Chapter 3

Calculation procedures

AquaCrop

Version 3.1

Reference Manual
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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.

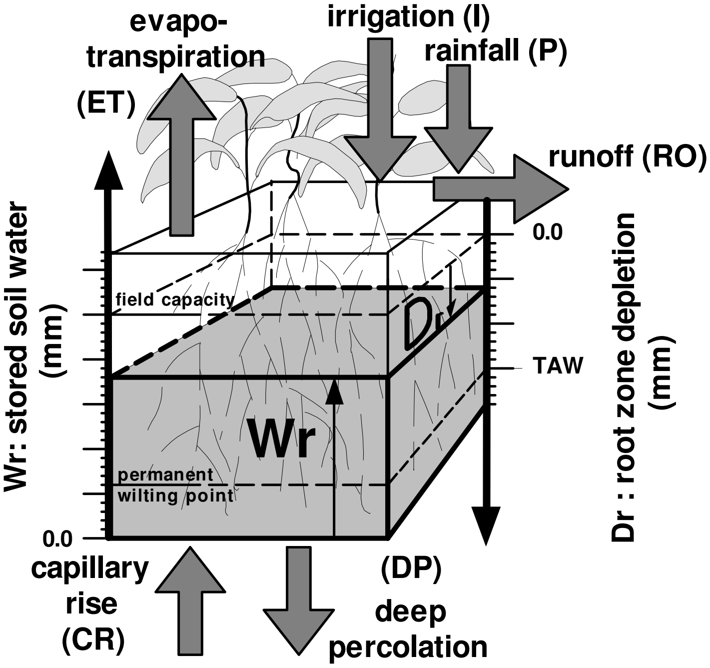

Figure 3.1a
The root zone as a reservoir

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 content 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 θ_{FC} Z);
	Wr	soil water content of the root zone expressed as depth [mm];
	θ_{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];
	θ_{FC}	volumetric water content at field capacity [m^3/m^3];
	θ_{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.

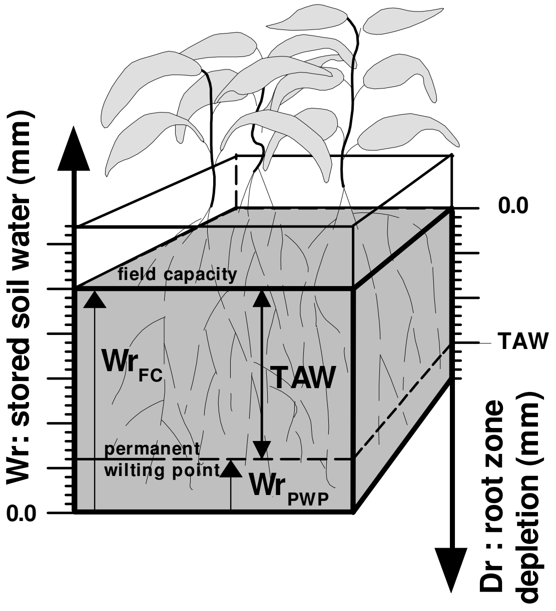

Figure 3.1b
The soil water content in the root zone at Field Capacity (Wr_{FC}) and at Permanent Wilting Point (WR_{PWP}), and the Total Available soil Water (TAW)

3.1.3 Soil water stress

- **Upper and lower thresholds for soil water stress**

Soil water stress affects the development of the canopy cover, the expansion of the root zone, results in stomata closure, in a reduction of crop transpiration rate, and in failure of pollination, alters the Harvest Index, and even triggers early canopy senescence. Soil water stress affects the above processes when the stored soil water in the root zone drops below a threshold level. The thresholds are expressed as root zone depletion, i.e. a fraction (p) of TAW.

For most processes a distinction is made between an upper and lower threshold (Fig. 3.1c). Water stress starts to affect the process when the soil water content drops below the upper threshold, i.e. when the root zone depletion (Dr) 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. Each of the processes affected by soil water stress has its own threshold levels. For leaf and hence canopy growth, the lower threshold is above PWP, where as for stomata closure, senescence and failure of pollination the lower threshold is fixed at PWP.

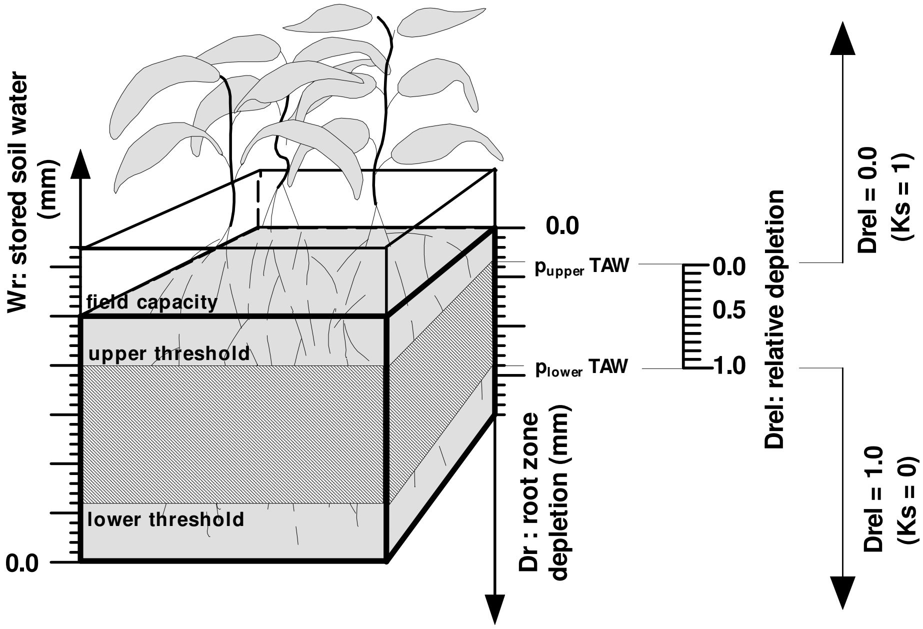

Figure 3.1c
The upper and lower thresholds for soil water content in the root zone for a mechanism affected by water stress, and the corresponding relative depletion

- **Stress response functions**

Effects of water stress on canopy development, stomatal conductance, early canopy senescence and failure of pollination 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 soil water content, water stress is non-existent and Ks is 1. Below the lower threshold, the effect is maximum and Ks is 0. Between the 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. 3.1d).

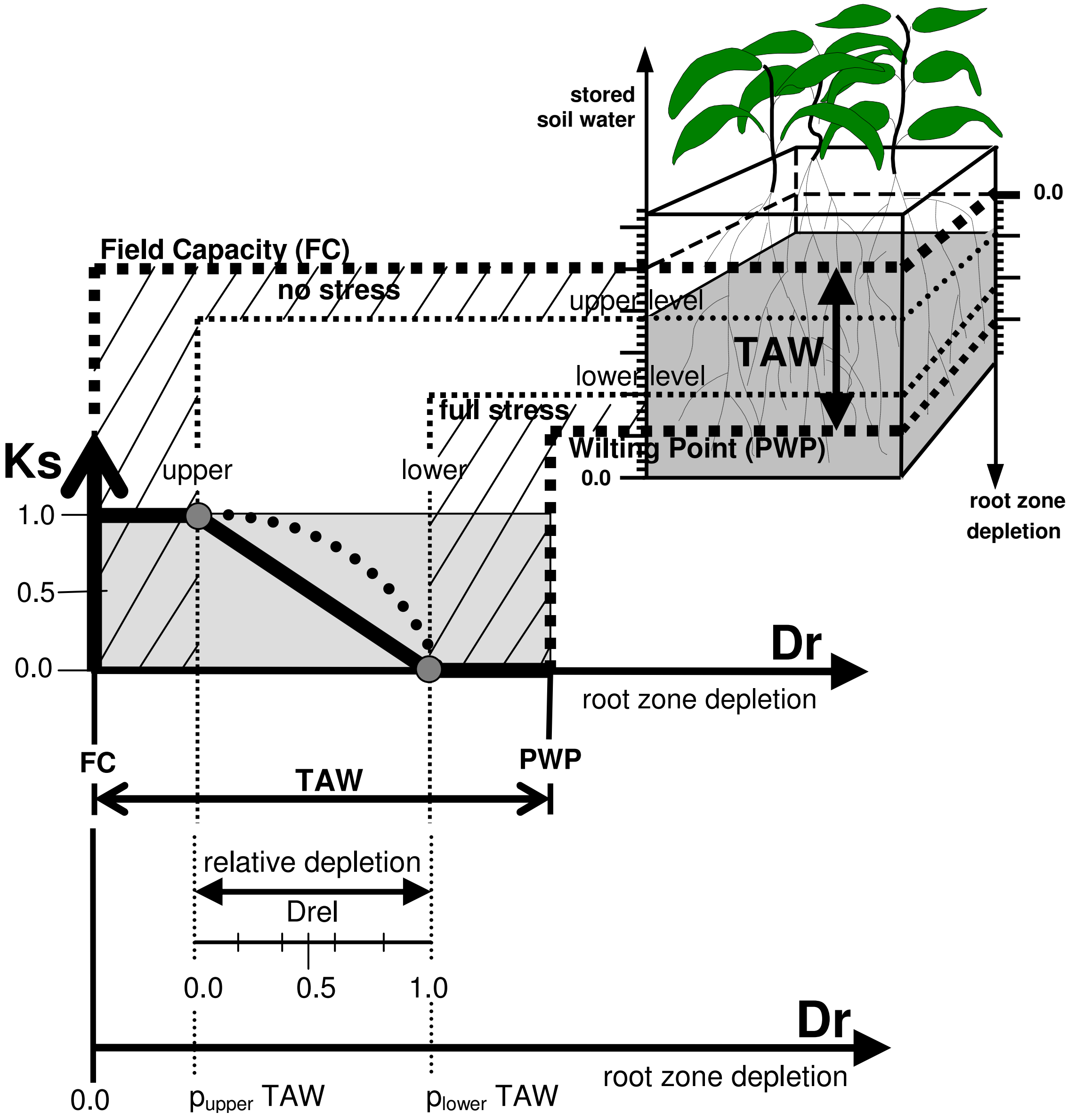

Figure 3.1d
The water stress coefficient (Ks) for various degrees of root zone depletion (Dr)

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

$$Ks = 1 - Drel \qquad \text{(Eq. 3.1d)}$$

Convex curves make that the process is only strongly affected when the water stress becomes severe. The shape and degree of curvature of the Ks curve in relation to root zone water depletion are described by the following equation:

$$Ks = 1 - \frac{e^{D_{rel}\, f_{shape}} - 1}{e^{f_{shape}} - 1} \qquad \text{(Eq. 3.1e)}$$

where D_{rel} (≤ 1) is the relative depletion, the fraction of water depleted relative to the full amount the soil can hold between the upper and lower threshold as define in p, and f_{shape} is the shape factor ($f_{shape} > 0$).

- **Adjustment of thresholds for water stress to ET_o**

The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ET_o. The only factors affecting ET_o are climatic parameters. Consequently, ET_o is a climatic parameter and can be computed from weather data. ET_o expresses the evaporating power of the atmosphere at a specific location and time of the year and does not consider the crop characteristics and soil factors (Allen et al., 1998).

The upper and lower thresholds for water stress (p) are adjusted in AquaCrop to the evaporating power of the atmosphere (ET_o). The stress response curve is for a reference evaporative demand of ET_o = 5 mm/day, and its p is adjusted at run time for different levels of ET_o by:

$$0 \leq p_{adj} = p_{given} + f_{adj}\left(0.04(5 - ET_0)\right)\left(\log_{10}(10 - 9\, p_{given}\right) \leq 1 \qquad \text{(Eq. 3.1f)}$$

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.

3.2 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}):

$$GDD = T_{avg} - T_{base} \qquad \text{(Eq. 3.2a)}$$

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. 3.2a. 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 3rd method is added.

3.2.1 Method 1

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

$$T_{avg} = \frac{(T_x + T_n)}{2} \qquad \text{(Eq. 3.2b)}$$

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}).

3.2.2 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:

$$T_{avg} = \frac{(T_x^* + T_n^*)}{2} \qquad \text{(Eq. 3.2c)}$$

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 $T_n^* = T_{base}$

3.2.3 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:

$$T_{avg} = \frac{\left(T_x^* + T_n\right)}{2} \qquad \text{(Eq. 3.2d)}$$

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).

3.3 Green canopy cover for optimal conditions

3.3.1 Green canopy cover throughout the crop cycle

The development and senescence of the green canopy under optimal conditions (Fig 3.3a) 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).

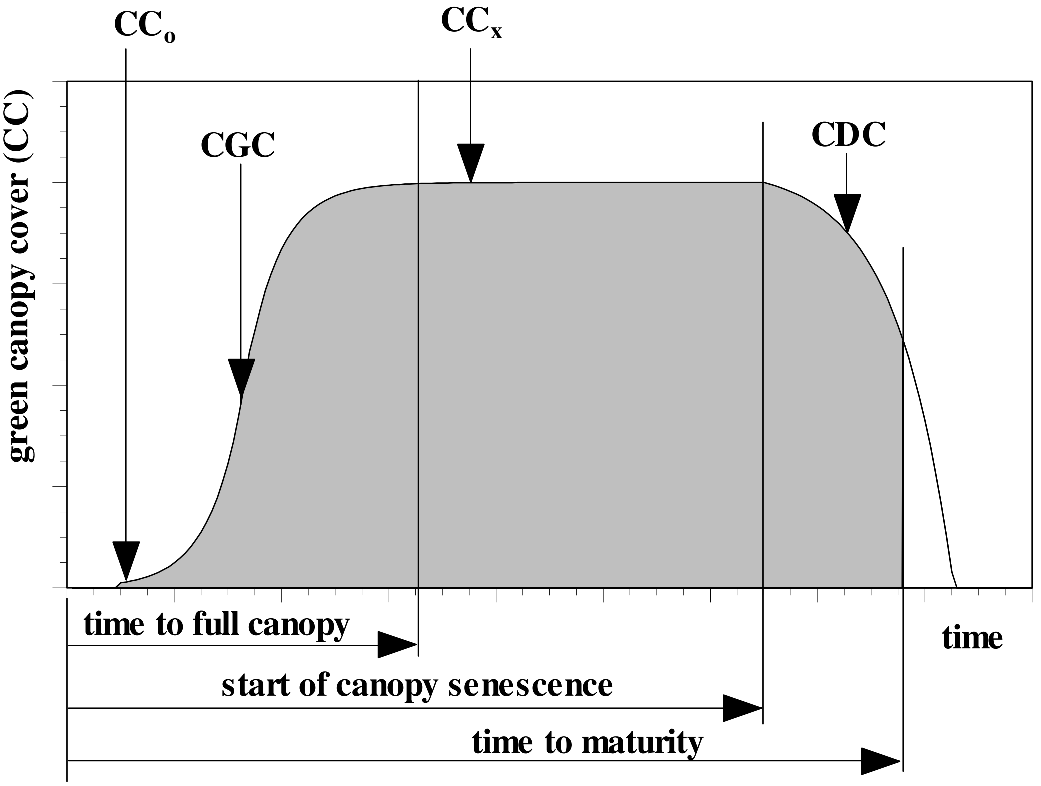

Figure 3.3a
Variation of green canopy cover
throughout the growing cycle under non-stress conditions

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.

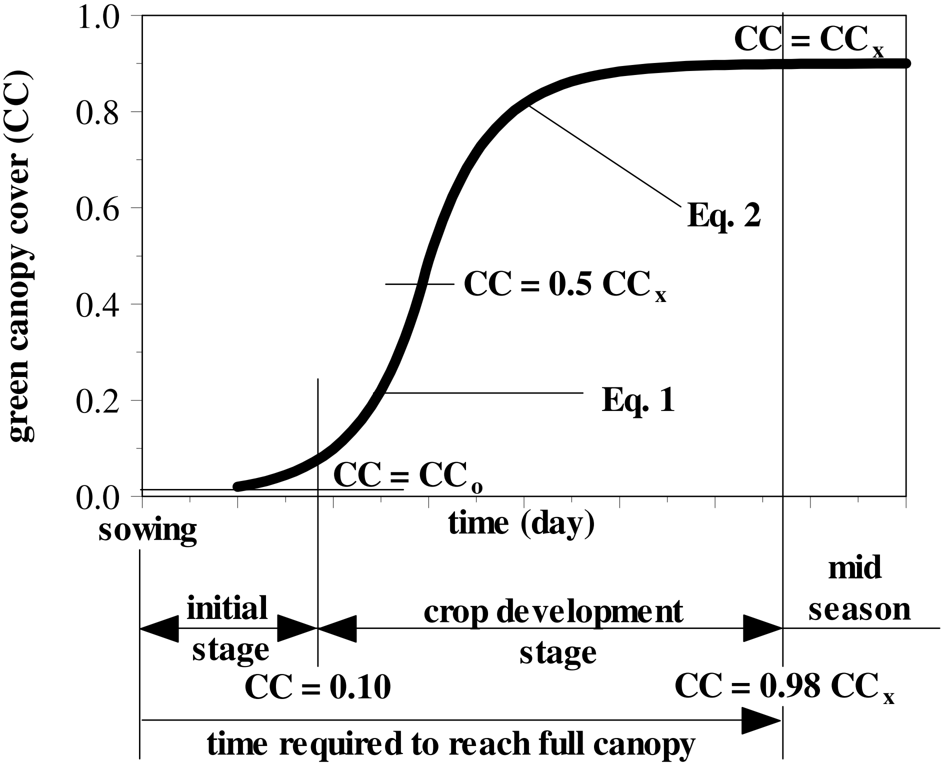

Figure 3.3b
Schematic representation of canopy development during the exponential growth (Eq. 1) and the exponential decay (Eq. 2) stages

3.3.2 Canopy development

Canopy development (Figure 3.3b) is simulated by two equations:

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

$$CC = CC_o \, e^{t \, CGC} \qquad \text{(Eq.3.3a)}$$

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

$$CC = CC_x - 0.25 \frac{(CC_x)^2}{CC_o} \, e^{-t \, CGC} \qquad \text{(Eq. 3.3b)}$$

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].

3.3.3 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 3.5.1).

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.

3.3.4 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.

3.3.5 Green canopy cover decline

The decline in green crop canopy is described by:

$$CC = CC_x \left[1 - 0.05 \left(e^{\frac{CDC}{CC_x} t} - 1 \right) \right] \qquad \text{(Eq. 3.3c)}$$

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. 3.3c).

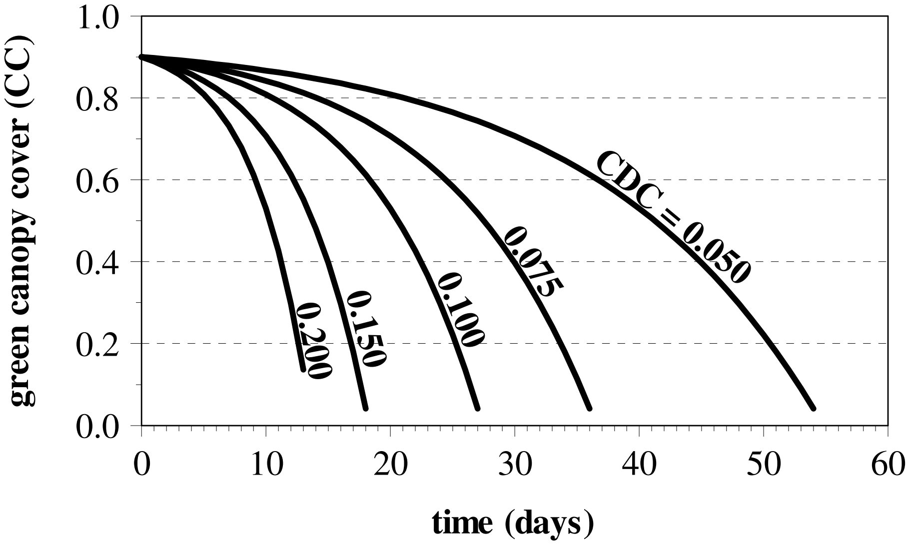

Figure 3.3c
Decline of green canopy cover during senescence for various canopy decline coefficients (CDC) as described by Eq. 3.3c. All lines have initial green canopy cover at 0.9 and starting time at 0

3.3.6 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

3.4 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.

3.4.1 Adjustment of canopy growth coefficient due to water stress

- **Soil water thresholds for leaf expansion growth**

Leaf growth by area expansion and therefore canopy development is sensitive to water stress (Figure 3.4a). Canopy development is reduced as soon as the soil water content in the root zone (Wr) drops below the upper threshold for leaf expansion growth:

$$Wr_{\exp,\, upper} = \left(\theta_{FC} - p_{\exp,\, upper}\left(\theta_{FC} - \theta_{PWP}\right)\right)\, 1000\, Z \qquad \text{(Eq. 3.4a)}$$

or the root zone depletion (Dr) exceeds:

$$Dr_{\exp,\, upper} = p_{\exp,\, upper}\; TAW \qquad \text{(Eq.3.4b)}$$

where	$Wr_{exp,upper}$	upper threshold expressed as an equivalent depth [mm];
	$Dr_{exp,upper}$	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;
	θ_{FC}	soil water content at field capacity [m^3(water)/m^3(soil)];
	θ_{PWP}	soil water content at permanent wilting point [m^3(water)/m^3(soil)];
	Z	effective rooting depth [m];
	TAW	total available soil water in the root zone [mm].

When the soil water content in the root zone reaches its lower limit, leaf expansion is completely halted:

$$Wr_{\exp,\, lower} = \left(\theta_{FC} - p_{\exp,\, lower}\left(\theta_{FC} - \theta_{PWP}\right)\right)\, 1000\, Z \qquad \text{(Eq.3.4c)}$$

or the root zone depletion (Dr) reaches:

$$Dr_{\exp,\, lower} = p_{\exp,\, lower}\; TAW \qquad \text{(Eq.3.4d)}$$

where	$Wr_{exp,lower}$	lower threshold expressed as an equivalent depth [mm];
	$Dr_{exp,lower}$	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.

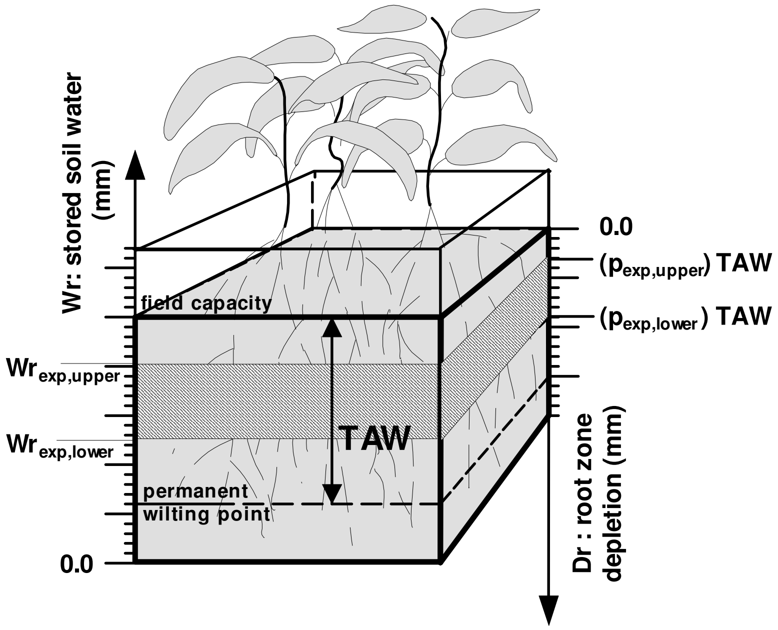

Figure 3.4a
The upper and lower threshold for the soil water content in the root zone affecting leaf growth by area expansion

- **Water stress coefficient for leaf expansion growth ($Ks_{exp,w}$)**

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 ($Ks_{exp,w}$):

$$CGC_{adj} = Ks_{\exp,w}\ CGC \qquad \text{(Eq. 3.4e)}$$

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].

The coefficient is 1 when there is no stress ($Dr \le p_{exp,upper}$ TAW), and decreases gradually to zero when the stress increases as a result of the soil water depletion from the root zone (Fig 3.4b). $Ks_{exp,w}$ is zero when the root zone depletion is at or exceeds its lower threshold ($Dr \ge p_{exp,lower}$ TAW). In AquaCrop the shape of the Ks curve between the upper and lower thresholds can be selected as linear or concave (see 3.1.3).

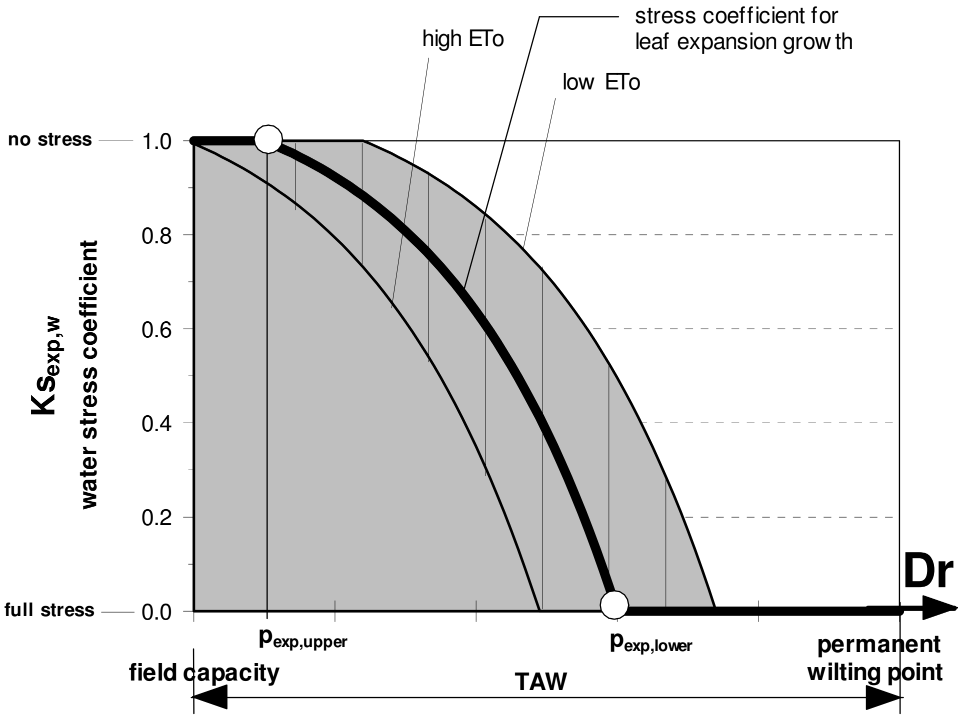

Figure 3.4b
Water stress coefficient for leaf expansion growth ($Ks_{exp,w}$)
for various degrees of root zone depletion (Dr)

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).

3.4.2 Period of potential vegetative growth

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. 3.4c).

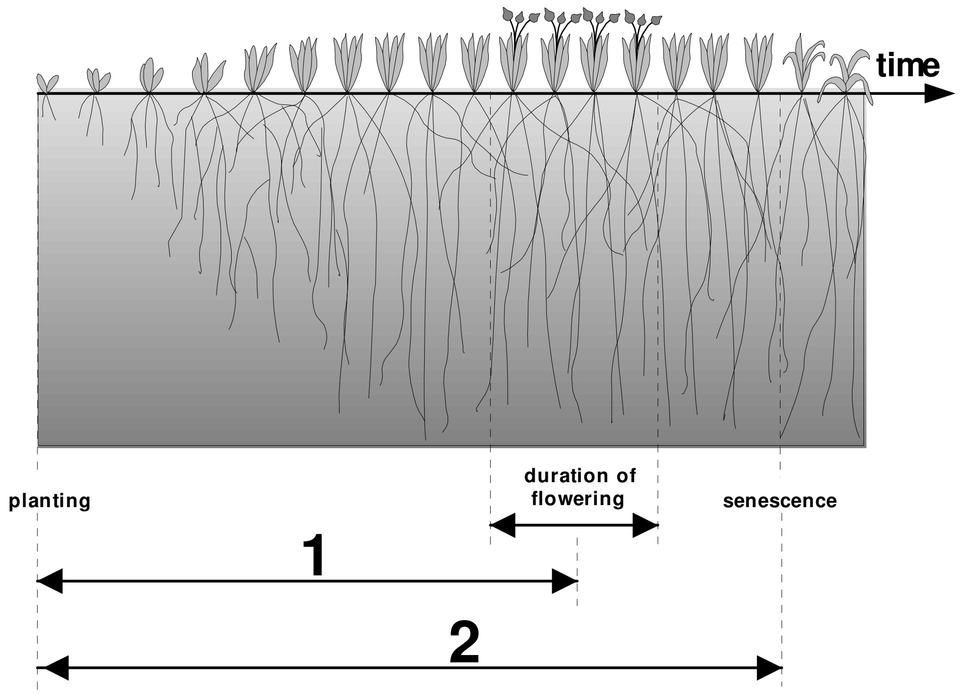

Figure 3.4c
Period of potential vegetative growth
for (1) determinant crops and (2) indeterminant crops

3.4.3 Early canopy senescence under severe water stress conditions

- **Triggering of canopy decline**

Under severe water stress conditions, canopy senescence will be triggered (Fig. 3.4d). Early canopy senescence will occur as soon as the soil water content in the root zone (Wr) drops below the threshold which triggers it:

$$Wr_{sen} = [\theta_{FC} - p_{sen}\,(\theta_{FC} - \theta_{PWP})]\ 1000\,Z \qquad \text{(Eq. 3.4f)}$$

or the root zone depletion (Dr) exceeds:

$$Dr_{sen} = p_{sen}\,TAW \qquad \text{(Eq.3.4g)}$$

where	Wr_{sen}	upper threshold expressed as an equivalent depth [mm];
	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;
	θ_{FC}	soil water content at field capacity [m^3(water)/m^3(soil)];
	θ_{PWP}	soil water content at permanent wilting point [m^3(water)/m^3(soil)];
	Z	the effective rooting depth [m];
	TAW	total available soil water in the root zone [mm].

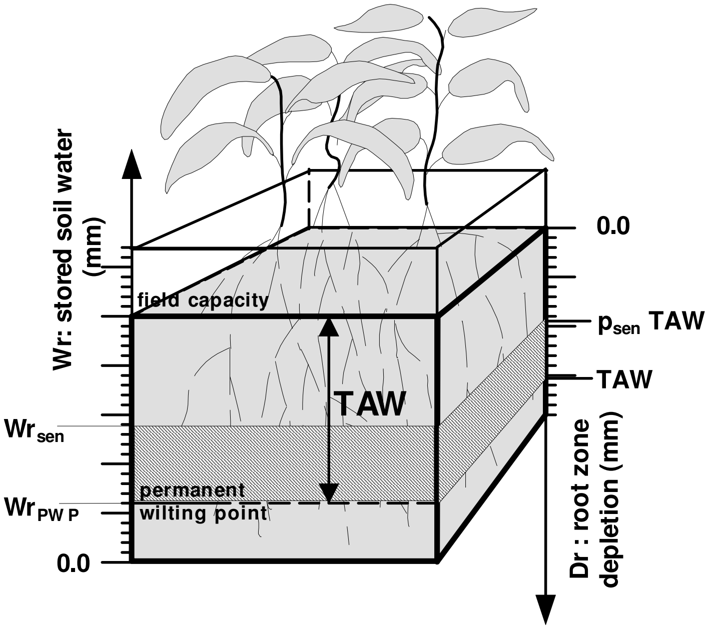

Figure 3.4d
The upper and lower threshold for the soil water content in the root zone affecting early canopy senescence

- **Water stress coefficient for early canopy decline (Ks_{sen})**

The rate of canopy decline (CDC) 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 8th power of Ks_{sen} is considered:

$$CDC_{adj} = \left(1 - Ks_{sen}^{8}\right) CDC \tag{Eq. 3.4h}$$

where	CDC	reference canopy decline coefficient;
	Ks_{sen}	water stress coefficient for early canopy senescence.

If the soil water depletion in the root zone is smaller than its threshold ($Dr < p_{sen}$ TAW), Ks_{sen} is 1 and early canopy senescence is not triggered ($CDC_{adj} = 0$). If the root zone depletion is at or exceeds its lower limit ($Dr \geq$ TAW), Ks_{sen} is 0 and the canopy decline is at full speed ($CDC_{adj} = CDC$). In AquaCrop, $p_{sen,lower}$ corresponds with the root zone depletion at wilting point ($p_{sen,lower} = 1$). In AquaCrop the shape of the Ks curve between the upper and lower thresholds (Fig. 3.4e) can be selected as linear or concave (see 3.1.3).

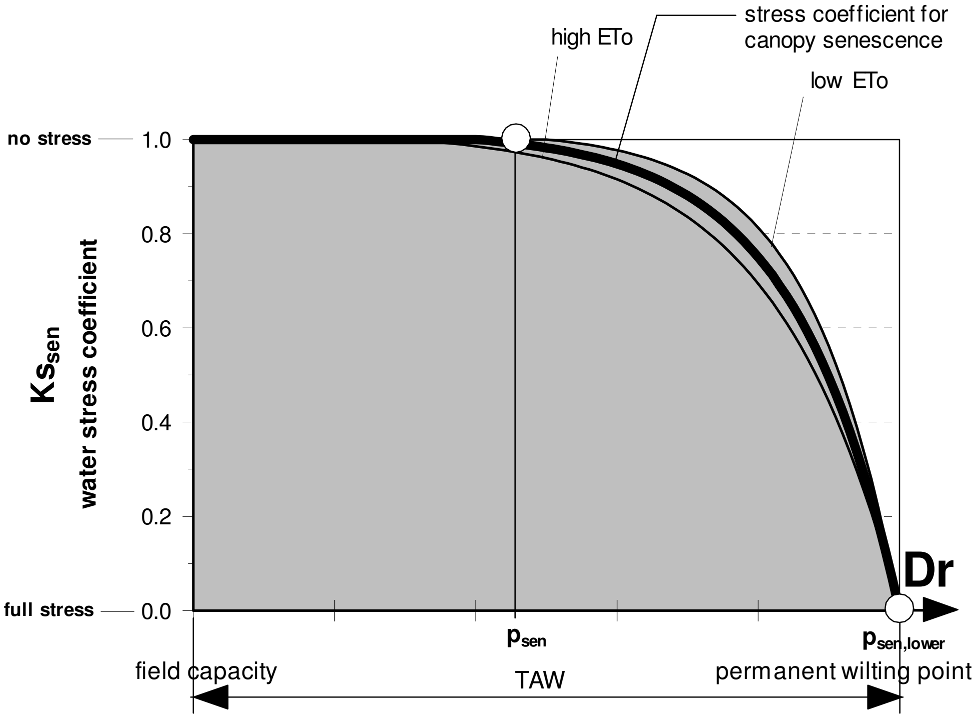

Figure 3.4e
Water stress coefficient for early canopy senescence (Ks_{sen})
for various degrees of root zone depletion (Dr)

- **Adjustment of p_{sen} once senescence is triggered**

A small amount of rain or a slight expansion of the root zone in a wet subsoil, might bring the water content in the root zone once again above Wr_{sen} 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:

$$p_{sen,\,adj} = p_{sen} \left(1 - \frac{\beta}{100}\right) \qquad \text{(Eq. 3.4i)}$$

β is a program parameter, and its value can vary between 0 % (no adjustment) to 25 %.

3.4.4 Canopy development under deficient aeration conditions

Crops sensitive to water logging experiences stress when the aeration condition in the root zone becomes deficient as a result of water logging. This affects their transpiration rate which will drop below the potential rate for the given environmental conditions. When the transpiration rate plunges to zero as a result of prolonged water logging, the development of the canopy will be brought to a standstill as a result of the feedback mechanism of transpiration on canopy development (see 3.8.7).

3.4.5 Canopy development under limited soil fertility

Limited soil fertility 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 are given by:

$$CGC_{adj} = Ks_{\exp,f}\ CGC \qquad \text{(Eq. 3.4j)}$$

$$CC_{x,\,adj} = Ks_{CCx}\ CC_x \qquad \text{(Eq. 3.4k)}$$

where CGC and CC_x are the canopy growth coefficient (fraction or percentage per day) and the maximum canopy cover (fraction or percentage) for the non limiting soil fertility conditions, and $Ks_{exp,f}$ and Ks_{CCx} soil fertility stress coefficients.

For non-limiting soil fertility (i.e. soil fertility stress is zero) the soil fertility stress coefficients are 1. When the soil fertility stress is complete (100% fertility stress), crop growth is no longer possible and the Ks coefficients reach their theoretical minimum of zero. Between the upper and lower limits for soil fertility the Ks coefficients vary between 1 and 0 (Fig. 3.4f).

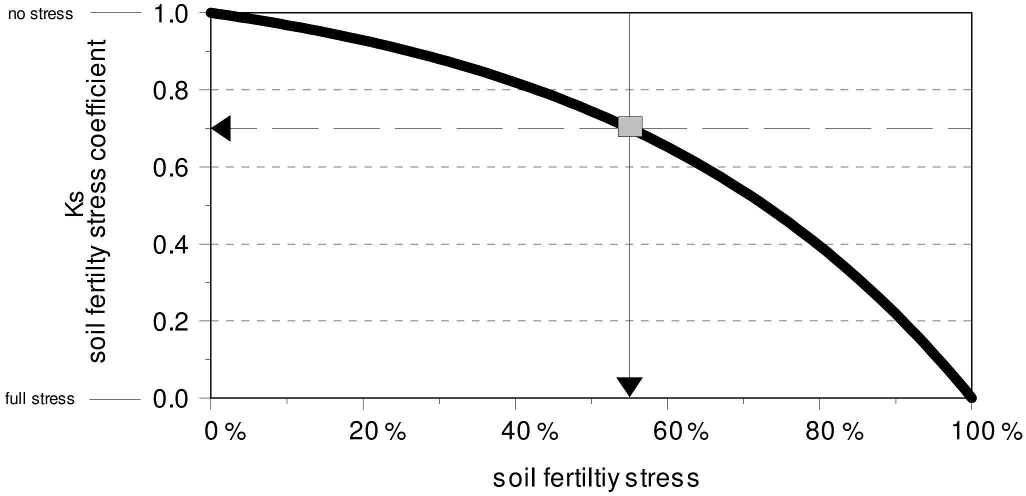

Figure 3.4f
Soil fertility stress coefficient for various soil fertility stresses (full line) with indication of the Ks and soil fertility stress used for calibration (square)

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).

Due to the limited nutrient status of the soil, the canopy cover (CC) will steadily decline once CC_x is reached at mid season (Fig. 3.4g). 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:

$$CC_{adj} = CC_{x,\,adj} - f_{CDecline}\,\frac{\left(t - t_{full\ canopy}\right)^2}{\left(t_{sen} - t_{full\ canopy}\right)} \qquad \text{(Eq. 3.4l)}$$

where t is the time (days or growing degree days) after full canopy is reached.

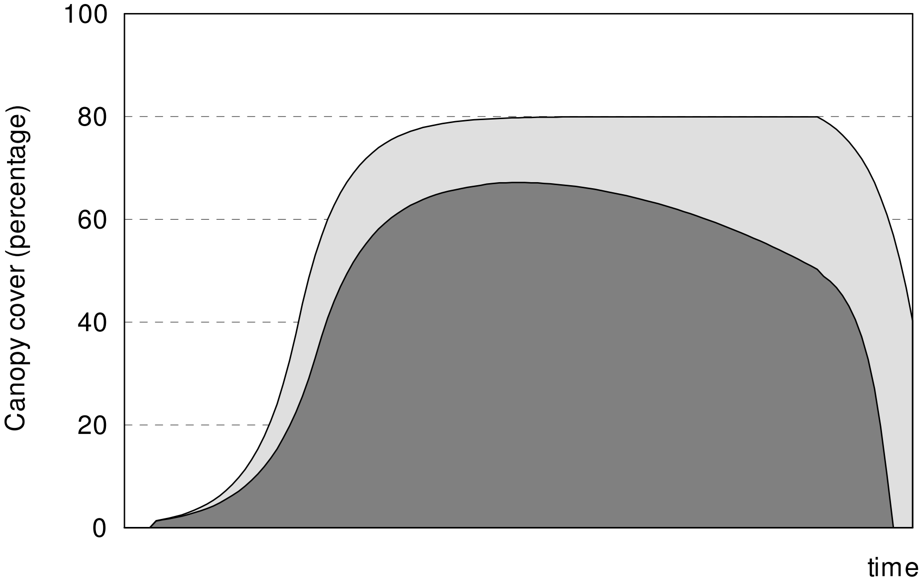

Figure 3.4g
Canopy cover for non limiting (light area) and limiting (dark area) soil fertility for $Ks_{exp,f}$ and Ks_{CCx} = 0.85 and $f_{CDecline}$ = 0.005 day^{-1})

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}. For non-limiting soil fertility (i.e. soil fertility stress is zero) the decline is zero (see Chapter 2, section 2.9.7 – Calibration for soil fertility). When the soil fertility stress is complete (100% fertility stress), a maximum decline of 1 % per day is assumed. Between the upper and lower limits for soil fertility $f_{CDecline}$ varies between 0 and 1 % per day.

3.5 Effective rooting depth

3.5.1 Effective rooting depth at planting

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.

3.5.2 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:

$$Z = Z_o + (Z_x - Z_o)\sqrt[n]{\frac{\left(t-\frac{t_0}{2}\right)}{\left(t_x-\frac{t_0}{2}\right)}} \tag{Eq. 3.5a}$$

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. 3.5a). At any time the effective rooting depth Z is given by

$$Z_n \le Z \le Z_x \tag{Eq. 3.5b}$$

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).

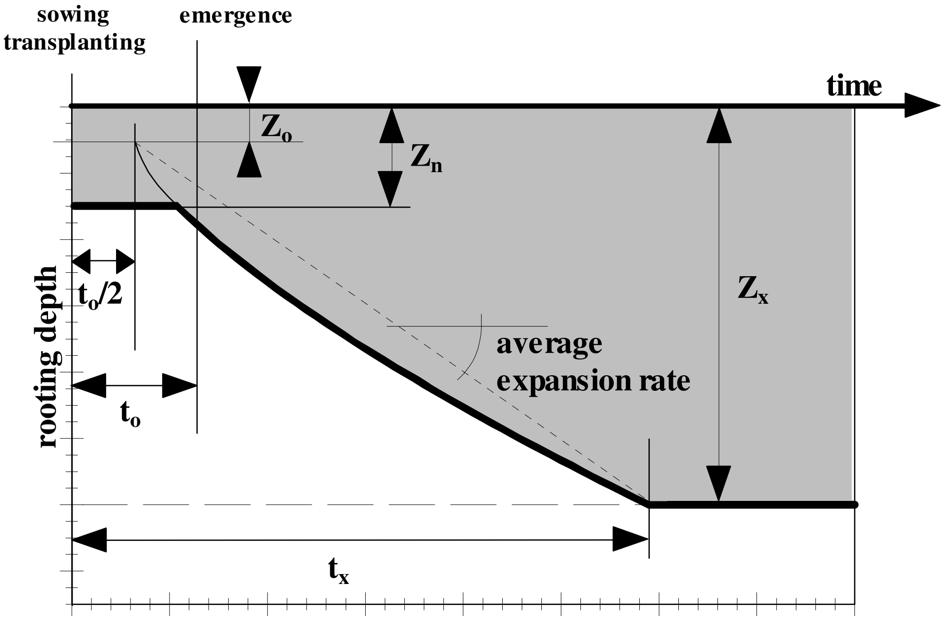

Figure 3.5a
Development of the effective rooting depth (shaded area) from sowing till the maximum effective rooting depth (Z_x) is reached

3.5.3 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.

3.5.4 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:

$$dZ_{adj} = Ks_{sto}\ dZ \qquad \text{(Eq. 3.5c)}$$

- **small to medium** for $-1 \le f_{shape} \le -8$, and given by an exponential relationship:

$$dZ_{adj} = dZ\ \frac{e^{Ks_{sto}\ f_{shape}} - 1}{e^{f_{shape}} - 1} \qquad \text{(Eq. 3.5d)}$$

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. 3.5b).

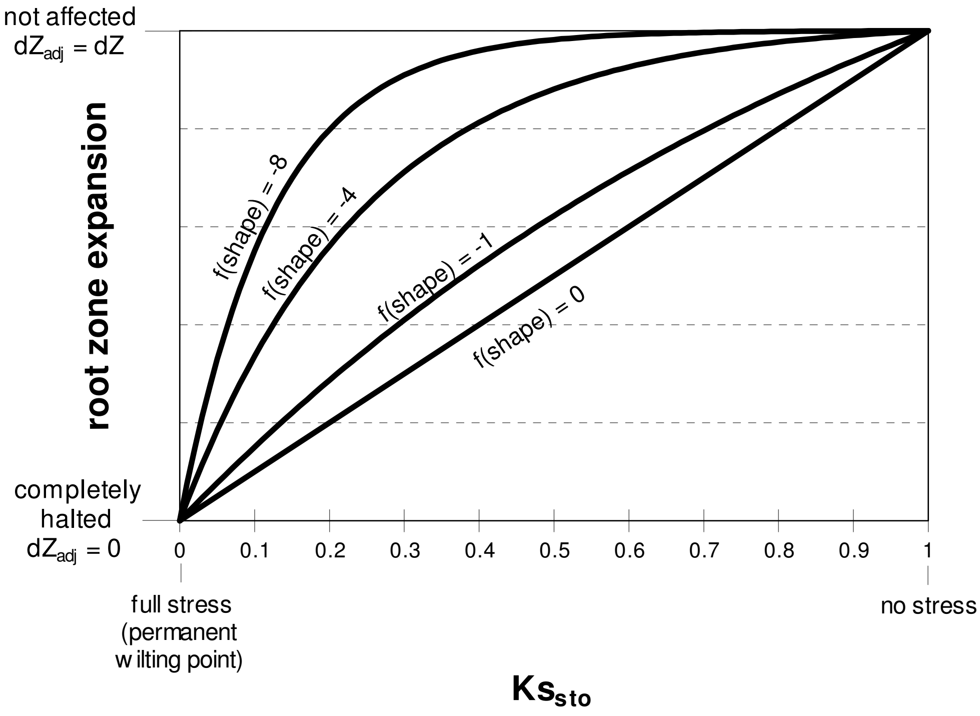

Figure 3.5b
The effect of water stress on the reduction of root zone expansion for various shape factors (f_{shape}) and water stress in the root zone (Ks_{sto})

3.5.5 Expansion of the root zone in a shallow soil

The effective rooting depth might not reach its maximum value if an impermeable soil layer limit root development or when the exploitable soil depth is smaller than Z_x. The root deepening rate is described by Eq. 3.5a, but once the effective rooting depth reaches the restrictive soil layer, the expansion is halted (Fig 3.5c).

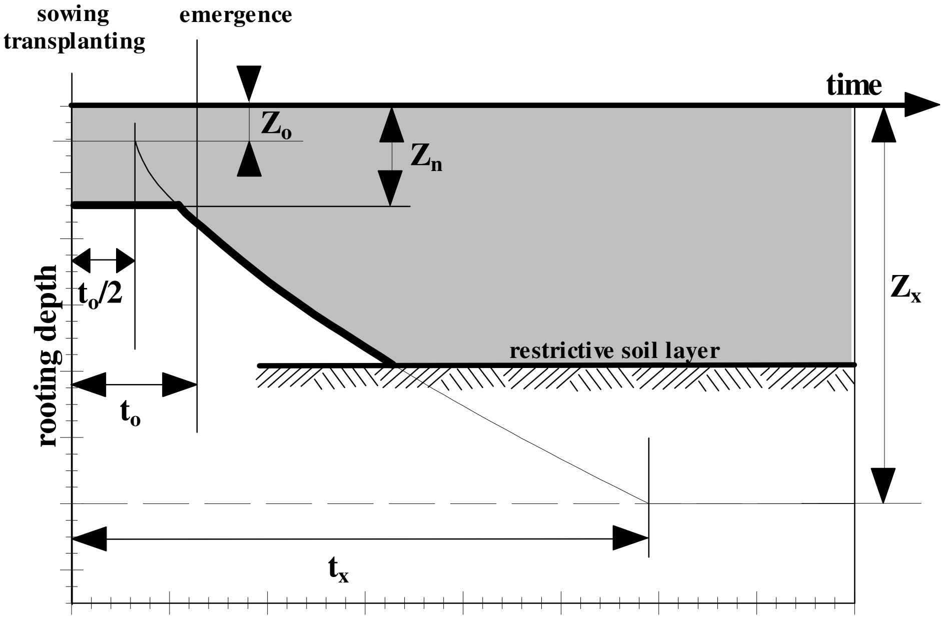

Figure 3.5c
Development of the effective rooting depth (shaded area)
in presence of a restrictive soil layer inhibiting the expansion of the root zone

3.6 Soil water balance

3.6.1 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 Δz and Δt 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.

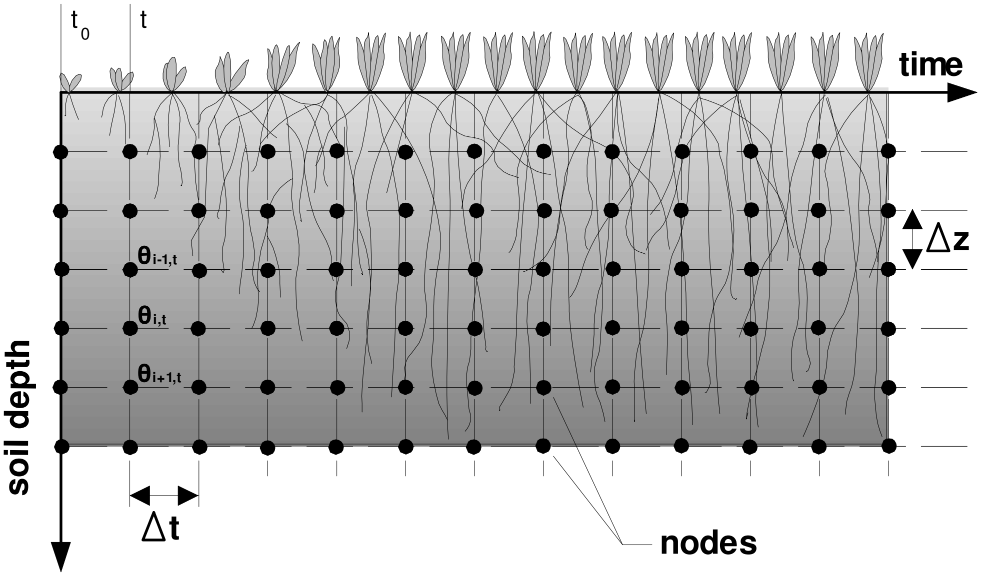

Figure 3.6a
The time(t) – depth (z) grid
for the solution of the soil water balance in AquaCrop

In AquaCrop the time increment is fixed at one day and the depth increment (Δz) is by default 0.1 m. The soil profile is such divided into soil compartments (12 by default) with thickness Δz (Fig 3.6b). 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 (Δz) to cover the entire root zone. For deep root zones, Δz 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.

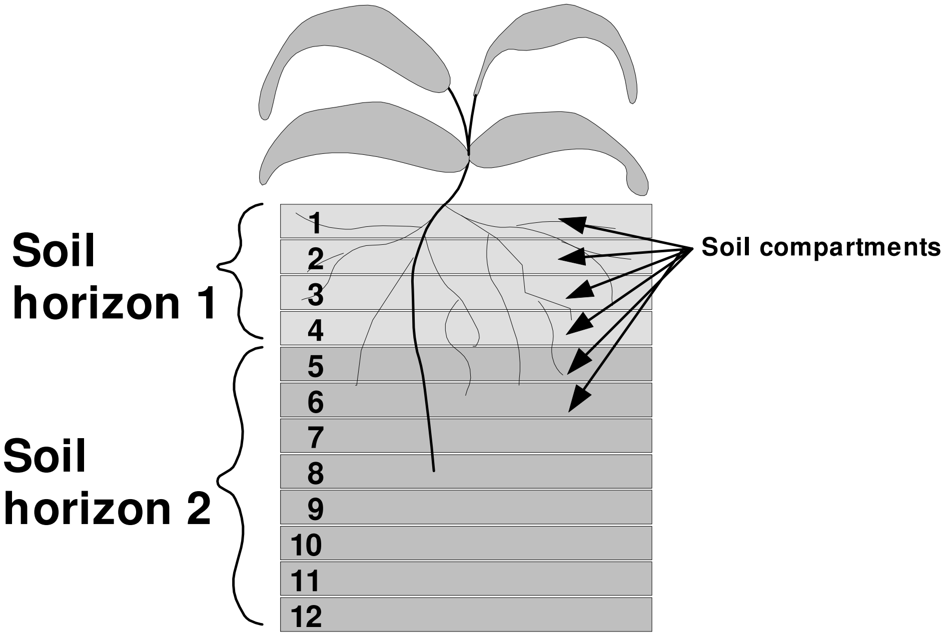

Figure 3.6b
Soil horizons and soil compartments

3.6.2 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. 3.6c). 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 ($\Delta\theta$). 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.

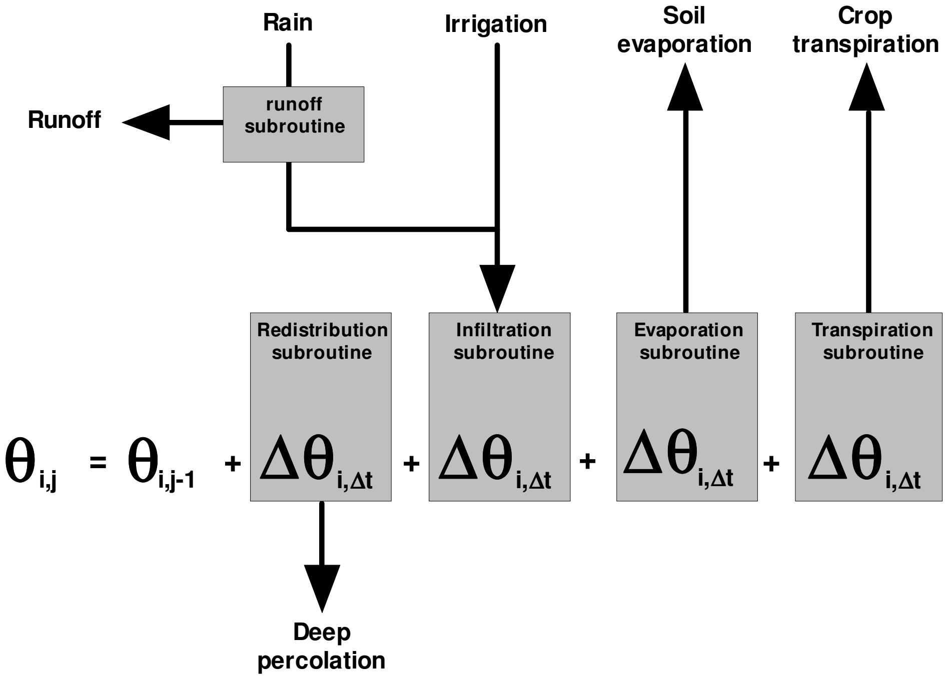

Figure 3.6c
Calculation scheme of the soil water balance in AquaCrop

3.6.3 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):

$$\frac{\Delta\theta_i}{\Delta t} = \tau\,(\theta_{SAT} - \theta_{FC})\,\frac{e^{\theta_i - \theta_{FC}} - 1}{e^{\theta_{sat} - \theta_{FC}} - 1} \qquad \text{(Eq. 3.6a)}$$

Where	$\Delta\theta_i/\Delta t$	decrease in soil water content at depth i, during time step Δt [$m^3.m^{-3}.day^{-1}$];
	τ	drainage characteristic [-];
	θ_i	actual soil water content at depth i [$m^3.m^{-3}$];
	θ_{SAT}	soil water content at saturation [$m^3.m^{-3}$];
	θ_{FC}	soil water content at field capacity [$m^3.m^{-3}$];
	Δt	time step [day].

note: IF $\theta_i = \theta_{FC}$ THEN $\Delta\theta_i/\Delta t = 0$
IF $\theta_i = \theta_{SAT}$ THEN $\Delta\theta_i/\Delta t = \tau\,(\theta_{SAT} - \theta_{FC})$

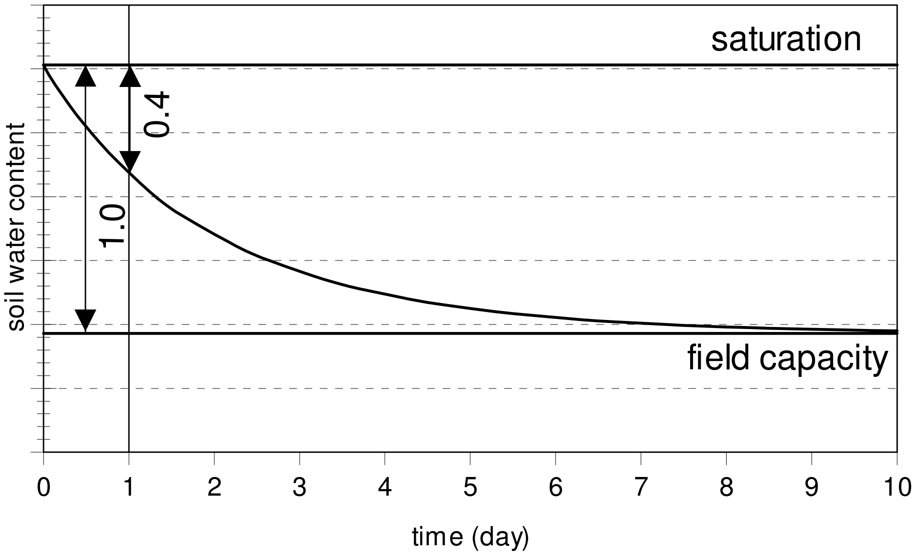

Figure 3.6d
Variation of soil water content over time
in a free draining soil layer with a drainage characteristic of $\tau = 0.4$

The drainage function describes the amount of water lost by free drainage over time between saturation and field capacity (Fig. 3.6d). 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 3.6d, 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:

$$0 \le \tau = 0.0866\ Ksat^{0.35} \le 1 \qquad \text{(Eq. 3.6b)}$$

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. 3.6a. 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:

$$DP = 1000 \quad \frac{\Delta\theta}{\Delta t} \quad \Delta z \quad \Delta t \qquad \text{(Eq. 3.6c)}$$

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. 3.6a. 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. 3.6a. The amount of water D_1 (mm) that percolates out of the top compartment at the end of a time step is given by:

$$D_1 = 1000 \quad \frac{\Delta\theta_1}{\Delta t} \quad \Delta z_1 \quad \Delta t \qquad \text{(Eq. 3.6d)}$$

where D_1 the flux between compartment 1 and 2 [mm];
θ_1 the soil water content of the top compartment [$m^3.m^{-3}$];
Δz_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, ΣD_i will be stored in that compartment, thereby increasing its soil water content and its drainage ability (Fig 3.6e). 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 3.6e). 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).

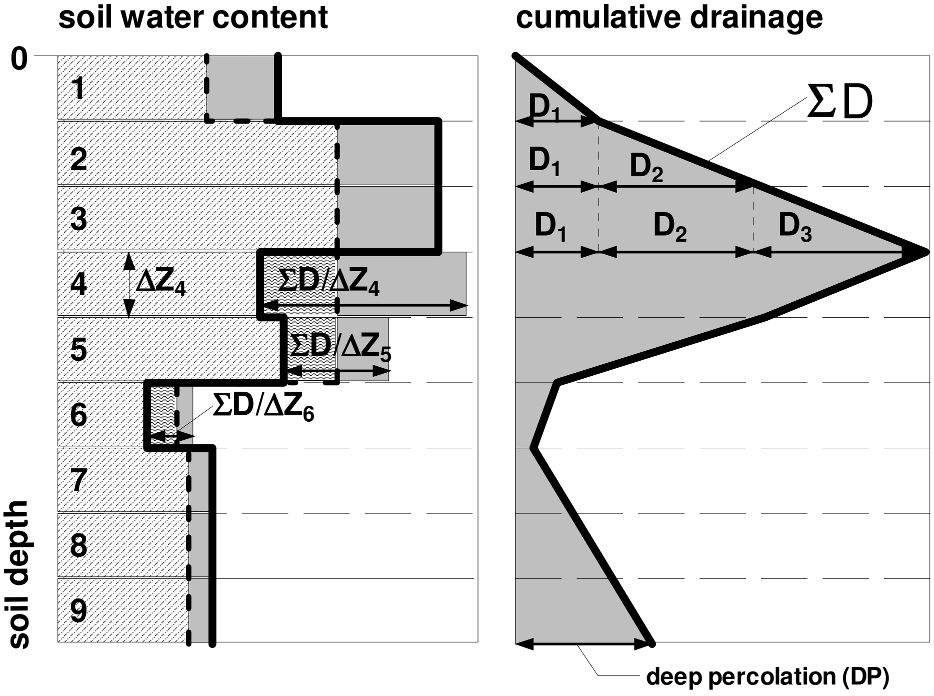

Figure 3.6e
Schematic presentation of a draining soil profile (left) with indication of the soil water content before (full line) and at the end (dotted line) of the process of internal redistribution of the water, and the calculated cumulative drainage (right)

In each compartment, the cumulative drainage amount ΣD_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 ΣD_i will be stored in that compartment, or if required in the compartments above, until the remaining part of ΣD_i equals the infiltration rate of the soil layer.

3.6.4 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):

$$RO = \frac{[P-(0.2)\,S]^2}{P+S-(0.2)\,S} \qquad \text{(Eq. 3.6e)}$$

$$S = 254\left(\frac{100}{CN}-1\right) \qquad \text{(Eq. 3.6f)}$$

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. 3.6f;
	CN	Curve Number

The runoff process is described by Eq. 3.6e. 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. 3.6a).

Table 3.6a
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	Permanent wilting point	45	56	63	70
II	**Default value**	**65**	**75**	**80**	**85**
III	Field capacity	84	88	91	93

In AquaCrop (soil characteristics) the specified CN value is the value that belongs to the antecedent moisture class AMC II. The specified Curve Number (CNII) is adjusted for the simulated wetness of the top soil layer. Relationships derived from Smedema and Rycroft (1983), presenting corresponding CN values for antecedent moisture class (AMC) I (dry), II, and III (wet), are used (Tab. 3.6a). 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. 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.

3.6.5 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.

3.6.6 Capillary rise

Not yet implemented

3.6.7 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 data 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 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 holds for the 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 stored in the top soil as effective rainfall, lost by surface runoff and by deep percolation (Fig. 3.6f).

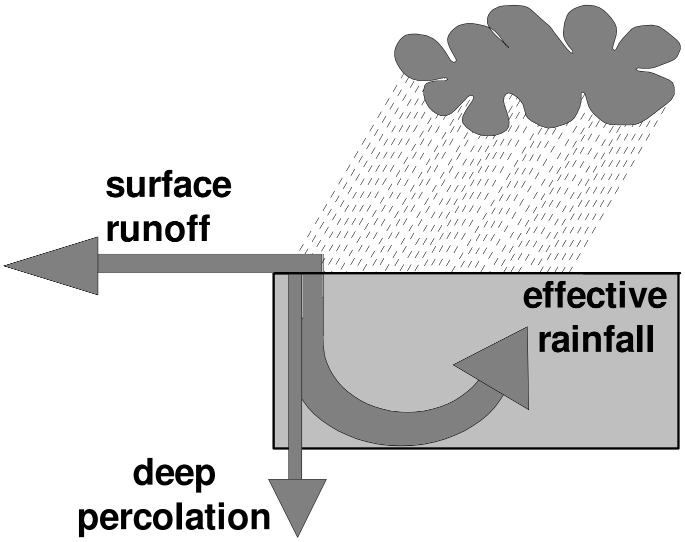

Figure 3.6f
Partitioning of rainfall in effective rainfall, surface runoff and deep percolation losses

- **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. 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 3.6.4). The more rainy days are considered during a period, the smaller the rainfall amount per event and the smaller the runoff will be. Since the number of rainy days is often strongly linked with the seasons, the user can specify the number of rainy days for each of the months. 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**

Effective rainfall is that part of rainfall that is stored in the root zone and not lost by surface runoff or deep percolation (Fig. 3.6f). 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 can not be determined by solving the water balance equation 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 can be selected to determine the effective rainfall when 10-day or monthly rainfall data is used:

- 100 percent effective
- USDA-SCS procedure
- Expresses as a percentage of rainfall

100 percent effective

All rainfall is stored in the root zone.

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). 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 %.

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 may vary over the season and will depend on the rainfall amount, the evapotranspiration rate and soil type. Indicative values are given in Table 3.6b. 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 for 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.

Table 3.6b

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

3.7 Salt balance

Salts enter the soil profile as solutes with the irrigation water. It is assumed that rainfall does not contain dissolved salts. The extent to which salts accumulate in the soil depends on the water quality and quantity that infiltrates into the soil, frequency of wetting, the adequacy of leaching, the importance of soil evaporation and crop transpiration, and the soil physical characteristics of the various layers of the soil profile.

Not yet implemented

3.8 Evapotranspiration

3.8.1 Calculation procedure

The dual crop coefficient approach (Allen et al., 1998) is used to determine evapotranspiration. Crop transpiration (Tr) and soil evaporation (E) are calculated by multiplying ET_o with their specific coefficients (Eq. 3.8a). 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. The effects of characteristics that distinguish the crop transpiration and soil evaporation from grass are integrated into the crop transpiration coefficient (Kcb) and the soil water evaporation coefficient (Ke). Soil evaporation, crop transpiration and ET_o are expressed in mm/day.

- **Well watered root zone and wet soil surface**

When the root zone is well watered and the soil surface wet, crop transpiration as well as soil evaporation are at their maximum rate and ET is given by:

$$ET = \left(Kcb + Ke\right) ET_o \qquad \text{(Eq. 3.8a)}$$

The value of both coefficients depends on canopy cover. The crop transpiration coefficient is proportional to the fractional canopy cover (Kcb ~ CC) and the soil water evaporation coefficient is proportional to the fraction of the soil surface not shaded by the canopy (Ke ~ (1-CC)).

- **Water stress affects evapotranspiration**

The rate of soil evaporation and crop transpiration drops below their maximum rates, when insufficient water is available in the soil to respond to the evaporative demand of the atmosphere. This is simulated by multiplying the crop transpiration coefficient with the water stress coefficient for stomatal closure (Ks_{sto}) and the soil water evaporation coefficient with a reduction coefficient (Kr):

$$ET = \left(Ks_{sto}\ Kcb + Kr\ Ke\right) ET_o \qquad \text{(Eq. 3.8b)}$$

3.8.2 The soil evaporation process

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), when water transport to the surface from layers below is limiting

- **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. 3.8a). As long as water remains in the evaporating soil surface layer, the evaporation rate is only determined by the energy available for soil evaporation and the evaporation stays in stage I.

- **Stage II - falling rate stage**

When all the water is evaporated from the evaporating soil surface layer, 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 is reduced as the soil water content in the soil profile decreases. As a result the evaporation rate decreases in function of time.

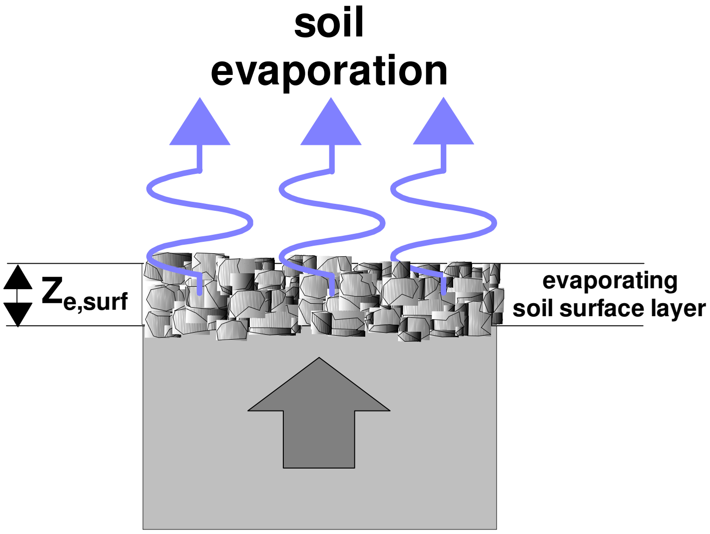

Figure 3.8a
The upward transport of water
from the soil profile to the evaporating soil surface layer

3.8.3 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 the soil 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. 3.8a). 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:

$$REW = 1000\left(\theta_{FC} - \theta_{air\ dry}\right) Z_{e,\ surf} \qquad \text{(Eq. 3.8c)}$$

where	θ_{FC}	volume water content at field capacity [m^3/m^3];
	θ_{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. 3.8c) and the cumulative evaporation for the energy limiting stage (Stage I evaporation), i.e., the U value of Ritchie (1972).

3.8.4 Maximum soil evaporation

- **Available energy for soil evaporation (E_x)**

The energy available for evaporation (E_x) which determines the soil evaporation in stage I is given by:

$$\begin{aligned} E_x &= Ke\ ET_o \\ &= \left[\left(1 - CC^*\right) Ke_x\right] ET_o \end{aligned} \qquad \text{(Eq. 3.8d)}$$

where		
	ET_o	reference crop evapotranspiration [mm.day^{-1}];
	$(1-CC^*)$	adjusted fraction of the non- covered soil surface;
	CC	green canopy cover [fraction soil cover];
	Ke	soil evaporation coefficient for fully wet soil surface
	Ke_x	soil evaporation coefficient for fully wet and not shaded soil surface

The 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. Relative maximum soil evaporation (with reference to a wet non shaded soil surface) for various fractions of canopy cover (CC) in the canopy development stage, is plotted in Figure 3.8b.

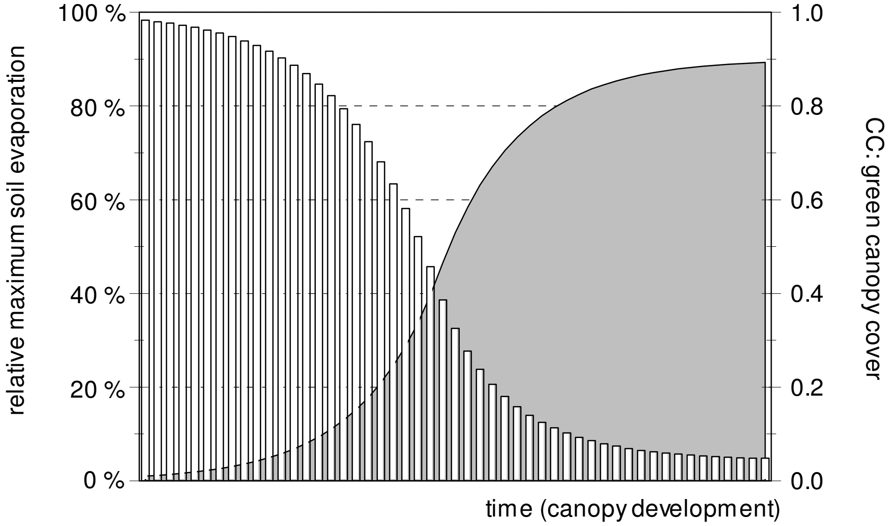

Figure 3.8b
Maximum relative soil evaporation rate (bars) for various fractions of green canopy cover (shaded area) with reference to a wet non shaded soil surface

- **Micro-advective effect**

In Eq. 3.8e, the fraction of the soil surface not covered by green canopy (1-CC*) is adjusted for micro-advective effects (Fig 3.8c). The adjustment equation for (1-CC*), based on the experimental data of Adams et al. (1976) and Villalobos and Fereres (1990), is:

$$(1-CC^*) = 1 - 1.72\ CC + CC^2 - 0.30\ CC^3 \qquad \geq 0 \qquad \text{(Eq. 3.8e)}$$

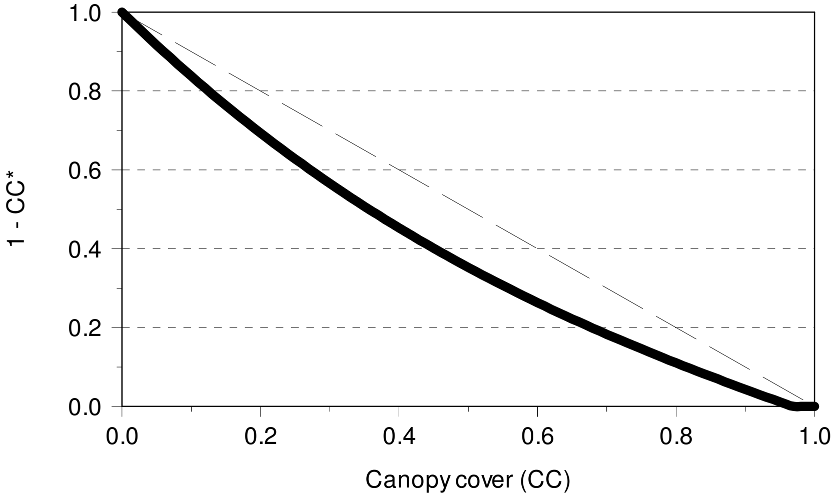

Figure 3.8c
Adjusted fraction (1-CC*) of not shaded soil surface (bold line) for various fractions of green canopy cover (CC)

- **Sheltering effect of withered canopy cover**

The soil evaporation 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 (Fig. 3.8d). 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:

- 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, $CC_{top} = CC_x$

$$E_x = \left(1 - CC^*\right)\left(1 - f_{cc}\ CC_{top}\right)\ Ke_x \quad ET_o \qquad \text{(Eq. 3.8f)}$$

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. The effect of the withered canopy shelter on the reduction of soil evaporation can be adjusted by the user. The maximum evaporation rate as green canopy cover declines in the late season stage is plotted in Figure 3.8d.

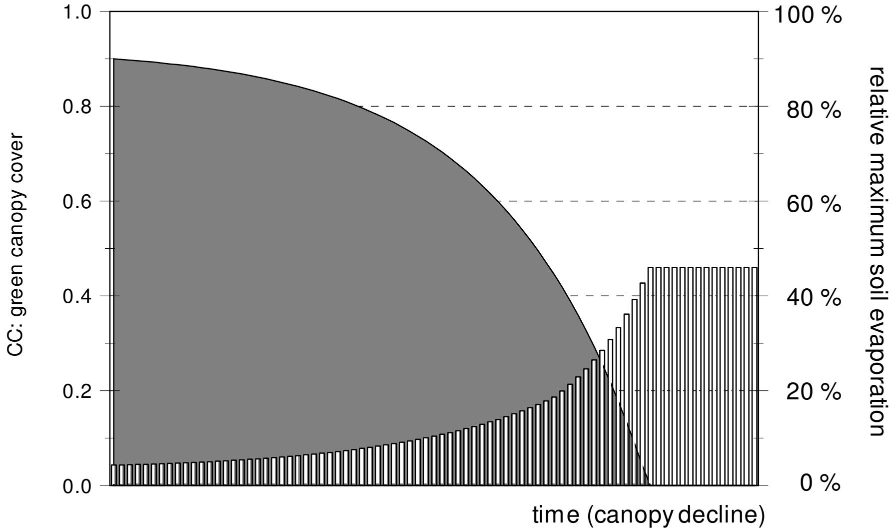

Figure 3.8d
Maximum relative soil evaporation adjusted for withered canopy (bars) for various fractions of green canopy cover (shaded area), with reference to a non shaded soil surface

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}.

- **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 (≤ 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 E_x by the correction factor:

$$E_{x,adj} = E_x \left(1 - f_m \frac{Percent\ covered\ by\ mulch}{100}\right) \qquad \text{(Eq. 3.8g)}$$

The adjustment is not applied when 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, E_x is multiplied by the fraction of the surface wetted (f_w) to adjust for partial wetting (Allen et al., 1998):

$$E_{x,adj} = E_x \; f_w \tag{Eq. 3.8h}$$

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. $E_{x,adj}$ is the minimum value obtained by Eq. 3.8g and 3.8h.

3.8.5 Actual 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 actual rate of soil evaporation is the maximum rate:

$$E_{Stage\,I} = E_x \tag{Eq. 3.8i}$$

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 2). The actual evaporation rate is given by:

$$E_{StageII} = Kr\ E_x \qquad \text{(Eq. 3.8j)}$$

where Kr is the dimensionless evaporation reduction coefficient (Fig 3.8e).

- **Evaporation reduction coefficient (Kr)**

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. The model considers the soil water content in the top soil to estimate the actual evaporation rate. The less water in the top soil, the stronger it is retained and the smaller Kr and the corresponding evaporation rate. 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.

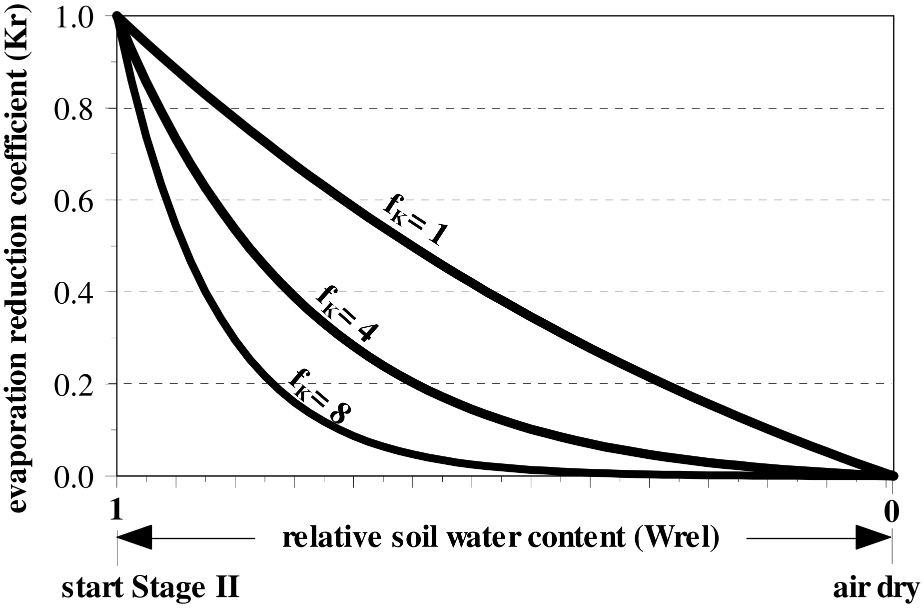

Figure 3.8e
The evaporation reduction coefficient Kr
for various levels of relative soil water content and decline factors (f_K)

Kr varies with the amount of water depleted from the upper layer of the soil. Its value 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 (Figure 3.8e). To account for the sharp decline in hydraulic conductivity (K_{Ψ}) with decreasing soil water content, an exponential equation is used to relate Kr to relative water content of the soil layer (W_{rel}):

$$0 \le Kr = \frac{\exp^{f_K W_{rel}} - 1}{\exp^{f_K} - 1} \le 1 \qquad \text{(Eq. 3.8k)}$$

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.

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. $Z_{e,top}$ is air dry) (Fig. 3.8e). 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. 3.8e). 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.

- **Calculation procedure**

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. 3.8j. At the end of each small time step, the water content of the soil profile is updated and Kr is estimated with Eq. 3.8k. Consequently the switch from stage I to II that can occur during the day, can be simulated as well.

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 as a program parameter. Its default value is 0.3 m and the range is 0.15 to 0.50 m.

3.8.6 Maximum crop transpiration from well watered soil (Tr_x)

- **Calculation procedure**

Crop transpiration is at its maximum rate if the root zone is well watered. Tr_x is proportional to the fractional canopy cover:

$$\begin{aligned} Tr_x &= Kcb\ ET_o \\ &= \left[CC^*\ Kcb_x\right] ET_o \end{aligned} \qquad \text{(Eq. 3.8l)}$$

where ET_o reference crop evapotranspiration [$mm.day^{-1}$];

Kcb_x coefficient for maximum crop transpiration (well watered soil and complete canopy, CC = 1);

CC* actual canopy cover adjusted for micro-advective effects:

$$CC^* = 1.72\ CC - CC^2 + 0.30\ CC^3 \qquad \text{(Eq. 3.8m)}$$

- **Canopy cover**

To estimate soil evaporation (see 3.8.4), CC is increased to CC^* to account for the micro-advective effects. As such less energy is available for soil evaporation. In AquaCrop it is assumed that this energy is available for extra crop transpiration.

- **Crop transpiration coefficient for complete canopy, Kcb_x**

Due to differences in albedo, crop height, aerodynamic properties, and leaf and stomata properties, the transpiration from full grown, well-watered crops differs from ET_o. The maximum crop coefficient Kcb_x represents an integration of the effects of the characteristics that distinguish the crop with a complete canopy from reference grass. The Kcb_x coefficient is often 5-10% higher than the reference, and even 15-20% greater for some tall crops such as maize, sorghum or sugar cane. The Kcb_x coefficient is approximately equivalent to the basal crop coefficient at mid-season for different crops found in Allen et al. (1998), but only for cases of full CC.

- **Ageing effects, $Kcb_{x,adj}$**

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. This is simulated by applying an adjustment factor (f_{age}) that decreases Kcb_x by a constant and slight fraction (e.g., 0.3%) per day, resulting in an adjusted crop coefficient ($Kcb_{x,adj}$). 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, $Kcb_{x,adj}$ is given by:

$$Kcb_{x,adj} = Kcb_x - (t-5)\ f_{age}\ CC_x \qquad \text{(Eq. 3.8n)}$$

where t is the time in days after t_{CCx} (t is zero 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.

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. 3.8n.

- **Efficiency once senescence is triggered, $Kcb_{x,sen}$**

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 $Kcb_{x,adj}$ 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 ($CC = 0$):

$$Kcb_{x,\,sen} = Kcb_{x,\,adj}\left(f_{sen}\right)$$

$$with \quad f_{sen} = \left(\frac{CC}{CC_x}\right)^a \qquad \text{(Eq. 3.8o)}$$

The exponent a is a program parameter and can be used to accentuate (a > 1) or to minimise (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.

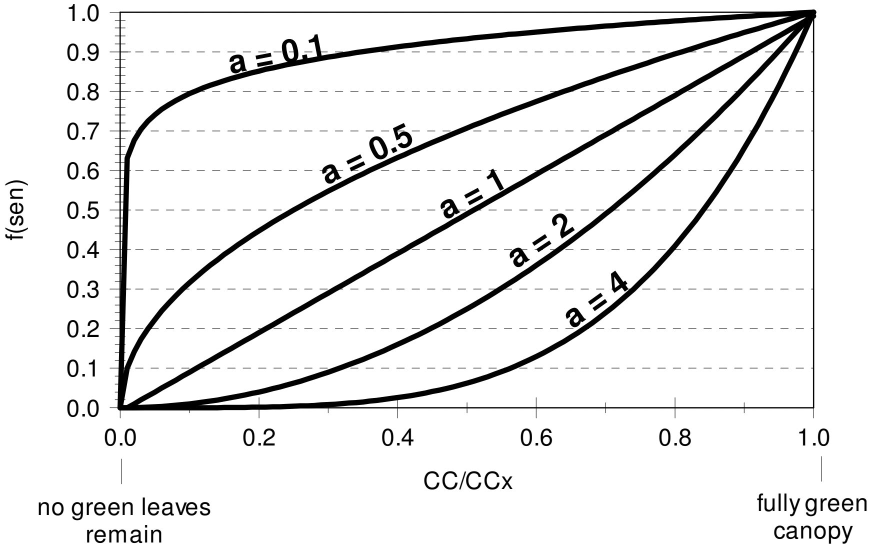

Figure 3.8f
The senescence factor (f_{sen})
for various degrees of withering (CC/CC_x) and various values of the exponent 'a'

3.8.7 Actual crop transpiration (Tr)

- **Thresholds for stomatal closure**

The actual rate of crop transpiration depends on the amount of water available in the root zone (Figure 3.8g). Crop transpiration is reduced below its maximum value as soon as the soil water content in the root zone (Wr) drops below the upper threshold for stomatal closure:

$$Wr_{sto,\,upper} = \left[\theta_{FC} - p_{sto}\,(\theta_{FC} - \theta_{PWP})\right] 1000\, Z \qquad \text{(Eq. 3.8p)}$$

or the root zone depletion (Dr) exceeds:

$$Dr_{sto,upper} = p_{sto}\, TAW \qquad \text{(Eq.3.8q)}$$

where	$Wr_{sto,upper}$	upper threshold expressed as an equivalent depth [mm];
	$Dr_{sto,upper}$	upper threshold expressed as root zone depletion [mm];
	p_{sto}	fraction of TAW at which stomata start to close;
	θ_{FC}	soil water content at field capacity [m^3(water)/m^3(soil)];
	θ_{PWP}	soil water content at permanent wilting point [m^3(water)/m^3(soil)];
	Z	effective rooting depth [m];
	TAW	total available soil water in the root zone [mm].

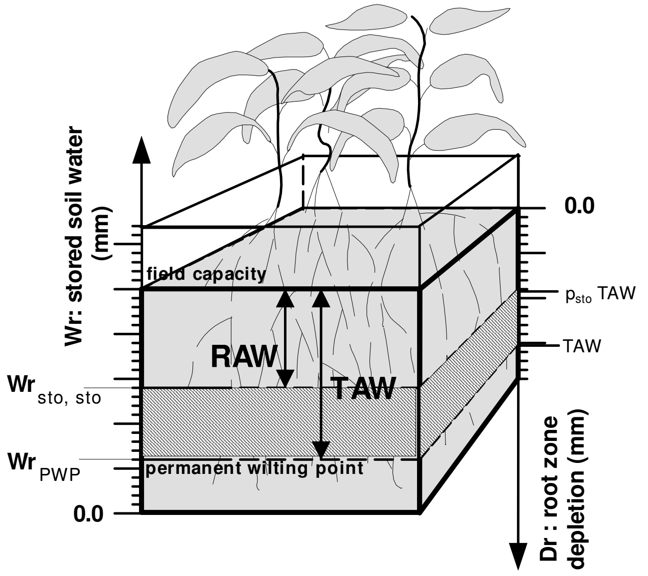

Figure 3.8g
The upper and lower threshold for the soil water content in the root zone affecting stomatal closure

The depletion coefficient p_{sto} is the fraction of TAW that can be depleted from the root zone before stomata start 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. 3.8g).

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:

$$Wr_{sto,\,lower} = Wr_{PWP} = \theta_{PWP}\ 1000\ Z \qquad \text{(Eq.3.8r)}$$

or the root zone depletion (Dr) reaches:

$$Dr_{sto,lower} = TAW \qquad \text{(Eq.3.8s)}$$

where	$Wr_{sto,lower}$	lower threshold expressed as an equivalent depth [mm];
	$Dr_{sto,lower}$	lower threshold expressed as root zone depletion [mm];
	TAW	Total Available soil Water [mm].

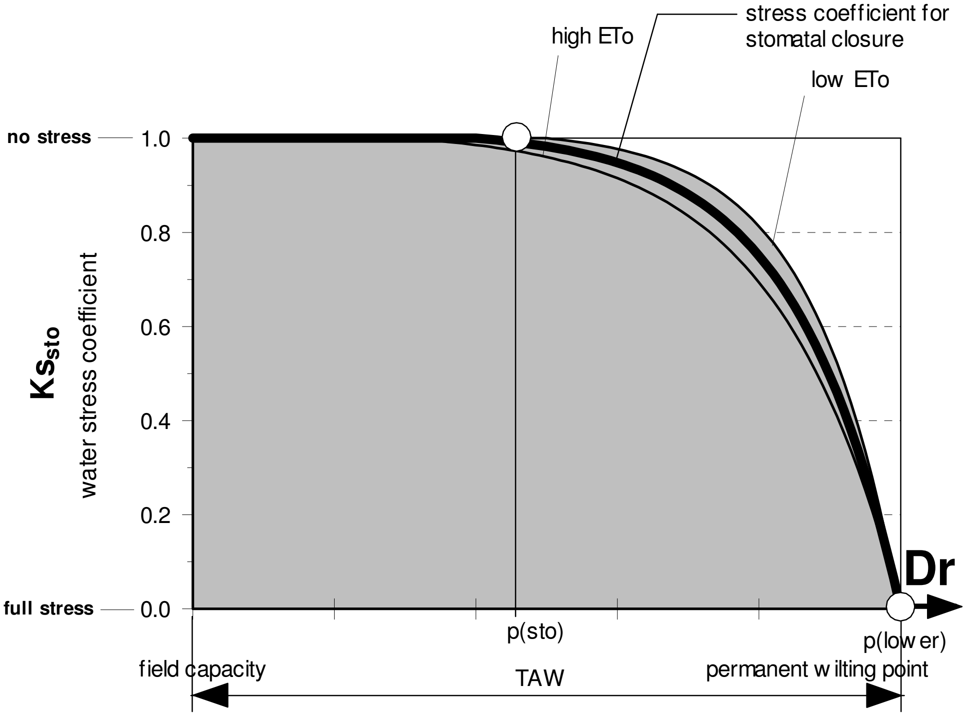

Figure 3.8h
The water stress coefficient for stomatal closure (Ks_{sto})
for various degrees of root zone depletion (Dr)

- **Water stress coefficient for stomatal closure**

To simulate the reduction in crop transpiration as a result of stomatal closure, the maximum transpiration rate (Tr_x) is multiplied by the water stress coefficient for stomatal closure (Ks_{sto}):

$$Tr = Ks_{sto}\ Tr_x \qquad \text{(Eq. 3.8t)}$$

The Ks_{sto} coefficient describes the effect of water stress on crop transpiration (Fig. 3.8h). When sufficient water remains in the root zone $Ks_{sto} = 1$. When the root zone depletion exceeds its upper limit, i.e. when Dr exceeds p_{sto} TAW, the water extracted by the crop becomes limited ($Ks_{sto} < 1$) and the crop is under water stress. In AquaCrop the shape of the Ks_{sto} curve between the threshold and permanent wilting point can be selected as linear or concave (see 3.1.3). At wilting point , where Dr is equal to TAW, Ks_{sto} becomes zero.

- **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. 3.8i). If the water content in the root zone is above the anaerobiosis point (θ_{air}) the root zone becomes water logged and transpiration is limited.

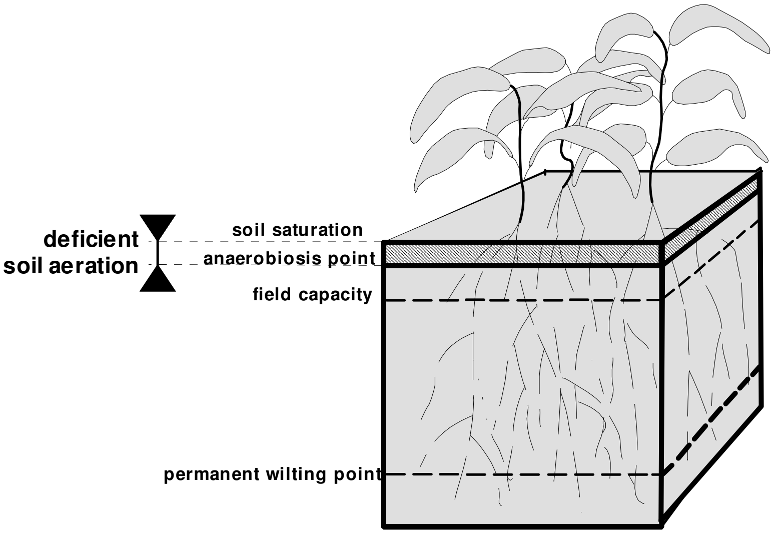

Figure 3.8i
The upper and lower threshold for the soil water content in the root zone resulting in deficient aeration conditions

The effect of water logging on crop transpiration is simulated by means of a water stress coefficient for water logging (Ks_{aer}):

$$Tr = Ks_{aer}\ Tr_x \qquad \text{(Eq. 3.8u)}$$

Ks_{aer} varies linearly between the anaerobiosis point where Ks_{aer} is 1 and soil saturation where Ks_{aer} is zero (Fig. 3.8j).

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.

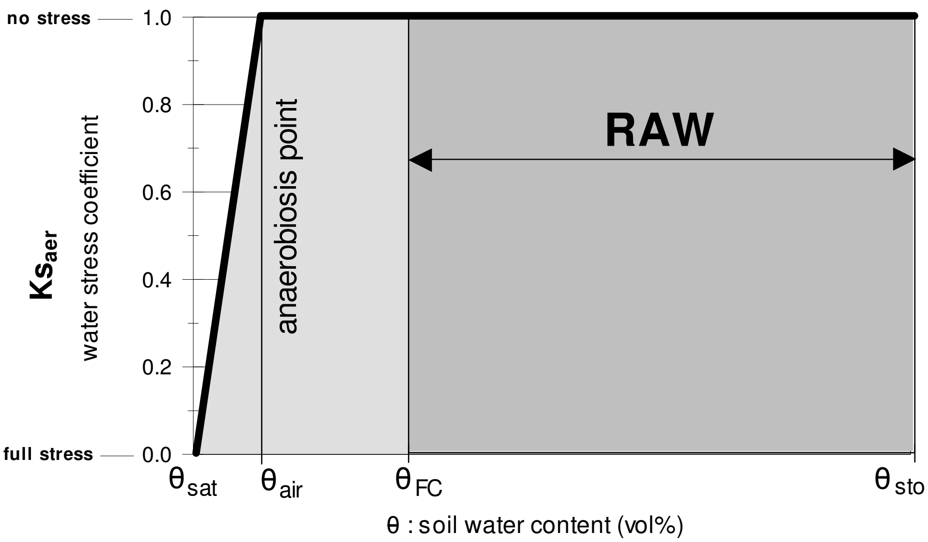

Figure 3.8j
The water stress coefficient for water logging (Ks_{aer})
for various levels of soil water content (θ)

- **Soil water extraction**

Water lost by transpiration is extracted out of the root zone. The root extraction term, S, (Feddes et al., 1978; Hoogland et al., 1981, Belmans et al., 1983) expresses the amount of water that is extracted by the roots at a specific depth per unit of bulk volume of soil, per unit of time ($m^3.m^{-3}.day^{-1}$). S, also denoted as the sink term, is obtained by multiplying a maximum sink term, S_x, with the water stress factor Ks (i.e. Ks_{sto} or Ks_{aer}):

$$S_i = Ks_i \quad S_{x,i} \qquad \text{(Eq. 3.8v)}$$

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 at soil depth i;
	$S_{x,i}$	maximum sink term ($m^3.m^{-3}.day^{-1}$) at soil depth i.

By integrating the equation over the entire rooting depth, the transpiration rate Tr is obtained. The integration starts at the top of the soil profile and is stopped when the sum $\Sigma(1000\ S_i\ dz)$ is equal to the transpiration demand or the bottom of the root zone is reached:

$$Tr = \int_{i=top}^{i=bottom} 1000 \left(Ks_i\ S_{x,i} \right) dz \quad \le \overline{Ks_{root\ zone}}\ Tr_x \qquad \text{(Eq. 3.8w)}$$

The water lost by crop transpiration (Tr in mm per day) can easily be extracted out of the root zone if S_x is sufficiently large. When S_x is large, the root zone well watered (Ks = 1) and Tr_x 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. Tr is less than Eq. 3.8w when the allowable extraction (S_x) restricts water uptake (limited root volume).

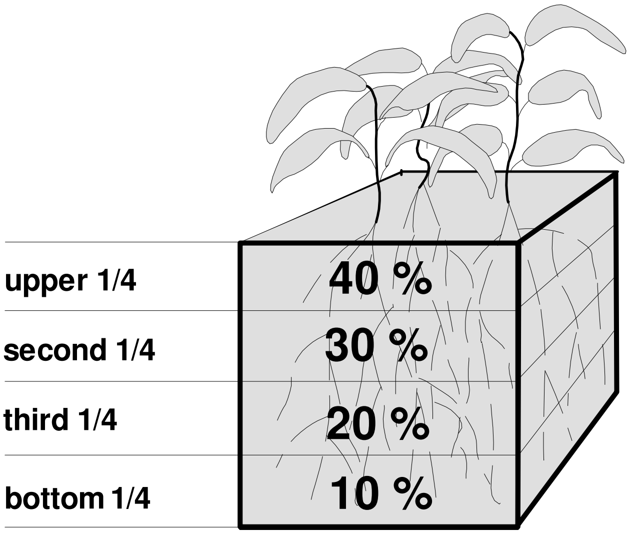

Figure 3.8k
Default extraction pattern in the root zone

In the model S_x at the top of the soil profile might be different from S_x at the bottom of the root zone. The assigned S_x values at different soil depths are proportional to the specified water extraction pattern (Fig. 3.8k). Apart from the root distribution, S_x is also determined by the total root volume. The total root volume determines the maximum amount of water that can be transpired by the crop (Tr_x). This maximum transpiration rate and the root distribution in the root zone are crop parameters which can be adjusted. The default values (which are assigned to the crop when the crop is created) are 3 mm/day for each 0.10 m of rooting depth for Tr_x (with a maximum value of 15 mm/day for the entire root zone) and a 40, 30, 20, 10% root distribution (where the values refer to the upper, second, third and bottom quarter of the root zone). Tr_x can range between 1 mm/day (extremely low root volume resulting in severely water stress even in a well watered soil when the climatic conditions are normal) and 20 mm/day.

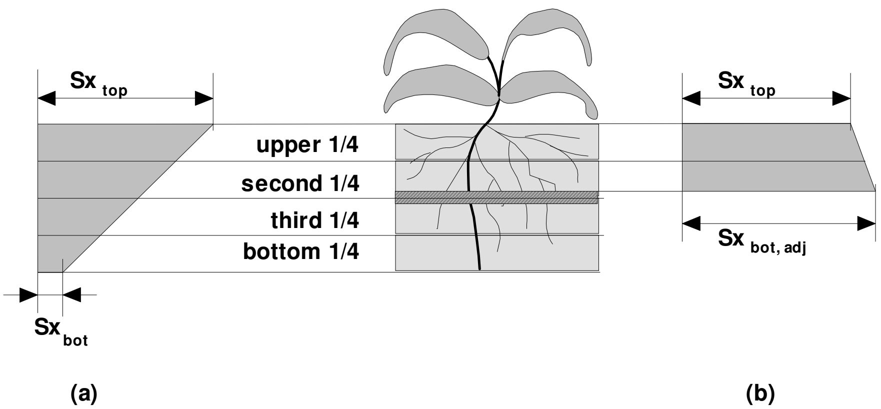

Figure 3.8l
Maximum sink term at the top ($S_{x,top}$) and bottom ($S_{x,bot}$) of the root zone (a) without and (b) with a soil layer inhibiting root zone expansion

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 with the soil profile without the restrictive layer (Fig. 3.8l).

- **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).

3.9 Biomass production

By considering the crop water productivity (WP), the aboveground biomass is derived from the simulated amount of water transpired. 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).

3.9.1 Normalized crop water productivity (WP^*)

- **Normalization for CO_2 and climate**

AquaCrop uses the normalized water productivity (WP^*) for the simulation of aboveground biomass. The WP is normalized for the atmospheric CO_2 concentration and for the climate.

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). WP for other CO_2 concentration can be derived from WP^* with the help of Eq. 3.9a and 3.9b.

Mauna Loa 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). 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).

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. 3.7a). 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).

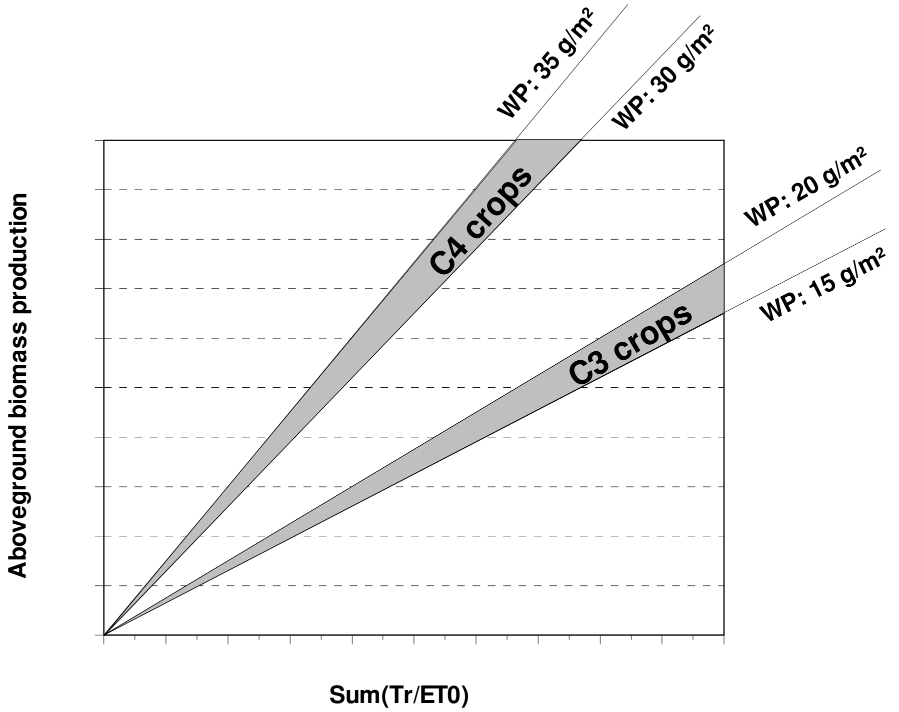

Figure 3.9a
The relationship between the aboveground biomass and the total amount of water transpired for C3 and C4 crops after normalization for CO_2 and ET_o

- **Adjustment of WP^* for atmospheric CO_2**

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} (Steduto et al., 2007). The coefficient considers the difference between the reference value and the atmospheric composition for that year:

$$WP^*_{adj} = f_{CO2}\, WP^* \qquad \text{(Eq. 3.9a)}$$

$$f_{CO2} = \frac{\left(C_{a,i} / C_{a,o}\right)}{1 + 0.000138\left(C_{a,i} - C_{a,o}\right)} \qquad \text{(Eq. 3.9b)}$$

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)

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. 3.9b).

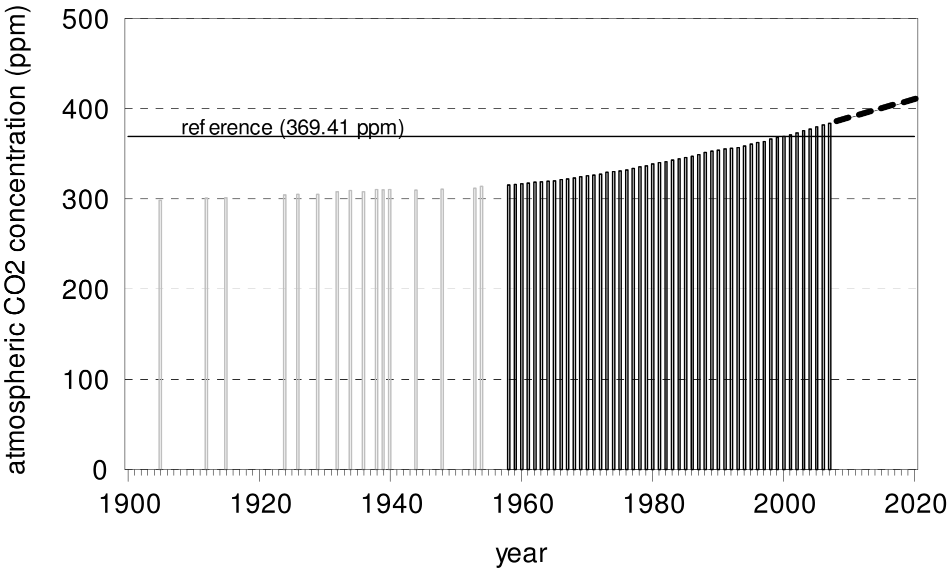

Figure 3.9b
Atmospheric CO_2 concentrations derived from frin and ice samples (light bars), observed at Mauna Loa Observation (dark bars), and predicted (dotted line) by assuming a continuous rise of 2 ppm/year, with indication of the reference value

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 2.19.3).

- **Adjustment of WP* during yield formation**

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:

$$WP^{*}_{adj} = f_{yield}\, WP^{*} \qquad \text{(Eq. 3.9c)}$$

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 the non adjusted WP^{*}. During yield formation, the water productivity switches gradually from WP^{*} to WP^{*}_{adj} (Fig. 3.9c). For determinant crops the transition takes place during the lag phase where the increase of the Harvest Index is slow (see 3.10). 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.

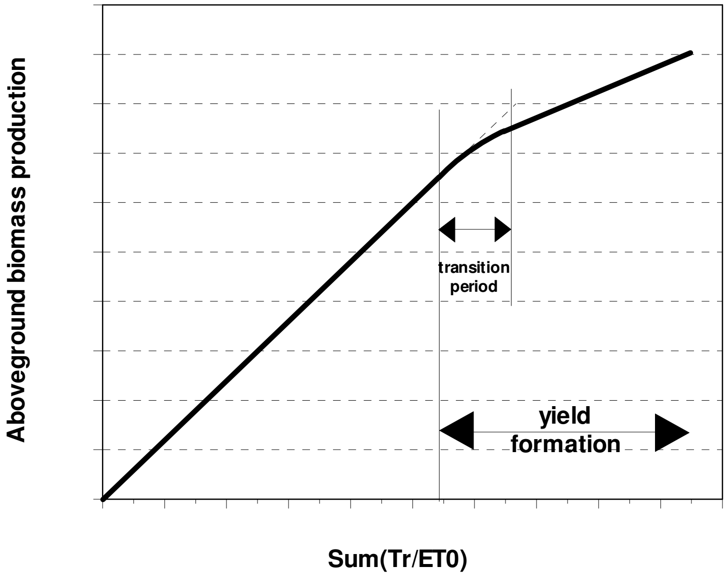

Figure 3.9c
The relationship between the aboveground biomass and the total amount of water transpired before an during yield formation for crops rich in lipids or proteins

- **Adjustment of WP^* for soil fertility**

If limited soil fertility affects crop water productivity, the adjusted productivity is given by:

$$WP^*_{adj} = Ks_{WP,\,x}\; WP^* \qquad \text{(Eq. 3.9d)}$$

where	WP^*_{adj}	WP adjusted for soil fertility
	$Ks_{WP,x}$	soil fertility stress coefficient for water productivity ($Ks_{WP} <= 1$)

$Ks_{WP,x}$ is 1 for non limiting soil fertility. The soil fertility stress coefficient decreases for decreasing soil fertility. 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} 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 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:

$$Ks_{WP,\,i} = 1 - f_{WP,x}\left(\frac{\sum_{j=1}^{i}\left(Ks_{b,\,j}\;(Tr_j\,/\,ETo_j)\right)}{\sum_{j=1}^{n}\left(Ks_{b,\,j}\;(Tr_{x,\,j}\,/\,ETo_j)\right)}\right)^2 \qquad \text{(Eq. 3.9e)}$$

where	$Ks_{WP,i}$	soil fertility stress coefficient for water productivity on day i
	$f_{WP,x}$	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 ($f_{WP} = 1 - Ks_{WP,x}$)
	$\sum(Tr_j/ETo_j)$	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	temperature stress coefficient for biomass production (see 3.9.2)
	n	number of days in the season

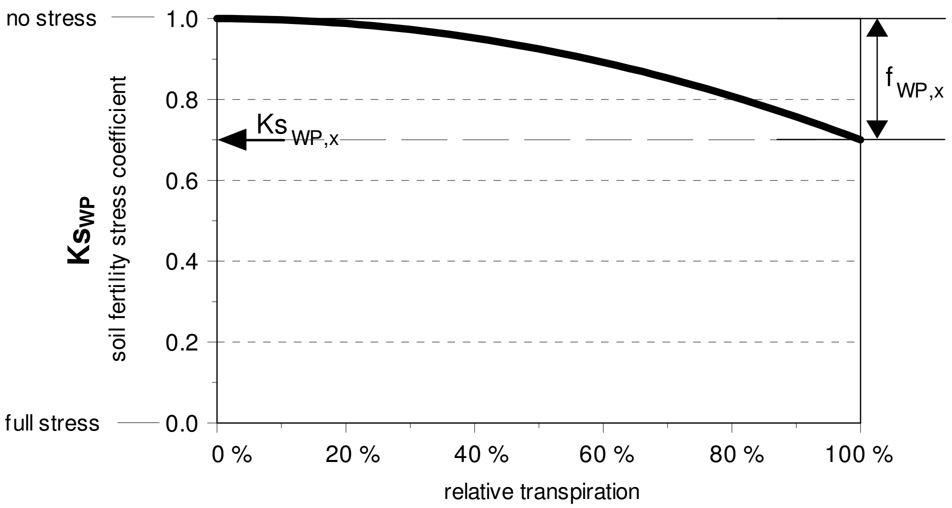

Figure 3.9d
Soil fertility stress coefficient for various degrees of relative transpiration
(for a $f_{WP,x}$ of 0.3 or a $Ks_{WP,x}$ of 0.7)

The variation of the soil fertility stress coefficient throughout the season is plotted in Fig. 3.7d. At the start of the season Ks_{WP} is 1 and WP^* is not adjusted. As more and more water is transpired during the season, Ks_{WP} will gradually decline as the relative transpiration increases. When the crop does not experience any water stress throughout its cycle, the relative transpiration becomes 1 at the end of the season and $Ks_{WP} = Ks_{WP,x}$. 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 ($Ks_{WP} > Ks_{WP,x}$).

- **Adjustment of WP^* for atmospheric CO_2, type of products synthesized and soil fertility**

The total adjustment of the normalized crop water productivity for atmospheric CO_2, type of products synthesized and soil fertility is given by:

$$WP^*_{adj} = f_{CO2}\ f_{yield}\ Ks_{WP}\ WP^* \qquad \text{(Eq. 3.9f)}$$

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, and the soil fertility. For limited soil fertility WP^*_{adj} will decline during the season as more biomass is produced.

3.9.2 Above ground biomass production

- **Daily aboveground biomass production**

The aboveground biomass production for every day of the crop cycle is obtained from the normalized water productivity, the daily crop transpiration for that day and the daily reference evapotranspiration for that day:

$$m_i = WP^*_{adj} \left(\frac{Tr_i}{ET_{o,i}} \right) \qquad \text{(Eq. 3.9g)}$$

where	m_i	daily aboveground biomass production [g/m^2 or ton/ha];
	Tr_i	daily crop transpiration [mm/day];
	$ET_{o,i}$	daily reference evapotranspiration [mm/day];
	WP^*_{adj}	adjusted normalized crop water productivity [g/m^2 or ton/ha] for atmospheric CO_2 concentration, for the type of products synthesized during yield formation, and soil fertility (Eq. 3.9f).

- **Adjustment of biomass production to air temperature**

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:

$$m_i = Ks_b \; WP^*_{adj} \left(\frac{Tr_i}{ET_{o,i}} \right) \qquad \text{(Eq. 3.9h)}$$

where	m_i	daily aboveground biomass production [g/m^2 or ton/ha];
	Tr_i	daily crop transpiration [mm/day];
	$ET_{o,i}$	daily reference evapotranspiration [mm/day];
	WP^*_{adj}	adjusted normalized crop water productivity [g/m^2 or ton/ha] for atmospheric CO_2 concentration, for the type of products synthesized during yield formation, and soil fertility (Eq. 3.7f);
	Ks_b	adjustment factor for growing degrees [dimensionless];

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).

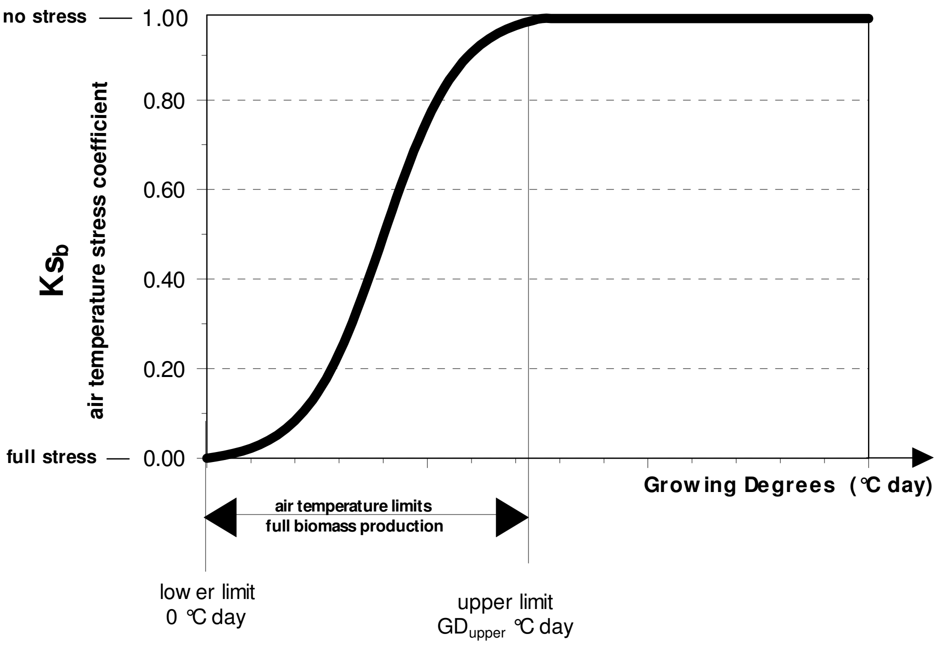

Figure 3.9e
The air temperature stress coefficient for reduction of biomass production (Ks_b) for various levels of growing degrees

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. 3.9c). In AquaCrop it is assumed that biomass production is completely halted when it becomes too cold to generate any growing degrees ($f_{GD} = 0$ 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.

- **Above ground biomass production between cuttings**

For forage and grass crops the above ground biomass production between cuts is simulated by Eq. 3.9g and 3.9h. It is thereby assumed that at each cut a similar 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.

3.10 Partition of biomass into yield part (yield formation)

The partition of biomass into yield part is simulated for leafy vegetable crops, fruit/grain producing crops and roots and tuber crops by means of a Harvest Index (HI). When water and/or temperature stresses develop 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. The resulting HI might differ from the reference harvest index (HI_0) which is specified as a crop the parameter.

3.10.1 Reference Harvest Index (HI_0)

The reference Harvest Index (HI_0) is the ratio of the yield mass to the total aboveground biomass that will be reached at maturity for non-stressed conditions.

3.10.2 Adjustment of HI_0 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. 3.10a). The flowering distribution curve is given by:

$$f_k = 0.00558\, k^{0.63} - 0.000969\, k - 0.00383 \qquad \text{(Eq. 3.10a)}$$

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.

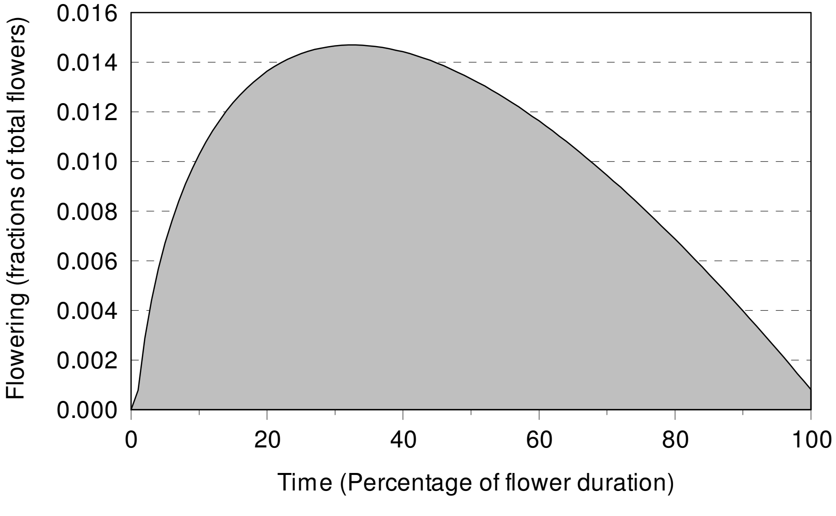

Figure 3.10a
Distribution of flowering during the flowering period

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_0. 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:

$$HI_{adj} = \sum_{1}^{j}\left(Ks_j \left(1 + \frac{f_{excess}}{100}\right) F_j \; HI_0 \right) \qquad \leq \; HI_0 \qquad \text{(Eq. 3.10b)}$$

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. 3.8a); 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.

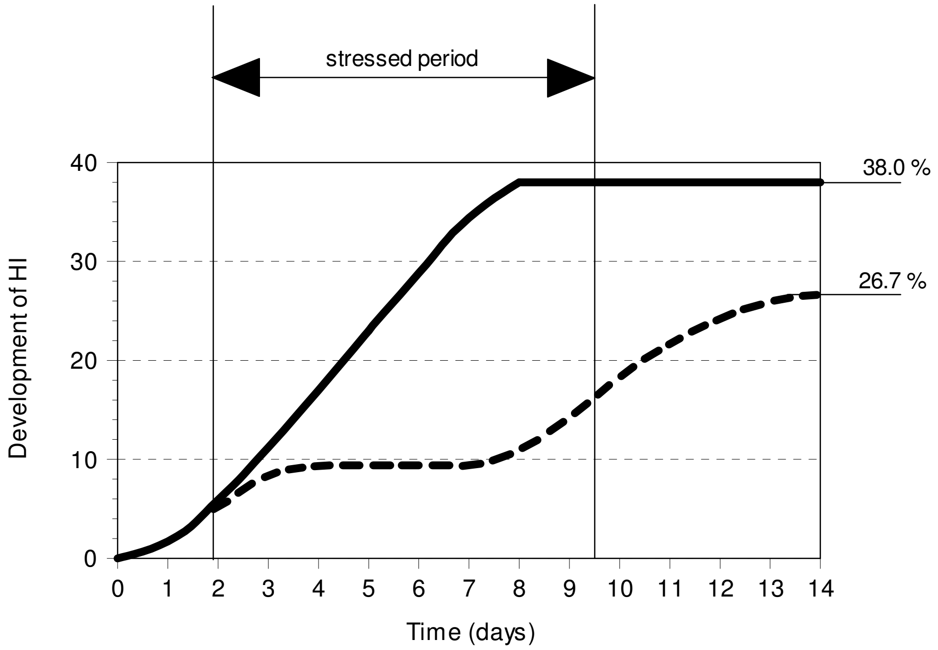

Figure 3.10b
The development of HI at flowering and the adjusted harvest indexes (HI_{adj}) for a non stressed (full) and a stressed (dotted line) flowering period of 14 days. (HI_0 = 38%, f_{excess} = 50%, and stress occurs (Ks < 1) from day 2 till day 9)

The excess of the sink made that if stress reduces pollination by a minor amount, HI_0 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_0 (Fig. 3.10b). 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. 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. 3.10c). $Ks_{pol,w}$ decreases linearly from 1 at the upper threshold (p_{pol}) to zero at the lower threshold (permanent wilting point).

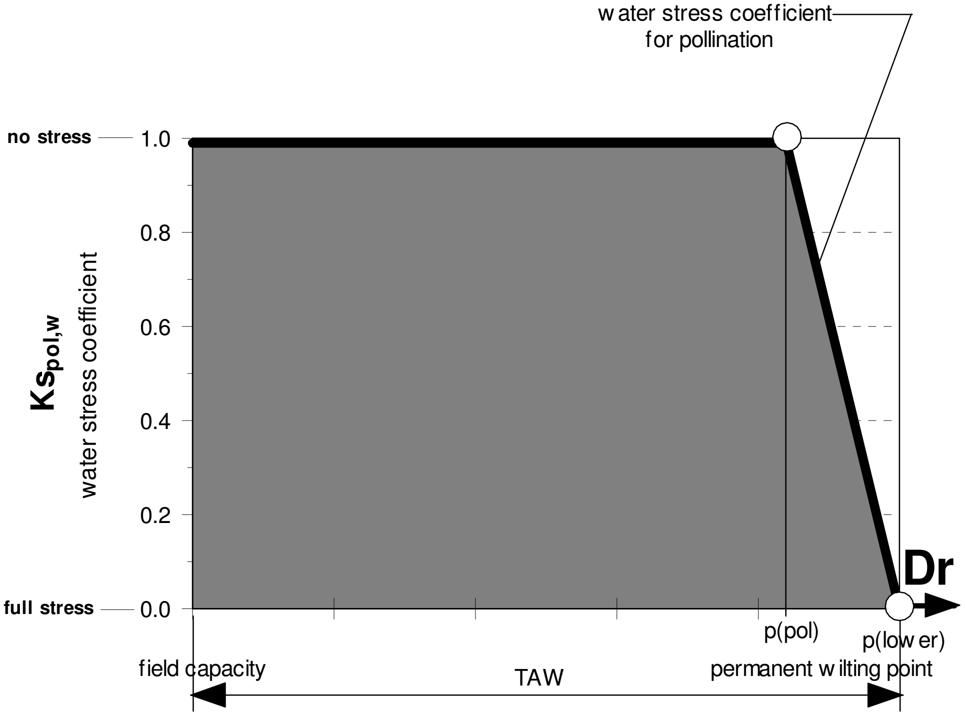

Figure 3.10c
The water stress coefficient for failure of pollination ($Ks_{pol,w}$)
for various degrees of root zone depletion (Dr)

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. To account for the temperature stress effects, the same approach is taken as those used for the water stress effects. 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. 3.10d). $Ks_{pol,c}$ 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 and upper temperature thresholds. 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.

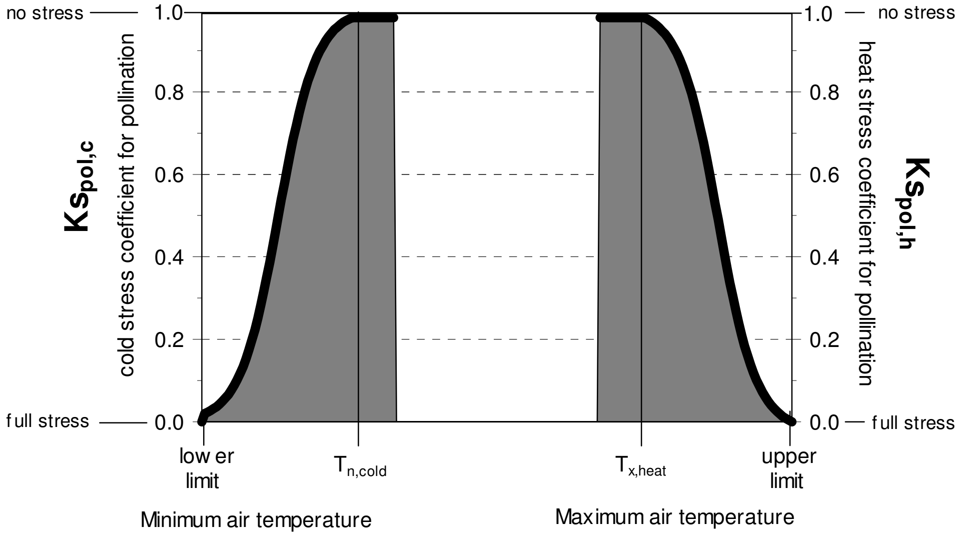

Figure 3.10d
The air temperature stress coefficients for failure of pollination due to cold ($Ks_{pol,c}$) and heat ($Ks_{pol,h}$) stress for various air temperatures

3.10.3 Building up of Harvest Index

The simulation of the building up of the Harvest Index differs along the crop types. Distinction is made between:

- leafy vegetable crops,
- root/tuber crops, and
- fruit/grain producing crops.

- **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. 3.10e). The time to reach HI_o is expressed as a fraction of the growing cycle (default is 20 %). The increase of HI is described by a logistic function:

$$HI_i = \frac{HI_{ini}\ HI_0}{HI_{ini} + \left(HI_0 - HI_{ini}\right)\exp^{-(HIGC)\,t}} \qquad \text{(Eq. 3.10c)}$$

where		
	HI_i	Harvest Index at day i after germination;
	HI_0	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 after germination [day].

Given HI_{ini}, HI_0 and the time required to obtain HI_0, the corresponding growth coefficient (HICG) for HI is derived in AquaCrop from Eq. 3.10c.

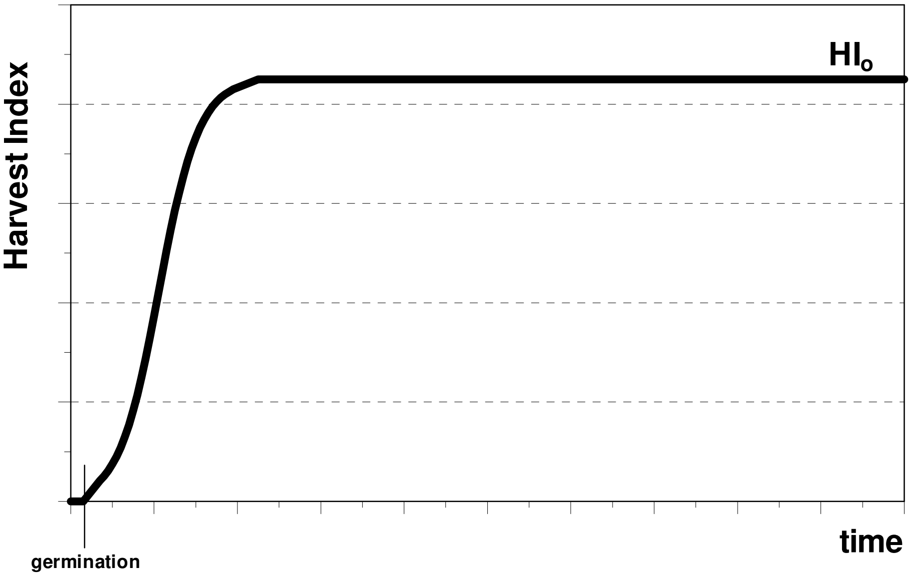

Figure 3.10e

Building up of Harvest Index along the growth cycle for leafy vegetable crops

- **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. 3.10f). The harvest index for any day of yield formation is given by Eq. 3.10c, where t is the time after the start of tuber formation or root enlargement. Given HI_{ini}, HI_0 and the length of yield formation (time required to obtain HI_0), the corresponding growth coefficient (HICG) for HI is derived in AquaCrop from Eq. 3.10c. When the building up of the Harvest Index is fast, the crop might have reached its reference value (HI_0) before the end of the crop cycle.

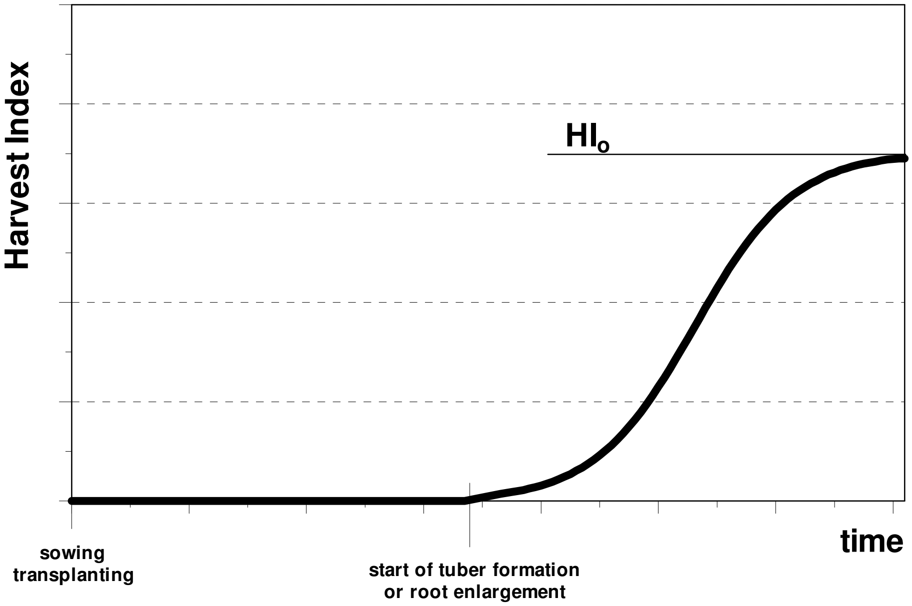

Figure 3.10f
Building up of Harvest Index along the growth cycle for root and tuber crops

- **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 a logistic function. The harvest index for any day in the lag phase is given by Eq. 3.10c where t is the time after flowering. Given HI_{ini}, HI_0 and the length of yield formation (time required to obtain HI_0), the corresponding growth coefficient (HICG) for HI is derived in AquaCrop from Eq. 3.10c. Once the increase of the Harvest Index is sufficient large to reach HI_0 at the end of yield formation, the lag phase is ended and the increase of HI becomes linear (Fig. 3.10g).

When the building up of the Harvest Index is fast, the crop might have reached its reference value (HI_0) 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.

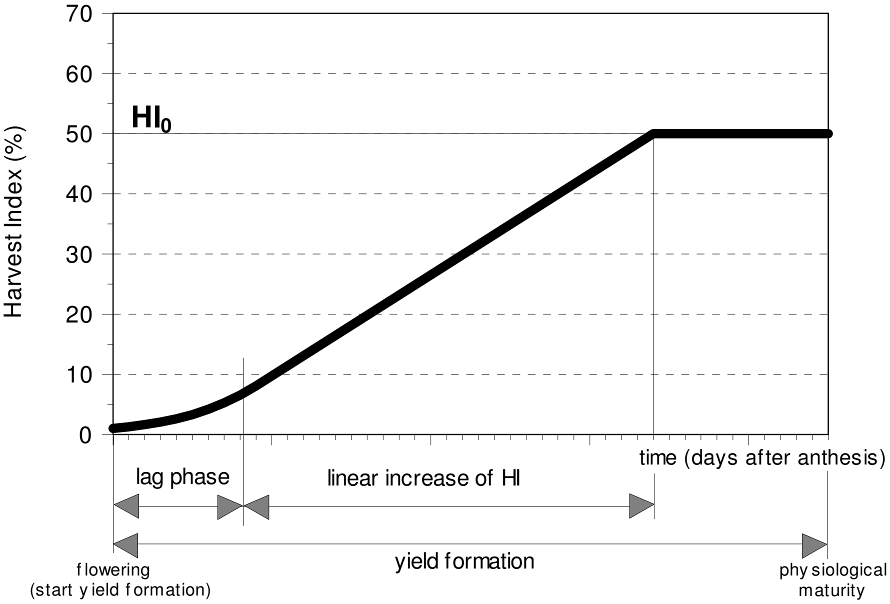

Figure 3.10g
Building up of Harvest Index from flowering till physiological maturity for fruit and grain producing crops

3.10.4 Adjustment of HI_0 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_0 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_0. 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. 3.10h). This results in an adjusted HI which is smaller than HI_0. The threshold green canopy cover below which the Harvest Index can no longer increase is a program parameter.

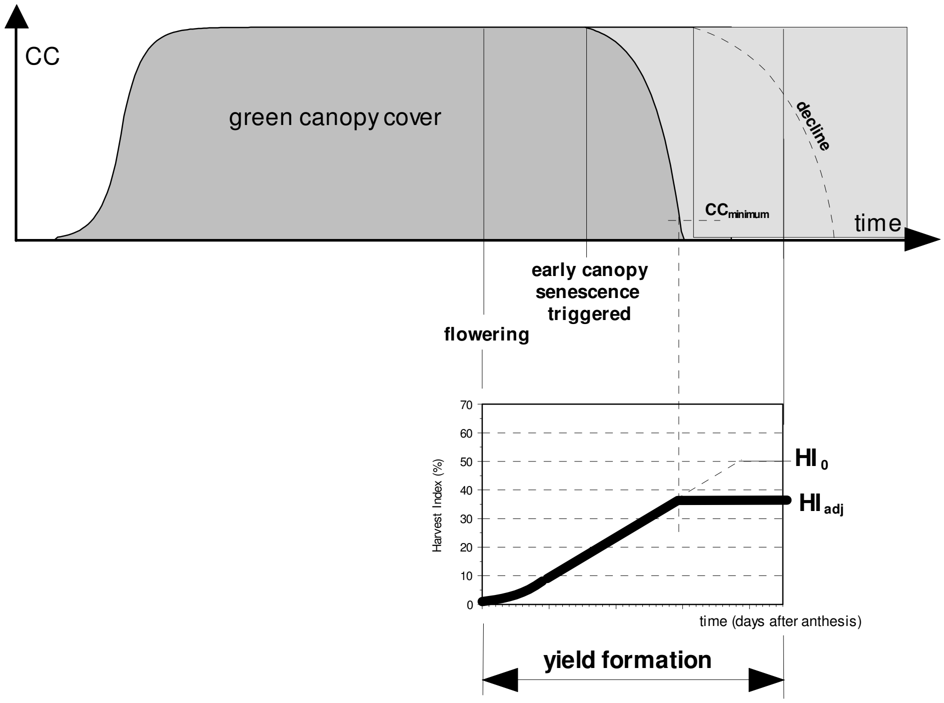

Figure 3.10h
Harvest index development (bold line) when insufficient green canopy cover remain during yield formation for crops with determinancy linked with flowering

3.10.5 Adjustment of HI_0 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_0 (Fig. 3.8i). The maximum allowable increase of HI_0 as the result of water stress before flowering (ΔHI_{ante}) is specified as a percentage of HI_0.

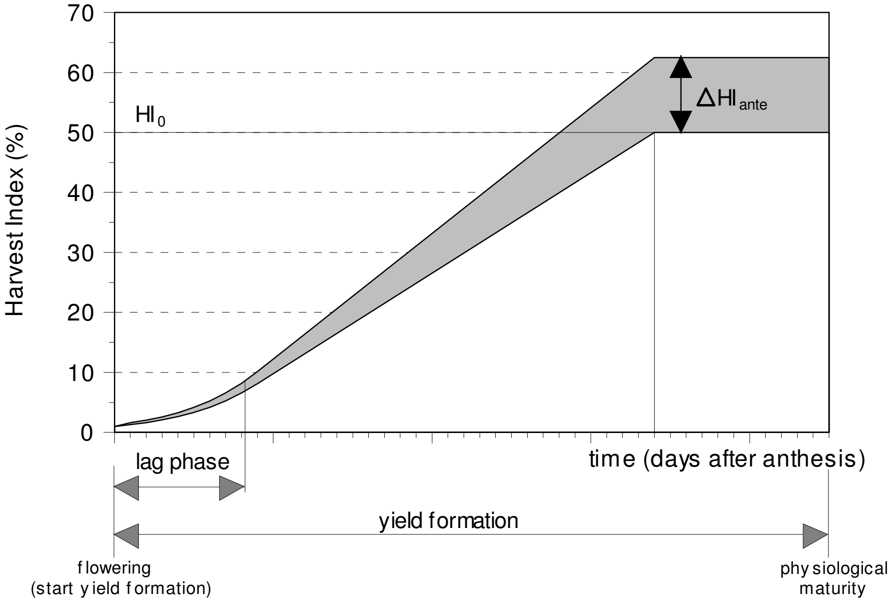

Figure 3.10i
Range (shaded area) in which the Harvest Index of
fruit/grain producing or root/tuber crops can increase
as a result of water stress before the start of yield formation

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):

$$B_{rel} = \frac{B}{B_0} \qquad \text{(Eq. 3.10d)}$$

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_0 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. 3.10j). Hence, the adjustment is restricted to a particular range of B_{rel}. The range valid for adjustment is given by:

$$Range(B_{rel}) = \frac{\ln(\Delta HI_{ante})}{5.62} \leq 1 \qquad \text{(Eq. 3.10e)}$$

where ΔHI_{ante} allowable increase of HI_0 as the result of water stress before flowering [%];

Range(B_{rel}) range of relative biomass (B_{rel}) in which HI_0 can be adjusted [fraction].

In AquaCrop the range is linked to the allowable increase (in percentage) of HI_0 specified by the user. The percentage is crop specific and gives the maximum possible increase of HI_0 as a result of water stress before flowering. The higher the specified increase ΔHI_{ante}, the larger the range for adjustment.

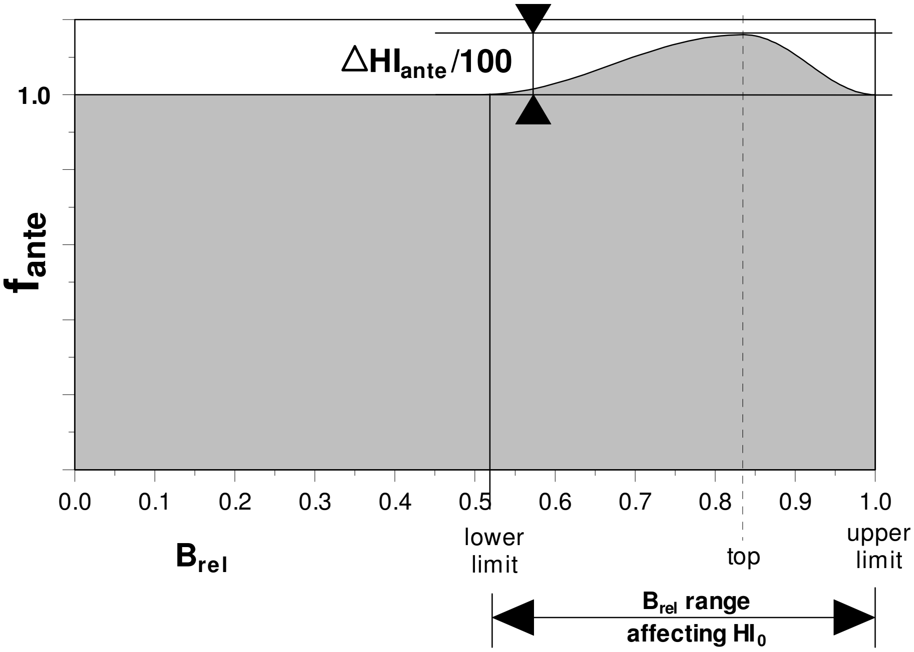

Figure 3.10j
Coefficient (f_{ante}) by which HI_0 has to be multiplied to consider the effect of water stress before the start of yield formation, for various relative biomass values (B_{rel}), and a given allowable increase (ΔHI_{ante})

Within the range where HI can be adjusted, the exact correction for HI_0 is given by a sine function (Fig. 3.10j):

- For B_{rel} between the lower limit and the top:

$$f_{ante} = 1 + \frac{1 + \sin\left(\left(1.5 - Ratio_{low}\right)\pi\right)}{2} \; \frac{\Delta HI_{ante}}{100} \qquad \text{(Eq. 3.10f)}$$

where	B_{rel}	relative biomass at the start of flowering (Eq. 3.8d);
	$B_{r,low}$	lower limit of the B_{rel} Range affecting HI_0;
	$B_{r,top}$	top of B_{rel} Range affecting HI_0;
	f_{ante}	coefficient by which HI_0 has to be multiplied to consider the effect of water stress before flowering;

$$0 \le Ratio_{low} = \frac{B_{rel} - B_{r,low}}{B_{r,top} - B_{r,low}} \le 1 \qquad \text{(Eq. 3.10g)}$$

- For B_{rel} between the top and the upper limit ($B_{rel} = 1$):

$$f_{ante} = 1 + \frac{1 + \sin\left(\left(0.5 + Ratio_{up}\right)\pi\right)}{2} \; \frac{\Delta HI_{ante}}{100} \qquad \text{(Eq. 3.10h)}$$

where	B_{rel}	relative biomass at the start of flowering (Eq. 3.8d);
	$B_{r,top}$	top of B_{rel} Range affecting HI_0;
	$B_{r,up}$	upper limit of B_{rel} Range affecting HI_0;
	f_{ante}	coefficient by which $HImax_0$ has to be multiplied to consider the effect of water stress before flowering.

$$0 \le Ratio_{up} = \frac{B_{rel} - B_{r,top}}{B_{r,up} - B_{r,top}} \le 1 \qquad \text{(Eq. 3.10i)}$$

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 $B_{r,low}$.

3.10.6 Adjustment of HI_0 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_0) as well. Depending on the moment when the water stress occurs and on its magnitude, the adjustment can be upwards or downwards (Fig. 3.10k).

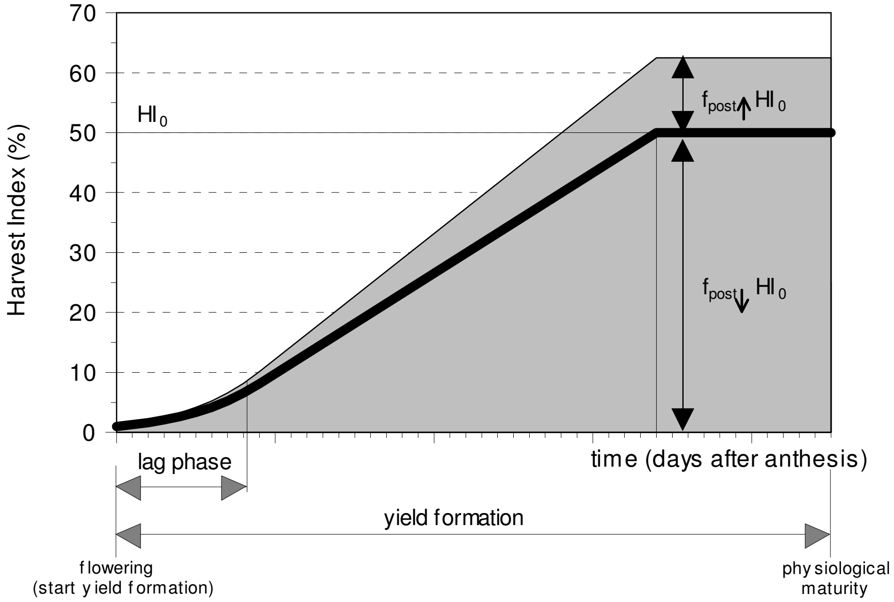

Figure 3.10k
Range (shaded area) in which the Harvest Index of fruit/grain producing or root/tuber crops can alter as a result of water stress during yield formation

- **Upward adjustment of HI_0**

As long as vegetative growth is still possible (Fig. 3.4c), 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:

$$\frac{dHI}{dt} = \left(1 + \frac{(1 - Ks_{\exp,i})}{a}\right)\left(\frac{dHI}{dt}\right)_O \qquad \text{(Eq. 3.10j)}$$

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 3.4.1). 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:

$$f_{post\uparrow} = 1 + \frac{\sum_{i=1}^{n(\exp)} \left(\frac{1 - Ks_{\exp,i}}{a} \right)}{n(\exp)} \qquad \text{(Eq. 3.10k)}$$

where		
	n(exp)	period when vegetative growth is still possible [days];
	$f_{post\uparrow}$	coefficient by which HI_0 has to be multiplied to consider the positive effect of water stress after flowering.

The adjustment of HI_0 is plotted in Figure 3.10l 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_0 which is the triple of HI_0.

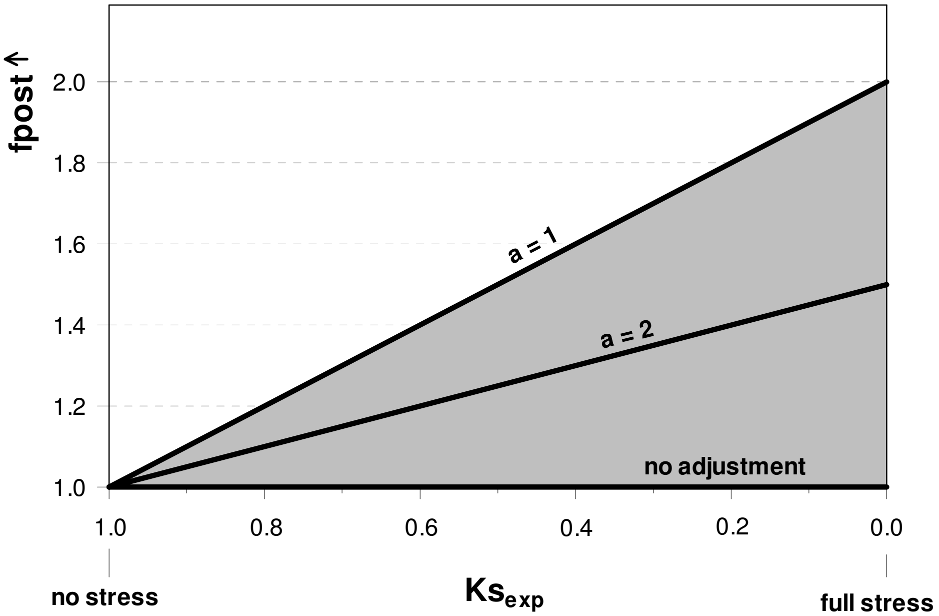

Figure 3.10l
Values for $f_{post\uparrow}$ if water stress after flowering occurs for various mean water stresses affecting leaf growth ($Ks_{exp,w}$) and 'a' values

- **Downward adjustment of HI_0**

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:

$$\frac{dHI}{dt} = \sqrt[10]{Ks_{sto}} \left(1 - \frac{1 - Ks_{sto,i}}{b}\right) \left(\frac{dHI}{dt}\right)_o \qquad \text{(Eq. 3.10l)}$$

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 3.8.7). 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).

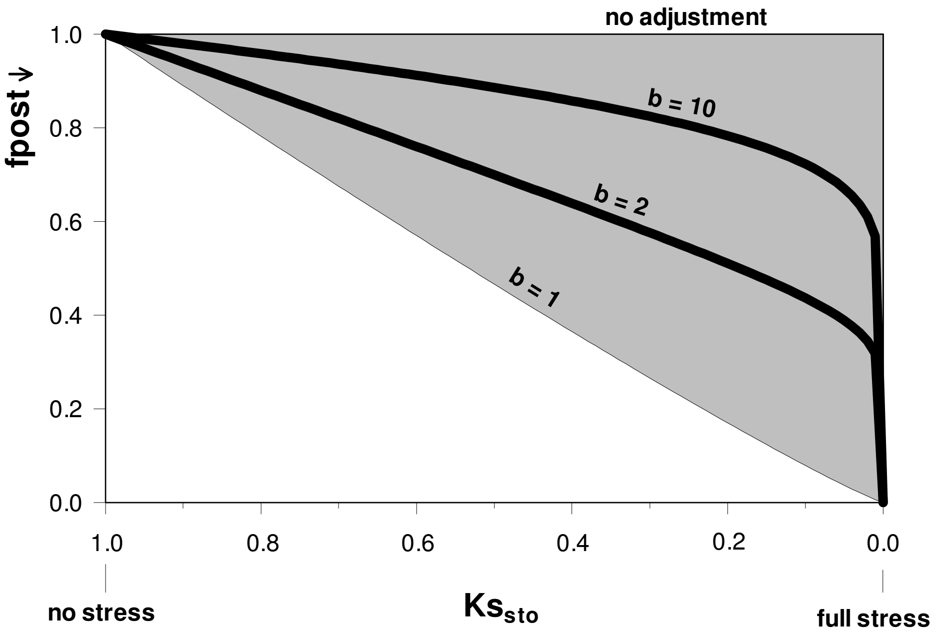

Figure 3.10m

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:

$$f_{post\downarrow} = \frac{\sum_{i=1}^{n(yield)} \left(\sqrt[10]{Ks_{sto,i}} \quad \left(1 - \frac{\left(1 - Ks_{sto,i}\right)}{b} \right) \right)}{n(yield)} \qquad \text{(Eq. 3.10m)}$$

where	n(yield)	period for building up the Harvest Index [days];
	$f_{post\downarrow}$	factor by which HI_0 has to be multiplied to consider the negative effect of water stress after flowering.

The adjustment of HI_0 is plotted in Figure 3.10m for various values of 'b'. The 10th root of Ks_{sto} in Eq. 3.10m makes that the effect of stomatal closure on HI_0 is small when Ks_{sto} is close to 1, i.e. crop transpiration is only slightly hampered. Severe water stress might strongly reduce HI_0 especially when b is small (close to 1).

- **Combined effect on HI_0**

The total adjustment for water stress after the start of yield formation on the Harvest Index is given by the product of the Eq. 3.10k and Eq. 3.10m. If the period where vegetative growth is still possible (n(lexp)) is smaller than the duration of building up the Harvest Index (n(yield)), the adjustments are weighed by their relative length:

$$f_{post} = \left(\frac{w_1 \, f_{post\uparrow} + \left(w_2 - w_1\right)}{w_2} \right) f_{post\downarrow} \qquad \text{(Eq. 3.10n)}$$

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_0 has to be multiplied to consider the combined effect of water stress after flowering.

3.10.7 Total effect of water and temperature stress on the Harvest Index

The total correction of HI_0 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. 3.10n).

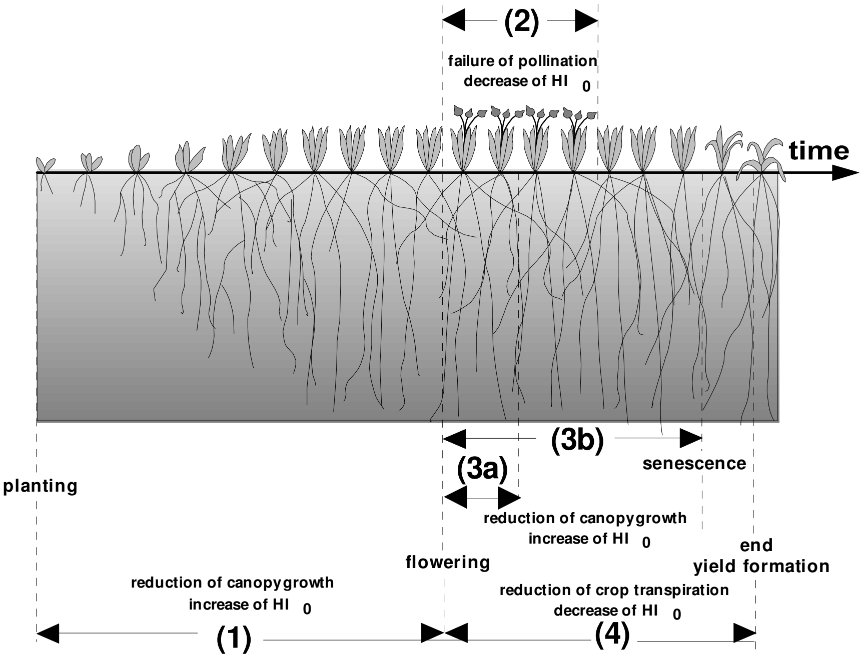

Figure 3.10n
Periods in which water stress might affect HI and its effect on HI_0.
(1) before yield formation; (2) during flowering; and (4) during yield formation,
with indication of (3) the period of possible vegetative growth
for (a) determinant crops and (b) indeterminant crops

The total correction of HI_0 at the end of the yield formation is given by:

$$HI = f_{ante}\ f_{post}\ HI_{adj} \qquad \text{(Eq. 3.10o)}$$

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. 3.10f and 3.10h);
	f_{post}	factor by which HI_{adj} has to be multiplied to consider the effect of water stress after flowering (Eq. 3.10n);
	HI_{adj}	reference Harvest Index adjusted for failure of pollination and inadequate photosynthesis

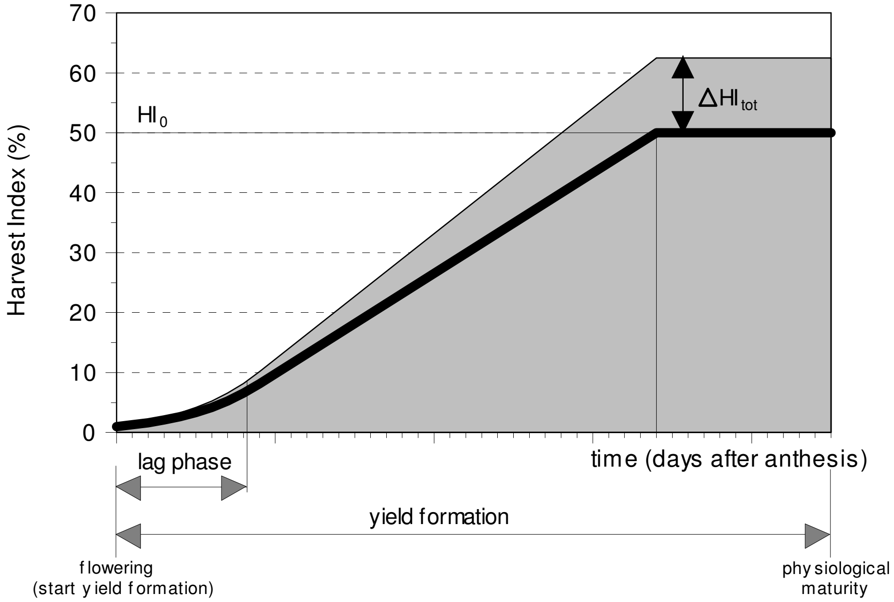

Figure 3.10o
Range (shaded area) in which the Harvest Index can increase or decrease as a result of water stress before and after the start of yield formation

The adjusted Harvest Index can range between an upper limit (larger than HI_0) and 0 (Fig. 3.10o):

- If HI is larger than HI_0, its value can however never exceed a maximum specified by the user. The allowable increase (ΔHI_{tot}) which is crop specific, is specified as a percentage of HI_0:

$$HI \le \left(1 + \frac{\Delta HI_{tot}}{100}\right) HI_0 \qquad \text{(Eq. 3.10p)}$$

- As a result of water stress at and after flowering, HI might be smaller than HI_0. 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.

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