*** menu, the selected input files for the simulation run are displayed and the program settings can be checked (Fig. 2.20g).

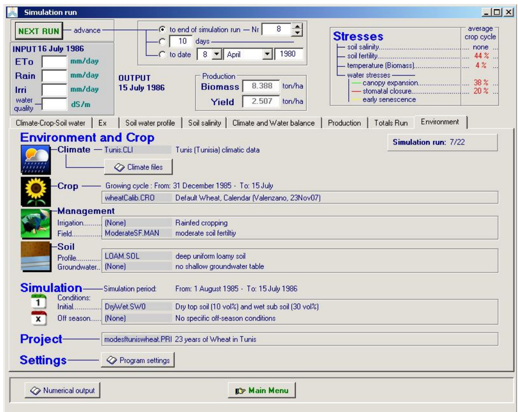


**Figure 2.20g**
**Display of the selected input files in the *Simulation run* menu**

### 2.20.2 Numerical output

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. 2.20h). The data can be aggregated in 10-day, monthly or yearly data.

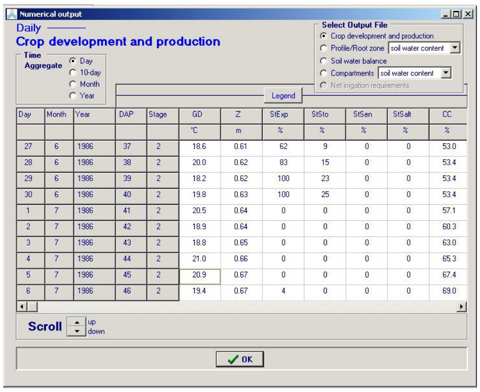



**Figure 2.19h**
**Display of data recorded in output files**



### 2.20.3 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 (see 2.19 Field observations). 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. 2.20i).

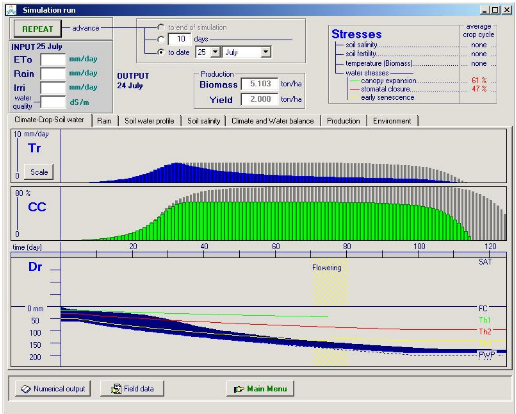



**Figure 2.20i** – The ***Simulation run*** menu with the **<Observations>** command in the command panel.

- **Graphical and numerical displays**

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

1. A graphical display where the simulated and observed (with their standard deviations) values are plotted (Fig. 2.20j);
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. 2.20k).



The assessment can be saved on disk for later use.

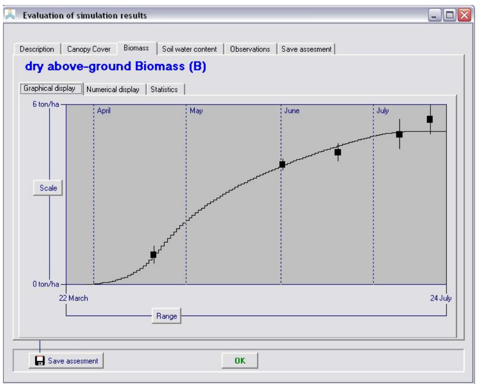



**Figure 2.20j** – Simulated (line) and observed (dots) dry above-ground Biomass with their standard deviations (vertical lines) in the ***Evaluation of simulation results*** menu.



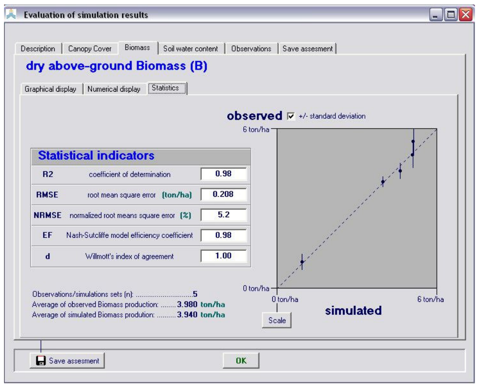



**Figure 2.20k** – Statistical indicators for the assessment of the simulated dry above-ground Biomass in the ***Evaluation of simulation results*** menu.

- **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, $\bar{O}$ and $\bar{P}$ their averages and n the number of observations.

**Coefficient of determination ($R^2$)**

The coefficient of determination r² is defined as the squared value of the Pearson correlation coefficient. r² 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 r² is that only the dispersion is quantified, which means that a model which systematically overestimates (or underestimates) the observations can still have a good r² value (Krause et al., 2005). Willmott (1982) also stated that within the context of atmospheric sciences both r and r² 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.

**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.

**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%.



**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 r², EF is not very sensitive to systematic over- or underestimations by the model (Krause et al., 2005).

**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 r² 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).

**References**

Jacovides, C. P., and Kontoyiannis, H. (1995). Statistical procedures for the evaluation of evapotranspiration computing models. Agricultural Water Management 27, 365–371.

Krause, P., Boyle, D. P., and Bäse, F. (2005). Advances in Geosciences Comparison of different efficiency criteria for hydrological model assessment. Advances In Geosciences, 89–97.

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



Loague, K., and Green, R. E. (1991). Statistical and graphical methods for evaluating solute transport models: Overview and application. Journal of Contaminant Hydrology 7, 51–73.

Moriasi, D. N., Arnold, J. G., Liew, M. W. V., Bingner, R. L., Harmel, R. D., and Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions Of The ASABE 50, 885–900.

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

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



## 2.20.4 Output files

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 files are stored by default in the OUTP directory of AquaCrop. By using different filenames (and even directories), the user can prevent that the simulation results are overwritten at each run. (Fig. 2.20l).

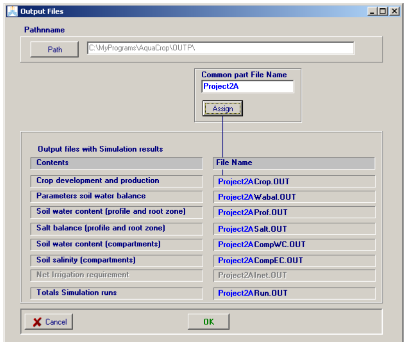



**Figure 2.20l**
**Specification of the path and file name for the Output files**

- **Daily results**

The output of the daily results consists of 7 files containing key variables (Tab.2.20c). In section 2.23 (Output files) the list of key variables is presented.

- **Seasonal results**

The output of the seasonal results can be stored as well (RUN.OUT).

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

**Table 2.20c**
**Default file name and content of the 7 output files with daily simulation results**

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



# Input/Output and program settings Files

When installing AquaCrop, the installation program (i) creates a FAO folder, (ii) creates the 'AQUACROP' folder (if not yet available) in the FAO folder, and (iii) finally installs the software in C:\ FAO\AquaCrop

```
C:\ ---- |-
         |-
         |-
         |-
         |- FAO -------- |-
         |-              |- AQUACROP -------|- DATA
                            AquaCrop.EXE    |
                            Default.PAR     |- OUTP
                            General.PAR     |
                            Planting.PAR    |- OBS
                            Onset.PAR       |
                            Soil.PAR        |- SIMUL
                            Rainfall.PAR
                            Crop.PAR
                            Field.PAR
                            Temperature.PAR
                            DEFAULT.CRO
                            DEFAULT.SOL
                            SOILS.DIR
```

If AquaCrop is correctly installed, the AquaCrop folder should contain:
(i) the following files:
- AquaCrop.EXE (the executable file );
- Files with default project settings (*.PAR);
- Files with default Crop and Soil parameters: DEFAULT.CRO, DEFAULT.SOL;
- SOILS.DIR (a file with default values for soil characteristics).

(ii) and four subdirectories:
- DATA (default subdirectory for the input files);
- OUTP (default subdirectory for the output files);
- OBS (default subdirectory for the field observations files);
- SIMUL (subdirectory for simulation purposes, containing between other files the MaunaLoa.CO2 file).



## 2.21 Input files

The input is stored in text files which are retrieved through the user-interface. By default the input files are stored in the DATA subdirectory of the AquaCrop folder. Distinction is made between:
- Climate files (*.CLI) which contains the names of a set of files containing
  - air temperature data (*.TMP),
  - reference evapotranspiration data (*.ETo),
  - rainfall data (*.PLU), and
  - atmospheric $CO_2$ data (*.CO2);
- Crop files (*.CRO) containing crop characteristics;
- Irrigation files (*.IRR) containing, apart from the irrigation method, (i) information for the calculation of the net irrigation requirement, (ii) the timing, applied irrigation amounts and the irrigation water quality of an irrigation schedule, or (iii) information for generating irrigation schedules;
- Field management files (*.Man) containing characteristics of the field on which the crop is cultivated;
- Soil profile files (*.SOL) containing characteristics of the soil profile;
- Groundwater files (*.GWT) containing characteristics of the groundwater table;
- Files with the specific conditions in the soil profile at the start of the simulation period (*.SW0);
- Files with off-season field management conditions (*.OFF); and
- Single run project files (*.PRO) containing information on the growing and simulation period, the settings of program parameters, and the names of the set of input files describing the environment, and the initial and off-season conditions;
- Multiple runs project files (*.PRM) containing information on the settings of program parameters and on the growing and simulation period, names of the set of input files describing the environment, and the initial and off-season conditions for each of the runs.

Also field observations can be stored in text files and retrieved through the user-interface for the evaluation of simulations results. By default the field observations files are stored in the OBS subdirectory of the AquaCrop folder.
- Files with field observations (*.OBS).



### 2.21.1 Climate file (*.CLI)

A climate file (Tab. 2.21a, Fig. 2.21) contains next to its description and the reference of the AquaCrop version, the names of the air temperature file (*.TMP), ETo file (*.ETo), rainfall file (*.PLU), and $CO_2$ file (*.CO2).

**Table 2.21a**
**Example of a climate file (files with extension CLI)**

| |
|---|
| Tunis (Tunisia) climatic data |
| 4.0 : AquaCrop Version (May 2012) |
| Tunis.TMP |
| Tunis.ETo |
| Tunis7902.PLU |
| MaunaLoa.CO2 |

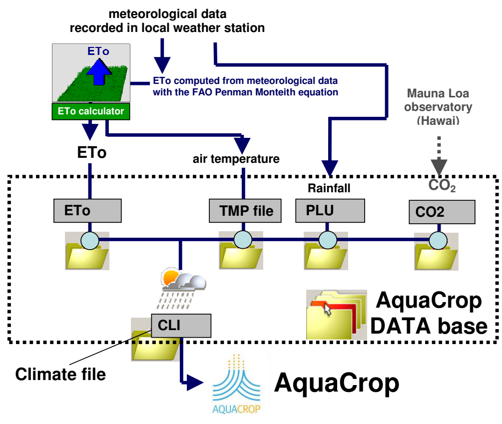



**Fig 2.21** – Climatic data and Climate file

### 2.21.2 Temperature (*.TMP), ETo (*ETo) and rainfall (*.PLU) files

Temperature (Tab. 2.21b), ETo (Tab. 2.21c) and Rainfall files (Tab. 2.21d) have all the same structure which consists of:

- 5 lines containing information required by the program;
- an empty line to separate the information from the records;
- 2 lines for the title of the records;
- list of records (1 line for each daily, 10-daily or monthly record). The records are the daily, mean 10-daily or monthly minimum and maximum air temperature in degrees Celsius, the daily, mean 10-daily or monthly ETo in mm/day and the total daily, 10-daily or monthly rainfall data in mm. The data may consists of integers or reals with 1 digit (1/10 of a degree or a millimeter).

**Table 2.21b**
**Structure of an air temperature file (files with extension TMP)**

| Line | File content |
|---|---|
| 1 | First line is a description which is displayed when selecting the file |
| 2 | 1 : Daily records (1=daily, 2=10-daily and 3=monthly data) |
| 3 | 1 : First day of record (1, 11 or 21 for 10-day or 1 for months) |
| 4 | 1 : First month of record |
| 5 | 1999 : First year of record (1901 if not linked to a specific year) |
| 6 | |
| 7 | Tmin (°C) TMax (°C) |
| 8 | ======================= |
| 9 | 7.0 15.0 |
| 10 | 8.0 16.0 |
| 11 | 9.0 18.0 |

**Table 2.21c**
**Structure of an ETo file (files with extension ETo)**

| Line | File content |
|---|---|
| 1 | First line is a description which is displayed when selecting the file |
| 2 | 1 : Daily records (1=daily, 2=10-daily and 3=monthly data) |
| 3 | 1 : First day of record (1, 11 or 21 for 10-day or 1 for months) |
| 4 | 1 : First month of record |
| 5 | 1999 : First year of record (1901 if not linked to a specific year) |
| 6 | |
| 7 | Average ETo (mm/day) |
| 8 | ======================= |
| 9 | 1.0 |
| 10 | 1.1 |
| 11 | 1.2 |



**Table 2.21d**
**Structure of a Rainfall file (files with extension PLU)**

| Line | File content |
|---|---|
| 1 | First line is a description which is displayed when selecting the file |
| 2 | 1 : Daily records (1=daily, 2=10-daily and 3=monthly data) |
| 3 | 1 : First day of record (1, 11 or 21 for 10-day or 1 for months) |
| 4 | 1 : First month of record |
| 5 | 1999 : First year of record (1901 if not linked to a specific year) |
| 6 | |
| 7 | Total Rain (mm) |
| 8 | ======================= |
| 9 | 0.0 |
| 10 | 0.0 |
| 11 | 16.6 |

### 2.21.3 CO2 file (*.CO2)

A CO2 file contains mean annual atmospheric $CO_2$ data (in ppm) for a series of years arranged in chronological order. For years not specified in the file, AquaCrop will derive at run time the $CO_2$ concentration by linear interpolation between the specified $CO_2$ values for an earlier and later year. For years out of the listed range, the atmospheric $CO_2$ concentration is assumed to be equal to the specified value of the first year (for earlier years) or the specified value of the last year (for later years). When creating CO2 file, the structure of the file needs to be respected (Tab. 2.21e).

**Table 2.21e**
**Structure of a CO2 file (files with extension CO2)**

| Line | File content | Explanation |
|---|---|---|
| 1 | First line is a description | description |
| 2 | Year CO2 (ppm by volume) | title |
| 3 | ============================ | title |
| 4 | 1940 310.5 | year(1) and corresponding $CO_2$ |
| 5 | 1960 316.91 | year(2) and corresponding $CO_2$ |
| 6 | 1961 317.65 | year(3) and corresponding $CO_2$ |
| ... | ... ..... | .................. |
| n-1 | 2007 383.72 | year(n-1) and corresponding $CO_2$ |
| n | 2020 409.72 | year(n) and corresponding $CO_2$ |



### 2.21.4 Crop file (*.CRO)

### 2.21.5 Irrigation file (*.IRR)

### 2.21.6 Field management file (*.MAN)

### 2.21.7 Soil profile file (*.SOL)

### 2.21.8 Groundwater file (*.GWT)

### 2.21.9 File with initial conditions (*.SW0)

### 2.21.10 File with off-season conditions (*.OFF)

### 2.21.11 Single run Project file (*.PRO)

### 2.21.12 Multiple run project file (*.PRM)

### 2.21.13 File with field data (*.OBS)



## 2.22 Files with program settings

## 2.23 Output files

Simulation results are stored in a set of output files. By default the output files are stored in the OUTP subdirectory of the AquaCrop folder. Distinction is made between output files containing daily data and seasonal results. The output files with daily data contain information on the:

- Crop development and production;
- Soil water content at various depths of the soil profile;
- Soil salinity at various depths of the soil profile;
- Soil water content in the soil profile and root zone;
- Soil salinity in the soil profile and root zone;
- Various parameters of the soil water balance;
- Net irrigation water requirement.

The variables listed in the output files are given in 2.23.1 to 2.23.7. The variables listed in the seasonal output file are given in 2.23.8. The data in the files can be retrieved in spread sheet programs for further processing and analysis.

### 2.23.1 Crop development and production

**Default file name: ProjectCROP.OUT**

| Nr | Symbol | Description | Unit |
|---|---|---|---|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage:<br>0: before or after cropping;<br>1: between sowing and germination or transplant recovering;<br>2: vegetative development;<br>3: flowering;<br>4: yield formation and ripening<br>-9: no crop as a result of early canopy senescence | - |
| 6 | GD | Growing degrees | °C-day |
| 7 | Z | Effective rooting depth | m |
| 8 | StExp | Percent water stress reducing leaf expansion | % |
| 9 | StSto | Percent water stress inducing stomatal closure | % |
| 10 | StSen | Percent water stress triggering early canopy senescence | % |
| 11 | StSalt | Percent salinity stress | % |
| 12 | CC | Green canopy cover | % |
| 13 | Kc(Tr) | Crop coefficient for transpiration | - |
| 14 | Trx | Maximum crop transpiration | mm |
| 15 | Tr | Actual crop transpiration | mm |
| 16 | T/Tx | Relative transpiration (100 Tr/Trx) | % |
| 17 | WP | Crop water productivity adjusted for CO2, soil fertility and products synthesized | $g/m^2$ |



| | | | |
|---|---|---|---|
| 18 | StBio | Percent temperature stress affecting biomass production | % |
| 19 | Biomass | Cumulative biomass produced | ton/ha |
| 20 | HI | Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress | % |
| 21 | Yield Part | Yield (HI x Biomass) | ton/ha |
| 22 | Brelative | : Relative biomass (Reference: no water, no soil fertility, no soil salinity stress) | % |
| 23 | WPet | ET Water productivity for yield part (kg yield produced per m3 water evapotranspired) | $kg/m^3$ |

### 2.23.2 Soil water balance

**Default file name: ProjectWABAL.OUT**

| Nr | Symbol | Description | Unit |
|---|---|---|---|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage:<br>0: before or after cropping;<br>1: between sowing and germination or transplant recovering;<br>2: vegetative development;<br>3: flowering;<br>4: yield formation and ripening<br>-9: no crop as a result of early canopy senescence | - |
| 6 | WCTot | Water content in total soil profile | mm |
| 7 | Rain | Rainfall | mm |
| 8 | Irri | Water applied by irrigation | mm |
| 9 | Surf | Stored water on soil surface between bunds | mm |
| 10 | Infilt | Infiltrated water in soil profile | mm |
| 11 | RO | Surface runoff | mm |
| 12 | Drain | Water drained out of the soil profile | mm |
| 13 | CR | Water moved upward by capillary rise | mm |
| 14 | Ex | Maximum soil evaporation | mm |
| 15 | E | Actual soil evaporation | mm |
| 16 | E/E | Relative evaporation (100 E/EX) | % |
| 17 | Trx | Maximum crop transpiration | mm |
| 18 | Tr | Actual crop transpiration | mm |
| 19 | T/T | Relative transpiration (100 Tr/Trx) | % |
| 20 | ETx | Maximum evapotranspiration | mm |
| 21 | ET | Actual evapotranspiration | mm |
| 22 | ET/ETx | Relative evapotranspriation (100 ET/ETx) | % |



### 2.23.3 Soil water content (profile and root zone)

**Default file name: ProjectProf.OUT**

| Nr | Symbol | Description | Unit |
|---|---|---|---|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage:<br>0: before or after cropping;<br>1: between sowing and germination or transplant recovering;<br>2: vegetative development;<br>3: flowering;<br>4: yield formation and ripening<br>-9: no crop as a result of early canopy senescence | - |
| 6 | WCTot | Water content total soil profile | mm |
| 7 | Wr(Zx) | Water content in maximum effective root zone | mm |
| 8 | Z | Effective rooting depth | m |
| 9 | Wr | Water content in effective root zone | mm |
| 10 | Wr(SAT) | Water content in effective root zone if saturated | mm |
| 11 | Wr(FC) | Water content in effective root zone at field capacity | mm |
| 12 | Wr(exp) | Water content in effective root zone at upper threshold for leaf expansion | mm |
| 13 | Wr(sto) | Water content in effective root zone at upper threshold for stomatal closure | mm |
| 14 | Wr(sen) | Water content in effective root zone at upper threshold for early canopy senescence | mm |
| 15 | Wr(PWP) | Water content in effective root zone at permanent wilting point | mm |

### 2.23.4 Soil salinity (profile and root zone)

**Default file name: ProjectSalt.OUT**

| Nr | Symbol | Description | Unit |
|---|---|---|---|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage:<br>0: before or after cropping;<br>1: between sowing and germination or transplant recovering;<br>2: vegetative development;<br>3: flowering;<br>4: yield formation and ripening | - |



| | | | |
|---|---|---|---|
| | | -9: no crop as a result of early canopy senescence | |
| 6 | SaltIn | Salt infiltrated in the soil profile | ton/ha |
| 7 | SaltOut | Salt drained out of the soil profile | ton/ha |
| 8 | SaltTot | Salt content in the total soil profile | ton/ha |
| 9 | SaltZ | Salt content in the effective root zone | ton/ha |
| 10 | Z | Effective rooting depth | m |
| 11 | ECe | Electrical conductivity of the saturated soil-paste extract from the root zone | dS/m |
| 12 | ECsw | Electrical conductivity of the soil water in the root zone | dS/m |
| 13 | StSalt | Salinity stress | % |
| 14 | Zgwt | Depth of the groundwater table | m |
| 15 | ECgw | Electrical conductivity of the groundwater | dS/m |

### 2.23.5 Soil water content (compartments)

**Default file name: ProjectCompWC.OUT**

| Nr | Symbol | Description | Unit |
|---|---|---|---|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage:<br>0: before or after cropping;<br>1: between sowing and germination or transplant recovering;<br>2: vegetative development;<br>3: flowering;<br>4: yield formation and ripening<br>-9: no crop as a result of early canopy senescence | - |
| 6 | WC1 | soil water content compartment 1 * | vol% |
| 7 | WC2 | soil water content compartment 2 | vol% |
| 8 | WC3 | soil water content compartment 3 | vol% |
| 9 | WC4 | soil water content compartment 4 | vol% |
| 10 | WC5 | soil water content compartment 5 | vol% |
| 11 | WC6 | soil water content compartment 6 | vol% |
| 12 | WC7 | soil water content compartment 7 | vol% |
| 13 | WC8 | soil water content compartment 8 | vol% |
| 14 | WC9 | soil water content compartment 9 | vol% |
| 15 | WC10 | soil water content compartment 10 | vol% |
| 16 | WC11 | soil water content compartment 11 | vol% |
| 17 | WC12 | soil water content compartment 12 | vol% |

* The soil depth (corresponding at the centre of the compartment) is specified for each compartment in the file

### 2.23.6 Soil salinity (compartments)

**Default file name: ProjectCompEC.OUT**

| Nr | Symbol | Description | Unit |
|---|---|---|---|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage:<br>0: before or after cropping;<br>1: between sowing and germination or transplant recovering;<br>2: vegetative development;<br>3: flowering;<br>4: yield formation and ripening<br>-9: no crop as a result of early canopy senescence | - |
| 6 | EC1 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 1 * | dS/m |
| 7 | EC2 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 2 | dS/m |
| 8 | EC3 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 3 | dS/m |
| 9 | EC4 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 4 | dS/m |
| 10 | EC5 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 5 | dS/m |
| 11 | EC6 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 6 | dS/m |
| 12 | EC7 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 7 | dS/m |
| 13 | EC8 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 8 | dS/m |
| 14 | EC9 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 9 | dS/m |
| 15 | EC10 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 10 | dS/m |
| 16 | EC11 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 11 | dS/m |
| 17 | EC12 | Electrical conductivity of the saturated soil-paste extract (ECe) - compartment 12 | dS/m |

* The soil depth (corresponding at the centre of the compartment) is specified for each compartment in the file



### 2.23.7. Net irrigation requirement

**Default file name: ProjectInet.OUT**

| Nr | Symbol | Description | Unit |
|---|---|---|---|
| 1 | Day | | - |
| 2 | Month | | - |
| 3 | Year | | - |
| 4 | DAP | Days after planting/sowing | - |
| 5 | Stage | Crop growth stage:<br>0: before or after cropping;<br>1: between sowing and germination or transplant recovering;<br>2: vegetative development;<br>3: flowering;<br>4: yield formation and ripening<br>-9: no crop as a result of early canopy senescence | - |
| 6 | E | Actual soil evaporation | mm |
| 7 | Trx | Maximum crop transpiration | mm |
| 8 | ET | Evapotranspiration: Sum of E and Trx | mm |
| 9 | Rain | Rainfall | mm |
| 10 | Inet | Net irrigation requirement | mm |



### 2.23.8. Seasonal output

**Default file name: ProjectRun.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 | |
| 7 | GD | Growing degrees | |
| 8 | CO2 | Atmospheric CO2 concentration | |
| 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 | |
| 12 | Drain | Water drained out of the soil profile | |
| 13 | Upflow | Water moved upward by capillary rise | |
| 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 | |
| 19 | SaltOut | Salt drained out of the soil profile | |
| 20 | SaltUp | Salt moved upward by capillary rise from groundwater table | |
| 21 | SaltProf | Salt stored in the soil profile | ton/ha |
| 22 | Cycle | Length of crop cycle: from germination to maturity (or early senescence) | |
| 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) | |
| 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 | - |



# Chapter 3
# Calculation procedures

# AquaCrop
***Version 4.0***

**Reference Manual**
**June 2012**

**Dirk RAES, Pasquale STEDUTO, Theodore C. HSIAO, and Elias FERERES**
**with contributions of the AquaCrop Network**

**FAO, Land and Water Division**
**Rome, Italy**

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**Disclaimer**

**Acknowledgments**

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**I. Crop parameters**

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# Chapter 3.
# Calculation procedures

AquaCrop is a general model, in that it is meant for a wide range of herbaceous crops, including forage, vegetable, grain, fruit, oil, and root and tuber crops.

Chapter 3 presents the software of AquaCrop for which:
- the concepts and underlying principles are described by Steduto et al. (2009);
- the structure and algorithm are found in Raes et al. (2009), and
- the parameterization for maize (the crop on which the efforts of parameterization were focused during the early phase of model development) are reported by Hsiao et al. (2009).

Examples of crop development and production for specific climate and growing conditions estimated by AquaCrop are given by Farahani et al. (2009), Garcia-Vila et al. (2009), Geerts et al. (2009) and Heng, et al. (2009).



## 3.1 The root zone as a reservoir

### 3.1.1 Incoming and outgoing water fluxes

In a schematic way, the root zone can be considered as a reservoir (Fig. 3.1a). By keeping track of the incoming and outgoing water fluxes at the boundaries of the root zone, the amount of water retained in the root zone can be calculated at any moment of the season by means of a soil water balance.

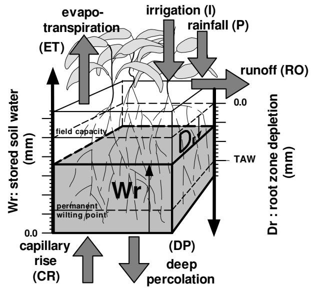



**Figure 3.1a**
**The root zone as a reservoir**

Water is added to the soil reservoir by rainfall and irrigation. When the rainfall intensity is too high, part of the precipitation might be lost by surface runoff and only a fraction will infiltrate. The infiltrated water can not always be retained in the root zone. When the root zone is too wet, part of the soil water percolates out of the root zone and is lost as deep percolation. Water can also be transported upward to the root zone by capillary rise from a shallow groundwater table. Processes such as soil evaporation and crop transpiration remove water from the reservoir.



### 3.1.2 Stored soil water and root zone depletion

When calculating the soil water balance, the amount of water stored in the root zone can be expressed (Fig. 3.1a) as an equivalent depth (Wr) or as depletion (Dr).

- **Stored soil water expressed as an equivalent depth**

Expressing the water content in a particular soil volume as an equivalent depth is useful when computing the soil water balance of the root zone. It makes the adding and subtracting of gains and losses of water straightforward since the various parameters of the soil water balance such as rain and evapotranspiration are usually expressed in terms of water depth. The stored soil water in the root zone expressed as a depth is given by:

$$Wr = 1000\,\theta\,Z \qquad \text{(Eq. 3.1a)}$$

where Wr soil water content of the root zone expressed as a depth [mm];
1000 θ average soil water content for the root zone expressed as equivalent depth per unit soil depth [mm(water)/m(soil depth)];
θ average volumetric water content in the root zone [$m^3/m^3$];
Z effective rooting depth [m].

- **Root zone depletion**

Expressing the soil water content in the root zone as a shortage is useful for irrigation planning and to asses water stresses. The root zone depletion refers to the amount of water that is required to bring the water amount in the root zone back to the reference level which is field capacity. Field capacity is selected as the reference since it expresses the maximum amount of water that can be retained against the gravitational forces. The root zone depletion is given by:

$$Dr = Wr_{FC} - Wr = 1000\left(\theta_{FC} - \theta\right) Z \qquad \text{(Eq. 3.1b)}$$

where Dr root zone depletion [mm];
$Wr_{FC}$ soil water content of the root zone at field capacity [mm] ( = 1000 $\theta_{FC}$ Z);
Wr soil water content of the root zone expressed as depth [mm];
$\theta_{FC}$ volumetric water content at field capacity [$m^3/m^3$];
θ average volumetric water content in the root zone [$m^3/m^3$].

After heavy rainfall or the application of a large amount of irrigation water the water content in the root zone can be temporarily above field capacity. This results in negative root zone depletion (i.e. excess of water).



- **Total Available soil Water (TAW)**

The total available soil water or plant extractable water is the amount of water a crop can theoretically extract from the root zone (Fig. 3.1b). Since (i) the water content above field capacity can not be retained in the soil and will be lost by drainage, and (ii) the water content below permanent wilting point is so strongly attached to the soil matrix that it can not be extracted by plant roots, the Total Available soil Water is the amount of water held in the root zone between field capacity and permanent wilting point:

$$TAW = 1000\left(\theta_{FC} - \theta_{WP}\right) Z = Wr_{FC} - Wr_{PWP} \qquad \text{(Eq. 3.1c)}$$

where TAW total available soil water in the root zone [mm];
$\theta_{FC}$ volumetric water content at field capacity [$m^3/m^3$];
$\theta_{WP}$ volumetric water content at permanent wilting point [$m^3/m^3$];
Z effective rooting depth [m];
$Wr_{FC}$ soil water content of the root zone at field capacity [mm];
$Wr_{PWP}$ soil water content of the root zone at permanent wilting point [mm].

At permanent wilting point the root zone depletion is equal to TAW.

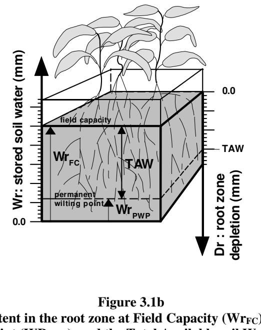



**Figure 3.1b**
**The soil water content in the root zone at Field Capacity ($Wr_{FC}$) and at Permanent Wilting Point ($WR_{PWP}$), and the Total Available soil Water (TAW)**

## 3.2 Stresses

Crop growth might be affected by soil water stress, air temperature stress, soil fertility stress or soil salinity stress.

### 3.2.1 Stress response functions

Effects of stresses on crop growth are described by stress coefficients Ks. In essence, Ks is a modifier of its target model parameter, and varies in value from one (no stress) to zero (full stress). Above the upper threshold of a stress indicator, the stress is non-existent and Ks is 1. Below the lower threshold, the effect is maximum and Ks is 0 (Fig. 3.2a).

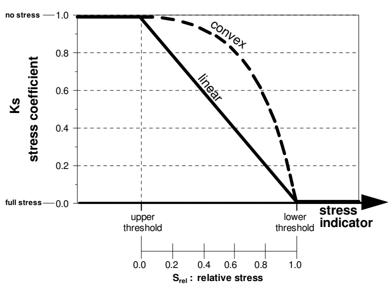



**Figure 3.2a**
**The stress coefficient (Ks) for various degrees of stress and for different shapes of the Ks curve**

The relative stress level ($S_{rel}$) and the shape of the Ks curve determines the magnitude of the effect of the stress on the process between the thresholds. $S_{rel}$ is 0.0 at the upper threshold and 1.0 at the lower threshold (Fig. 3.2a). The shape can be linear, convex, or logistic.

- **Linear shape**

If a ***linear shape*** is considered, the effect of water stress on the process is directly proportional to the relative stress:

$$Ks = 1 - S_{rel} \qquad \text{(Eq. 3.2a)}$$



- **Convex shape**

Convex curves (curves outwards) make that the process is only strongly affected when the water stress becomes severe. The shape and degree of curvature of the Ks curve are described by:

$$Ks = 1 - \frac{e^{S_{rel}\, f_{shape}} - 1}{e^{f_{shape}} - 1} \qquad \text{(Eq. 3.2b)}$$

where $S_{rel}$ ($\leq 1$) is the relative stress level and $f_{shape}$ is the shape factor. The shape factor is positive ($f_{shape} > 0$) for convex curves.

- **Logistic shape**

For the logistic shape, Ks for various $S_{rel}$ is given by:

$$Ks = \frac{S_n\, S_x}{S_n + (S_x - S_n)\exp^{-r(1-S_{rel})}} \qquad \text{(Eq. 3.2c)}$$

where $S_n$ and $S_x$ are the relative stress levels at the lower and upper threshold respectively, and r the rate factor. Given that Ks is 0.5 midway the lower and upper threshold, the rate factor can be obtained by solving Eq. 3.2c for Ks = 0.5 and $S_{rel}$ = 0.5. Since $S_{rel}$ is zero at the lower threshold, a small value for $S_n$ has to be considered. After solving Eq. 3.2c, Ks has to be corrected for the considered small value.



### 3.2.2 Soil water stress

Soil water stress affects the development of the canopy cover, the expansion of the root zone, results in stomata closure and a reduction of crop transpiration rate, and alters the Harvest Index. If the soil water stress is severe it can result in failure of pollination, and can trigger early canopy senescence. The soil water stress coefficients considered by AquaCrop and their effects on crop growth are presented in Table 3.2a.

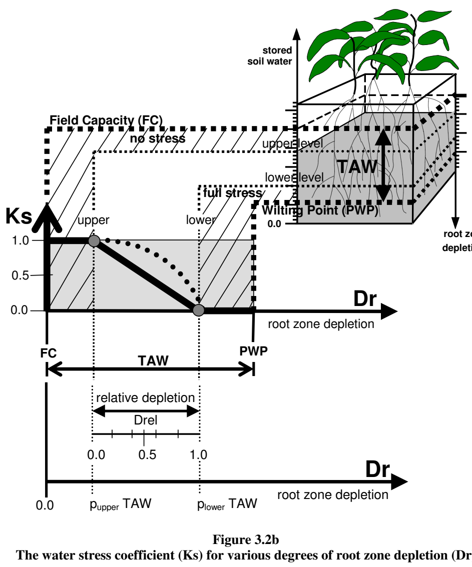



**Figure 3.2b**
**The water stress coefficient (Ks) for various degrees of root zone depletion (Dr)**

The stress indicator for soil water stress is the root zone depletion (Dr) which is expressed as a fraction (p) of TAW depleted. Water stress starts to affect the process when the root zone depletion exceeds $p_{upper}$ TAW. At the lower threshold, when the root



zone depletion is equal to $p_{lower}$ TAW, the effect of water stress is at its full strength (Fig. 3.2b). Each of the processes affected by soil water stress has its own threshold levels. For leaf and hence canopy growth ($Ks_{exp,w}$) the lower threshold is above PWP, where as for stomata closure ($Ks_{sto}$), senescence ($Ks_{sen}$) and failure of pollination ($Ks_{pol,w}$) the lower threshold is fixed at PWP. The shape of the Ks curve can be linear or convex.

Since the stress response curves are defined for an evaporating power of the atmosphere ($ET_o$) of 5 mm/day, the upper and lower thresholds for water stress (p) needs to be adjusted for $ET_o$:

$$0 \leq p_{adj} = p_{given} + f_{adj}\left(0.04\,(5 - ET_0)\right)\left(\log_{10}(10 - 9\, p_{given}\right) \leq 1 \qquad \text{(Eq. 3.2d)}$$

where $f_{adj}$ (default value = 1) is a program parameter which can be varied to increase (> 1) or decrease (< 1) the adjustment. The log term in the equation makes the adjustment greater when the soil is wet then when it is dry, based on the likely restriction of stomata and transpiration (and hence less impact of evaporative demand) when the soil is dry.

**Table 3.2a**
**Considered soil water stress coefficients and their effect on crop growth**

| **Soil water stress coefficient** | **Direct effect** | **Target model parameter** |
|---|---|---|
| **$Ks_{aer}$** Soil water stress coefficient for water logging (aeration stress) | Reduces crop transpiration | $Tr_x$ |
| **$Ks_{exp,w}$** Soil water stress coefficient for canopy expansion | Reduces canopy expansion and (depending on timing and strength of the stress) might have a positive effect on the Harvest Index | CGC and HI |
| **$Ks_{pol,w}$** Soil water stress coefficient for pollination | Affects flowering and (depending on duration and strength of the stress) might have a negative affect on the Harvest Index | $HI_o$ |
| **$Ks_{sen}$** Soil water stress coefficient for canopy senescence | Reduces green canopy cover and hence affects crop transpiration | CC |
| **$Ks_{sto}$** Soil water stress coefficient for stomatal closure | Reduces crop transpiration and the root zone expansion, and (depending on timing and strength of the stress) might have a negative effect on the Harvest Index | $Tr_x$ and HI |

### 3.2.3 Air temperature stress

Production of biomass and pollination of flowers might be affected by air temperature stress. The air temperature stress coefficients considered by AquaCrop and their effects on crop growth are presented in Table 3.2b.

**Table 3.2b**
**Considered air temperature stress coefficients and their effect on crop growth**

| Air temperature stress coefficient | Direct effect | Target model parameter |
|---|---|---|
| **$Ks_b$** Cold stress coefficient for biomass production | Reduces biomass production | WP* |
| **$Ks_{pol,c}$** Cold stress coefficient for pollination | Affects flowering and (depending on duration and strength of the stress) might have a negative affect on the Harvest Index | $HI_o$ |
| **$Ks_{pol,h}$** Heat stress coefficient for pollination | Affects flowering and (depending on duration and strength of the stress) might have a negative affect on the Harvest Index | $HI_o$ |

Stress indicators for air temperature stress are growing degrees ($Ks_b$), minimum air temperature ($Ks_{pol,c}$) or maximum air temperature ($Ks_{pol,h}$). If it is a cold stress, the process is completely halted (Ks = 0) at and below the lower threshold, and not affected (Ks = 1) at and above the upper threshold (Fig. 3.2c). For heat stress it is the other way round: below the lower threshold of the maximum air temperature Ks is 1, and above the upper threshold Ks becomes zero. For air temperatures stresses a logistic shape of the Ks curve is considered.

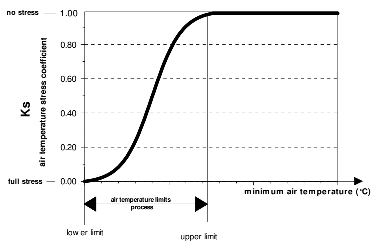



**Figure 3.2c**
**The cold stress coefficient (Ks) for various air temperatures**



### 3.2.4 Soil fertility stress

Canopy development and biomass production might be affected by soil fertility stress. The stress coefficients considered by AquaCrop and their effects on crop growth are presented in Table 3.2c. Next to the 3 stress coefficients (Ks), AquaCrop considers also a decline coefficient ($f_{CDecline}$) which uses the same stress indicator and is also a modifier of a model parameter.

**Table 3.2c**
**Considered soil fertility stress coefficients and their effect on crop growth**

| Soil fertility stress coefficient | Direct effect | Target model parameter |
|---|---|---|
| **$Ks_{CCx}$** Stress coefficient for maximum Canopy Cover | Reduces canopy cover | $CC_x$ |
| **$Ks_{exp,f}$** Stress coefficient for canopy expansion | Reduces canopy expansion | CGC |
| **$Ks_{WP}$** Stress coefficient for Water Productivity | Reduces biomass production | WP* |
| | | |
| **$f_{CDecline}$** Decline coefficient of canopy cover | Decline of the canopy cover once the maximum canopy cover is reached | $CC_x$ |

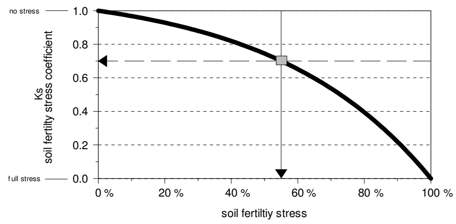



**Figure 3.2d**
**The soil fertility stress coefficient (Ks) for various levels of stress, with indication of the calibration point (square) determining the shape of the Ks curve.**



The stress indicator for soil fertility stress is the degree of soil fertility stress which varies from 0 %, when soil fertility is non-limiting, to a theoretical 100 % when soil fertility stress is so severe that crop production is no longer possible (Fig 3.2d). Between the upper and lower limits for soil fertility, Ks varies from 1 (no stress) to 0 (full stress).

The shape of the Ks curves is determined at calibration by specifying a Ks value between 1 and 0 for the particular soil fertility stress at which the crop response is calibrated (see Chapter 2, Section 2.9.7 Calibration for soil fertility or soil salinity stress). Once a curve is calibrated, the Ks corresponding to other degrees of soil fertility stress is obtained from the curve.



### 3.2.5 Soil salinity stress

- **Soil salinity stress coefficient**

Crop production might be affected by soil salinity stress. The soil salinity stress coefficient considered by AquaCrop and its effect is presented in Table 3.2e.

**Table 3.2e**
**Considered soil salinity stress coefficient and its effect on crop production**

| Soil salinity stress coefficient | Direct effect | Target model parameter |
|---|---|---|
| **$Ks_{salt}$** Soil salinity stress coefficient | Reduces biomass production | Tr |

The average electrical conductivity of saturation soil-paste extract (ECe) from the root zone is the indicator for soil salinity stress. At the lower threshold of soil salinity ($ECe_n$) the stress starts to affect crop production and Ks becomes smaller than 1. At and above the upper threshold for soil salinity ($ECe_x$) the stress becomes so severe that crop production ceases and Ks is zero (Fig. 3.2e). The shape of the Ks curve may be linear, concave, 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.

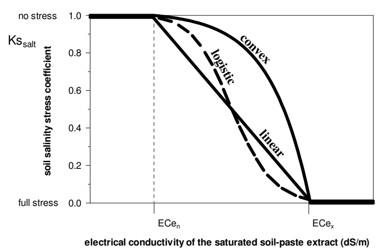



**Figure 3.2e**
**Linear, convex, and logistic shapes of the $Ks_{salt}$ curve**

- **Simulating the effect of soil salinity on crop 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. 3.2e) determines the relative biomass production ($B_{rel}$):

$$B_{rel} = 100\,(1 - Ks_{salt}) \qquad \text{(Eq. 3.2e)}$$

$B_{rel}$ 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 water and soil fertility stress.

To simulate the effect of soil salinity on biomass production (B), AquaCrop considers a set of stress coefficients which (i) affect canopy development (assumed to be similar as the effect of soil fertility stress) and (ii) induces stomatal closure. The stress coefficients considered by AquaCrop and their effects on crop growth are presented in Table 3.2d. Next to the 3 stress coefficients (Ks), AquaCrop considers also a decline coefficient ($f_{CDecline}$) which uses the same stress indicator and is also a modifier of a model parameter.

**Table 3.2d**
**Considered soil salinity stress coefficients and their effect on crop growth**

| Soil salinity stress coefficient | Direct effect | Target model parameter |
|---|---|---|
| **$Ks_{CCx}$** Stress coefficient for maximum Canopy Cover | Reduces canopy cover | $CC_x$ |
| **$Ks_{exp,f}$** Stress coefficient for canopy expansion | Reduces canopy expansion | CGC |
| **$Ks_{sto,salt}$** Soil salinity stress coefficient for stomatal closure | Reduces crop transpiration | $Ks_{sto}$ |
| | | |
| **$f_{CDecline}$** Decline coefficient of canopy cover | Decline of the canopy cover once the maximum canopy cover is reached | $CC_x$ |

.



## 3.3 Growing Degree Days

Heat units, expressed in growing degree-days (GDD), can be used in AquaCrop to describe crop development. With this method, the duration of a process or the time required to reach a particular stage is expressed in GDD (°C day) in stead of number of days.

Growing degree days (GDD) are calculated by subtracting the base temperature from the average air temperature ($T_{avg}$):

$$GDD = T_{avg} - T_{base} \qquad \text{(Eq. 3.3a)}$$

The base temperature ($T_{base}$) is the temperature below which crop development does not progress. In AquaCrop an upper threshold temperature ($T_{upper}$) is considered as well. The upper temperature threshold specifies the temperature above which crop development no longer increases with an increase in air temperature.

McMaster and Wilhelm (1997) present two methods for calculating $T_{avg}$ in Eq. 3.3a. The authors report that Method 1 predominates among researchers and practitioners involved with small grain cereals such as wheat and barley. Method 2 is the most commonly used in calculating GDD for corn, but it is used for other crops as well. In AquaCrop a 3[rd] method is added.

### 3.3.1 Method 1

The average air temperature ($T_{avg}$) is given by:

$$T_{avg} = \frac{(T_x + T_n)}{2} \qquad \text{(Eq. 3.3b)}$$

where $T_x$ is the daily maximum air temperature and $T_n$ the daily minimum air temperature. Once $T_{avg}$ is calculated, it is checked if the average air temperature is between $T_{base}$ and $T_{upper}$. If $T_{avg}$ is less than $T_{base}$, then $T_{avg}$ is taken as $T_{base}$ (resulting in 0 °C day for that day). If $T_{avg}$ is greater than $T_{upper}$, then $T_{avg}$ is taken equal to $T_{upper}$ and the growing degrees for that day are at its maximum ($T_{upper}$ - $T_{base}$).

### 3.3.2 Method 2

In this method the comparison to $T_{base}$ and $T_{upper}$ occurs before the calculation of the average temperature. $T_n$ and $T_x$ are adjusted if they drop below $T_{base}$ or exceed $T_{upper}$ before $T_{avg}$ is calculated. The average temperature is given by:

$$T_{avg} = \frac{(T_x^* + T_n^*)}{2} \qquad \text{(Eq. 3.3c)}$$



where $T_x^*$ and $T_n^*$ are the adjusted maximum and/or minimum air temperatures. The following rules apply:

- $T_x^*$ is the maximum air temperature ($T_x^* = T_x$)
  If $T_x$ is greater than $T_{upper}$, then $T_x^* = T_{upper}$,
  If $T_x$ is smaller than $T_{base}$, then $T_x^* = T_{base}$
- $T_n^*$ is the minimum air temperature ($T_n^* = T_n$)
  If $T_n$ is greater than $T_{upper}$, then $T_n^* = T_{upper}$,
  If $T_n$ is smaller than $T_{base}$, then $T_n^* = T_{base}$

### 3.3.3 Method 3

As in method 2, the comparison to $T_{base}$ and $T_{upper}$ occurs before the calculation of the average temperature. However the check is only on the maximum air temperature. The average temperature is given by:

$$T_{avg} = \frac{(T_x^* + T_n)}{2} \qquad \text{(Eq. 3.3d)}$$

where $T_x^*$ is the adjusted maximum air temperature and $T_n$ the minimum air temperature. The following rules apply:

- $T_x^*$ is the maximum air temperature ($T_x^* = T_x$)
  If $T_x$ is greater than $T_{upper}$, then $T_x^* = T_{upper}$,
  If $T_x$ is smaller than $T_{base}$, then $T_x^* = T_{base}$
- $T_n$ is not adjusted. However if $T_n$ exceeds $T_{upper}$, $T_n$ will be set equal to $T_{upper}$.

Once $T_{avg}$ is calculated, it is checked if the average air temperature is above the base temperature. If $T_{avg}$ is less than $T_{base}$, then $T_{avg}$ is taken as $T_{base}$ (resulting in 0 °C day on that day).



## 3.4 Green canopy cover for optimal conditions

### 3.4.1 Green canopy cover throughout the crop cycle

The development and senescence of the green canopy under optimal conditions (Fig 3.4a) is described by four parameters:

- $CC_o$ : initial canopy cover at the time of 90% crop emergence or when the transplant is recovered [fraction or percentage ground cover]. The initial canopy cover is the product of plant density and the size of the canopy cover per seedling;
- CGC : canopy growth coefficient [fraction or percentage ground cover increase per day or growing degree day];
- $CC_x$ : maximum canopy cover for that plant density under optimal conditions [fraction or percentage ground cover];
- CDC: canopy decline coefficient [fraction or percentage ground cover decline per day or growing degree day];

and the moment when green canopy senescence is triggered (i.e. the start of canopy senescence counting from sowing or transplanting).

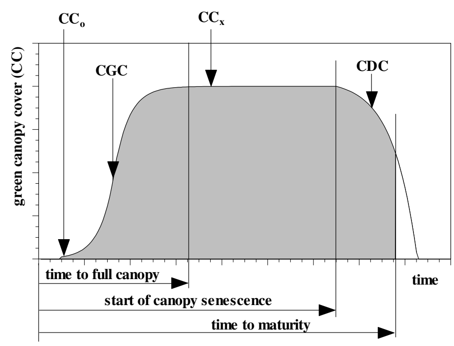



**Figure 3.4a**
**Variation of green canopy cover**
**throughout the growing cycle under non-stress conditions**

$CC_o$, CGC and $CC_x$ determine the time required to reach maximum canopy cover. If $CC_o$ and CGC are large, the maximum canopy ($CC_x$) is reached quickly. If crop development starts with a small $CC_o$, the period to reach maximum canopy cover will be longer. The canopy decline coefficient CDC determines the rate of the green canopy decline in the late season. Often crops will be mature and be ready to harvest before the full canopy decline is achieved.

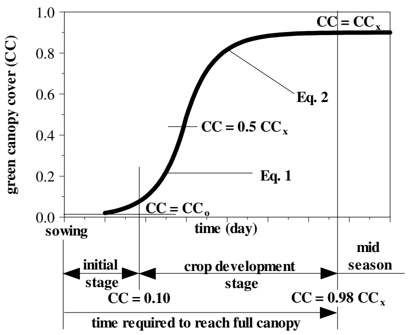



**Figure 3.4b**
**Schematic representation of canopy development during the exponential growth (Eq. 1) and the exponential decay (Eq. 2) stages**

### 3.4.2 Canopy development

Canopy development (Figure 3.4b) is simulated by two equations:

- Equation 1 (exponential growth) is valid when $CC \leq CC_x/2$

$$CC = CC_o \, e^{t\,CGC} \qquad \text{(Eq.3.4a)}$$

- Equation 2 (exponential decay) is valid when $CC > CC_x/2$

$$CC = CC_x - 0.25 \frac{(CC_x)^2}{CC_o} e^{-t\,CGC} \qquad \text{(Eq. 3.4b)}$$



where
- CC canopy cover at time t [fraction ground cover];
- $CC_o$ initial canopy size at t=0 [fraction ground cover];
- $CC_x$ maximum canopy cover [fraction ground cover];
- CGC canopy growth coefficient [increase of fraction ground cover per day or growing degree day];
- t time [day or growing degree day].

### 3.4.3 Germination and initial canopy cover at 90% crop emergence

To trigger germination during a simulation run, the soil water content in the top soil needs to be above a threshold value. The threshold value for the soil water content is expressed as a fraction of TAW and is a program parameter. The top soil considered at germination is the effective rooting depth at planting ($Z_n$) and refers to the soil depth from which the germinating seed can extract water (see 3.6.1 – Effective rooting depth at planting).

The initial canopy cover at germination is determined by the sowing or planting density. $CC_o$ is estimated from the sowing or planting density (plants per hectare) and the canopy cover of the seedling ($cm^2$). Options are available to estimate the planting density from sowing rate and approximate germination rate, or from plant spacing.

### 3.4.4 Maximum canopy cover ($CC_x$)

For no stress conditions, the canopy cover will reach the maximum canopy cover, $CC_x$. For optimal conditions $CC_x$ is determined by crop species and plant density.

### 3.4.5 Green canopy cover decline

The decline in green crop canopy is described by:

$$CC = CC_x \left[ 1 - 0.05 \left( e^{\frac{CDC}{CC_x} t} - 1 \right) \right] \qquad \text{(Eq. 3.4c)}$$

where
- CC canopy cover at time t [fraction ground cover];
- $CC_x$ maximum canopy cover at the start of senescence (t=0) [fraction ground cover];
- CDC canopy decline coefficient [$day^{-1}$ or growing degree $day^{-1}$];
- t time [days or growing degree days].

The Canopy Decline Coefficient (CDC) is a measure for the speed of decline of the green canopy once it is triggered. A large CDC results in a steep decline of the canopy, while the canopy senescence will be more gradually by selecting a smaller CDC (Fig. 3.4c).



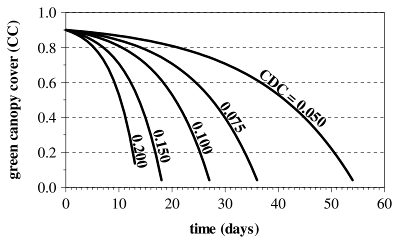



**Figure 3.4c**
**Decline of green canopy cover during senescence for various canopy decline coefficients (CDC) as described by Eq. 3.4c. All lines have initial green canopy cover at 0.9 and starting time at 0**

### 3.4.6 Green canopy cover for forage crops

Forage crops are (perennial) crops that are usually cut several times per season. At each cut the major part of the above-ground biomass is harvested.

*under development*



## 3.5 Green canopy cover for stress conditions

The effects of stress on canopy development are manifested through series of stress coefficients. Stress coefficients (Ks) are indicators of the relative intensity of the effect. In essence, Ks is a modifier of its target model parameter, and varies in value from one, when the effect is non-existent, to zero when the effect is maximum (see 3.2 Stresses).

Soil water, soil fertility and soil salinity stress decrease canopy expansion. As a result, the expected maximum canopy cover $CC_x$ might not be achieved or achieved much later in the season. The adjustment on canopy expansion is simulated by multiplying the target model parameter CGC (canopy growth coefficient) with the corresponding stress coefficient (Ks < 1). Under severe water stress, the canopy development might be brought to a standstill and canopy senescence might even be triggered. Also when the crop transpiration is fully inhibited CC no longer can increase. Soil fertility and soil salinity stress do not only decrease the growing capacity of the crop but affect as well the maximum canopy that can be reached ($CC_x$) and result in a steady decline of the canopy cover once $CC_x$ is reached at mid season. The effect of stresses on green canopy cover (CC) is schematically presented in Fig. 3.5a.

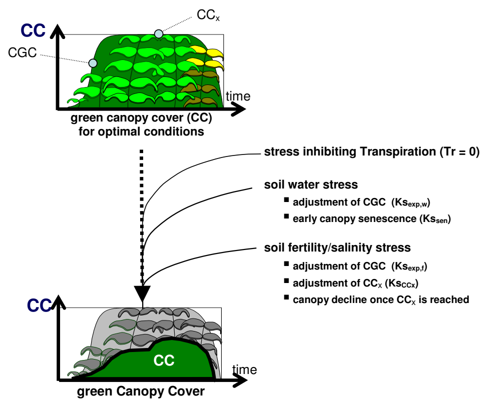



**Figure 3.5a**
**Stresses affecting green canopy cover (CC)**

### 3.5.1 Period of potential vegetative growth

The achievement of the maximum canopy cover $CC_x$ is delayed when stresses affect the canopy growth coefficient CGC and reduce leaf growth. If the period of potential vegetative growth is too short, $CC_x$ might not be achieved at all.

The period of potential vegetative growth depends on how determinant is the crop's growth habit. For determinant crops, once peak flowering is passed and fruits or grain begin to fill, CC has reached its maximum regardless of whether the CC at that time has or has not been reduced by stress. For indeterminant crops the canopy development stage can be stretched till canopy senescence (Fig. 3.5b).

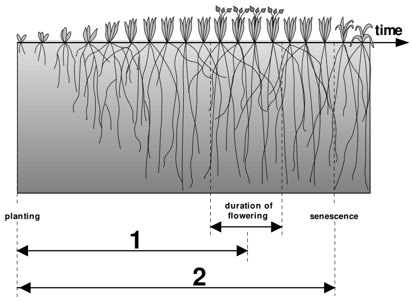



**Figure 3.5b**
**Period of potential vegetative growth for (1) determinant crops and (2) indeterminant crops**



### 3.5.2 Adjustment of canopy growth coefficient due to water stress

Leaf growth by area expansion and therefore canopy development is sensitive to water stress. To simulate the reduction in leaf growth as a result of water stress, the crop growth coefficient (CGC) is adjusted for the stress effect by multiplying it with the water stress coefficient for leaf expansion growth ($Ks_{exp,w}$):

$$CGC_{adj} = Ks_{exp,w}\ CGC \qquad \text{(Eq. 3.5a)}$$

where $Ks_{exp,w}$ water stress coefficient for leaf expansion growth;
CGC — CGC for optimal conditions [fraction or percentage ground cover increase per day or growing degree day];
$CGC_{adj}$ — CGC adjusted for water stress [fraction or percentage ground cover increase per day or growing degree day].

Between the upper and lower threshold for root zone depletion, the water stress coefficient decreases gradually from one to zero (Fig 3.5c). $Ks_{exp,w}$ is zero when the root zone depletion is at or exceeds its lower threshold.

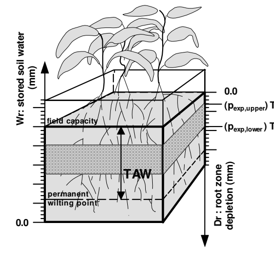



**Figure 3.5c**
**The upper and lower threshold for root zone depletion affecting leaf growth by area expansion**

Canopy development is reduced as soon as the root zone depletion (Dr) exceeds the upper threshold:

$$Dr_{exp,upper} = p_{exp,upper}\ TAW \qquad \text{(Eq.3.5b)}$$

where $Dr_{exp,upper}$ upper threshold expressed as root zone depletion [mm];
$p_{exp,upper}$ — fraction of TAW that can be depleted from the root zone before leaf expansion starts to be limited;
TAW — total available soil water in the root zone [mm].



When the root zone depletion (Dr) reaches its lower limit, leaf expansion is completely halted:

$$Dr_{exp,lower} = p_{exp,lower}\ TAW \qquad \text{(Eq.3.5c)}$$

where $Dr_{exp,lower}$ lower threshold expressed as root zone depletion [mm];
$p_{exp,lower}$ — depletion fraction of TAW at which there is no longer any leaf expansion growth.

Between the upper and lower thresholds the shape of the Ks curve determines the magnitude of the stress (Fig. 3.5d). In AquaCrop the shape of the Ks curve can be selected as linear or concave (see 3.2 Stresses).

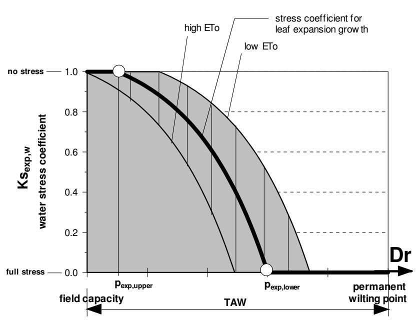



**Figure 3.5d**
**Water stress coefficient for leaf expansion growth ($Ks_{exp,w}$) for various degrees of root zone depletion (Dr)**

When water stress reduces leaf growth, the expected maximum canopy cover $CC_x$ might not be achieved or achieved only much later in the season. Therefore the program will stretch the canopy development to the time when $CC_x$ can be reached with the adjusted CGC. Once $CC_x$ is reached, it is assumed in the model that reduced leaf growth has virtually no direct effect on canopy cover anymore (and consequently on crop transpiration, soil evaporation and biomass production).



### 3.5.3 Early canopy senescence under severe water stress conditions

Under severe water stress conditions, canopy senescence will be triggered. Early canopy senescence will occur as soon as the root zone depletion (Dr) exceeds the upper threshold:

$$Dr_{sen,upper} = p_{sen}\ TAW \qquad \text{(Eq.3.5d)}$$

where $Dr_{sen}$ upper threshold expressed as root zone depletion [mm];
$p_{sen}$ — fraction of TAW that can be depleted from the root zone before canopy senescence is triggered;
TAW — total available soil water in the root zone [mm].

Once the root zone depletion reaches the lower limit (which is permanent wilting point):

$$Dr_{sen,lower} = TAW \qquad \text{(Eq. 3.5e)}$$

the canopy decline is at full speed. The upper and lower threshold for root zone depletion are plotted in Figure 3.5e

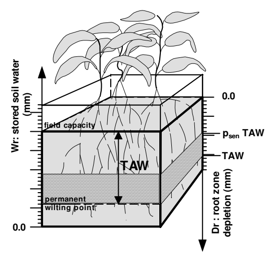



**Figure 3.5e**
**The upper and lower threshold for root zone depletion affecting early canopy senescence**

Between the upper and lower threshold the rate of canopy decline (CDC), which simulates the early canopy senescence, is adjusted to the degree of water stress. The canopy decline will be very small when water stress is limited, but increases with larger water stresses. This is simulated by adjusting the canopy decline coefficient with the water stress coefficient for senescence ($Ks_{sen}$). To guarantee a fast enough decline at strong root zone depletion, the 8[th] power of $Ks_{sen}$ is considered:

$$CDC_{adj} = \left(1 - Ks_{sen}^{8}\right) CDC \qquad \text{(Eq. 3.5f)}$$

where CDC reference canopy decline coefficient;
$Ks_{sen}$ water stress coefficient for early canopy senescence.

Between the upper and lower thresholds the shape of the Ks curve determines the magnitude of the stress (Fig. 3.5f). In AquaCrop the shape of the Ks curve can be selected as linear or concave (see 3.2 Stresses).

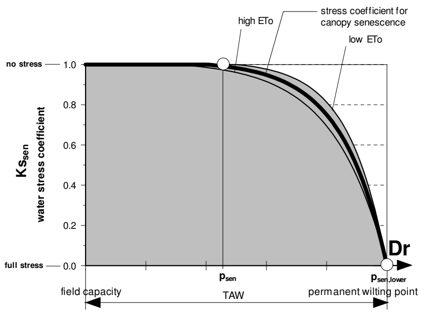



**Figure 3.5f**
**Water stress coefficient for early canopy senescence ($Ks_{sen}$) for various degrees of root zone depletion (Dr)**

A small amount of rain or a slight expansion of the root zone in a wet subsoil, might reduce the root zone depletion above $Dr_{sen,upper}$ and de-activate as such the canopy senescence. To avoid such an overreaction of the program, $p_{sen}$ is reduced with a few percentages (β) once early canopy senescence is triggered:

$$p_{sen,adj} = p_{sen} \left(1 - \frac{\beta}{100}\right) \qquad \text{(Eq. 3.5g)}$$

β is a program parameter, and its value can vary between 0 % (no adjustment) to 25 %.



### 3.5.4 Canopy development when transpiration is inhibited

Severe water or salinity stress or deficient aeration conditions in the root zone will affect crop transpiration (see 3.10 Crop transpiration). When the transpiration rate plunges to zero as a result of prolonged water logging, the absence of an evaporative demand, when permanent wilting point is reached or when the soil salinity exceeds the upper thresholds, the development of the canopy will be brought to a standstill as a result of the feedback mechanism of transpiration on canopy development (see 3.10.7).

### 3.5.5 Canopy development for soil fertility or soil salinity stress

Limited soil fertility or soil salinity stress decreases the growing capacity of the crop (CGC) as well as the maximum canopy cover ($CC_x$) that can be reached at mid season. The adjustments of CGC and $CC_x$ for soil fertility/salinity stress are given by:

$$CGC_{adj} = Ks_{exp,f}\ CGC \qquad \text{(Eq. 3.5h)}$$

$$CC_{x,adj} = Ks_{CCx}\ CC_x \qquad \text{(Eq. 3.5i)}$$

where CGC and $CC_x$ are the canopy growth coefficient (fraction or percentage per day) and the maximum canopy cover (fraction or percentage) in the absence of soil fertility or soil salinity stress, and $Ks_{exp,f}$ and $Ks_{CCx}$ the stress coefficients.

For non-limiting soil fertility (i.e. soil fertility stress is zero) and in the absence of soil salinity stress the stress coefficients are 1. When the soil fertility/salinity stress is complete, crop growth is no longer possible and the Ks coefficients reach their theoretical minimum of zero. Between the upper and lower limits the Ks coefficients vary between 1 and 0 (Fig. 3.5g).

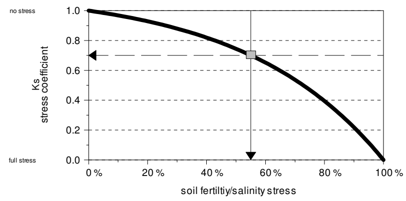



**Figure 3.5g**
**Soil fertility stress coefficient for various soil fertility/salinity stresses (full line) with indication of the Ks and soil fertility/salinity stress used for calibration (square)**



The shape of the Ks curves can be convex, linear or concave and may differ between the 2 Ks curves. The shape of each of the curves is determined at calibration by specifying a value between 1 and 0 for $Ks_{exp,f}$ and $Ks_{CCx}$ for the particular soil fertility stress at which the crop response is calibrated (see Chapter 2, section 2.9.7 – Calibration for soil fertility or soil salinity stress).

Due to the fertility/salinity stress in the soil, the canopy cover (CC) will steadily decline once $CC_x$ is reached at mid season (Fig. 3.5h). The average daily decline of the canopy cover is given by $f_{CDecline}$ (fraction per day). Since the decline becomes stronger when time advances, the adjustment for the Canopy Cover between the time when full canopy cover is reached ($t_{full\ canopy}$) and the start of canopy senescence at late season ($t_{sen}$), is simulated by:

$$CC_{adj} = CC_{x,adj} - f_{CDecline} \frac{\left(t - t_{full\ canopy}\right)^2}{\left(t_{sen} - t_{full\ canopy}\right)} \qquad \text{(Eq. 3.5j)}$$

where t is the time (days or growing degree days) after full canopy is reached.

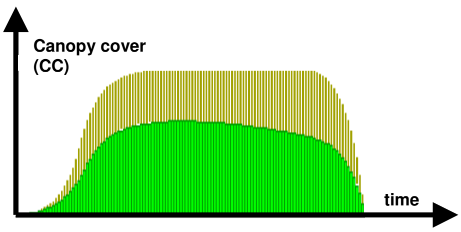



**Figure 3.5h**
**Canopy cover in the absence (light area) and in the presence (dark area) of soil fertility/salinity stress**

The calibration for the average daily decline of the canopy cover ($f_{CDecline}$) follows the same approach as for $Ks_{exp,f}$ and $Ks_{CCx}$. In the absence of soil fertility or soil salinity stress the decline is zero (see Chapter 2, section 2.9.7 – Calibration for soil fertility or soil salinity stress). When the stress is complete (100%), a maximum decline of 1 % per day is assumed. Between the upper and lower limits $f_{CDecline}$ varies between 0 and 1 % per day.



### 3.5.6 The effect of soil salinity stress on the thresholds for soil water depletion

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 ($Ks_{leaf}$), 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. 3.5i).

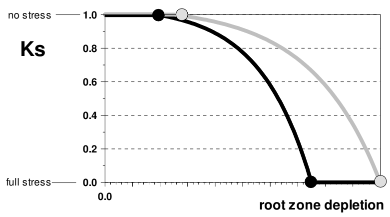



**Figure 3.5i –** Shift of the thresholds (circles) for root zone depletion and its effect on th threshold for leaf expansion and canopy senescence (lines) with (black) and without (gray) the effect of soil salinity on the thresholds.

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).

## 3.6 Effective rooting depth

The effective rooting depth is defined as the soil depth where root proliferation is sufficient to extract most of the crop water demand. The expansion of the effective rooting depth (Z) in a well water soil is simulated by considering an exponential root deepening function till the maximum rooting depth ($Z_x$) is reached (Fig. 3.6a (a)). Since in AquaCrop the time to reach maximum canopy cover ($CC_x$) is independent from the time to reach $Z_x$, the interdependence between root and shoot is not tight.

Since root growth is more resistant to water stress than leaf growth, root development is not affected when canopy expansion starts to be reduced. Only when the soil water stress starts to affect crop transpiration, the incremental daily root deepening under normal condition is adjusted to the water stress (Fig. 3.6a (b)). If there is at a certain depth a layer of soil restrictive to root growth, roots should deepen normally until the restrictive layer is reached (Fig. 3.6a (c)).

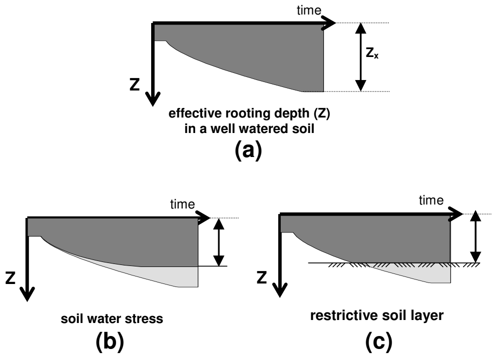



**Figure 3.6a**
**Calculation scheme in AquaCrop for root deeping: (a) in a well watered soil, (b) when water stress affects crop transpiration, and (c) in the presence of a restrictive soil layer inhibiting root development**



### 3.6.1 Effective rooting depth at planting ($Z_n$)

The rooting depth at planting is very small and corresponds with the sowing depth or the rooting depth of the transplanted seedling. The effective rooting depth at planting, $Z_n$, is the soil depth from which the germinating seed or the young seedling can extract water and is larger than the sowing depth. For water balance calculation, a minimum effective rooting depth of 0.2 to 0.3 meter is generally considered appropriate.

### 3.6.2 Expansion of the root zone in a well watered soil

The root deepening rate is a function of crop type and time. In AquaCrop the development of the rooting depth is simulated by considering the $n^{th}$ root of time. Once half of the time required for crop emergence (or plant recovery in case of transplanting) is passed by ($t_0/2$), the rooting depth starts to increase from an initial depth $Z_o$ till the maximum effective rooting depth $Z_x$ is reached:

$$Z = Z_o + (Z_x - Z_o)\sqrt[n]{\frac{\left(t - \frac{t_0}{2}\right)}{\left(t_x - \frac{t_0}{2}\right)}} \qquad \text{(Eq. 3.6a)}$$

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

The development of the effective root zone starts when Z exceeds the minimum effective rooting depth ($Z_n$) and advances till the maximum effective rooting depth ($Z_x$) is reached (Fig. 3.6b). At any time the effective rooting depth Z is given by

$$Z_n \leq Z \leq Z_x \qquad \text{(Eq. 3.6b)}$$

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

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



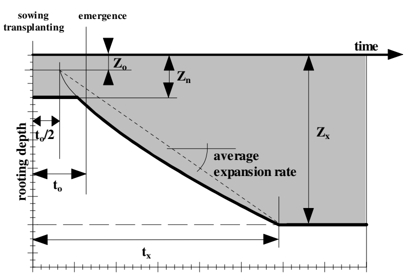



**Figure 3.5b**
**Development of the effective rooting depth (shaded area) from sowing till the maximum effective rooting depth ($Z_x$) is reached**

### 3.6.3 Rooting depth for Forage crops

The rooting depth of perennial forage and pasture crops develops only in the first season. From the second season onwards, the rooting depth is constant and equal to $Z_x$.

### 3.6.4 Expansion of the root zone when the crop is water stressed

Water stress affects crop development. Leaf expansion can already be reduced at small root zone depletions. The development of the root zone starts to be affected when the root zone depletion exceeds the upper threshold for stomatal closure (Dr > $p_{sto}$ TAW). At this depletion the water stress coefficient for stomatal closure ($Ks_{sto}$) becomes smaller than 1. The reduction in the expansion of effective rooting depth is determined by the magnitude of the $Ks_{sto}$ and a (negative) shape factor, $f_{shape}$.



The shape factor, $f_{shape}$, is a program parameter which can be adjusted by the user. The effect of water stress on the reduction of the root zone expansion is:

- **strong** for $f_{shape}$ = 0, and given by the linear relationship:

$$dZ_{adj} = Ks_{sto}\ dZ \qquad \text{(Eq. 3.6c)}$$

- **small to medium** for -1 ≤ $f_{shape}$ ≤ -8, and given by an exponential relationship:

$$dZ_{adj} = dZ\ \frac{e^{Ks_{sto}\ f_{shape}} - 1}{e^{f_{shape}} - 1} \qquad \text{(Eq. 3.6d)}$$

Making $f_{shape}$ (default is -6.0) more negative minimizes the effect of water stress on root zone development, whereas root zone development is slowed significant in the early period of stress development if $f_{shape}$ is close to -1.0 (Fig. 3.6c).

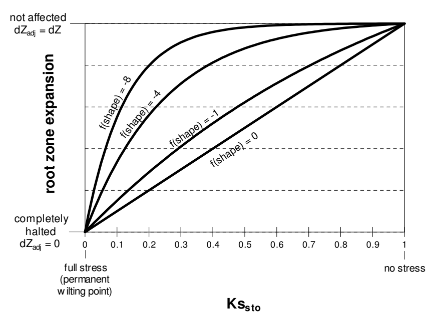



**Figure 3.6c**
**The effect of water stress on the reduction of root zone expansion for various shape factors ($f_{shape}$) and water stress in the root zone ($Ks_{sto}$)**

### 3.6.5 Expansion of the root zone in a shallow soil

The effective rooting depth might not reach its maximum value if a restrictive soil layer limit root development or when the exploitable soil depth is smaller than $Z_x$. The root deepening rate is described by Eq. 3.6a, but once the effective rooting depth reaches the restrictive soil layer, the expansion is halted (Fig 3.6d).

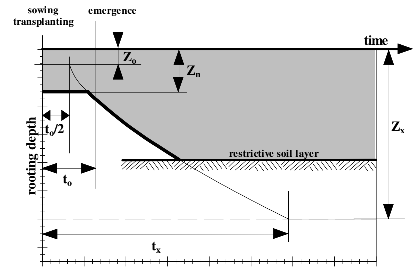



**Figure 3.6d**
**Development of the effective rooting depth (shaded area) in presence of a restrictive soil layer inhibiting the expansion of the root zone**



## 3.7 Soil water balance

### 3.7.1 Time - depth grid

To describe accurately the retention, movement and uptake of water in the soil profile throughout the growing season, AquaCrop divides both the soil profile and time into small fractions (Fig. 3.6a). As such the one-dimensional vertical water flow and root water uptake can be solved by means of a finite difference technique (Carnahan et al., 1969; Bear, 1972). A mesh of grid lines with spacing $\Delta z$ and $\Delta t$ is established throughout the region of interest occupied by the independent variables: soil depth (z) and time (t). The flow equation and water extraction by plant roots is solved for each node at different depths $z_i$ and time levels $t_j$ so that the dependent variable – the moisture content $\theta_{i,j}$ - is determined for each node of the solution mesh and for every time step.

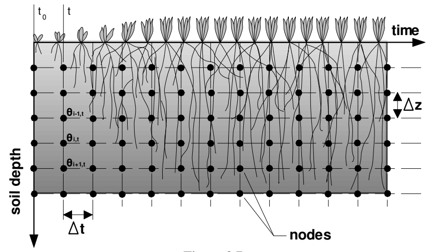



**Figure 3.7a**
**The time(t) – depth (z) grid for the solution of the soil water balance in AquaCrop**

In AquaCrop the time increment is fixed at one day and the depth increment ($\Delta z$) is by default 0.1 m. The soil profile is such divided into soil compartments (12 by default) with thickness $\Delta z$ (Fig 3.7b). The hydraulic characteristics of each compartment are that of the soil horizon to which it belongs. If a crop is selected with a deep effective root zone, AquaCrop will adjust the size of the compartments ($\Delta z$) to cover the entire root zone. For deep root zones, $\Delta z$ is not constant but increases exponentially with depth, so that infiltration, soil evaporation and crop transpiration from the top soil horizon can be described with sufficient detail. Program settings allow the user to adjust the number and size of the soil compartments.



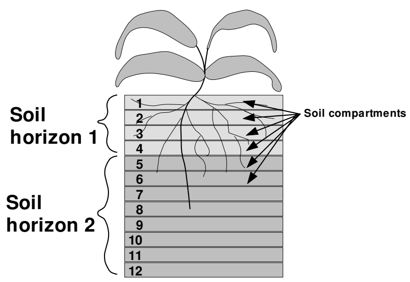



**Figure 3.7b**
**Soil horizons and soil compartments**

### 3.7.2 Calculation scheme

In AquaCrop, the differential flow equation is replaced by a set of finite difference equations (subroutines), written in terms of the dependent variable θ (Fig. 3.7c). The simulation starts with the drainage of the soil profile. Subsequently water infiltrates into the soil profile (after the subtraction of surface runoff), and finally the amount of water lost by soil evaporation and crop transpiration is calculated. In each of the described subroutines, the soil water content is updated at the end of the time step (j) and at each grid point (i), according to the calculated water content variation (Δθ). The final water content variation at the end of a time step is the result from various processes described in different subroutines.

Since the magnitude of the changes in soil water content, simulated in each of the subroutines, depends on the actual soil water content, the sequence of the calculations might theoretically have an influence on the final simulation result. The effect however will be small since the time step is restricted to one day. Further on, major changes in soil water content of the soil profile as a result of infiltration, internal redistribution of soil water and drainage, will only occur in a wet soil profile. But since in a wet soil the evaporation and transpiration are at their maximum rate, evapotranspiration is at that moment only dictated by the atmospheric water demand and crop development and hence independent of the soil water content in the soil profile. On the other hand, when the soil profile is dry, the simulated evaporation and transpiration rate depends strongly on the soil water content but at that moment soil water flow in the soil profile does not take place.



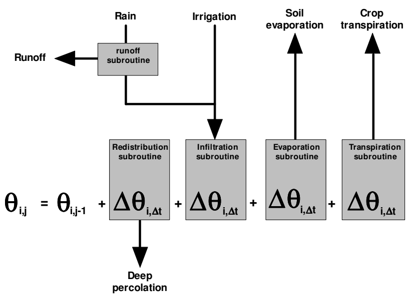



**Figure 3.7c**
**Calculation scheme of the soil water balance in AquaCrop**

### 3.7.3 Redistribution and drainage subroutine

▪ **Drainage function**

To simulate the redistribution of water into a soil layer, the drainage out of a soil profile, and the infiltration of rainfall and/or irrigation, AquaCrop makes use of a drainage function (Raes, 1982; Raes et al., 1988; Raes et al., 2006):

$$\frac{\Delta\theta_i}{\Delta t} = \tau\,(\theta_{SAT} - \theta_{FC})\,\frac{e^{\theta_i - \theta_{FC}} - 1}{e^{\theta_{sat} - \theta_{FC}} - 1} \qquad \text{(Eq. 3.7a)}$$

Where $\Delta\theta_i/\Delta t$ decrease in soil water content at depth i, during time step $\Delta t$ [$m^3.m^{-3}.day^{-1}$];
- $\tau$ drainage characteristic [-];
- $\theta_i$ actual soil water content at depth i [$m^3.m^{-3}$];
- $\theta_{SAT}$ soil water content at saturation [$m^3.m^{-3}$];
- $\theta_{FC}$ soil water content at field capacity [$m^3.m^{-3}$];
- $\Delta t$ time step [day].

note: IF $\theta_i = \theta_{FC}$ THEN $\Delta\theta_i/\Delta t = 0$
IF $\theta_i = \theta_{SAT}$ THEN $\Delta\theta_i/\Delta t = \tau\,(\theta_{SAT} - \theta_{FC})$

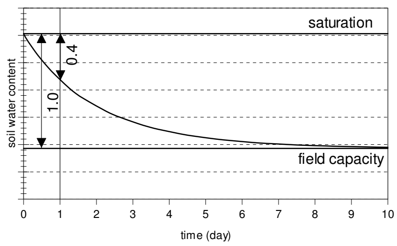



**Figure 3.7d**
**Variation of soil water content over time**
**in a free draining soil layer with a drainage characteristic of $\tau = 0.4$**

The drainage function describes the amount of water lost by free drainage over time between saturation and field capacity (Fig. 3.7d). The function is assumed to be exponential. When field capacity is reached further drainage of the soil is disregarded. The drainage function mimics quite realistically the infiltration and internal drainage as observed in the field (Raes, 1982; Feyen, 1987; Hess, 1999; Wiyo, 1999; Barrios Gonzales, 1999, Raes et al., 2006).

- **Drainage characteristic τ (tau)**

The drainage is described by the dimensionless drainage characteristic τ (tau). The drainage characteristic (τ) expresses the decrease in soil water content of a soil layer, originally at saturation, at the end of the first day of free drainage. It is expressed as a fraction of the total drainable amount of water, which is the water content between saturation and field capacity. In Figure 3.7d, τ is 0.4, which means that 40 % of the total drainable amount of water is lost from the fully saturated soil layer after one day of free drainage. The value of τ may vary between 1 (complete drainage after one day) and 0 (impermeable soil layer). The larger τ, the faster the soil layer will reach field capacity. A coarse textured sandy soil layer has a large τ while the τ value for a heavy clay layer is very small. In AquaCrop the close relationship (Barrios Gonzales, 1999) between the dimensionless drainage characteristics (ι) and the hydraulic conductivity at saturation ($K_{sat}$) is used to estimate the tau value:

$$0 \le \tau = 0.0866\ Ksat^{0.35} \le 1 \qquad \text{(Eq. 3.7b)}$$

where $K_{sat}$ is given in mm/day.



- **Calculation procedure**

In a uniform soil equally wet it can be assumed that the decrease in soil water content per day (Δθ/Δt) is constant throughout the draining profile. Given the actual soil water content, the corresponding drainage ability Δθ/Δt ($m^3.m^{-3}.day^{-1}$) is given by Eq. 3.7a. The amount of water DP (mm), which percolates out of the bottom of the soil profile at the end of each day, is given by:

$$DP = 1000\ \frac{\Delta\theta}{\Delta t}\ \Delta z\ \ \Delta t \qquad \text{(Eq. 3.7c)}$$

where θ the soil water content of the draining soil profile [$m^3.m^{-3}$];
Δθ/Δt drainage ability given by Eq. 3.6a [$m^3.m^{-3}.day^{-1}$];
Δz the thickness of the draining soil profile [m];
Δt the time step (1 day).

To simulate internal drainage in a profile composed of various compartments, not necessarily equally wet and may belong to soil horizons with different τ values, the calculation procedure considers the drainage ability ($\Delta\theta_i/\Delta t$) of the different compartments. The drainage ability for a particular soil water content between saturation and field capacity is given by Eq. 3.7a. The drainage ability is zero when the soil water content is lower than or equal to field capacity.

Given the soil water content of compartment 1, the decrease in soil water content during time step Δt is given by Eq. 3.7a. The amount of water $D_1$ (mm) that percolates out of the top compartment at the end of a time step is given by:

$$D_1 = 1000\ \frac{\Delta\theta_1}{\Delta t}\ \Delta z_1\ \ \Delta t \qquad \text{(Eq. 3.7d)}$$

where $D_1$ the flux between compartment 1 and 2 [mm];
$\theta_1$ the soil water content of the top compartment [$m^3.m^{-3}$];
$\Delta z_1$ the thickness of the top compartment [m];
Δt the time step (1 day).

Subsequently the soil water content of the top compartment is updated. The same calculations are repeated for the successive compartments. It is thereby assumed that the cumulative drainage amount $\Sigma D_i = D_1 + D_2 + \ldots$ will pass through any compartment as long as its drainage ability is greater than or equal to the drainage ability of the upperlying compartment. By comparing drainage abilities and not soil water contents, the calculation procedure is independent of the soil layer to which succeeding compartments may belong.

If a compartment is reached which drainage ability is smaller than the upperlying compartment, $\Sigma D_i$ will be stored in that compartment, thereby increasing its soil water



content and its drainage ability (Fig 3.7e). If the soil water content of the compartment becomes thereby as high that its drainage ability becomes equal to the drainage ability of the upperlying compartment, the excess of the cumulative drainage amount, increased with the calculated drainage amount $D_i$ of that compartment, will be transferred to the underlying compartment (as is the case in compartment 4 and 5 of Figure 3.7e). If the entire cumulative drainage amount can be stored in a compartment without increasing its soil water content in such a way that its drainage ability becomes equal to that of the upperlying compartment (as is the case in compartment 6), only the calculated drainage amount of that compartment will be transferred to the underlying compartment. If in a compartment the soil water content remains below field capacity, its drainability is zero and no water is transferred to the underlying compartment. At the bottom of the soil profile, the remaining part of ΣD will be lost as deep percolation (ΣD = DP).

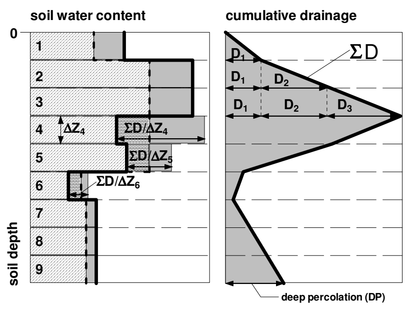



**Figure 3.7e**
**Schematic presentation of a draining soil profile (left) with indication of the soil water content before (full line) and at the end (dotted line) of the process of internal redistribution of the water, and the calculated cumulative drainage (right)**

In each compartment, the cumulative drainage amount $\Sigma D_i$ that passes through should be smaller than or equal to the maximum infiltration rate of the soil layer to which the soil compartment belongs. If not so, part of the $\Sigma D_i$ will be stored in that compartment, or if required in the compartments above, until the remaining part of $\Sigma D_i$ equals the infiltration rate of the soil layer.



### 3.7.4 Runoff subroutine

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

$$RO = \frac{[P - (0.2)\ S]^2}{P + S - (0.2)\ S} \qquad \text{(Eq. 3.7e)}$$

$$S = 254\left(\frac{100}{CN} - 1\right) \qquad \text{(Eq. 3.7f)}$$

where RO amount of water lost by surface runoff [mm];
P rainfall amount [mm];
(0.2)S initial abstraction [mm];, or
the amount of water that can infiltrate before runoff occurs
S potential maximum storage [mm], Eq. 3.7f;
CN Curve Number

The runoff process is described by Eq. 3.7e. Rain that falls on unsaturated soil infiltrates, increasing the soil water content until the topsoil becomes saturated (P = 0.2S), after which additional rainfall becomes surface runoff. A soil with a high Curve Number (CN) will have a small potential storage (S) and may loose a large amount of rainfall as runoff. The Curve Number of a soil is a function of its type, slope, land use, cover and the relative wetness of the top soil (Tab. 3.7a).

**Table 3.7a**
**Indicative CN values for various Antecedent Moisture Classes (AMC) II and their corresponding values for AMC I (dry) and III (wet) for various infiltration rates.**

| AMC | Soil water content | Infiltration rate (mm/day) | | | |
|---|---|---|---|---|---|
| | | >250 | 250-50 | 50-10 | <10 |
| I | $\theta = \theta_{PWP}$ | 45 | 56 | 63 | 70 |
| **II** | $\boldsymbol{\theta = (\theta_{FC} + \theta_{PWP})/2}$ | **65** | **75** | **80** | **85** |
| III | $\theta = \theta_{FC}$ | 84 | 88 | 91 | 93 |

In AquaCrop (soil characteristics) the specified CN value is the value that belongs to the antecedent moisture class AMC II ($CN_{AMC\ II}$). This value is considered when the soil water content in the top soil is half way between Field Capacity and Permanent Wilting Point. At run time, the specified Curve Number ($CN_{AMC\ II}$) is adjusted for the simulated wetness of the top soil layer. To adjust CN to the antecedent moisture class, relationships derived from CN values for various AMC presented by Smedema and Rycroft (1983) are used (Tab. 3.7a). The relationships used in AqauCrop to derive $CN_{AMC\ I}$ and $CN_{AMC\ II}$ from $CN_{AMC\ II}$ are:

$$CN_{AMC\,I} = -16.91 + 1.348\, CN_{AMC\,II} - 0.01379\, CN^2_{AMC\,II} + 0.0001172\, CN^3_{AMC\,II}$$
with $0 \le CN_{AMC\,I} \le 100$ (Eq.3.7g)

$$CN_{AMC\,III} = 2.5838 + 1.9449\, CN_{AMC\,II} - 0.014216\, CN^2_{AMC\,II} + 0.000045829\, CN^3_{AMC\,II}$$
with $0 \le CN_{AMC\,III} \le 100$ (Eq.3.7h)

The storage capacity of a soil is indeed somewhat larger (smaller CN value) if it is dry than when it is wet. By linear interpolation between the corresponding CN values at various antecedent moisture classes, CN is adjusted to the wetness of the topsoil.

The calculation of the relative wetness of the topsoil extends to a depth of 0.3 meter. In the calculation, the soil water content at the soil surface has a larger weight than the soil water content at 0.3 meter (Fig. 3.7f):

$$w_{rel} = 1 - \frac{\exp^{f\, d/dx} - 1}{\exp^{f} - 1} \qquad \text{(Eq. 3.7i)}$$

where $w_{rel}$ relative weighing factor
f shape factor (fixed at -4)
d soil depth (m)
dx the maximum depth considered as relevant for the adjustment of CN (default = 0.3 m)

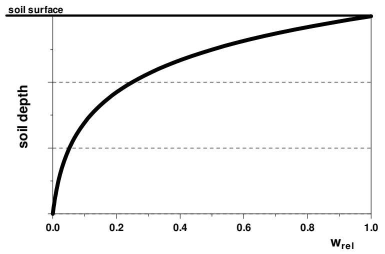



**Figure 3.7f**
**The value for the relative weighing factor ($w_{rel}$) at various soil depths**



Program settings allow the user to switch off the adjustment of CN for soil wetness and to adjust the default thickness of 0.3 m. Current thinking (Hawkins (personal communication) 2002) is that the AMC-I and AMC-III CN's are 'error-bands' to describe departure of surface runoff from all kind of sources, including soil moisture. There seems to be no much literature references to show real consistent impacts of prior soil water content on surface runoff on the scale proposed by USDA.

For simplicity, irrigation is assumed to be fully controlled; hence the runoff subroutine (for rainfall) is bypassed for irrigation water infiltration and tailwater is assumed to be zero. If surface runoff from the field is important when irrigating, the above assumption requires that irrigation be specified as a net application amount. The maximum amount that can infiltrate the soil, either as rainfall or irrigation, is however limited by saturated hydraulic conductivity of the topsoil layer. Excess water, is considered as lost by surface runoff.

Field practices (ploughing practices, ridges or soil bunds) might limit or prevent soil surface runoff. In case the field is surrounded by soil bunds, the runoff subroutine is bypassed. Water that cannot infiltrate as a result of excessive rainfall or irrigation will be stored between the bunds. The storage capacity is however limited by the height of the bunds. Water that overtops the bunds is assumed to be lost by surface runoff.

### 3.7.5 Infiltration subroutine

After the subtraction of surface runoff, the remaining part of the rainfall and irrigation water will infiltrate into the soil profile. In AquaCrop the amount of water that infiltrates in the soil profile is stored into succeeding compartments from the top downwards, thereby not exceeding a threshold soil water content $\theta°_i$ ($m^3.m^{-3}$). The threshold $\theta°_i$ at a particular soil depth, depends on the infiltration rate of the corresponding soil layer and on the amount of infiltrated water that is not yet stored in the soil profile. The drainage rate at $\theta°_i$, should correspond with the amount of water that still has to pass through the compartment during the time step. If the flux exceeds the maximum infiltration rate of the corresponding soil layer ($\theta°_i = \theta sat$), extra water will be stored in the compartments above, until the remaining part, that has to pass through the compartment per unit of time step, is equal to the maximum infiltration rate.

The calculation procedure is not completely independent of the thickness of the soil compartments. However, the simulation mimics quite realistic the infiltration process, by taking into account the initial wetness of the soil profile, the amount of water that infiltrates during the time step, the infiltration rate and drainage characteristics of the various soil layers of the soil profile.



### 3.7.6 Capillary rise

- **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:

$$CR = \exp\left(\frac{\ln(z) - b}{a}\right) \qquad \text{(Eq. 3.7j)}$$

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. 3.7g).

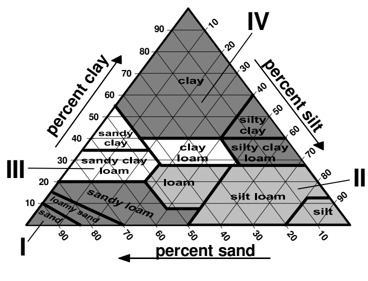



**Figure 3.7g –**Textural triangle with indication of the 12 different soil types and the 4 soil Classes considered for the determination of the a and b parameters of Eq. 6.1a.
I. Sandy soils (dark area), II. Loamy soils (grey area),
III. Sandy clayey soils (white area) and IV. Silty clayey soils (dark 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. 3.7g). 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. 3.7b);
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 3.7k and 3.7l in Tab. 3.7b) were always high ($R^2 > 0.96$).

The capillary rise from a shallow groundwater table (Eq. 3.7j) for the 4 soil classes and for various depths of the groundwater table are plotted in Figure 3.7h.

**Table 3.7b –** Equation 3.7k and 3.7l 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. 3.7k | b Eq. 3.7l |
|---|---|---|---|
| **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 | $-0.6366 + 8\,(10^{-4})\,K_{sat}$ | $-1.9165 + 0.7063 \ln(K_{sat})$ |

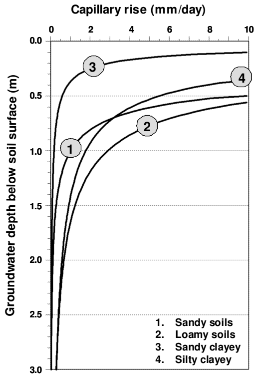



**Figure 3.7h –** Capillary rise to a bare soil surface, as obtained with Eq. 6.1a, for the 4 considered soil Classes and for various depths of a shallow groundwater table and by assuming a typical saturated hydraulic conductivity (Ksat) of 500 mm/day for Class I (Sandy soils), 250 mm/day for Class II (Loamy soils), 100 mm/day for Class III (Sandy clayey soils) and 25 mm/day for Class IV (Silty clayey soils).



- **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 ($\theta_{Sat}$), field capacity ($\theta_{FC}$), and permanent wilting point ($\theta_{PWP}$), and the value for the hydraulic conductivity at soil saturation (Ksat).

To generate default values for the a and b soil parameters (Eq. 3.7j), 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. 3.7c);
- in the next step, the a and b soil parameters for each soil layer with Eq. 3.7k and 3.7l (Tab. 3.7b) by considering (i) the soil class and (ii) the specified saturated hydraulic conductivity (Ksat).

**Table 3.7c –** 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. 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 Chapter 2, section 2.13 Soil profile characteristics).

- **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. 3.7i).

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:

$$\theta_{FCadj,i} = \theta_{FC} + \Delta\theta_{FC,i} \qquad \text{(Eq. 3.7m)}$$



$$\text{with } \Delta\theta_{FC,i} = \left[\frac{(\theta_{Sat} - \theta_{FC})}{x^2}\right](x - z_i)^2 \qquad \text{for } z_i \le x \qquad \text{(Eq. 3.7n)}$$

where $\theta_{FC}$ 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 ($m^3\ m^{-3}$)
$\theta_{sat}$ 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

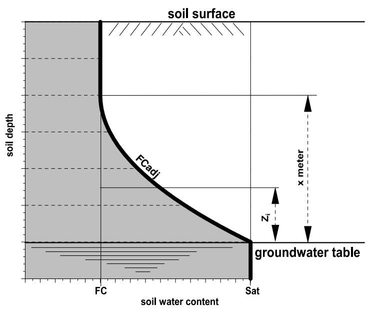



**Figure 3.7i –** Soil water profile in equilibrium with the groundwater table

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 $\theta_{sat}$, and at a height of x meter or more above the groundwater table (where $z_i \ge x$), $\theta_{FCadj,i}$ is equal to $\theta_{FC}$ (Fig. 3.7i).

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:



$$x = \frac{10^{2+0.3\left(\frac{\theta_{FC}-10}{30-10}\right)}}{100} \qquad \text{(Eq. 3.7o)}$$

where $\theta_{FC}$ the soil water content at FC (vol %) varying between 10 and 30 vol% (Tab. 3.7d).

**Table 3.7d –** The soil water content at Field Capacity ($\theta_{FC}$) and the height (x) above which the effect of the groundwater table on FC can be neglected (Eq. 3.7o).

| $\theta_{FC}$ (vol%) | x (meter) |
|---|---|
| $\theta_{FC} \le 10$ vol% | 1.00 |
| 15 | 1.19 |
| 20 | 1.41 |
| 25 | 1.68 |
| $\theta_{FC} \ge 30$ vol% | 2.00 |

- **Calculation procedure**

<u>**Concept**</u>

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. 3.7j);
2. Storage of water in that compartment till $\theta_i$ is equal to $\theta_{FCadj,i}$ or all the $CR_{max,i}$ has been stored. The amount of water stored in compartment i is:

IF $\theta_i \le \theta_{FCadj,I}$ THEN $W_{stored,i} = 1000\left(\theta_{FCadj,i} - \theta_i\right)\Delta z_i \le f_{CR,i}\ CR_{max,i}$ (Eq. 3.7p)
ELSE $W_{stored,i} = 0$ (Eq. 3.7q)

where $\Delta z_i$ is the thickness of the compartment (m), $f_{CR,i}$ the capillary rise factor (Eq. 3.7u), 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 $CR_{max,i}$

$$W_{remain} = CR_{max,i} - W_{stored,i} \qquad \text{(Eq. 3.7r)}$$

where $W_{remain}$ is the amount of water still to store (mm). If the soil water content ($\theta_i$) 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;

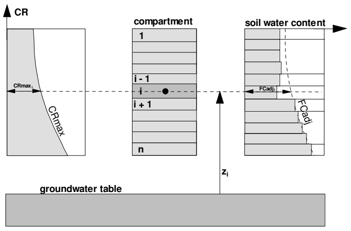



**Figure 3.7j –** The maximum amount of water that can be transported upward by capillary rise ($CR_{max,i}$) and the adjusted field capacity ($FC_{adj,i}$) for the node of compartment i, at a height of $z_i$ meter above the groundwater table

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:

$$CR = \sum_{i=1}^{n} W_{stored,i} \qquad \text{(Eq. 3.7s)}$$



**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 ($\theta$) in the profile is at $\theta_{FCadj}$ (Fig. 3.7i). Water moves downward (drainage) if $\theta > \theta_{FCadj}$ and upwards (capillary rise) when $\theta < \theta_{FCadj}$. The larger the difference between $\theta$ and $\theta_{FCadj}$, 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:

$$relative\ wetness = \frac{\theta_i - \theta_{PWP}}{\theta_{FCadj,i} - \theta_{PWP}} \qquad \text{(Eq. 3.7t)}$$

where $\theta_i$ is the soil water content at a height $z_i$ above the groundwater table, and $\theta_{PWP}$ 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 ($f_{CR,i}$):

$$f_{CR,i} = 1 - \left( \frac{\theta_i - \theta_{PWP}}{\theta_{FCadj,i} - \theta_{PWP}} \right)^x \qquad \text{(Eq. 3.7u)}$$

The capillary rise factor, $f_{CR,i}$, varies with the soil water content ($\theta_i$) and ranges between 1 and 0 (Fig. 3.7k). 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. The power (x) in Equation 6.4f is a program parameter and set at 16 for testing.



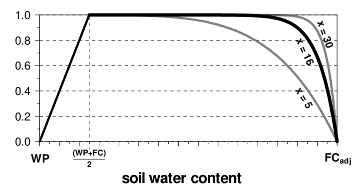



**Figure 3.7k –** The capillary rise factor (Eq. 3.7u) for different soil water content in the soil profile above the groundwater table and values for the power x.

The power (x) in Equation 3.7u is a program parameter which can vary between 5 and 30 (with 16 as default). 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. 3.7k).

**Capillary rise versus drainage**

The calculation of upward movement from a groundwater table, which starts at the bottom compartment 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, $\theta_i$ is equal to $\theta_{FCadj,i}$ and $f_{CR,i}$ is zero (Eq. 3.7u). 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. 3.7u).



**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.

**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. 3.7i).

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 (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.

### 3.7.7 Processing of 10-day and monthly climatic data

- **Daily climatic data**

For each day of the simulation period, AquaCrop requires:
- the minimum ($T_n$) and maximum ($T_x$) air temperature;
- the reference evapotranspiration ETo; and
- rainfall depth.

The input may consist of daily, 10-day or monthly $T_n$, $T_x$, ETo and Rainfall data. At run time, the 10-day and monthly data are processed to derive daily minimum and maximum air temperatures, ETo and rain data.

By weighing the reference evapotranspiration rates and air temperatures in the previous, actual and next 10-day period or month, daily ETo rates, and the daily maximum and minimum air temperatures are obtained in AquaCrop. The calculation procedure is based on the interpolation procedure presented by Gommes (1983). The same interpolation procedure is applied for 10-day and monthly rainfall data but since it is highly unlikely that rainfall is homogenously distributed over all the days of the 10-day period or month, some further processing is required to determine the amount of rainfall that is (i) lost by surface runoff, (ii) stored in the top soil as effective rainfall, (iii) lost by deep percolation and (iv) by soil evaporation (Fig. 3.7f).

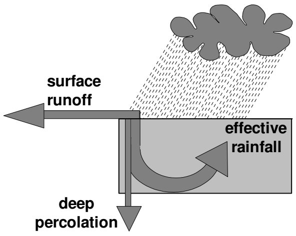



**Figure 3.7l**
**Partitioning of rainfall in effective rainfall, surface runoff and deep percolation losses**



- **Estimation of surface runoff**

To estimate surface runoff with 10-day or monthly Rainfall data, a specific number of rainy events is assumed during a 10-day period (the default is 2 showers per 10-day). By dividing the total rainfall amount for the period by the number of events in that period, the rainfall amount per shower is obtained and the surface runoff can be calculated (see 3.7.4 – Runoff subroutine). The more rainy days are considered during the 10-day period, the smaller the rainfall amount per event and the smaller the runoff will be. Because the day(s) at which it rains, are unknown the Curve Number is not corrected for soil wetness and the CN value for Antecedent Moisture Class II is used.

- **Estimation of effective rainfall and deep percolation**

Effective rainfall is that part of rainfall that is stored in the root zone and not lost by surface runoff or deep percolation (Fig. 3.7f). If the rainfall data consist of 10-day or monthly values, the rainfall distribution over the period is unknown and the amount of water lost by deep percolation cannot be determined by solving the water balance on a daily basis (time step). After the subtraction of the amount of rainfall lost by surface runoff, the effective rainfall is estimated by one or another procedure determined by the user. If the amount of rainfall that is stored in the root zone will also be effectively retained in the root zone depends on the storage capacity of the root zone at the moment of rainfall.

The following procedures are available in AquaCrop to determine the effective rainfall when 10-day or monthly rainfall data is given as input:
- 100 percent effective
- USDA-SCS procedure
- Expressed as a percentage of rainfall

***100 percent effective***

All rainfall is stored in the root zone. Excess water that cannot be retained, will drain out of the root zone and will be lost by deep percolation.

***USDA-SCS procedure***

SCS scientists analysed 50 years of rainfall records at 22 locations throughout the United Sates of America to predict effective rainfall (SCS, 1993). A daily soil water balance incorporating crop evapotranspiration, rainfall, irrigation and the storage capacity of the root zone was used to determine the effective rainfall (Tab. 3.6b). By considering the monthly crop evapotranspiration ($ETc_m$) and rainfall ($P_m$), the monthly effective rainfall ($Pe_m$) is obtained by the following empirical equation (USDA, 1970):

$$Pe_m = \left(0.70917\ P_m^{0.82416} - 0.11556\right) 10^{0.02426\ ETc_m} \qquad \text{(Eq.3.7v)}$$

where $Pe_m$, $P_m$ and $ETc_m$ are given in inches (1 inch = 25.4 mm). In the above equation $ETc_m$ is the sum of the soil evaporation and crop transpiration by assuming that the processes are not affected by water stress. The difference between rainfall ($P_m$) and the estimated effective rainfall ($Pe_m$) is regarded as being lost by deep percolation.



Simulations (Naesens, 2002) with rainfall data from various climatic zones indicates that the procedure predicts effective rainfall with an accuracy of +/- 20 %. The procedure is also valid for 10-day rainfall data but the accuracy decreases to +/- 40 %.

**Table 3.7e**
**Effective rainfall (expressed as a percentage of monthly rainfall) for various levels of crop evapotranspiration and for a root zone with a RAW of 75 mm, as determined by the USDA-SCS procedure.**

| | Monthly crop evapotranspiration [mm/month] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **30** | **60** | **90** | **120** | **150** | **180** | **210** | **240** |
| **Monthly Rain [mm/month]** | Effective rainfall [%] | | | | | | | |
| **10** | 58 | 62 | 66 | 71 | 75 | 81 | 86 | 92 |
| **20** | 63 | 68 | 72 | 77 | 82 | 88 | 94 | 100 |
| **30** | 63 | 67 | 72 | 77 | 82 | 88 | 94 | 100 |
| **40** | 62 | 66 | 71 | 76 | 81 | 86 | 92 | 99 |
| **50** | 61 | 65 | 70 | 74 | 79 | 85 | 91 | 97 |
| **60** | 60 | 64 | 68 | 73 | 78 | 83 | 89 | 95 |
| **70** | 59 | 63 | 67 | 72 | 77 | 82 | 88 | 93 |
| **80** | 58 | 62 | 66 | 71 | 76 | 81 | 86 | 92 |
| **90** | 57 | 61 | 65 | 70 | 74 | 80 | 85 | 91 |
| **100** | 56 | 60 | 64 | 69 | 73 | 78 | 84 | 90 |
| **120** | 55 | 59 | 63 | 67 | 72 | 77 | 82 | 87 |
| **140** | 54 | 58 | 61 | 66 | 70 | 75 | 80 | 85 |
| **160** | 53 | 56 | 60 | 64 | 69 | 74 | 79 | 84 |
| **180** | 52 | 55 | 59 | 63 | 68 | 72 | 77 | 82 |
| **200** | 51 | 55 | 58 | 62 | 67 | 71 | 76 | 81 |

***Expressed as a percentage of rainfall***

The user specifies the percentage of the 10-day/monthly rainfall that is stored in the root zone. The ineffective part of the rainfall is assumed to have drained out of the root zone and is stored immediately below the root zone.

The percentage will depend on the rainfall amount, the evapotranspiration rate and soil type. Indicative values are given in Table 3.7b. The percentage can be obtained with greater accuracy by simulating the drainage out of the root zone for those years were daily rainfall data is available (or available in a nearby representative station). As such the characteristics of the climate, cropping period, irrigation schedules and drainage characteristics of the soil can be fully considered.



- **Estimation of soil evaporation**

The calculation procedure for soil evaporation (E) assumes that the evaporation takes places in two stages (See 3.9 Soil evaporation). By distributing rainfall homogenously over all the days of the 10-day period or month, soil evaporation is likely to be over-estimated. Simulations (Mihutu, 2011) with rainfall data from various climatic zones indicated that the two stage calculation procedure over predicts E by some 10 to 30 % depending on soil type. The soil evaporation rate is adjusted by multiplying the estimated daily evaporation (E) with a reduction factor:

$$E_{adj} = \left(\sqrt[n]{\frac{REW + 1}{20}}\right) E \qquad \text{(Eq. 3.7w)}$$

where REW is the readily evaporable water (mm) and n a program parameter which may vary between 1 (strong reduction) and 10 (light reduction). Its default value is 5.

The optimal setting of the program parameter can be obtained by simulating the soil evaporation for those years were daily rainfall data is available (or available in a nearby representative station). As such the characteristics of the climate (rainfall distribution and evaporating power of the atmosphere), the degree of canopy cover and the characteristics of the soil type can be fully considered.

## 3.8 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; Raes et al., 2006) to simulate salt movement and retention in the soil profile.

### 3.8.1 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 Chapter 3, section 3.7 Soil water balance). Due to soil evaporation water will evaporate at the soil surface while the dissolved salts remain in the top compartment.

### 3.8.2 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. 3.7b). 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. 3.8a).



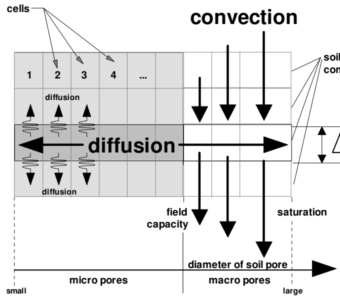



**Figure 3.8a**
**Convection and diffusion of salts in the cells of a soil compartment**

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 clay content. The number of cells is obtained by considering the Ksat of the soil horizon to which the soil compartment belongs:

$$2 \leq \; n = ROUND\left(1.6 + \frac{1000}{Ksat}\right) \; \leq 11 \qquad \text{(Eq. 3.8a)}$$

where Ksat is 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:

$$W_{cell} = 1000 \, \frac{\theta_{sat}}{n} \, \Delta z \qquad \text{(Eq.3.8b)}$$

where $W_{cell}$ is the volume of the cell in mm(water), $\theta_{sat}$ 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. 3.8a).



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.

The salt concentration in a cell can never exceed a threshold value. The threshold value is determined by the solubility of the salt (see Chapter 2: 2.13 Soil profile characteristics, 2.13.6 Program settings). 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.

### 3.8.3 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:

$$EC_{j,t+\Delta t} = EC_{j,t} + f_{diff}\left(\frac{EC_{j,t}\,W_{cell,j} + EC_{j+1,t}\,W_{cell,j+1}}{W_{cell,j} + W_{cell,j+1}} - EC_{j,t}\right) \qquad \text{(Eq. 3.8c)}$$

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.

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).



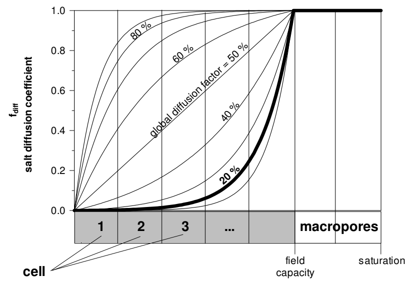
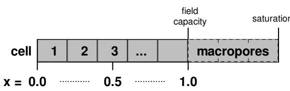



**Figure 3.8b**
**The salt diffusion coefficient ($f_{diff}$) for the various cells**
**and for various global diffusion factors**

The salt diffusion coefficient for the various cells is plotted in Figure 3.8b, for various global salt diffusion factors. The global diffusion factor is a program parameter 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 3.8a the calculation procedure (Eq. 3.8d) for $f_{diff}$ is presented.

**Table 3.8a** - Equation 3.8d: 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. 3.8d1) | $1-\frac{a\,b^{(1-x)}-a}{a\,b-a}$ | (Eq. 3.8d2) |
| **a** | $a=2\,\frac{GDF}{100}$ | (Eq. 3.8d3) | $a=2\left(1-\frac{GDF}{100}\right)$ | (Eq. 3.8d5) |
| **b** | $b=10^{10\,(0.5-GDF/100)}$ | (Eq. 3.8d4) | $b=10^{10\,(GDF/100-0.5)}$ | (Eq. 3.8d6) |

### 3.8.4 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 3.9 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. 3.8c). The relative soil water content of the upper soil layer determines the fraction of the dissolved salts that moves with the evaporating water:

$$f_{salt}=\frac{SWC_{rel}}{10}\,10^{SWC_{rel}} \qquad \text{(Eq. 3.8e)}$$



$$SWC_{rel}=\frac{\theta-\theta_{air\,dry}}{\theta_{sat}-\theta_{air\,dry}} \qquad \text{(Eq. 3.8f)}$$

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 $Z_{e,top}$
- $\theta$ soil water content of the upper soil layer ($m^3.m^{-3}$)
- $\theta_{sat}$ 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 ($\theta_{air\,dry} = \theta_{PWP}/2$)

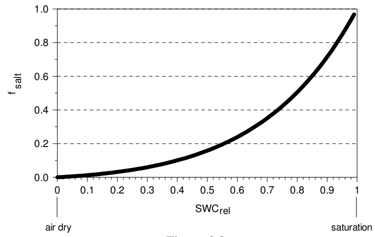



**Figure 3.8c**
**Fraction of dissolved salts ($f_{salt}$) that moves with the evaporating water for various relative soil water contents ($SWC_{rel}$) of the upper soil layer**

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. 3.8c).

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 3.9.5 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.



### 3.8.5 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 3.7 Soil water balance), the salinity of the groundwater and leaching by excessive rainfall or irrigation.

### 3.8.6 Soil salinity content

The salt content of a cell is given by:

$$Salt_{cell}=0.64\;W_{cell}\;EC_{cell} \qquad \text{(Eq. 3.8g)}$$

where $Salt_{cell}$ is the salt content expressed in grams salts per $m^2$ soil surface, $W_{cell}$ (Eq. 3.8b) 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:

$$EC_{sw}=\frac{\sum_{j=1}^{n}Salt_{cell,j}}{0.64\,(1000\,\theta\,\Delta z)} \qquad \text{(Eq. 3.8h)}$$

$$ECe=\frac{\sum_{j=1}^{n}Salt_{cell,j}}{0.64\,(1000\,\theta_{sat}\,\Delta z)} \qquad \text{(Eq. 3.8i)}$$

where n is the number of salt cells of the soil compartment, $\theta$ the soil water content ($m^3/m^3$), $\theta_{sat}$ the soil water content ($m^3/m^3$) at saturation, and $\Delta z$ (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.



## 3.9 Soil evaporation

$ET_o$ is the evapotranspiration rate from a grass reference surface, not short of water and is an index for the evaporating power of the atmosphere. Soil evaporation (E) is calculated by multiplying $ET_o$ with the soil water evaporation coefficient (Ke) and by considering the effect of water stress:

$$E=(Kr\;Ke)\,ET_o \qquad \text{(Eq. 3.9a)}$$

where Kr is the evaporation reduction coefficient which becomes smaller than 1, and as such reduces soil evaporation, when insufficient water is available in the soil to respond to the evaporative demand of the atmosphere. The soil evaporation coefficient Ke is proportional to the fraction of the soil surface not covered by canopy (1-CC). The proportional factor is the maximum soil evaporation coefficient ($Ke_x$) which integrates the effects of characteristics that distinguish soil evaporation from the evapotranspiration from the grass reference surface. The calculation procedure is presented in Fig. 3.9a.

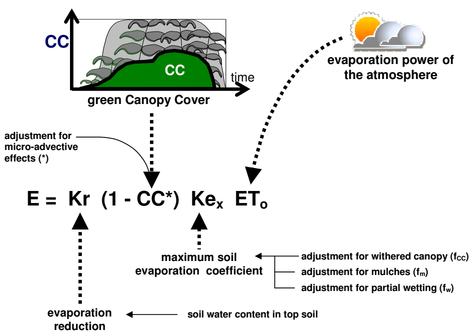



**Figure 3.9a**
**Calculation scheme in AquaCrop for soil evaporation (E)**

### 3.9.1 A two stage calculation method

Evaporation from soil takes place in two stages (Philip, 1957; Ritchie, 1972): an energy limiting stage (Stage I) and a falling rate stage (Stage II).

- **Stage I - energy limiting stage**

When the soil surface is wetted by rainfall or irrigation, soil evaporation switches to stage I. In this stage, water is evaporated from a thin soil surface layer ($Z_{e,surf}$) which is in direct contact with the atmosphere (Fig. 3.9b). As long as water remains in the evaporating soil surface layer, the evaporation rate is fully determined by the energy available for soil evaporation and the evaporation stays in stage I.

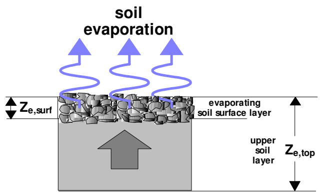



**Figure 3.9b**
**The upward transport of water**
**from the upper soil layer to the evaporating soil surface layer**

- **Stage II - falling rate stage**

When all the water is evaporated from the evaporating soil surface layer ($Z_{e,surf}$), soil evaporation switches to stage II and water flows from the soil layer below ($Z_{e,top}$) to the surface layer. In this stage the evaporation is not only determined by the available energy but depends also on the hydraulic properties of the soil. The ability to transfer water to the evaporating soil surface layer reduces as the soil water content in the soil profile decreases. As a result the evaporation rate decreases in function of time.

### 3.9.2 Readily Evaporable Water (REW)

The Readily Evaporable Water, REW, expresses the maximum amount of water (mm) that can be extracted by soil evaporation from the soil surface layer in stage I. Once REW is removed from the soil, the evaporation rate switches to the falling rate stage. REW corresponds to the U value presented by Ritchie (1972). Water lost by soil evaporation in stage I comes mainly from a thin soil surface layer which is in direct contact with the air above the field (Fig. 3.9b). When the soil surface layer is sufficiently wetted by rainfall or irrigation, its soil water content is at field capacity. When the Readily Evaporable Water



is removed from the surface layer, its soil water content will be in equilibrium with the atmosphere, i.e air dry; Hence REW is given by:

$$REW = 1000\left(\theta_{FC} - \theta_{air\ dry}\right) Z_{e,\,surf} \qquad \text{(Eq. 3.9b)}$$

where $\theta_{FC}$ volume water content at field capacity [$m^3/m^3$];
$\theta_{air\ dry}$ volume water content at air dry [$m^3/m^3$];
$Z_{e,surf}$ thickness of the evaporating soil surface layer in direct contact with the atmosphere [m].

The soil water content at air dry is estimated by applying the rule of thumb, stating that the soil water content at air dry is about half of the soil water at wilting point ($\theta_{air\ dry} \approx 0.5\ \theta_{WP}$). By assuming 40 mm for $Z_{e,surf}$, an agreement was found between REW (Eq. 3.9b) and the cumulative evaporation for the energy limiting stage (Stage I evaporation), i.e., the U value of Ritchie (1972).

### 3.9.3 Soil evaporation coefficient for wet soil surface (Ke)

When the surface is wet, soil evaporation is calculated by multiplying the reference evapotranspiration ($ET_o$) with the soil evaporation coefficient (Eq. 3.9a). The soil evaporation coefficient, Ke, considers the characteristics of the soil surface and the fraction of the soil not covered by the canopy:

$$Ke = \left(1 - CC^*\right) Ke_x \qquad \text{(Eq. 3.9.c)}$$

where $(1\text{-}CC^*)$ adjusted fraction of the non-covered soil surface;
$Ke_x$ maximum soil evaporation coefficient for fully wet and not shaded soil surface.

The maximum soil evaporation coefficient $Ke_x$ for a wet non shaded soil surface is a program parameter. The default value is 1.10 (Allen et al., 1998) and can be adjusted by the user. When the canopy cover (CC) expands in the crop development stage, the soil evaporation coefficient Ke declines gradually (Fig. 3.9c).

In Eq. 3.9c, the fraction of the soil surface not covered by green canopy (1-CC*) is adjusted for micro-advective effects (Fig 3.9d). The adjustment for (1-$CC^*$) is based on the experimental data of Adams et al. (1976) and Villalobos and Fereres (1990):

$$(1 - CC^*) = 1 - 1.72\ CC + CC^2 - 0.30\ CC^3 \qquad \geq 0 \qquad \text{(Eq. 3.9d)}$$

The microadvection cause E to be less than just being proportional to CC. The extra energy is used for crop transpiration (see 3.10 Crop transpiration).



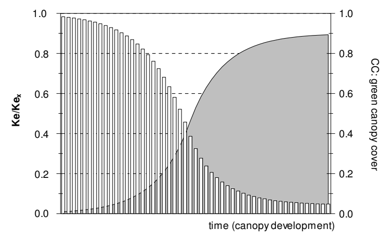



**Figure 3.9c**
**Decline (bars) of the soil evaporation coefficient Ke with reference to the wet non shaded soil surface ($Ke_x$) in the crop development stage when the green canopy cover (shaded area) increases**

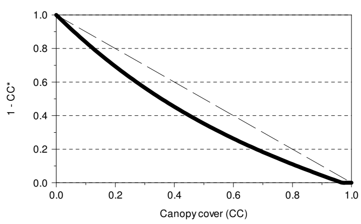



**Figure 3.9d**
**Adjusted fraction (1-$CC^*$) of not shaded soil surface (bold line) for various fractions of green canopy cover (CC)**



### 3.9.4 Adjustment of Ke for withered canopy, mulches and partial wetting by irrigation

- **Sheltering effect of withered canopy cover**

The soil evaporation coefficient needs to be adjusted for the sheltering effect of withered canopy when the green canopy cover declines during periods of severe water stress or in the late season stage as dictated by phenology. The dying crop will act as a shelter which reduces soil evaporation much stronger then described by (1-CC*). Although in this stage the green canopy decreases, the soil remains well sheltered by the withered canopy even when the green canopy cover becomes zero (CC = 0) at the end of the growing cycle.

Two factors are considered for the adjustment of the soil evaporation coefficient:
- $f_{cc}$ a coefficient expressing the sheltering effect of the dead canopy cover [0 … 1];
- $CC_{top}$ the canopy cover prior to senescence. If the canopy cover has reached its maximum size, $CC_{top} = CC_x$

$$Ke_{adj} = \left(1 - f_{cc}\ CC_{top}\right)\left(1 - CC^*\right) Ke_x \qquad \text{(Eq. 3.9e)}$$

Notwithstanding the rule of thumb (Allen et al., 1998) to reduce the amount of soil water evaporation by about 5% for each 10 % of soil surface that is effectively covered by an organic mulch the default value for $f_{cc}$ is 0.60 and not 0.50, because a standing crop gives better shelter against the effect of dry wind than an organic mulch that covers the soil surface. To simulate a smooth increase of evaporation in the late season stage when senescence occurs, $f_{cc}$ increases gradually from 0 (at the start of the late-season stage) to its final value when CC is half of $CC_{top}$.

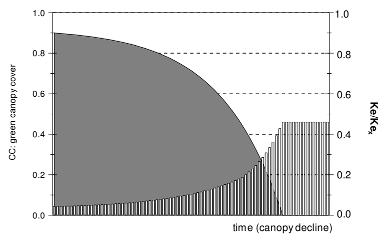



**Figure 3.9e**
**Increase (bars) of the soil evaporation coefficient Ke adjusted for withered canopy with reference to the wet non shaded soil surface ($Ke_x$) in the late season stage when the green canopy cover (shaded area) decreases**

The effect of the withered canopy shelter on the reduction of soil evaporation is plotted in Figure 3.9e. The effect is a program parameter which can be adjusted by the user.

- **Adjustment for mulches**

To reduce evaporation losses from the soil surface, mulches can be considered. The effect of mulches on crop evaporation is described by two factors (Allen et al., 1998):
- soil surface covered by mulch (from 0 to 100%); and
- $f_m$ ($\leq 1$), the adjustment factor for the effect of mulches on soil evaporation, which varies between 0.5 for mulches of plant material and is close to 1.0 for plastic mulches (Allen et al., 1998).

The adjustment for soil evaporation consists in multiplying Ke by the correction factor:

$$Ke_{adj} = \left(1 - f_m \frac{Percent\ covered\ by\ mulch}{100}\right)\left(1 - CC^*\right) Ke_x \qquad \text{(Eq. 3.9f)}$$

The adjustment is not applied when standing water remains on the soil surface (between soil bunds).

- **Adjustment for partial wetting by irrigation**

When only a fraction of the soil surface is wetted by irrigation, Ke is multiplied by the fraction of the surface wetted ($f_w$) to adjust for partial wetting (Allen et al., 1998):

$$Ke_{adj} = f_w \left(1 - CC^*\right) Ke_x \qquad \text{(Eq. 3.9g)}$$

The fraction $f_w$ is an irrigation parameter, and can be adjusted when selecting an irrigation method in the ***Irrigation Management*** Menu. The adjustment for partial wetting is not applied when:
- surface is wetted by irrigation and rain on the same day;
- surface is wetted by rain; and
- irrigation and/or rain water remains on the soil surface (between the soil bunds).

- **Adjustment for mulches and partial wetting by irrigation**

If the soil surface is covered by mulches and at the same time partial wetted by irrigation, only one of the above adjustments is valid. Ke is the minimum value obtained from Eq. 3.9f and 3.9g.



### 3.9.5 Evaporation reduction coefficient (Kr)

When insufficient water is available at the soil surface soil evaporation switches from Stage I (energy limiting stage) to Stage II (falling rate stage). This simulated with the introduction of an evaporation reduction coefficient (Eq. 3.9a). The evaporation reduction coefficient (Kr) varies with the amount of water available in the upper soil layer from where water is transferred to the evaporating soil surface layer. Kr is 1 if the soil is sufficiently wet and the soil evaporation is not hampered by water depletion, which is the case in Stage I. Kr decreases when the soil water depletion increases and is zero when the upper layer of the soil becomes air dry (Fig. 3.9f).

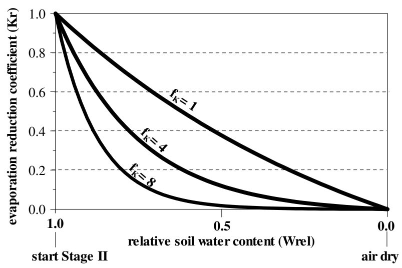



**Figure 3.9f**
**The evaporation reduction coefficient Kr**
**for various levels of relative soil water content and decline factors ($f_K$)**

In stead of using the square root of time (Ritchie type of model), a mechanistic approach is used to describe the evaporation rate in the falling rate stage. With this approach not only time but also the amount of water extracted from the top soil by transpiration, groundwater contribution from a shallow water table and the weather conditions (Rain and $ET_o$) are considered for the determination of Kr.

To account for the sharp decline in hydraulic conductivity with decreasing soil water content, an exponential equation is used to relate Kr to the relative water content of the upper soil layer:

$$0 \leq Kr = \frac{\exp^{f_K W_{rel}} - 1}{\exp^{f_K} - 1} \leq 1 \qquad \text{(Eq. 3.9h)}$$



where $f_K$ is a decline factor and $W_{rel}$ the relative water content of the soil layer through which water moves to the evaporating soil surface layer (upper soil layer with thickness $Z_{e,top}$). A thickness of 0.15 m is assigned initially for $Z_{e,top}$. However, when $W_{rel}$ drops below a threshold (set at $W_{rel}$ = 0.4), $Z_{e,top}$ expands to a maximum depth which is a program parameter. Its default value is 0.3 m and the range is 0.15 to 0.50 m.

At the start of Stage II, $W_{rel}$ begins to decline below 1 and becomes 0 when there exist no longer a hydraulic gradient i.e. when $Z_{e,top}$ is air dry (Fig. 3.9f). The decline factor $f_K$ depends on the hydraulic properties of the soil and can be used to calibrate Kr when measurements of soil evaporation are available. The decline of Kr with decreasing $W_{rel}$ alters by varying the value of $f_K$ (Fig. 3.9f). When $f_K$ takes a value of 4, a good fit was obtained between the square root of time approach (Ritchie, 1972) and the soil water content approach used by AquaCrop in the simulation of Stage II evaporation. Even after three weeks of evaporation (21 days) the cumulative amount of water lost by soil evaporation remained in the same range for both approaches and for most soil textural classes.

### 3.9.6 Calculation of soil evaporation (E)

- **Energy limiting stage (Stage I)**

When rainfall occurs or water is added by irrigation, the infiltrated water replenishes the soil surface layer till REW is reached. As long as readily evaporable water remains in the surface layer, E is in the energy limiting stage, and the rate of soil evaporation is the maximum rate:

$$E_{Stage\ I} = \left(1 - CC^*\right) Ke_x\ ET_o \qquad \text{(Eq. 3.9i)}$$

The following rules are applied:
- The maximum amount of water that can be stored in the surface layer is REW. Light wetting events do not necessarily completely replenished the soil surface;
- If the soil surface is only partly wetted by irrigation, only the wetted fraction of the surface layer is replenished;
- When the soil is flooded and water remains between soil bunds on top of the field, evaporation takes places from the water layer at the soil surface. When the water layer is completely evaporated, it is assumed that the total REW is still available in the soil surface layer and soil evaporation starts in stage I.

- **Falling rate stage (Stage II)**

When all the readily evaporable water is removed from the evaporating soil surface layer, the soil evaporation switches to the falling rate stage (Stage II). The evaporation rate is given by:

$$E_{StageII} = Kr \left(1 - CC^*\right) Ke_x\ ET_o \qquad \text{(Eq. 3.9j)}$$



where Kr is the dimensionless evaporation reduction coefficient.

The relative water content at which Kr is 1 (upper limit) is the soil water content of the top soil at the end of stage I. The upper limit will be close to saturation when the soil is slow draining and close to field capacity when the soil drains quickly. However, it is assumed in the model that the upper limit cannot drop below the soil water content at field capacity minus REW. As such the expected sharp drop in evaporation when the top soil is only slightly wetted by rainfall or irrigation can be simulated.

Since Kr varies strongly with $W_{rel}$ especially at the beginning of Stage II, the routine daily time step is inadequate and had to be divided into 20 equal fractions to obtain a differential solution for Eq. 3.9j. At the end of each small time step, the water content of the soil profile is updated and Kr is estimated with Eq. 3.9h. Consequently the switch from stage I to II occurring during the day, can be simulated as well.

## 3.10 Crop transpiration

$ET_o$ is the evapotranspiration rate from a grass reference surface, not short of water and is an index for the evaporating power of the atmosphere. Crop transpiration (Tr) is calculated by multiplying $ET_o$ with the crop transpiration coefficient ($Kc_{Tr}$) and by considering the effect of water stress:

$$Tr = \left(Ks\ Kc_{Tr}\right) ET_o \qquad \text{(Eq. 3.10a)}$$

where Ks is the soil water stress coefficient which becomes smaller than 1, and as such reduces crop transpiration, when insufficient water is available in the root zone to respond to the evaporative demand of the atmosphere. The crop transpiration coefficient $Kc_{Tr}$ is proportional with the green canopy cover (CC). The proportional factor is the maximum crop transpiration coefficient ($Kc_{Tr,x}$) which integrates the effects of characteristics that distinguish the crop transpiration from the evapotranspiration from the grass reference surface. The calculation procedure is presented in Fig. 3.10a.

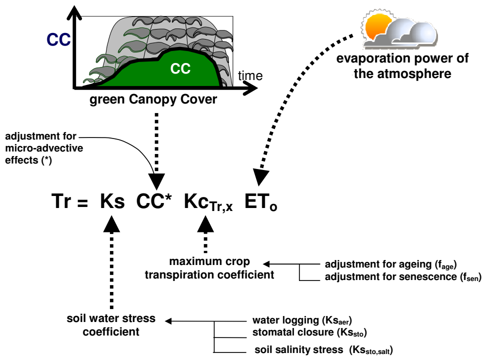



**Figure 3.10a**
**Calculation scheme in AquaCrop for crop transpiration (Tr)**



### 3.10.1 Crop transpiration coefficient ($Kc_{Tr}$)

Crop transpiration is calculated by multiplying the reference evapotranspiration with the crop transpiration coefficient (Eq. 3.10a). The crop transpiration coefficient ($Kc_{Tr}$) considers (i) the characteristics that distinguish the crop with a complete canopy cover from the reference grass and (ii) the fraction by which the canopy covers the ground:

$$Kc_{Tr} = CC^{*}\ Kc_{Tr,x} \qquad \text{(Eq. 3.10b)}$$

where $Kc_{Tr,x}$ coefficient for maximum crop transpiration (well watered soil and complete canopy, CC = 1);
$CC^{*}$ actual canopy cover adjusted for micro-advective effects.

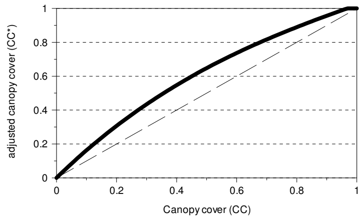



**Figure 3.10b**
**Canopy cover ($CC^{*}$) adjusted for micro-advective effects (bold line) for various fractions of green canopy cover (CC)**

To estimate crop transpiration, CC is increased to $CC^{*}$ to account for interrow micro-advective and sheltering effect by partial canopy cover (Fig. 3.10b). The adjustment is based on studies of Adams et al. (1976) and Villalobos and Fereres (1990):

$$CC^{*} = 1.72\ CC - CC^{2} + 0.30\ CC^{3} \qquad \text{(Eq. 3.10c)}$$

When the canopy cover is incomplete extra energy is available for crop transpiration (Tr) and less for soil evaporation (E). The microadvection cause Tr to be more than just being proportional to CC and E less than being proportional to 1-CC (see 3.9 Soil evaporation).



### 3.10.2 Coefficient for maximum crop transpiration ($Kc_{Tr,x}$)

Due to differences in albedo, crop height, aerodynamic properties, and leaf and stomata properties, $Kc_{Tr,x}$ differs from 1. The $Kc_{Tr,x}$ coefficient is often 5-10% higher than the reference grass, and even 15-20% greater for some tall crops such as maize, sorghum or sugar cane. The $Kc_{Tr,x}$ coefficient is approximately equivalent to the basal crop coefficient at mid-season for different crops (Allen et al., 1998), but only for cases of full CC.

### 3.10.3 Adjustments of $Kc_{Tr,x}$ for ageing and senescence

- **Adjustment of $Kc_{Tr,x}$ for ageing effects**

After the time $t_{CCx}$ required to reach $CC_x$ under optimal conditions and before senescence, the canopy ages slowly and undergoes a progressive though small reduction in transpiration and photosynthetic capacity (Fig. 3.10c). This is simulated by applying an adjustment factor ($f_{age}$) that decreases $Kc_{Tr,x}$ by a constant and slight fraction (e.g., 0.3%) per day, resulting in an adjusted crop coefficient. The ageing comes in effect at $t_{CCx}$ which is the time when $CC_x$ (maximum canopy cover) would have been reached without water stress (i.e. at the beginning of the mid-season). A short lag phase of 5 days is assumed. After the lag phase of 5 days, $Kc_{Tr,x,adj}$ is given by:

$$Kc_{Trx,adj} = Kc_{Tr,x} - (t-5)\ f_{age}\ CC_x \qquad \text{(Eq. 3.10d)}$$

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

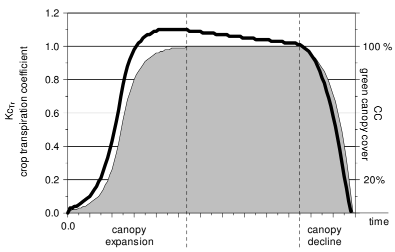



**Figure 3.10c**
**Canopy development (shaded area) and crop transpiration coefficient $Kc_{Tr}$ (line) throughout the crop cycle for $Kc_{Tr,x}$ = 1.1, $CC_x$ = 100%, and $f_{age}$ 0.16%/day**



The same apply for forage and pasture crop. However, since the canopy is harvested at each cut, a new canopy has to develop which cancels the ageing. Once $CC_x$ is reached after a cutting, the ageing kicks in again and is described by Eq. 3.10d.

- **Adjustment of $Kc_{Tr,x}$ once senescence is triggered**

When senescence is triggered, the transpiration and photosynthetic capacity of the green portion of the canopy drops more markedly with time. This is simulated by multiplying $Kc_{Trx,adj}$ (Eq. 3.10d) with another adjustment factor, $f_{sen}$, which declines from 1 at the start of senescence (CC = $CC_x$) to 0 when no green canopy cover remains (CC = 0):

$$Kc_{Trx,sen} = Kc_{Trx,adj}\left(f_{sen}\right)$$
$$\text{with}\quad f_{sen} = \left(\frac{CC}{CC_x}\right)^{a} \qquad \text{(Eq. 3.10e)}$$

The exponent a is a program parameter and can be used to accentuate (a > 1) or to minimize (a < 1) the drop in the transpiration/photosynthetic efficiency of the declining canopy. In the program 'a' can vary between an upper limit of 4 (very strong effect) and a lower limit of 0.1 (very limited effect). Its default value is 1. The senescence factor ($f_{sen}$) for various degrees of withering ($CC/CC_x$) and various values of the exponent 'a' is plotted in Fig. 3.10d.

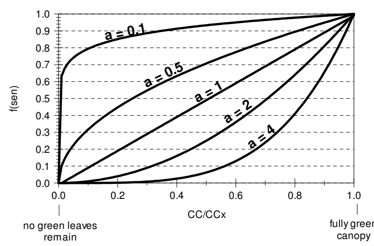



**Figure 3.10d**
**The senescence factor ($f_{sen}$)**
**for various degrees of withering ($CC/CC_x$) and various values of the exponent 'a'**

### 3.10.4 Soil water stress coefficient (Ks)

Crop transpiration can be affected by a shortage of water and an excess of water. This simulated with the help of a soil water stress coefficient for stomatal closure ($Ks_{sto}$) and for water logging ($Ks_{aer}$).

- **Water stress coefficient for stomatal closure ($Ks_{sto}$)**

To simulate the result of stomatal closure induced by water stress, the coefficient for crop transpiration ($Kc_{Tr}$) is multiplied by the water stress coefficient for stomatal closure ($Ks_{sto}$):

$$Tr = Ks_{sto}\ Kc_{Tr}\ ET_0 \qquad \text{(Eq. 3.10f)}$$

The $Ks_{sto}$ coefficient describes the effect of water stress on crop transpiration (see 3.2.2: Soil water stress). When sufficient water remains in the root zone, transpiration is unaffected and $Ks_{sto} = 1$. When the root zone depletion exceeds an upper threshold ($p_{sto}$ TAW), the water extracted by the crop becomes limited ($Ks_{sto} < 1$) and the crop is under water stress (Fig. 3.10e). When the soil water content in the root zone reaches its lower limit (which is permanent wilting point), the stomata are completely closed, and crop transpiration is halted ($Ks_{sto} = 0$). In AquaCrop the shape of the $Ks_{sto}$ curve between the upper and lower threshold can be selected as linear or concave. Since the stress response curve are defined for an evaporating power of the atmosphere (ETo) of 5 mm/day, the upper threshold for water stress needs to be adjusted for ETo.

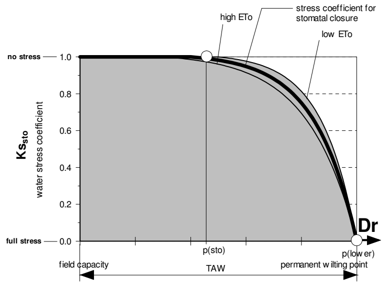



**Figure 3.10e**
**The water stress coefficient for stomatal closure ($Ks_{sto}$) for various degrees of root zone depletion (Dr)**



The upper threshold of root zone depletion ($Dr_{sto,upper}$) is given by:

$$Dr_{sto,upper} = p_{sto}\ TAW \qquad \text{(Eq.3.10g)}$$

where $p_{sto}$ fraction of TAW at which stomata start to close;
TAW Total Available soil Water in the root zone [mm].

At the lower threshold, which corresponds with permanent wilting point, the root zone depletion ($Dr_{sto,lower}$) is:

$$Dr_{sto,lower} = TAW \qquad \text{(Eq.3.10h)}$$

The depletion coefficient $p_{sto}$ is the fraction of TAW that can be depleted from the root zone before stomata starts to close. The p factor divides the Total Available soil Water (TAW), in two parts: water that can be extracted without stress (RAW) and water that is more difficult to extract (Fig. 3.10f).

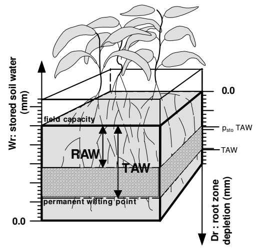



**Figure 3.10f**
**The upper and lower threshold of root zone depletion affecting stomatal closure**

- **Effect of soil salinity on the water stress coefficient for stomatal closure**

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 ($Ks_{sto,salt}$):

$$Ks_{sto,adj} = Ks_{sto,salt}\ Ks_{sto} \qquad \text{(Eq. 3.10i)}$$



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 affects stomatal closure ($Ks_{sto}$). This is simulated by multiplying the fractions ($p_{upper}$ and $p_{lower}$) of TAW with $Ks_{sto,salt}$ (Fig. 3.10g).

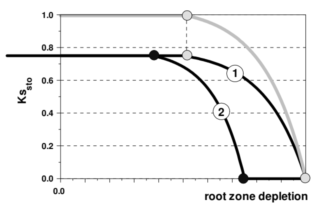



**Fig. 3.10g –** The soil water coefficient for stomatal closure ($Ks_{sto}$) without (gray line) and with (black line 1) the effect of soil salinity stress, and the shift of the thresholds (circles) by considering (black line 2) the effect of soil salinity stress on the thresholds.

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 crop transpiration, but has no effect on the adjustment of the Harvest Index (to avoid the double effect of soil salinity on crop yield).

- **Water stress coefficient for deficient aeration conditions**

Transpiration is hampered not only when the water content in the root zone is limited but also when the root zone is water logged, resulting in deficient soil aeration (Fig. 3.10h). If the water content in the root zone is above the anaerobiosis point ($\theta_{air}$) the root zone becomes water logged and transpiration is limited.

The effect of water logging on crop transpiration is simulated by means of a water stress coefficient for water logging ($Ks_{aer}$):

$$Tr = Ks_{aer}\ Kc_{Tr}\ ET_o \qquad \text{(Eq. 3.10j)}$$

$Ks_{aer}$ varies linearly between the anaerobiosis point where $Ks_{aer}$ is 1 and soil saturation where $Ks_{aer}$ is zero (Fig. 3.10i).



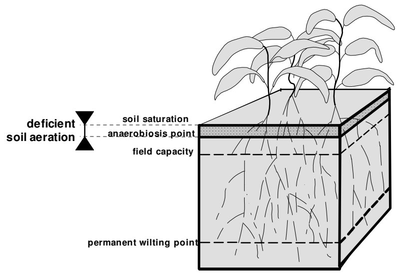



**Figure 3.10h**
**The upper and lower threshold for the soil water content in the root zone resulting in deficient aeration conditions**

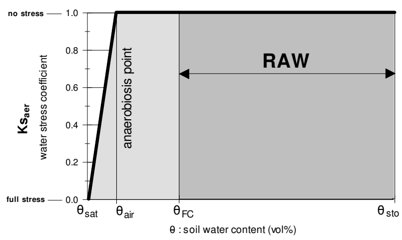



**Figure 3.10i**
**The water stress coefficient for water logging ($Ks_{aer}$) for various levels of soil water content (θ)**

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. The anaerobiosis point is a crop parameter. To simulate the resistance of crops to short periods of waterlogging, the full effect will only be reached after a specified number of days (which is a program parameter).

### 3.10.5 Soil water extraction

- **Calculation procedure**

The calculation procedure consists of the following steps:

1. Determination of the transpiration demand by considering the average soil water content in the root zone and as such the average total water stress in the root zone:

$$Tr = \overline{Ks_{root\ zone}}\ Kc_{Tr}\ ET_o \qquad \text{(Eq. 3.10k)}$$

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

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

$$S_i = Ks_i\ S_{x,i} \qquad \text{(Eq. 3.10l)}$$

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

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

3. By integrating Eq. 3.10l over the different compartments of the root zone, the exact amount of water that can be extracted by transpiration is obtained:

$$Tr = \sum_{top}^{bottom} 1000\left(Ks_i\ S_{x,i}\right) dz_i \quad \le \quad \overline{Ks_{root\ zone}}\ Kc_{Tr}\ ET_o \qquad \text{(Eq. 3.10m)}$$



where $dz_i$ is the thickness of the soil compartment (m). The integration starts at the top of the soil profile and is stopped when the sum is equal to the transpiration demand given by Eq. 3.10k or the bottom of the root zone is reached.

When the maximum root extraction rate over the entire root zone ($\Sigma\ S_x dz$) is too small (as a result of a limited root volume), the amount of water that can be extracted by transpiration will be smaller than the demand (Eq. 3.10k). The transpiration demand can easily be extracted out of the root zone if $S_x$ at the various depths is sufficiently large. When $S_x$ is large, the root zone well watered (Ks = 1) and the transpiration demand small, water will only be extracted from the top of the root zone. When the top becomes increasingly drier ($Ks_i$ < 1), more and more water will need to be extracted at the lower part of the root zone.

- **Maximum root extraction rate ($S_x$) and the total extraction rate** ($\Sigma\ S_x dz$)

In the model the maximum root extraction rate at the top of the soil profile ($S_{x,top}$) might be different from the maximum extraction rate at the bottom of the root zone ($S_{x,bottom}$). The assigned $S_x$ values at different soil depths are proportional to the specified water extraction pattern (Fig. 3.10j). Apart from the root distribution, $S_x$ is also determined by the total root volume. The total root volume determines the total amount of water that can be extracted out of the root zone, i.e. the total extraction rate ($\Sigma\ S_x dz$).

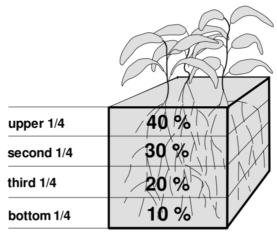



**Figure 3.10j**
**Default extraction pattern in the root zone**

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

- for root distribution: 40, 30, 20, 10% (where the values refer to the upper, second, third and bottom quarter of the root zone as in Fig. 3.10j), and



- for total extraction rate $\Sigma\ S_x dz$: A default 3 mm/day for each 0.10 m of rooting depth with a maximum value of 15 mm/day for the entire root zone is considered. $\Sigma\ S_x dz$ can range between 1 mm/day (extremely low root volume resulting in severely water stress even in a well watered soil for normal climatic conditions) and 20 mm/day.

If a soil layer blocks the root zone expansion, the maximum sink term at the bottom of the root zone ($S_{x,bot}$) increases when the root zone reaches the restrictive layer. This simulates the concentration of roots above the restrictive soil layer. The adjustment of $S_{x,bot}$ guarantees that the total amount of water that can be extracted by the roots remains at any time identical the specified $\Sigma\ S_x dz$ (Fig. 3.10k).

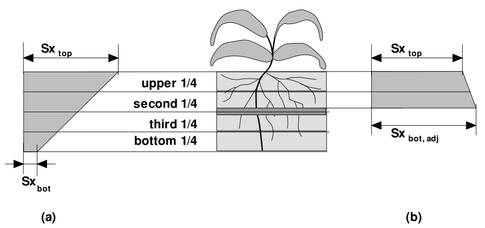



**Figure 3.10k**
**Maximum sink term at the top ($S_{x,top}$) and bottom ($S_{x,bot}$) of the root zone**
**(a) without and (b) with a soil layer inhibiting root zone expansion**

### 3.10.6 Feedback mechanism of transpiration on canopy development

A feedback mechanism is added to the model to guarantee that when crop transpiration drops to zero, the canopy development is halted as well under all circumstances. As such leaf growth stops when the root zone is water logged (at least for crops sensitive to water logging) or in the absence of any atmospheric water demand ($ET_o$ is zero).



## 3.11 Above ground biomass

The daily (m) and the cumulative (B) aboveground biomass production biomass is obtained from the normalized water productivity (WP*), and the ratio of the daily crop transpiration (Tr) over the reference evapotranspiration for that day (ETo):

$$m = Ks_b\ WP^* \left(\frac{Tr}{ET_o}\right) \qquad \text{(Eq. 3.11a)}$$

$$B = Ks_b\ WP^* \sum\left(\frac{Tr}{ET_o}\right) \qquad \text{(Eq. 3.11b)}$$

where $Ks_b$ is an air temperature stress coefficient which becomes smaller than 1, and reduces biomass production, when it becomes too cold to guarantee a specific number of growing degrees in the day. The calculation scheme is presented in Fig. 3.11a.

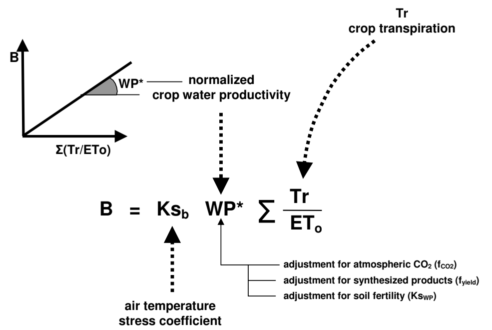



**Figure 3.11a**
**Calculation scheme in AquaCrop for above ground biomass (B)**

### 3.11.1 Normalized crop water productivity ($WP^*$)

By considering the crop water productivity (WP), the aboveground biomass can be derived from the simulated transpiration. The crop water productivity expresses the aboveground dry matter (g or kg) produced per unit land area ($m^2$ or ha) per unit of water transpired (mm). Many experiments have shown that the relationship between biomass produced and water consumed by a given species is highly linear (Steduto et al., 2007). AquaCrop uses the normalized water productivity ($WP^*$) for the simulation of aboveground biomass (Eq. 3.11a and b). The WP is normalized for the atmospheric $CO_2$ concentration and for the climate. The units of crop water productivity after the adjustment for climate are mass of aboveground dry matter (g or kg) per unit land area ($m^2$ or ha).

- **Normalization for atmospheric $CO_2$**

The normalization for $CO_2$ consists in considering the crop water productivity for an atmospheric $CO_2$ concentration of 369.41 ppm (parts per million by volume). The reference value of 369.41 is the average atmospheric $CO_2$ concentration for the year 2000 measured at Mauna Loa Observatory in Hawaii (USA). The observatory was selected as the reference location because the air at the site is very pure due to its remote location in the Pacific Ocean, high altitude (3397 m.a.s.l), and great distance from major pollution sources.

- **Normalization for the climate**

The WP is normalized for climate by dividing the amount of water transpired (Tr) with the reference evapotranspiration ($ET_o$). Asseng and Hsiao (2000) argued that $ET_o$ would be better than vapor pressure deficit (VPD) for normalization because the FAO Penman-Monteith equation takes into account the difference in temperature between the air and evaporation surface. Further Steduto and Albrizio (2005) demonstrated with experimental data that more consistent results were obtained when normalizing with $ET_o$ as compared with VPD. The reference evapotranspiration $ET_o$ is obtained from meteorological data with the help of the FAO Penman-Monteith equation (Allen et al., 1998).

- **Classes for C3 and C4 groups**

After normalization for atmospheric $CO_2$ concentrations and climate, recent findings indicate that crops can be grouped in classes having a similar $WP^*$ (Fig. 3.11b). Distinction can be made between C4 crops with a $WP^*$ of 30 - 35 g/$m^2$ (or 0.30 – 0.35 ton per ha) and C3 crops with a $WP^*$ of 15 - 20 g/$m^2$ (or 0.15 – 0.20 ton per ha).

Some leguminous crops may have WP* values below 15 g/m² due to their biological nitrogen fixation process.



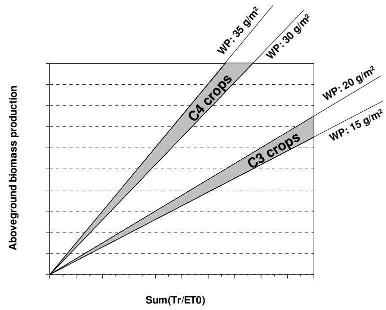



**Figure 3.11b**
**The relationship between the aboveground biomass and the total amount of water transpired for C3 and C4 crops after normalization for $CO_2$ and $ET_o$**

### 3.11.2 Adjustments of WP* for atmospheric $CO_2$, type of products synthesized, and soil fertility

- **Adjustment of $WP^*$ for atmospheric $CO_2$ ($f_{CO2}$)**

AquaCrop will adjust $WP^*$ when running a simulation for a year at which the atmospheric $CO_2$ concentration differs from its reference value (369.41 ppm). The adjustment is obtained by multiplying $WP^*$ with the correction coefficient $f_{CO2}$. The coefficient considers the difference between the reference value and the atmospheric composition for that year:

$$WP^*_{adj} = f_{CO2}\, WP^* \qquad \text{(Eq. 3.11c)}$$

$$f_{CO2} = \frac{\left(C_{a,i} / C_{a,o}\right)}{1+\left(C_{a,i} - C_{a,o}\right)\left[(1-w)b_{Sted} + w\left(f_{sink}\, b_{Sted} + (1-f_{sink})b_{FACE}\right)\right]} \qquad \text{(Eq. 3.11d)}$$

where $WP^*_{adj}$ WP adjusted for $CO_2$
$f_{CO2}$ correction coefficient for $CO_2$
$C_{a,o}$ reference atmospheric $CO_2$ concentration (369.41 ppm)
$C_{a,i}$ atmospheric $CO_2$ concentration for year i (ppm)



$b_{Sted}$ 0.000138 (Steduto et al., 2007);
$b_{FACE}$ 0.001165 (derived from FACE experiments);
w weighing factor;
$f_{sink}$ crop sink strength coefficient

To consider the discrepancy between the observed (FACE experiments) and theoretical adjustment (Steduto et al., 2007) of WP*, two coefficients ($b_{Sted}$ and $b_{FACE}$) are considered. The weighing factor (w) makes that in Eq. 3.11d $b_{FACE}$ gradually replaces $b_{Sted}$ starting from the reference atmospheric $CO_2$ concentration (Ca,o = 369.41 ppm) and becomes fully applicable for $C_{a,i}$ larger than or equal to 550 ppm:

$$0 \le \quad w = \left(1 - \frac{\left(550 - C_{a,i}\right)}{\left(550 - C_{o,i}\right)}\right) \quad \le 1 \qquad \text{(Eq. 3.11e)}$$

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.

The crop sink strength coefficient in Eq. 3.11d considers that the theoretical adjustment (with $b_{Sted}$) 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.

**Table 3.11 –** Range of indicative values for $f_{sink}$ for 10 crops available in the database of AquaCrop (Vanuytrecht et al., 2011).

| Crop | Class and indicative value range for $f_{sink}$ |
|---|---|
| Cereals | |
| - Maize | Low (0.0 – 0.2) |
| - Rice | Low (0.0 – 0.2) |
| - Wheat | Low (0.0 – 0.2) |
| - Sunflower | Low (0.0 – 0.2) |
| Legumes | |
| - Soybean | Moderate low (0.2 – 0.4) |
| Indeterminate crops | |
| - Tomato | Moderate low (0.2 – 0.4) |
| - Quinoa | Moderate low (0.2 – 0.4) |
| Woody species | |
| - Cotton | Moderate high (0.4 – 0.6) |
| Root and tuber crops | |
| - Potato | High (0.4 – 0.6) |
| - Sugar beet | High (0.4 – 0.6) |



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). Indicative values for $f_{sink}$ for crops available in the AquaCrop library are presented in Table 3.11.

The values of $f_{sink}$ reported in Table 3.11 should be considered as a good starting value but not as definitive. 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 higher than the indicative value in Table 3.11.

Next to air temperature, $ET_o$ and rainfall data, the $CO_2$ concentration is climatic input. By default AquaCrop obtains the atmospheric $CO_2$ concentration for a particular year from the 'MaunaLoa.CO2' file in its database which contains observed and expected concentrations at Mauna Loa Observatory. For years before 1958 (the start of observations at the Observatory) $CO_2$ data obtained from firn and ice samples are used. These samples were collected close to the coast of Antarctica (Etheridge et al., 1996). For future years an expected increase of 2 ppm is considered (Fig. 3.11c).

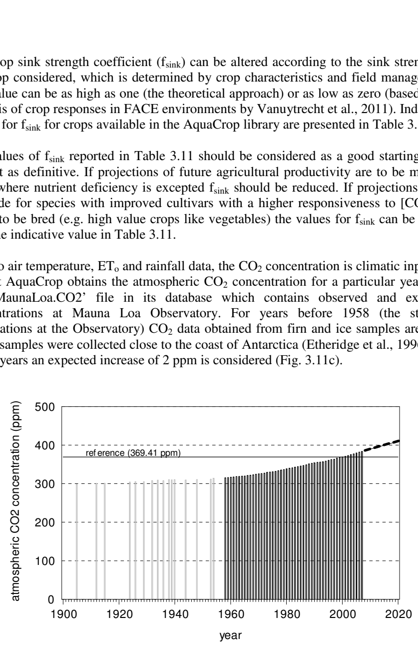



**Figure 3.11c**
**Atmospheric $CO_2$ concentrations derived from frin and ice samples (light bars), observed at Mauna Loa Observation (dark bars), and predicted (dotted line) by assuming a continuous rise of 2 ppm/year, with indication of the reference value**

Years before 2000, have an atmospheric $CO_2$ concentration which is lower than the reference value of 369.41 ppm and hence a smaller WP ($f_{CO2} < 1$). Years after 2000 have a higher atmospheric $CO_2$ concentration, and hence a higher WP ($f_{CO2} > 1$). For scenario analysis the user can use other 'CO2' files containing own estimates as long as the structure of the CO2 files is respected (see Chapter2, section 2.20.3 CO2 file).

- **Adjustment of WP* for types of products synthesized ($f_{yield}$)**

If products that are rich in lipids or proteins are synthesized during yield formation, considerable more energy per unit dry weight is required than for the synthesis of carbohydrates (Azam-Ali and Squire, 2002). As a consequence, the water productivity during yield formation needs to be adjusted for the type of products synthesized during yield formation:

$$WP^*_{adj} = f_{yield}\ WP^* \qquad \text{(Eq. 3.11f)}$$

where $WP^*_{adj}$ WP adjusted for type of products synthesized
$f_{yield}$ reduction coefficient for the products synthesized ($f_{yield}$ <= 1).

In the vegetative stage, the aboveground biomass is derived from the simulated amount of water transpired by means of $WP^*$. During yield formation, the water productivity switches gradually from $WP^*$ to $WP^*_{adj}$ (Fig. 3.11d). For determinant crops the transition takes place during the lag phase where the increase of the Harvest Index is slow (see 3.12.3 Building up of Harvest Index). For indeterminant crops it is assumed that the crop water productivity is fully adjusted after 1/3 of the length of the yield formation stage.

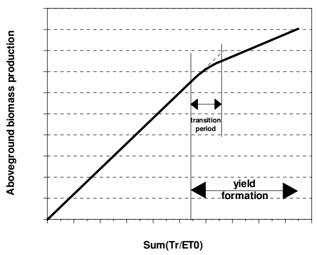



**Figure 3.11d**
**The relationship between the aboveground biomass and the total amount of water transpired before an during yield formation for crops rich in lipids or proteins**



- **Adjustment of WP* for soil fertility ($Ks_{WP}$)**

If limited soil fertility affects crop water productivity, the adjusted productivity is given by:

$$WP^*_{adj} = Ks_{WP}\ WP^* \qquad \text{(Eq. 3.11g)}$$

where $WP^*_{adj}$ WP adjusted for soil fertility
$Ks_{WP}$ soil fertility stress coefficient for water productivity ($Ks_{WP}$ <= 1)

$Ks_{WP}$ is 1 for non limiting soil fertility. The stress coefficient decreases for increasing soil fertility stress (see 3.2. Stresses). Biomass production is no longer possible when the stress coefficient reaches the theoretical minimum of 0.

Because the reservoir of nutrients gradually depletes when the crop develops, the effect of soil fertility on the adjustment of WP is not linear throughout the season. As long as the canopy is small, the daily biomass production will be rather similar to the daily production for non limited soil fertility, and $Ks_{WP,i}$ at day i will be close to 1 (no fertility stress). This is the case early in the season when sufficient nutrients are still available in the root zone. If the crop does not experience water stress, the canopy will further develop during the season but this will result in a progressive depletion of nutrients from the reservoir. Consequently the daily biomass production will gradually decline when more and more biomass is produced. This is simulated in AquaCrop by making the stress coefficient $Ks_{WP,i}$ a function of the relative amount of biomass produced ($B_{rel}$). For every day in the season $B_{rel}$ is given by the ratio between the amount of biomass produced on that day and the maximum amount of biomass that can be obtained at the end of the season for the given soil fertility level. The maximum amount refers to a production without any water stress during the season.

Since $B_{rel}$, after correction for temperature stress, is proportional to the relative amount of water that has been transpired, $Ks_{WP,i}$ for any day in the season is given by:

$$Ks_{WP,i} = 1 - f_{WP} \left( \frac{\sum_{j=1}^{i} \left( Ks_{b,j}\ (Tr_j / ETo_j) \right)}{\sum_{j=1}^{n} \left( Ks_{b,j}\ (Tr_{x,j} / ETo_j) \right)} \right)^2 \qquad \text{(Eq. 3.11h)}$$

where $Ks_{WP,i}$ soil fertility stress coefficient for water productivity at day i
$f_{WP}$ maximum reduction for WP (expressed as a fraction) for the given soil fertility level, that can be observed at the end of the season when the crop does not experience water stress ($f_{WP} = 1 - Ks_{WP}$)
$\sum(Tr_j/ETo_j)$ sum of water transpired at day i (normalized for climate)
$\sum(Tr_{x,j}/ETo_j)$ sum of water that will have been transpired at the end of the season (normalized for climate) for the given soil fertility level when the crop does not experience water stress
$Ks_b$ temperature stress coefficient for biomass production (see 3.11.3)
n number of days in the season



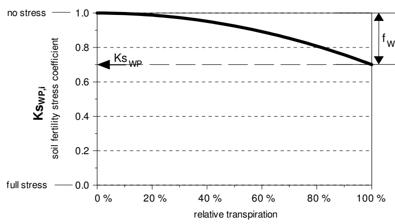



**Figure 3.11e**
**Soil fertility stress coefficient for various degrees of relative transpiration (for a $f_{WP}$ of 0.3 or a $Ks_{WP}$ of 0.7)**

The variation of the soil fertility stress coefficient throughout the season is plotted in Fig. 3.11e. At the start of the season $Ks_{WP,i}$ is 1 and $WP^*$ is not adjusted. As more and more water is transpired during the season, $Ks_{WP,i}$ will gradually decline. When the crop does not experience any water stress throughout its cycle, the relative transpiration becomes 1 at the end of the season and $Ks_{WP,i=n} = Ks_{WP}$. However, if water stress hampers the canopy development and/or result in stomatal closure, the relative transpiration will remain smaller than 1 throughout the season, resulting in a smaller adjustment of WP ($Ks_{WP,i=n} > Ks_{WP,x}$).

- **Adjustment of WP* for atmospheric $CO_2$, type of products synthesized and soil fertility or soil salinity stress**

The total adjustment of the normalized crop water productivity for atmospheric $CO_2$, type of products synthesized and soil fertility/salinity stress is given by:

$$WP^*_{adj} = f_{CO2}\ f_{yield}\ Ks_{WP,i}\ WP^* \qquad \text{(Eq. 3.11i)}$$

How strongly $WP^*_{adj}$ differs from $WP^*$, depends on the deviation of the atmospheric $CO_2$ concentration from its 369.47 ppm reference value, the growth stage (vegetative or yield formation), the type of products synthesized during yield formation, the amount of biomass produced, the soil fertility and /or soil salinity stress. For soil fertility/salinity stress, $WP^*_{adj}$ will decline during the season as more biomass is produced and $Ks_{WP,i}$ gradually decreases.



### 3.11.3 Air temperature stress coefficient for biomass production

The production of biomass might be hampered when the air temperature is too cool. This is simulated in AquaCrop by considering a temperature stress coefficient $Ks_b$ (see 3.2.3 Air temperature stress). Depending on the number of growing degrees generated on a day, the value of $Ks_b$ varies between 0 (resulting in no biomass production on a day) and 1 (biomass production is not restricted by temperature for that day).

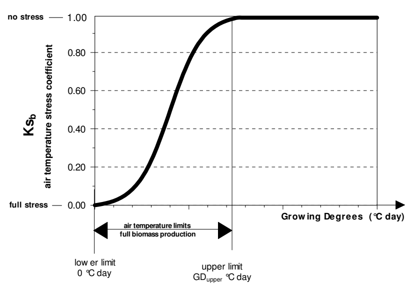



**Figure 3.11f**
**The air temperature stress coefficient for reduction of biomass production ($Ks_b$) for various levels of growing degrees**

If the growing degrees generated in a day drops below an upper threshold ($GD_{upper}$) the biomass production is limited by air temperature and $Ks_b$ is smaller than 1 (Fig. 3.11f). In AquaCrop it is assumed that biomass production is completely halted when it becomes too cold to generate any growing degrees ($Ks_b$ = 0 for 0 °C day). Between the lower (0°C day) and upper limit ($GD_{upper}$) the variation of the adjustment factor is described by a logistic function. The upper threshold ($GD_{upper}$) is a crop parameter, and its value can be adjsuted between 0.1 and 20 °C day.

### 3.11.4 Above ground biomass production between cuttings

For forage and grass crops the above ground biomass production between cuts is simulated by Eq. 3.11b. It is thereby assumed that at each cut a volume of biomass remains on the field. The biomass harvested at the first cut in the season can only be estimated if the initial biomass at the start of the season is known.

## 3.12 Partition of biomass into yield part (yield formation)

The partition of biomass into yield part (Y) is simulated by means of a Harvest Index (HI):

$$Y = HI\ B \qquad \text{(Eq. 3.12a)}$$

where B is the total above-ground biomass produced at crop maturity (Eq. 3.11b) and HI the fraction of B that is the yield part. When water and/or temperature stress develops during the crop cycle, the Harvest Index is adjusted to the stresses at run time for fruit/grain producing crops and roots and tuber crops and might be different from the reference harvest index ($HI_o$). The adjustment can be positive or negative and depends on the timing and the extent of the stress. The calculation scheme is presented in Fig. 3.12a.

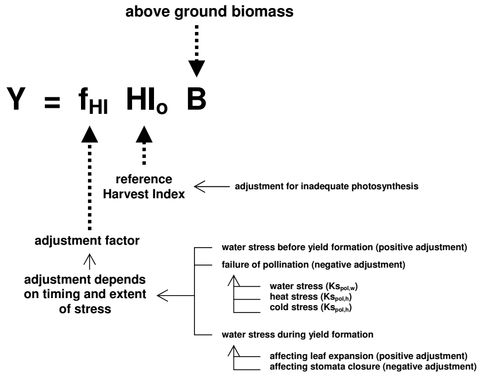



**Figure 3.12a**
**Calculation scheme in AquaCrop for yield (Y)**



### 3.12.1 Reference Harvest Index ($HI_o$)

The reference Harvest Index ($HI_o$) is the ratio of the yield mass to the total aboveground biomass that will be reached at maturity for non-stressed conditions. $HI_o$ is a crop a parameter that is cultivar specific.

### 3.12.2 Building up of Harvest Index

The increase of HI is described by a logistic function:

$$HI_i = \frac{HI_{ini}\ HI_0}{HI_{ini} + \left(HI_0 - HI_{ini}\right)\exp^{-(HIGC)t}} \qquad \text{(Eq. 3.12b)}$$

where
- $HI_i$ Harvest Index at day i;
- $HI_o$ specified reference Harvest Index [fraction];
- $HI_{ini}$ initial value for HI ($HI_{ini}$ is 0.01);
- HIGC growth coefficient for HI [$day^{-1}$];
- t time [day].

The simulation of the building up of the Harvest Index differs along the crop types. Distinction is made between leafy vegetable crops (Fig. 3.12b), root/tuber crops (Fig. 3.12c), and fruit/grain producing crops (Fig. 3.12d).

- **Building up of Harvest Index for leafy vegetable crops**

After germination of leafy vegetable crops the Harvest Index builds up quickly and reaches after a short while the reference value $HI_o$ (Fig. 3.12b). The time to reach $HI_o$ is expressed as a fraction of the growing cycle (default is 20 %).

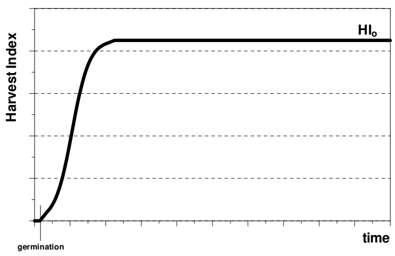



**Figure 3.12b**
**Building up of Harvest Index along the growth cycle for leafy vegetable crops**



In Eq. 3.12b, t is the time after germination. Given $HI_{ini}$, $HI_o$ and the time required to obtain $HI_o$, the corresponding growth coefficient (HICG) for HI is derived in AquaCrop from Eq. 3.12b.

- **Building up of Harvest Index for root/tuber crops**

Just after the start of tuber formation or root enlargement the increase of the Harvest Index is described by a logistic function (Fig. 3.12c). The harvest index for any day of yield formation is given by Eq. 3.12b, where t is the time after the start of tuber formation or root enlargement. The growth coefficient (HICG) is determined with the help of the specified length of yield formation (time required to obtain $HI_o$). When the building up of the Harvest Index is fast, the crop might have reached its reference value ($HI_o$) before the end of the crop cycle.

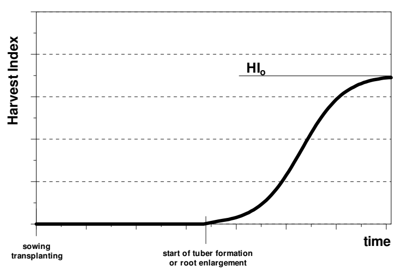



**Figure 3.12c**
**Building up of Harvest Index for root and tuber crops**



- **Building up of Harvest Index for fruit/grain producing crops**

Just after flowering the increase of the Harvest Index is slow (lag phase) and described by the logistic function. The harvest index for any day in the lag phase is given by Eq. 3.12b where t is the time after flowering. The growth coefficient (HICG) is determined with the help of the specified length of yield formation (time required to obtain $HI_o$).

Once the increase of the Harvest Index is sufficient large to reach $HI_o$ at the end of yield formation, the lag phase is ended and the increase of HI becomes linear (Fig. 3.12d). When the building up of the Harvest Index is fast, the crop might have reached its reference value ($HI_o$) before the end of the crop cycle. Given the excess of potential fruits, the period of building up of HI cannot be smaller in AquaCrop than the time required to have 100% potential fruits.

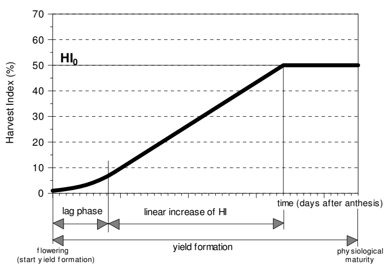



**Figure 3.12d**
**Building up of Harvest Index from flowering till physiological maturity for fruit and grain producing crops**

### 3.12.3 Adjustment of $HI_o$ for inadequate photosynthesis

For root/tuber crops and fruit/grain producing crops the Harvest Index might need to be adjusted for insufficient green canopy cover. A too short grain/fruit filling stage or tuber formation stage might result in inadequate photosynthesis and a reduction of the reference Harvest Index ($HI_{adj}$) at run time.

Before $HI_o$ is reached, the remaining green canopy cover might be very small as a result of early canopy cover. If the remaining canopy cover at the end of yield formation is below a minimum value ($CC_{minimum}$), the crop is unable to reach $HI_o$. This is detected by the program by comparing for each day during the yield formation stage, the actual green canopy cover (CC) with the minimum canopy cover required for yield formation. If CC is smaller than or equal to the minimum value, the Harvest Index can no longer increase (Fig. 3.12e). This results in an adjusted HI which is smaller than $HI_o$. The threshold green canopy cover below which the Harvest Index can no longer increase is a program parameter.

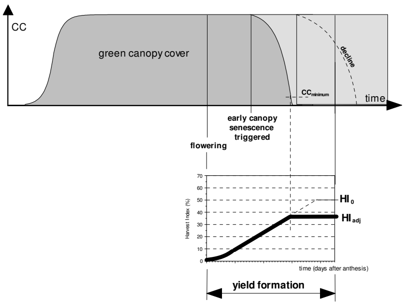



**Figure 3.12e**
**Harvest index development (bold line) when insufficient green canopy cover remains during yield formation for crops with determinancy linked with flowering**



### 3.12.4 Adjustment of $HI_o$ for water stress before the start of yield formation

When a fruit/grain producing or root/tuber crop has spent less energy in its vegetative growth, the Harvest Index might be higher than $HI_o$ (Fig. 3.12f). The maximum allowable increase of $HI_o$ as the result of water stress before flowering ($\Delta HI_{ante}$) is specified as a percentage of $HI_o$.

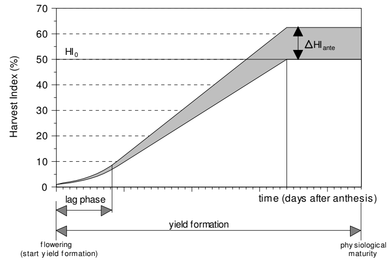



**Figure 3.12f**
**Range (shaded area) in which the Harvest Index of fruit/grain producing or root/tuber crops can increase as a result of water stress before the start of yield formation**

In AquaCrop the relative biomass is used to asses the saving in energy in the vegetative growth stage. The relative biomass ($B_{rel}$), determined at the start of flowering (tuber formation), is the ratio between the actual biomass (B) and the potential biomass ($B_0$):

$$B_{rel} = \frac{B}{B_0} \qquad \text{(Eq. 3.12c)}$$

The actual biomass is the biomass derived from the cumulative amount of water transpired at the moment of flowering. The potential value is the biomass that could have been obtained in the same period in the given environment if there was not any stress resulting in stunned growth, stomatal closure or early senescence.

$HI_o$ might be adjusted upward if $B_{rel}$ is smaller than 1 at the start of flowering. However, it is the magnitude of $B_{rel}$ that determine the magnitude of the adjustment. A too high or a



too low $B_{rel}$ will result in only a slight correction or no adjustment at all (Fig. 3.12g). Hence, the adjustment is restricted to a particular range of $B_{rel}$. The range valid for adjustment is given by:

$$Range(B_{rel}) = \frac{\ln(\Delta HI_{ante})}{5.62} \le 1 \qquad \text{(Eq. 3.12d)}$$

where $\Delta HI_{ante}$ allowable increase of $HI_o$ as the result of water stress before flowering [%];
*Range($B_{rel}$)* range of relative biomass ($B_{rel}$) in which $HI_o$ can be adjusted [fraction].

In AquaCrop the range is linked to the allowable increase (in percentage) of $HI_o$ specified by the user. The percentage is crop specific and gives the maximum possible increase of $HI_o$ as a result of water stress before flowering. The higher the specified increase $\Delta HI_{ante}$, the larger the range for adjustment.

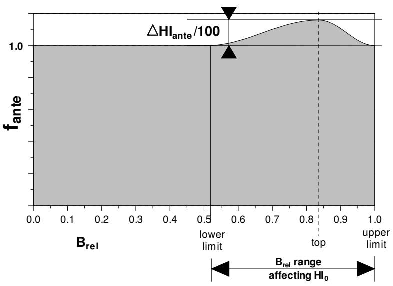



**Figure 3.12g**
**Coefficient ($f_{ante}$) by which $HI_o$ has to be multiplied to consider the effect of water stress before the start of yield formation, for various relative biomass values ($B_{rel}$), and a given allowable increase ($\Delta HI_{ante}$)**



Within the range where HI can be adjusted, the exact correction for $HI_o$ is given by a sine function (Fig. 3.12g):

- For $B_{rel}$ between the lower limit and the top:

$$f_{ante} = 1 + \frac{1+\sin((1.5 - Ratio_{low})\pi)}{2}\,\frac{\Delta HI_{ante}}{100} \qquad \text{(Eq. 3.12e)}$$

where $B_{rel}$ relative biomass at the start of flowering (Eq. 3.12c);
$B_{r,low}$ lower limit of the $B_{rel}$ Range affecting $HI_o$;
$B_{r,top}$ top of $B_{rel}$ Range affecting $HI_o$;
$f_{ante}$ coefficient by which $HI_o$ has to be multiplied to consider the effect of water stress before flowering;

$$0 \le Ratio_{low} = \frac{B_{rel} - B_{r,low}}{B_{r,top} - B_{r,low}} \le 1 \qquad \text{(Eq. 3.12f)}$$

- For $B_{rel}$ between the top and the upper limit ($B_{rel}$ = 1):

$$f_{ante} = 1 + \frac{1+\sin((0.5 + Ratio_{up})\pi)}{2}\,\frac{\Delta HI_{ante}}{100} \qquad \text{(Eq. 3.12g)}$$

where $B_{rel}$ relative biomass at the start of flowering (Eq. 3.12c);
$B_{r,top}$ top of $B_{rel}$ Range affecting $HI_o$;
$B_{r,up}$ upper limit of $B_{rel}$ Range affecting $HI_o$;
$f_{ante}$ coefficient by which $HI_o$ has to be multiplied to consider the effect of water stress before flowering.

$$0 \le Ratio_{up} = \frac{B_{rel} - B_{r,top}}{B_{r,up} - B_{r,top}} \le 1 \qquad \text{(Eq. 3.12h)}$$

The response in the *Range($B_{rel}$)* is assumed to be asymmetric. The top is at 1/3 of $B_{r,up}$ and at 2/3 of $B_{r,low}$.

### 3.12.5 Adjustment of $HI_o$ for failure of pollination (only for fruit/grain producing crops)

- **Flowering**

In AquaCrop the pattern of flowering is assumed to be asymmetric with time (Fig. 3.12h). The flowering distribution curve is given by:

$$f_k = 0.00558\, k^{0.63} - 0.000969\, k - 0.00383 \qquad \text{(Eq. 3.12i)}$$

where k is the relative time in percentage of the total flowering duration and $k_t$ is the fraction of flowers flowering a time k.

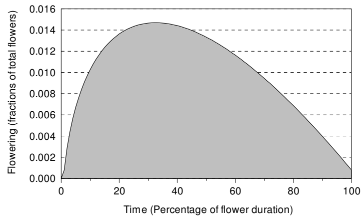



**Figure 3.12h**
**Distribution of flowering during the flowering period**

Generally a crop will produce flowers in excess. When conditions are favorable, the crop sets more fruits than needed for a good harvest. The excessive young fruits are aborted as the older fruits grow. The excess ($f_{excess}$) is a crop parameter.

- **Failure of pollination**

Severe water stress, cold stress, or heat stress at flowering might induce a reduction in the reference harvest index because insufficient flowers are pollinated to reach $HI_o$. The effect is dynamic, affecting only the population of flowers that is due to pollinate at the time of the stress, but not the younger flowers due to pollinate days later or the flowers already pollinated. To estimate $HI_{adj}$ AquaCrop calculates for each day of the flowering period, the HI that can be reached with the number of flowers already pollinated:

$$HI_{adj} = \sum_{1}^{j}\left(Ks_j\left(1+\frac{f_{excess}}{100}\right)F_j\; HI_0\right) \quad \le\; HI_0 \qquad \text{(Eq. 3.12j)}$$



where j number of days since the start of flowering (j = 1 at the start of flowering)
$f_{excess}$ excess of the sink (percentage);
$F_j$ fractional flowering on day j (derived from Eq. 3.12i); To be able to account for cold and heat stress at flowering, the calculation procedure works with calendar days;
$Ks_j$ stress factor limiting pollination on day j.

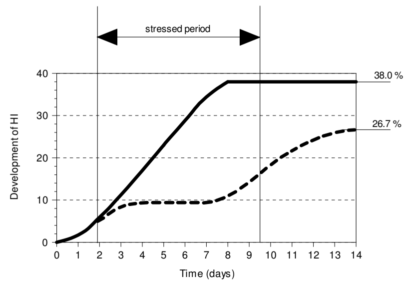



**Figure 3.12i**
**The development of HI at flowering and the adjusted harvest indexes ($HI_{adj}$) for a non stressed (full) and a stressed (dotted line) flowering period of 14 days. ($HI_o$ = 38%, $f_{excess}$ = 50%, and stress occurs (Ks < 1) from day 2 till day 9)**

The excess of the sink made that if stress reduces pollination by a minor amount, $HI_o$ might not be affected because the excessive young fruits are given the change to grow, instead of dropping off, if stress is ameliorated after the flowering period and canopy photosynthesis is adequate. An import stress, during several days at flowering, might result in a $HI_{adj}$ that is smaller than the specified $HI_o$ (Fig. 3.12i). The smaller the excess of flowers ($f_{excess}$) and the more severe the stress (Ks), the stronger the reduction of the reference harvest index.

***Failure of pollination due to water stress ($Ks_{pol,w}$)***

Severe water stress at the time of flowering, can markedly inhibit pollination and fruit setting. This is simulated by considering a soil water stress coefficient for pollination, $Ks_{pol,w}$ (see 3.2.2 Soil water stress). If the root zone depletion drops below a threshold ($p_{pol}$ TAW), $Ks_{pol,w}$ becomes smaller than 1 and pollination starts to fail (Fig. 3.12j).



$Ks_{pol,w}$ decreases linearly from 1 at the upper threshold ($p_{pol}$) to zero at the lower threshold (permanent wilting point).

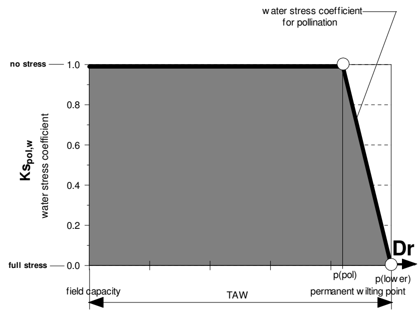



**Figure 3.12j**
**The water stress coefficient for failure of pollination ($Ks_{pol,w}$) for various degrees of root zone depletion (Dr)**

Since pollination is inhibited only be severe stress, the fraction of TAW that can be depleted from the root zone before pollination is affected ($p_{pol}$) is large. The threshold should be set lower than the threshold for the effect for stomatal closure ($p_{sto}$) and senescence ($p_{sen}$). Since by then stomata are largely closed and most of the transpiration is eliminated, the stress effect on pollination needs not to be adjusted to $ET_o$. Because the data on pollination failure are limited and insufficient to determine the shape of the response curve, a linear function is considered for $Ks_{pol,w}$.

***Failure of pollination due to cold ($Ks_{pol,c}$) and heat stress ($Ks_{pol,h}$)***

If the minimum air temperature drops below a threshold ($T_{n,cold}$) or the maximum air temperature rises above a threshold ($T_{x,heat}$), pollination might be affected. This simulated by considering a cold stress ($Ks_{pol,c}$) coefficient and heat stress ($Ks_{pol,h}$) coefficient for pollination (see 3.2.3 Air temperature stress).

When the minimum air temperature on a day drops below the specified threshold temperature ($T_{n,cold}$), the cold stress coefficient $Ks_{pol,c}$ will be smaller than 1 (Fig. 3.12k). $Ks_{pol,c}$ becomes zero at the lower threshold which is set at 5 degrees below $T_{n,cold}$. A



logistic function is used as the response function between the lower temperature threshold and $T_{n,cold}$. Similarly, when the maximum air temperature rises above the specified threshold temperature ($T_{x,heat}$), the heat stress coefficient $Ks_{pol,h}$ will be smaller than 1. $Ks_{pol,h}$ becomes zero at the upper threshold which is set at 5 degrees above $T_{x,heat}$. Outside the stressed period, the air temperature stress coefficients $Ks_{pol,c}$ and $Ks_{pol,h}$ are 1.

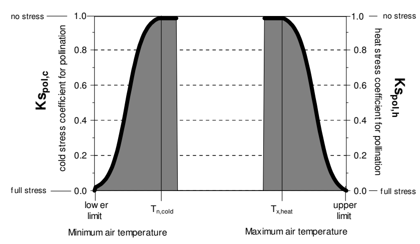



**Figure 3.12k**
**The air temperature stress coefficients for failure of pollination due to cold ($Ks_{pol,c}$) and heat ($Ks_{pol,h}$) stress for various air temperatures**

### 3.12.6 Adjustment of $HI_o$ for water stress during yield formation

Water stress after flowering (fruit/grain producing crops) or after the start of tuber formation or root enlargement (root/tuber crops) might affect the reference Harvest Index ($HI_o$) as well. Depending on the moment when the water stress occurs and on its magnitude, the adjustment can be upwards or downwards (Fig. 3.12l).

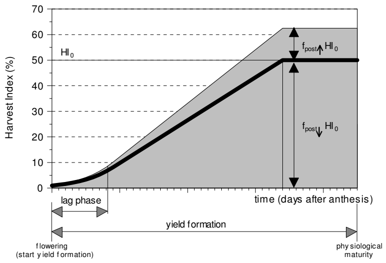



**Figure 3.12l**
**Range (shaded area) in which the Harvest Index of fruit/grain producing or root/tuber crops can alter as a result of water stress during yield formation**

- **Upward adjustment of $HI_o$**

As long as vegetative growth is still possible (see 3.5.2 Period of potential vegetative growth), the daily rate with which the Harvest Index increases (dHI/dt) might be adjusted if water stress affects leaf expansion. This results in an increase of dHI/dt and is given by:

$$\frac{dHI}{dt} = \left(1+\frac{(1-Ks_{\exp,i})}{a}\right)\left(\frac{dHI}{dt}\right)_o \qquad \text{(Eq. 3.12k)}$$

where $(dHI/dt)_o$ reference increase of the Harvest Index after flowering;
$Ks_{exp,i}$ value for the water stress coefficient for leaf expansion growth at day i (see 3.5.1). $Ks_{exp}$ is 1 for no stress and 0 for full stress;
a crop parameter (the value is crop specific and can vary between 0.5 (strong effect) and 40 (very small effect).



By keeping track of the daily values for $Ks_{exp,i}$ during the period when vegetative growth is still possible, the positive adjustment of the Harvest Index at the end of the period is given by:

$$f_{post\uparrow} = 1+\frac{\sum_{i=1}^{n(\exp)}\left(\frac{1-Ks_{\exp,i}}{a}\right)}{n(\exp)} \qquad \text{(Eq. 3.12l)}$$

where n(exp) period when vegetative growth is still possible [days];
$f_{post\uparrow}$ coefficient by which $HI_o$ has to be multiplied to consider the positive effect of water stress after flowering.

The adjustment of $HI_o$ is plotted in Figure 3.12m for various values of 'a'. When a is 0.5 and the average root zone depletion during the potential period of vegetative growth is large ($Dr \geq p_{exp,lower}$ TAW), $f_{post\uparrow}$ might increase up to 3. This will result in a $HI_o$ which is the triple of $HI_o$.

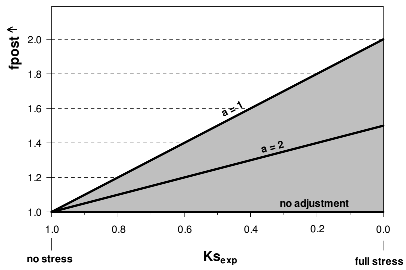



**Figure 3.12m**
**Values for $f_{post\uparrow}$ if water stress after flowering occurs for various mean water stresses affecting leaf growth ($Ks_{exp,w}$) and 'a' values**



- **Downward adjustment of $HI_o$**

During the total period of the building up of the Harvest Index, the daily rate with which the Harvest Index increases (dHI/dt), might be adjusted if water stress affects crop transpiration. This results in a decrease of dHI/dt, and is given by:

$$\frac{dHI}{dt} = \sqrt[10]{Ks_{sto}}\left(1-\frac{1-Ks_{sto,i}}{b}\right)\left(\frac{dHI}{dt}\right)_o \qquad \text{(Eq. 3.12m)}$$

where $(dHI/dt)_o$ reference increase of the Harvest Index after flowering;
$Ks_{sto,i}$ value for the water stress coefficient for stomatal closure (or for deficient aeration conditions) at day i (see 3.10.2). $Ks_{sto}$ is 1 for no stress and 0 for full stress;
b crop parameter (the value is crop specific and can vary between 1 (strong effect) and 20 (small effect).

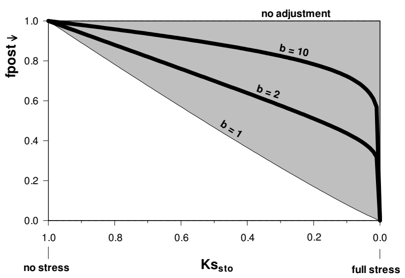



**Figure 3.12n**
**Values for $f_{post\downarrow}$ if water stress after flowering occurs for various mean water stresses affecting crop transpiration ($Ks_{sto}$) and 'b' values**



By keeping track of the daily values for $Ks_{sto,i}$ during the period of the building up of HI, the negative adjustment of the Harvest Index at the end of the period is given by:

$$f_{post\downarrow} = \frac{\sum_{i=1}^{n(yield)}\left(\sqrt[10]{Ks_{sto,i}}\left(1-\frac{(1-Ks_{sto,i})}{b}\right)\right)}{n(yield)} \qquad \text{(Eq. 3.12n)}$$

where n(yield) period for building up the Harvest Index [days];
$f_{post\downarrow}$ factor by which $HI_o$ has to be multiplied to consider the negative effect of water stress after flowering.

The adjustment of $HI_o$ is plotted in Figure 3.12n for various values of 'b'. The $10^{th}$ root of $Ks_{sto}$ in Eq. 3.12n makes that the effect of stomatal closure on $HI_o$ is small when $Ks_{sto}$ is close to 1, i.e. crop transpiration is only slightly hampered. Severe water stress might strongly reduce $HI_o$ especially when b is small (close to 1).

- **Combined effect on $HI_o$**

The total adjustment for water stress after the start of yield formation on the Harvest Index is given by the product of the Eq. 3.12l and Eq. 3.12n. If the period where vegetative growth is still possible (n(exp)) is smaller than the duration of building up the Harvest Index (n(yield)), the adjustments are weighed by their relative length:

$$f_{post} = \left(\frac{w_1\, f_{post\uparrow} + (w_2 - w_1)}{w_2}\right) f_{post\downarrow} \qquad \text{(Eq. 3.12o)}$$

where $w_1$ length of the period when vegetative growth is still possible [days];
$w_2$ length of the period of building up the harvest Index [days];
$f_{post}$ coefficient by which $HI_o$ has to be multiplied to consider the combined effect of water stress after flowering.

### 3.12.7 Total effect of water and temperature stress on the Harvest Index

The total correction of $HI_o$ at the end of the yield formation is obtained by considering the adjustments of water stress before and after yield formation and during flowering (Fig. 3.12o).

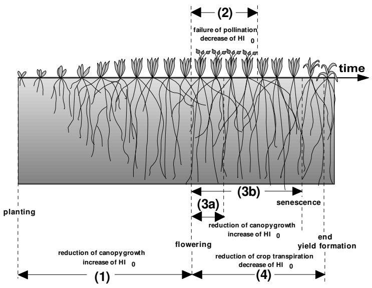



**Figure 3.12o**
**Periods in which water stress might affect HI and its effect on $HI_o$.**
**(1) before yield formation; (2) during flowering; and (4) during yield formation, with indication of (3) the period of possible vegetative growth for (a) determinant crops and (b) indeterminant crops**

The total correction of $HI_o$ at the end of the yield formation is given by:

$$HI = f_{ante}\ f_{post}\ HI_{adj} \qquad \text{(Eq. 3.12p)}$$

where HI — Harvest Index reached at the end of yield formation;
$f_{ante}$ — factor by which $HI_{adj}$ has to be multiplied to consider the effect of water stress before flowering (Eq. 3.12e and 3.12g);
$f_{post}$ — factor by which $HI_{adj}$ has to be multiplied to consider the effect of water stress after flowering (Eq. 3.12o);
$HI_{adj}$ — reference Harvest Index adjusted for failure of pollination and inadequate photosynthesis



The adjusted Harvest Index can range between an upper limit (larger than $HI_o$) and 0 (Fig. 3.12p):

- If HI is larger than $HI_o$, its value can however never exceed a maximum specified by the user. The allowable increase ($\Delta HI_{tot}$) which is crop specific, is specified as a percentage of $HI_o$:

$$HI \leq \left(1 + \frac{\Delta HI_{tot}}{100}\right) HI_0 \qquad \text{(Eq. 3.12q)}$$

- As a result of water stress at and after flowering, HI might be smaller than $HI_o$. If the water stress during yield formation is very severe and results in a crop transpiration rate far below its potential value, HI might become very small. HI will be zero (resulting in no yield) if the average water content in the root zone is at wilting point during yield formation.

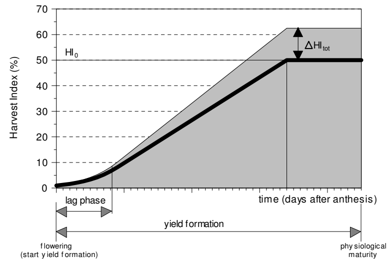



**Figure 3.12p**
**Range (shaded area) in which the Harvest Index can increase or decrease as a result of water stress before and after the start of yield formation**



## 3.13 Schematic outline of the model operation

The model operation as explained in this chapter is schematic depicted in Figure 3.13.

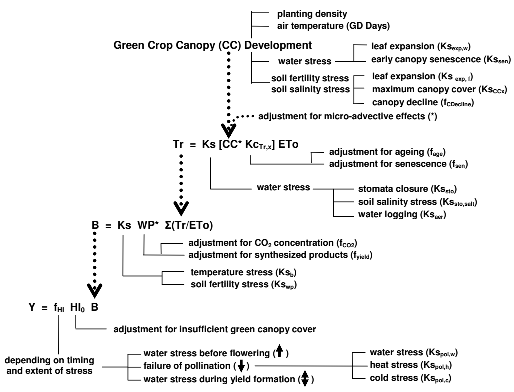



**Figure 3.13**
**Schematic outline of the model operation of AquaCrop.**



## 3.14 Simulation of the effect of soil fertility stress

### 3.14.1 Calibration of the crop response to soil fertility stress

To describe the effect of soil fertility stress on crop development and production, AquaCrop makes use of 4 stress coefficients (Table 3.14).

**Table 3.14 - Soil fertility stress coefficients and their effect on crop growth**

| Soil fertility stress coefficient | Direct effect | Target model parameter |
|---|---|---|
| **$Ks_{CCx}$**: Stress coefficient for maximum Canopy Cover | Reduces canopy cover | $CC_x$ |
| **$Ks_{exp,f}$** : Stress coefficient for canopy expansion | Reduces canopy expansion | CGC |
| **$f_{CDecline}$** : Decline coefficient of canopy cover | Decline of the canopy cover once the maximum canopy cover is reached | $CC_x$ |
| **$Ks_{WP}$** : Stress coefficient for Water Productivity | Reduces biomass production | $WP^*$ |

The shape of each of the 4 soil fertility stress coefficients are fixed when calibrating the crop response to soil fertility stress (Fig. 3.14a). The calibration process is described in Chapter 2 (see 2.9.8 Calibration for soil fertility stress in the Reference Manual) by considering the effect of soil fertility stress in a stressed field. The calibration is done in the ***Crop characteristics*** menu.

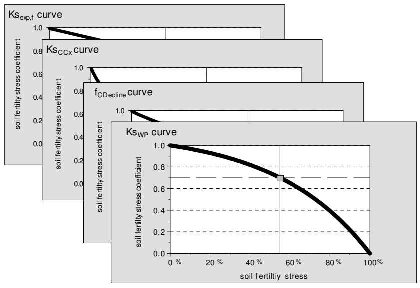



**Figure 3.14a –** The shape of the 4 Ks curves as determined by calibration.

From the 4 calibrated Ks curves, the relation between Biomass and soil fertility stress (Fig. 3.14b) is obtained:

(i) by defining for various soil fertility stress levels the individual effect on (a) CGC, (b) CCx, (c) canopy decline, and on (d) WP* (as obtained from the 4 stress curves, Fig. 3.14a); and

(ii) by subsequently calculating for each of those soil fertility stress levels the corresponding biomass production (B) by considering the specific decrease of CGC, CCx, canopy decline and WP*.

Since the shapes of the 4 Ks curve are not necessary identical and the effect of stress on WP* increases when the canopy cover increases, the Biomass – soil fertility stress relationship is not linear (Fig. 3.14b).

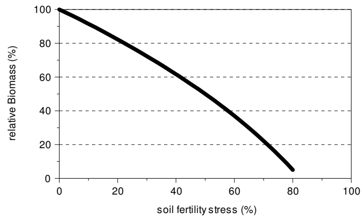



**Figure 3.14b –** Relationship between relative Biomass and soil fertility stress.

### 3.14.2 Selection of a soil fertility level for simulation

In the ***Field management*** menu, the soil fertility level is specified indirectly when the user specifies the maximum *biomass* that can be expected in the field affected by soil fertility stress. The selected biomass is the biomass production that can be expected for the selected crop, for the given soil fertility level in the field, under the given climatic conditions, and in absence of any other stresses than soil fertility stress. It is the biomass that can be locally produced in a good rainy year or under irrigation when there is no water stress. This level of biomass might be available in statistical reports of local crop productions, or might be obtained from farmers. The selected biomass is expressed as a percentage of the biomass that can be obtained in the same field but for unlimited soil fertility.



From the relationship between relative Biomass and soil fertility stress (Fig. 3.14b), AquaCrop derives the 'corresponding' soil fertility stress in the field. This corresponding soil fertility stress level is required to know the corresponding values for each of the 4 stress coefficients. These values are derived from the shapes of the individual Ks curves (Fig. 3.14a).

### 3.14.3 Running a simulation

When running a simulation, AquaCrop considers the effect of soil fertility stress on canopy development and crop production with the help of the 4 stress coefficients and calculates at each time step the Biomass. When due to soil water stress, the Biomass is less than what can be expected for the given soil fertility stress, AquaCrop decreases the soil fertility stress in its next time step(s). As such AquaCrop considers the rise in soil fertility because a water stressed crop is limited in its uptake of nutrients. The stronger the water stress, the more nutrients remain in the soil reservoir and the stronger the rise in soil fertility. If at a later stage the water stress is relieved by ample rainfall or irrigation, the soil fertility decreases and eventually returns to its original state if the Biomass production is in line with the one specified in the ***Field management*** menu. This dynamic adjustment of the soil fertility level makes that the effect of soil fertility stress is automatically adjusted to the effect of other stresses.



## 3.15 Simulation of the effect of soil salinity stress

### 3.15.1 Calibration of the crop response to soil salinity stress

To describe the effect of soil salinity stress on crop development and production, AquaCrop makes use of 4 stress coefficients (Table 3.15a).

**Table 3.15a - Soil salinity stress coefficients and their effect on crop growth**

| **Soil fertility stress coefficient** | **Direct effect** | **Target model parameter** |
|---|---|---|
| **$Ks_{CCx}$:** Stress coefficient for maximum Canopy Cover | Reduces canopy cover | $CC_x$ |
| **$Ks_{exp,f}$ :** Stress coefficient for canopy expansion | Reduces canopy expansion | CGC |
| **$f_{CDecline}$ :** Decline coefficient of canopy cover | Decline of the canopy cover once the maximum canopy cover is reached | $CC_x$ |
| **$Ks_{sto,salt}$ :** Stress coefficient for stomatal closure | Reduces crop transpiration | $Ks_{sto}$ |

The shape of each of the 4 soil salinity stress coefficients are fixed when calibrating the crop response to soil salinity stress (Fig. 3.15a). The calibration process is described in Chapter 2 (see 2.9.10 Calibration for soil salinity stress in the Reference Manual) by considering the effect of soil salinity stress in a stressed field. The calibration is done in the ***Crop characteristics*** menu.

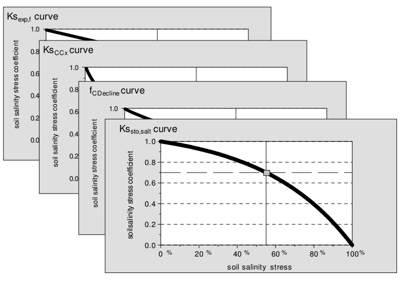



**Figure 3.15a –** The shape of the 4 Ks curves as determined by calibration.



In AquaCrop the effect of soil salinity stress on canopy development is assumed to be identical to the effect of soil fertility stress on CC. Hence the Ks curves for CGC, CCx and canopy decline are identical for the 2 stresses. The difference between soil salinity and soil fertility stress is that, on top of affecting CC, soil salinity stress triggers stomatal closure (described by $Ks_{sto,salt}$) while soil fertility decreases the biomass water productivity (described by $Ks_{WP}$).

From the 4 calibrated Ks curves, the relation between Biomass and soil salinity stress (Fig. 3.15b) is obtained:

(iii) by defining for various soil salinity stress levels the individual effect on (a) CGC, (b) CCx, (c) canopy decline, and (d) stomatal closure (as obtained from the 4 stress curves, Fig. 3.15a); and

(iv) by subsequently calculating for each of those soil salinity stress levels the corresponding biomass production (B) by considering the specific decrease of CGC, CCx, canopy decline and crop transpiration.

Since the shapes of the 4 Ks curve are not necessary identical and the effect of soil salinity stress on crop transpiration is not identical to the effect of soil fertility on WP*, the Biomass – soil salinity stress relationship is not linear and differs from the Biomass – soil fertility stress relationship (Fig. 3.15b).

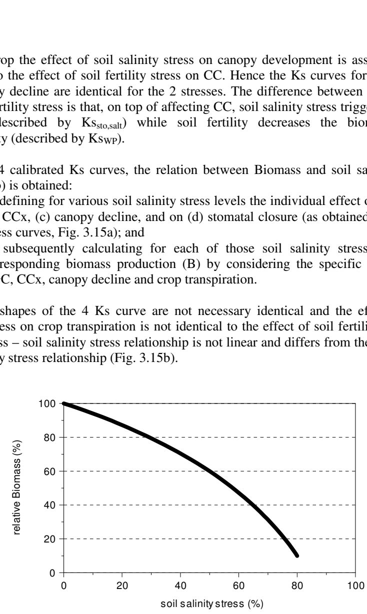



**Figure 3.15b –** Relationship between relative Biomass and soil salinity stress.

### 3.15.2 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 3.15b).

**Table 3.15b –** 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. 3.15c). 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.

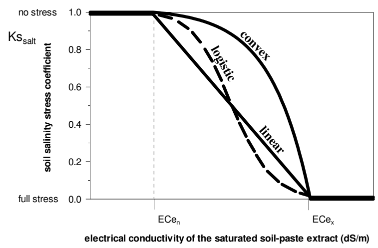



**Figure 3.15c –** Various shapes for the $Ks_{salt}$ curve



### 3.15.3 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. 3.15c) determines the reduction in relative biomass production ($B_{rel}$):

$$B_{rel} = 100\,(1 - Ks_{salt}) \qquad \text{(Eq. 3.15a)}$$

$B_{rel}$ 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.

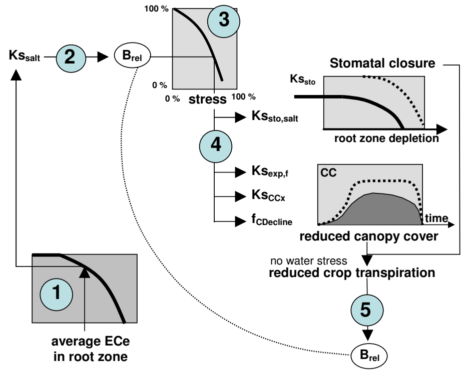



**Figure 3.15d –** The effect of soil salinity on biomass production in a well watered soil with unlimited soil fertility

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 3.15d and consists of the following 5 steps:

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. 3.15c;
2. the relative biomass ($B_{rel}$) that can be produced with the salinity stress ($Ks_{salt}$) is obtained by Eq. 3.15a;
3. the stress inducing stomatal closure and affecting canopy development is derived from the user calibrated relationship between relative biomass production and soil salinity stress (Fig. 3.15b);
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 (Fig. 3.15a);
5. as a result of the calibration the resulting $B_{rel}$ is identical to the expected $B_{rel}$ (Eq. 3.15a) 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.

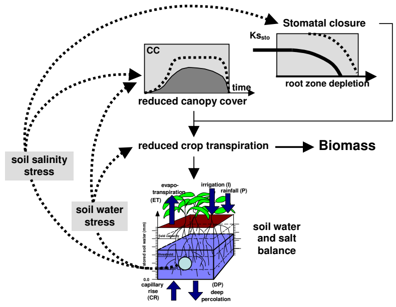



**Figure 3.15e –** The combined effect of soil salinity and soil water stress on the biomass production



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. 3.15e).

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.

### 3.15.4 The effect of soil salinity stress on the 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 ($Ks_{sto,salt}$):

$$Ks_{sto,adj} = Ks_{sto,salt}\ Ks_{sto} \qquad \text{(Eq. 3.15b)}$$

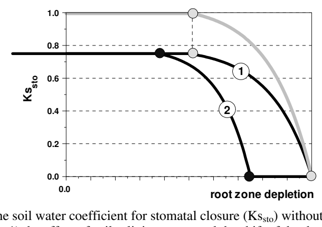



**Fig. 3.15f –** The soil water coefficient for stomatal closure ($Ks_{sto}$) without (gray line) and with (black line 1) the effect of soil salinity stress, and the shift of the thresholds (circles) by considering (black line 2) the effect of soil salinity stress on the thresholds.

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. 3.15f and 3.15g). 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).

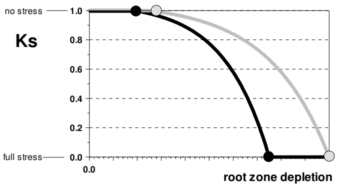



**Figure 3.15g –** Shift of the thresholds (circles) for root zone depletion and its effect on $Ks_{exp}$ and $Ks_{sen}$ for leaf expansion and canopy senescence (lines) with (black) and without (gray) the effect of soil salinity on the thresholds.



## References

Adams, J. E., G. F. Arkin and J. T. Ritchie 1976. Influence of row spacing and straw mulch on first stage drying. Soil Sci. Soc. Am. J. 40: 436-442.

Allen, R.G., L.S. Pereira, D. Raes and M. Smith 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage Paper n. 56. FAO, Rome, Italy, 300 pp.

Asseng, S. and T.C. Hsiao 2000. Canopy $CO_2$ assimilation, energy balance, and water use efficiency of an alfalfa crop before and after cutting. Field Crops Res. 67: 191-206.

Ayers, R.S., Westcot, D.W., 1985. Water quality for agriculture. FAO Irrigation and Drainage Paper no 29. FAO, Rome.

Azam-Ali, S.N. and G.R. Squire 2002. Principles of Tropical Agronomy. CABI Publishing, Wallingford, UK.

Barrios Gonzales, J.M. 1999. Comparative study of three approaches in the computation of soil water balance. Master Dissertation IUPWARE. K.U.Leuven University, Leuven, Belgium. 93 pp.

Bear, J. 1972. Dynamics of fluids in porous media. American Elsevier, NY, USA: 338-346.

Belmans, C., J.G. Wesseling and R.A. Feddes 1983. Simulation of the water balance of a cropped soil: SWATRE. J. of Hydrol., 63: 271-286.

Carnahan, B., H.A. Luther and J.O. Wilkes 1969. Applied numerical methods. John Wiley & Sons Inc., NY, USA: 429-444.

Doorenbos, J. and A.H. Kassam 1979. Yield response to water. Irrigation and Drainage Paper n. 33. FAO, Rome, Italy, 193 pp.

Etheridge D. et al. (1996), J. Geophys. Research vol. 101, 4115-4128.

Farahani, H.J., G. Izzi, P. Stento, and T.Y. Oweis. 2009. Parameterization adn evaluation of AquaCrop for full and deficit irrigated coton. Agron. J. 101: 469-476.

Feddes, R.A., P.J. Kowalik and H. Zaradny 1978. Simulation of field water use and crop yield. Pudoc, Simulation Monographs, Wageningen, The Netherlands. 189 p.

Feyen, J. 1987. Field validation of soil water and crop models. In J. Feyen (Ed.) Simulation models for cropping systems in relation to water management. Proceedings of a symposium in the Community programme for coordination of



agricultural research, Nov. 1986, Louvain, Belgium. Office for Official Publications of the European Communities, Luxembourg: 105-131.

Garcia-Vila, M., E. Fereres, L. Mateos, F. Orgaz, and P. Steduto. 2009. Déficit irrigation optimization of cotton with AquaCrop. Agron. J. 101: 477-487.

Geerts, S., D. Raes, M. Garcia, R. Miranda, J.A. Cusicanqui, C. Taboada, J. Mendoza, R. Huanca, A. Mamani, O. Condori, J. Mamani, B. Morales, V. Osco, and P. Steduto. 2009. Simulating yield response to water of quinoa (Chenopodium quinoa Willd.) with FAO-AquaCrop. Agron. J. 101: 499-508.

Gommes, R.A. 1983. Pocket computers in agrometeorlogy. FAO Plant Production and Protection Paper N° 45. FAO, Rome, Italy. 140 p.

Hsiao, T.C., Heng, L., Steduto, P., Rojas-Lara, B., Raes, D., and Fereres, E. 2009. AquaCrop-The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. Agronomy Journal, 101(3): 448-459

Heng, L.K., S.R. Evett, T.A. Howell, and T.C. Hsiao. 2009. Calibration and testing of FAO aquacrop model for rainfed and irrigated maize. Agron. J., 101: 488-498.

Hess, T.M. 1999. The impact of climatic variability over the period 1961-1990 on the soil water balance of upland soils in the north East Arid Zone of Nigeria. Institute of Water and Environment, Cranfield University, Silsoe, UK. 166 p.

Hoogland, J.C., C. Belmans and R.A. Feddes 1981. Root water uptake model depending on soil water pressure heads and maximum water extraction rate. Acta Hort. 119: 123-135.

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.

McMaster, G. S. and W.W. Wilhelm 1997. Growing degree-days: one equation, two interpretations. Agricultural and Forest Meteorology 87: 291-300.

Naesens, K. 2002. Berekening van effectieve neerslag en oppervlakkige afstroming in waterbalansmodellen. MSc dissertation Fac. of Applied and Biological Sciences, K.U.Leuven, Leuven, Belgium. 92 p.

Philip, J.R. 1957. Evaporation, moisture and heat fields in the soil. J. Meteorol. 14:354-366.

Raes, D. 1982. A summary simulation model of the water budget of a cropped soil. Dissertationes de Agricultura n° 122. K.U.Leuven University, Leuven, Belgium. 110 p.



Raes, D., 2002. BUDGET, a soil water and salt balance model: reference manual. K.U.Leuven, Belgium, 80 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.

Raes, D., H. Lemmens, P. Van Aelst, M. Vanden Bulcke and M. Smith 1988. IRSIS – Irrigation scheduling information system. Volume 1. Manual. K.U.Leuven, Dep. Land Management, Reference Manual 3. 199 p.

Raes, D., S. Geerts, E. Kipkorir, J. Wellens and A. Sahli 2006. Simulation of yield decline as a result of water stress with a robust soil water balance model. Agricultural Water Management 81(3): 335-357.

Raes, D., Steduto, P., Hsiao, T.C., and Fereres, E. 2009. AquaCrop-The FAO crop model to simulate yield response to water: II. Main algorithms and software description. Agronomy Journal, 101(3): 438-447

Raes, D., B. Van Goidsenhoven, K. Goris, B. Samain, E. De Pauw, M. El Baba, K. Tubail, J. Ismael and E. De Nys. 2001. BUDGET, a management tool for assessing salt accumulation in the root zone under irrigation. 4th Inter Regional Conference on Environment-Water, ICID. 27-30 Aug., Fortaleza, Brazil: 244-252

Rallison, R.E. 1980. Origin and evolution of the SCS runoff equation. Symp. On Watershed Management, ASCE, New York, N.Y.: 912-924.

Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resources Research 8(5): 1204-1213.

SCS 1993. Irrigation water requirements. National Engineering Handbook, part 623. Soil Conservation Service, US Dept. Of Agriculture. Washington, USA, 284 p.

Smedema, L.K., and D.W. Rycroft. 1983. Land drainage – planning and design of agricultural drainage systems. Batsford Ltd., London, U.K.

Steenhuis, T.S., M. Winchell, J. Rossing, J.A. Zollweg and M.F. Walter 1995. SCS Runoff equation revisited for variable-source runoff areas. Journal of Irrigation and Drainage Eng. 121(3): 234-238.

Steduto, P. 2003. Biomass Water-Productivity. Comparing the Growth-Engines of Crop Models. FAO Expert Consultation on Crop Water Productivity Under Deficient Water Supply, 26 - 28 February 2003, Rome, Italy.

Steduto, P. and R. Albrizio 2005. Resource-use efficiency of field grown sunflower, sorghum, wheat and chickpea. II Water use efficiency and comparison with radiation use efficiency. Agric. For. Meteorol. 130: 269-281.

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

Steduto, P., Hsiao, T.C., Raes, D. and Fereres, E. 2009. AquaCrop-The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. Agronomy Journal, 101(3): 426-437

USDA 1964. Estimation of direct runoff from storm rainfall. National Engineering Handbook, Washington DC, USA. Section 4 Hydrology, Chapter 4: 1-24.

USDA. 1970. Irrigation water requirements. Technical Release no. 21. USDA. Soil Conservation Service, Washington, DC.

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.

Villalobos, F. J. and E. Fereres. 1990. Evaporation measurements beneath corn, cotton, and sunflower canopies. Agron. J. 82:1153-1159.

Wiyo, K.A. 1999. Effect of tied-ridging on soil water status and maize yield under Malawi conditions. Dissertationes de Agricultura N° 397. K.U.Leuven University, Leuven, Belgium. 200 p.



AQUACROP

# Reference Manual

## *AquaCrop Version 4.0*

**June 2012**

**Dirk RAES, Pasquale STEDUTO, Theodore C. HSIAO, and Elias FERERES**
**with contributions of the AquaCrop Network**

**FAO, Land and Water Division**
**Rome, Italy**



**Contact:** **aquacrop@fao.org**

**Web site:** **http://www.fao.org/nr/water/aquacrop.html**



## List of principal symbols

| Symbol | Description | Unit |
|---|---|---|
| B | dry (above ground) biomass | Mg $ha^{-1}$ |
| CC | Green Canopy Cover | $m^2$ $m^{-2}$ |
| CC* | Green Canopy Cover adjusted for micro advection | $m^2$ $m^{-2}$ |
| $cc_o$ | Canopy size of the average seedling at 90% emergence | $cm^2$ |
| $CC_o$ | Canopy Cover at 90% emergence or after transplanting | $m^2$ $m^{-2}$ |
| $CC_x$ | Maximum green Canopy Cover | $m^2$ $m^{-2}$ |
| CDC | Canopy Decline Coefficient | $d^{-1}$ or °C-$d^{-1}$ |
| CGC | Canopy Growth Coefficient | $d^{-1}$ or °C-$d^{-1}$ |
| $CN_{II}$ | Curve Number for antecedent moisture class II | - |
| CR | Capillary Rise | mm $d^{-1}$ |
| Dr | Root zone depletion | mm |
| DP | Deep percolation | mm $d^{-1}$ |
| E | Soil evaporation | mm $d^{-1}$ |
| $E_x$ | Soil evaporation in Stage I (wet soil surface) | mm $d^{-1}$ |
| $ECe_n$ | Electrical conductivity of the saturated soil-paste extract: lower threshold (at which soil salinity stress starts to occur) | dS $m^{-1}$ |
| $ECe_x$ | Electrical conductivity of the saturated soil-paste extract: upper threshold (at which soil salinity stress has reached its maximum effect) | dS $m^{-1}$ |
| $EC_w$ | Electrical conductivity of the irrigation water | dS $m^{-1}$ |
| ET | Evapotranspiration (soil water evaporation and crop transpiration) | mm $d^{-1}$ |
| $ET_o$ | Reference crop evapotranspiration (evaporating power of the atmosphere) | mm $d^{-1}$ |
| f | Adjustment factor | - |
| $f_{age}$ | Reduction coefficient describing the effect of ageing, nitrogen deficiency, etc. on the crop transpiration coefficient | $d^{-1}$ |
| $f_{sen}$ | Reduction coefficient describing the effect of canopy senescence on the crop transpiration coefficient | - |
| $f_{yield}$ | Reduction coefficient describing the effect of the products synthesized during yield formation on the normalized water productivity | - |
| FC | Field Capacity | |
| GDD | Growing Degree Days | °C-d |
| HI | Harvest Index | % |
| $HI_o$ | Reference Harvest Index | % |
| I | Irrigation | mm $d^{-1}$ |
| $K_{sat}$ | Saturated hydraulic conductivity | mm $d^{-1}$ |
| Kcb | Crop transpiration coefficient | - |
| $Kcb_x$ | Crop transpiration coefficient when complete canopy cover (CC = 1) but prior to senescence | - |
| Ke | Soil evaporation coefficient for fully wet soil surface | - |
| $Ke_x$ | Soil evaporation coefficient for fully wet and non-shaded soil surface | - |

| | | |
|---|---|---|
| Kr | Evaporation reduction coefficient | - |
| $Ks_{aer}$ | Water stress coefficient for water logging (aeration stress) | - |
| $Ks_b$ | Cold stress coefficient for biomass production | - |
| $Ks_{CCx}$ | Soil fertility stress coefficient for maximum Canopy Cover | - |
| $Ks_{exp,f}$ | Soil fertility stress coefficient for canopy expansion | - |
| $Ks_{exp,w}$ | Water stress coefficient for canopy expansion | - |
| $Ks_{pol,c}$ | Cold stress coefficient for pollination | - |
| $Ks_{pol,h}$ | Heat stress coefficient for pollination | - |
| $Ks_{pol,w}$ | Water stress coefficient for pollination | - |
| $Ks_{salt}$ | Soil salinity stress coefficient | - |
| $Ks_{sen}$ | Water stress coefficient for canopy senescence | - |
| $Ks_{sto}$ | Water stress coefficient for stomatal closure | - |
| $Ks_{WP}$ | Soil fertility stress coefficient for Water Productivity | - |
| $p_{exp, lower}$ | Fraction of TAW at which CGC becomes 0 | - |
| $p_{exp, upper}$ | Fraction of TAW at which CGC starts to be reduced | - |
| $p_{pol}$ | Fraction of TAW at which pollination starts to fail | - |
| $p_{sen}$ | Fraction of TAW at which early canopy senescence is triggered | - |
| $p_{sto}$ | Fraction of TAW at which stomata start to close | - |
| P | Precipitation | $mm.d^{-1}$ |
| PWP | Permanent Wilting Point | |
| RAW | Readily Available soil Water in the root zone | mm |
| REW | Readily Evaporable Water | mm |
| RO | Surface runoff | $mm.d^{-1}$ |
| S | Root extraction term | $m^3.m^{-3}.d^{-1}$ |
| $S_x$ | Maximum root extraction term | $m^3.m^{-3}.d^{-1}$ |
| t | Time | GDD or d |
| T | Air temperature | °C |
| $T_{avg}$ | Average air temperature | °C |
| $T_{base}$ | Base temperature (below which crop development does not progress) | °C |
| $T_n$ | Daily minimum air temperature | °C |
| $T_{upper}$ | Upper temperature (above which crop development no longer increases with an increase in air temperature) | °C |
| $T_x$ | Daily maximum air temperature | °C |
| Tr | Crop transpiration | $mm.d^{-1}$ |
| $Tr_x$ | Maximum crop transpiration (for a well watered crop) | $mm.d^{-1}$ |
| TAW | Total Available soil Water (between FC and PWP) in the root zone | mm |
| Wr | Soil water content of the root zone expressed as an equivalent depth | mm |
| WP | Crop water productivity | $Mg\ ha^{-1}mm$ |
| $WP^*$ | Crop water productivity normalized for $ET_o$ and air $CO_2$ concentration | $Mg\ ha^{-1}$ |
| | | |
| $Z_{e,surf}$ | Evaporating soil surface layer | m |
| $Z_{e,top}$ | Top soil layer from which water flows to the evaporating surface layer | m |
| Z | Effective rooting depth | m |



| | | |
|---|---|---|
| $Z_n$ | Minimum effective rooting depth | m |
| $Z_x$ | Maximum effective rooting depth | m |
| $\Delta z$ | Soil compartment (depth layer) | m |
| $\theta$ | Volumetric soil water content | $m^3.m^{-3}$ |
| $\theta_{air\ dry}$ | Soil water content when air dry | $m^3.m^{-3}$ |
| $\theta_{FC}$ | Soil water content at FC | $m^3.m^{-3}$ |
| $\theta_{PWP}$ | Soil water content at PWP | $m^3.m^{-3}$ |
| $\theta_{sat}$ | Soil water content at soil saturation | $m^3.m^{-3}$ |
| $\tau$ | Drainage coefficient | - |



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### II. Indicative values for lengths of crop development stages

### III. Indicative values for soil salinity tolerance for some agriculture crops