3 Methodology

The concept for the investigations is oriented towards the main problems of the region: water scarcity and water stress in a terraced agricultural catchment. The guiding themes are:

1. A terrain analysis to achieve a conceptional model for the estimation of the effects and supplemental irrigation potential of **water harvesting.**
2. A statistical analysis of the regional precipitation data with respect to **agricultural water availability.** A comparison with a generalised crop water requirement estimation allows the detection of periods of principal water scarcity and its magnitude.
3. A **rainfall-evapotranspiration model** which is derived from and applied to the growing season 1998 in Mia‘amirah. This case study analyses the effects of agricultural water availability under rainfed conditions with and without water harvesting and management influences. The use of a “rainfall-evapotranspiration” rather than a “rainfall-runoff” approach is justified by the following observations:

- For the main task, the determination of water availability for agriculture, the water balance components precipitation and evapotranspiration are the most relevant features.
- The average potential evapotranspiration is higher than the average rainfall in every month of the year. Hence it is likely that most water follows that way back to the atmosphere.
- Runoff occurs ephemeral. If runoff occurs at the catchment outlet the runoff coefficient (φ) remains small in proportion to the rainfall.

3.1 Geomorphological Terrain Survey and Analysis

Terraced slopes have particular hydrological and geomorphological properties which require adapted methods to achieve the desired information. For the current study the following features have to be addressed:

- The relief as the prevailing geomorphological factor for the runoff generation.
- The ratio between related runoff and runon areas to determine the effect of water harvesting.

- Runoff paths and partitioning of the runoff into different terraces.
- The volume of the terrace bodies to estimate the potential soil moisture storage.
- Soil properties as soil type and stone content.

To work on those features different methods were combined during the field work and the later data processing. The base of all field investigations is a geodetic survey which results in a base map for all further mapping and surveying activity. Special attention was paid to the shape and the volume of terraces.[7] Together with soil texture and stone content of the terrace bodies it determines the potential plant available water storage capacity. The digital elevation model derived from the base map was used for the demarcation of the water harvesting areas. From the outlet of each water harvesting area the corresponding catchment was defined. Furthermore all runoff paths and inlets from channels into terraces were mapped. Those data were used for the calculation of the runoff partitioning described in chapter 3.1.1.

3.1.1 The Concept of Water Harvesting and Redistribution: Runoff–Runon Irrigation

Rainwater harvesting and redistribution work on the principle of collecting rainwater and divert it on agricultural area (figure 2.1). The main conceptional difference to conventional irrigation systems is that timing and amount of the application cannot be determined a priori [Ben-Asher and Berliner (1994)]. Water harvesting serves several purposes, depending on the local climatic and environmental conditions [Prinz (1996)]:

- Restoring the productivity of land that suffers from inadequate rainfall.
- Increasing and stabilising yields in rainfed farming.
- Minimising risk in drought-prone areas.
- Combatting desertification by tree cultivation.

Depending on the *P/ET* ratio of the growing season, it requires a minimum precipitation of between 100 to 200 mm/a [Pacey and Cullis (1986)]. Such conditions are met where the rainy season is during winter time when evapotranspiration is lower [Kutsch (1982)] and

7 It will be later expressed as mean terrace depth.

the runoff-runon area ratio can exceed 30:1. In general, precipitation should not drop below 200 – 300 mm/a, for on-site schemes precipitation should range between 500 – 600 mm/a [PACEY and CULLIS (1986)].

Runoff from water harvesting areas occurs as "direct runoff" with high runoff coefficients and short concentration times. The major parameter for water harvesting schemes is the runoff efficiency, generally referred as runoff coefficient. For the event based runoff generation for water harvesting BOERS ET AL (1986) [in: BEN-ASHER and BERLINER (1994)] used a linear regression model with a threshold value:

$$q_d = P_{eff} = (P - I_a) \cdot \varphi \qquad (3.1)$$

with:
- q_d — direct runoff in terms of discharge per unit area [mm/m²]
- P_{eff} — effectiv rainfall [mm]
- P — total rainfall [mm]
- I_a — initial abstraction
- φ — runoff coefficient or rainfall efficiency [%]

Such simple linear models have been approved as well as more sophisticated approaches on the basis of the partial area contribution (PAC) concept without showing weaker results.[8] Also the SCS-formula for direct runoff [SCS (1972)], which was originally designed to estimate runoff volume for design of soil conservation works and flood-control projects, was used for direct runoff generation [PILGRIM and CORDERY (1992)]:

$$q_d = P_{eff} = \frac{(P - 0.2\ S_m)^2}{P + 0.8\ S_m} \qquad (3.2)$$

with: S_m — potential maximum retention [mm].

The current study compares the linear model with and without initial abstraction [equation (3.1)] and the SCS-equation (3.2).

8 BOERS ET AL. (1986); KARNIELI ET AL. (1988); HUMBORG (1990); BEN-ASHER and HUMBORG (1992) in: BEN-ASHER and BERLINER (1994)

The runoff of the water harvesting zones has to be divided into the flow on adjacent terrace zones and the connected channels. It is not practicable to measure runoff at each partitioning point in the catchment. Therefore, the redistribution of runoff is based on qualitative field observations and mapping, which results in a perceptional flow partitioning. Figure 3.1 displays the schematic distribution scheme.

Runoff division to adjacent terrace zones was done according to the size of the terrace zones:

$$q_{T_j} = \frac{A_i}{\sum_{i=1}^{n} A_i} \cdot q_{WH} \tag{3.3}$$

with	q_{T_j}	discharge on terrace zone j [m³]
	A_j	area of terrace zone j [m²]
	q_{WH}	discharge on the water harvesting zone [m³]
	n	number of adjacent terrace zones

If the water harvesting area contributes a channel that transports the water to remote terrace zones, it is divided among the different zones by the number of inlets from the channel to the terraces of the respective zone:

$$q_{T_i} = \frac{In_i}{\sum_{i=1}^{n} In_i} \cdot q_{ch} \tag{3.4}$$

with	In_i	number of inlets entering the terrace zone T_i [1]
	q_{ch}	discharge entering the channel [m³]

The splitting of runoff between adjacent terraces and channels was done manually on the basis of field experience and advice by local farmers. Usually the channel receives 50 – 70 % of the of the discharge.

The advantage of this kind of distribution scheme is that each terrace zone will get a constant factor by which the precipitation will by multiplied. Therefore, the flow partitioning must be done only once for the hole catchment (in comparison to Thiesen-polygons for areal rainfall calculation). The disadvantage is that this distribution scheme does not incorporate individual decisions of the farmers on opening or closing their channels. But the experience of the author is that opening and closing of individual inlets happens, but not at a large extent. Most of the time the channels remain open. Therefore, this simplification was considered acceptable.

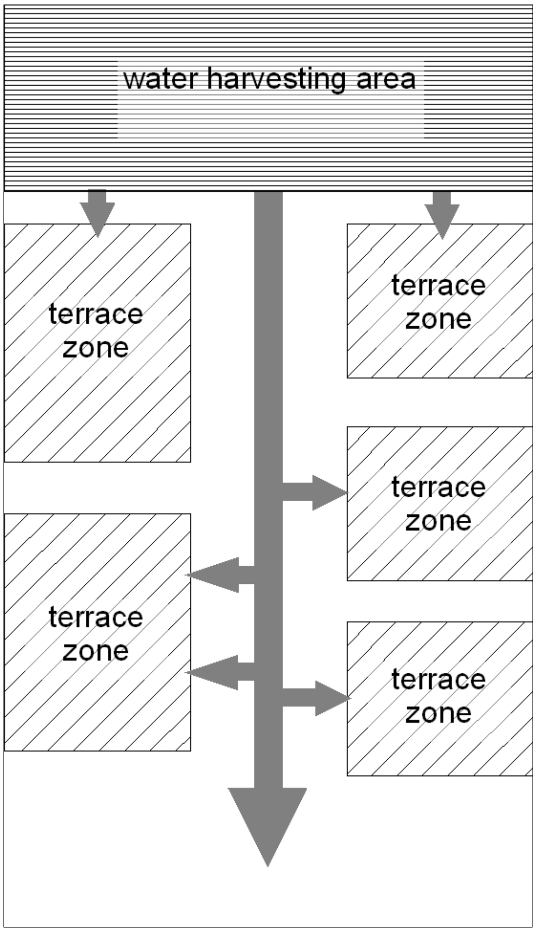

Figure 3.1 Scheme of runoff distribution from water harvesting areas

3.2 Determination of Agricultural Water Availability and Rainfall Reliability

The agricultural water availability relies on a statistical rainfall probability analysis. To obtain a temporal resolution, 10-day intervals (decades) were chosen as appropriate time intervals to access agricultural water availability. Monthly intervals were considered too long, and for shorter intervals than decades data quality was not sufficient. The analysis partly follows an analysis of extreme events. But with respect to that, it focuses on the reliability of rainfall rather than the probability of extrems. The method investigates the total rainfall of the considered period (decades) as a whole and does not consider single events (such as the biggest rainfall or flood event) as conventional extreme analysis does.

Plotting positions are the basis for any hydrological probability consideration. The non-exceedance probability of the decade precipitation was calculated using the Weibull formula (equation 3.5). Weibull was chosen as an unbiased estimation (STEDINGER et al 1992), although BERAN and RODIER (1985) reject this formula in the context of drought analysis, mentioning the inappropriate recurrence interval of $n+1$, and promote the Gringorten (1.79n + 0.2) or Hazen (2n) formula. Comparisons among the different formulas based on annual data (chapter 6.1.2, figure 6.5) show that the differences of the plotting positions (linear axes) are negligible.[9]

$$y=\frac{i}{n+1} \qquad (3.5)$$

where	i	rank
	n	number of observations (here: years)

To overcome the drawbacks of the empirical discrete plotting positions, a theoretical probability model was applied to the plotting position data.

The cumulative density function (CDF) of the Weibull distribution given in equation (3.6) was chosen. It belongs to the “generalised extreme value” (GEV) distribution family.[10]

$$F_x(x)=1-\exp[-(x/\alpha)^k] \qquad (3.6)$$

where	x	observation
	α	scale parameter
	k	shape parameter

The choice was made due to the flexibility of this distribution to adapt to the shape of many empirical distributions. As a consequence, this distribution might be more affected by noise than some other distributions.[11] Alternative tests with the Gumble distribution had

9 BERAN and RODIER (1985) promotes graphical methods on probability paper which are not suitable here.
10 It is important to mention to distinguish between the Weibull plotting positions and Weibull distribution, which are two completely different things.
11 BATTALA , RAMON, personnel comunication Dec. 2001

been conducted without major differences. The fitting of the Weibull distribution to the plotting positions was done with a routine using the MINIPACK-1 algorithm. It uses the Levenberg-Marquardt technique to solve the least-squares problem.[12]

With the theoretical Weibull distribution in equation (3.6) it is possible to calculate the probability of any given amount of rainfall. For the inverse case, to compute the precipitation for a given rainfall probability, equation (3.6) need to be rearranged:

$$P_F = \alpha(-\ln(1-F))^{1/k} \tag{3.7}$$

where P_F precipitation computed from the probability function.

If the agricultural water requirements are known, it is possible with equation (3.7) to quantify how reliable the demand can be covered by rainfall or – if the water harvesting effects are incorporated by runoff irrigation schemes. Since the equation (3.7) will be applied to every decade, a time specification of the water availability is possible and potential periods of water scarcity can be detected.

3.3 The Evapotranspiration Approach for Computing Crop Water Requirements

The determination of crop water needs is the key question of agriculture in semi-arid to arid environments to achieve appropriate water supply for the crops. The crop water requirements are usually determined as a function of the evapotranspiration.

On principle, the water consumption of plants is regulated by :

a) the water supply (precipitation and/or irrigation and/or storage of water in the ground),
b) the energy supplied by radiation and tangible heat as driving forces and
c) the water intake into the atmosphere.

For the evaluation of crop water requirements these three factors have to be tackled. For water demand, the factors “energy supply” (a) and “water intake” (b) need to be calculated in order to determine if the water supply (a) is sufficient. The process of water withdrawal can be interpreted as an interaction between the supplied energy and the plant-soil system. While the energy is relatively easy to determine, the soil water in the root zone is highly complex and affected by many soil specific parameters (texture, micro- and macro

12 Markwardt (2001) userhelp MPFIT –IDL routine

porosity). The aim is to keep the complex modelling of water in soils simple. Therefore, the current approach determinates the water withdrawal by the supplied energy. Of cause it is necessary to include the principal soil components to achieve representative results.

The basic source of rainfed agriculture with water harvesting is precipitation. It infiltrates the soil where it is supplied to the root system of the plant (beside other processes like deep percolation). The actual water withdrawal from the source soil is done by the processes ***transpiration*** and ***evaporation***, conventionally combined in the expression ***evapotranspiration***.

The two different processes, evaporation and transpiration, are combined in the term evapotranspiration (ET) mainly because they both redirect water from the same source "soil" into the same sink "atmosphere" and are difficult to separate. Nevertheless, it is essential to divide these two processes at least conceptually. Transpiration is a process indispensable for plant/crop production and therefore ***transpiration is productive by definition.*** Evaporation is inevitable as soon as water is available but not essential for plant production, therefore it is not necessarily productive and should be minimised if water is scarce.

The evapotranspiration is conceptionally divided into "potential", "reference", "actual" and "crop" evapotranspiration. [ALLEN et al. (1998)] Most relevant, but most difficult to determine is the actual evapotranspiration (ET_{act}). It is the amount of water which is transferred into the atmosphere under the given conditions of a natural vegetated surface (SCHRÖDTER 1985). Beside evaporation from soil and transpiration from plants it includes components such as dew and interception. Due to the many factors affecting ET_{act}, it is not possible to determine ET_{act} precisely. Easier to determine is the potential evaporation (ET_{pot}), basically converting the available energy into a quantity of water (usually [mm]) that can be vaporised. The most popular definition is given by PENMAN (1963):

> ***ET_{pot} is "the rate of evapotranspiration from an extensive surface of short green crop, actively growing, completely shading the ground, of uniform height and not short of water."***

This definition has some shortcomings. The term “extensive” fails to take into account the convective influences, and with the expression “completely shading the ground” it misses evaporation from the soil surface. SHUTTLEWORTH (1992) inversely determines the potential evapotranspiration as the evaporation from an open water surface by:

> ***“ET_{pot} is the quantity of water evaporated per unit area, per unit time from an idealized surface under existing atmospheric conditions.”***

Thus he ascribes the control over the evapotranspiration to the meteorological conditions. Hence, the definition of ET_{pot} has never been unambiguous. To achieve standardisation, the “crop reference evapotranspiration” was introduced by DOORENBROS and PRUITT (1977). It largely relies on the definition of PENMAN (1963):

> ***ET_0 is “the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall green grass cover of uniform height, actively growing, completely shading the ground and not short of water”.***

However, it more clearly defines the surface conditions as a short grass cover under optimal growing conditions. The recent FAO publication “Crop Evapotranspiration”[13] modified this to a clearly defined but theoretical reference surface:

> ***“A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23.”***

Both concepts, potential and reference evapotranspiration, represent ideal situations, not applicable to individual sites with real world conditions. But they make values comparable.

3.3.1 Determination of Evapotranspiration

The methods to determine evapotranspiration are either direct methods such as lysimeters, pan evaporation and evaporation from ceramic surfaces, simulating as “dummy-device” a plant stoma surface, or indirect methods which derive the evapotranspiration from a set of climatological parameters. The latter can be divided into long term water

13 ALLEN, et al. (1998) **Crop Evaporation**, Rome, FAO Irrigation and Drainage Paper No. 56.

balance methods, empirical methods (Blaney-Criddle, Haude), energy balance methods (Makkink) and thermodynamic methods (Dalton/Monteith) or a combination (Penman-Monteith) of them.[14]

For direct measurements, weighing lysimeters are the "state of the art" measurement device because they represent the closest to natural conditions. Due to the technical and financial effort of this method, it can not be used as a standard device and is limited to special scientific work. De Jong (2000) successfully used weighing micro lysimeters on the basis of standard electronic balances to investigate alpine evapotranspiration.

The indirect methods derive the evapotranspiration from the energy supplied by radiation and sensible heat (temperature). In simple empirical relations such as the Haude-equation,[15] only the vapour pressure deficit is taken as an indicator for the supplied energy and transformed into an evapotranspiration depth.

Water balance approaches give work for long term considerations. Also empirical approaches such as the widespread formula by Blaney and Criddle (1950) promoted by the FAO[16] are recommended for monthly time steps or longer. The work with higher temporal resolutions such as daily time steps or decades, requires a more detailed physical understanding of the processes as given by the Penman-Monteith (PM) equation explained below.

Originally Penman (1948) achieved a combination of the energy balance with an aerodynamic approach by:

$$ET = \frac{s_a}{s_a \gamma}(R_n - G) + (1 - \frac{s_a}{s_a \gamma})(e_{sat} - e_a) f(u) \tag{3.8}$$

where e_{sa} saturation vapour pressure for given air temperature

e_a vapour pressure at given air temperature

$f(u)$ wind function for vegetated surfaces:[17]

$$f(u) = 0.26 + 0.14 v_{2m}$$

v_{2m} wind speed at 2 m above surface.

14 A comprehensive overview and discussion of evapotranspiration is given in Schrödter (1985)
15 The Haude equation [Haude (1952)] is adapted to German logitude-latitute conditions and cannot be transferred to other climatological conditions (Schrödter 1985)
16 Irrigation and Drainage Paper No 24 and No 56
17 Wind function: Penman (1963)

To achieve a better understanding of the actual evapotranspiration process and to eliminate the empirical wind function, MONTEITH (1976) simulated vegetation by resistance networks. He introduced two resistance factors, surface resistance and aerodynamic resistance, to model the complex aerodynamics of a vegetated surface. Although this is a rather simple approach to the complexity of the aerodynamics of a vegetation, it reaches a good correlation between measured and calculated evapotranspiration rates, and the Penmann-Monteith-equation (PM) is the state of art for evapotranspiration.[18] In practical hydrology, the original PM-equation is modified to fit standard meteorological parameters. They result in different versions depending on the references.[19] A comparison of different versions is described in VENTURA (1999) where all used versions gave acceptable results, but the following FAO-PM version for short grass surfaces (reference evapotranspiration) performed best.

$$ET_0 = \frac{0.408\, s_a (R_n - G_d) + \gamma \dfrac{900}{T+273} v_{2m}(e_s - e_a)}{s_a + \gamma(1 + 0.34\, v_{2m})} \tag{3.9}$$

where	ET_0	reference evapotranspiration [mm d^{-1}]
	R_n	net radiation at the crop surface [MJ m^{-2} d^{-1}]
	G_d	soil heat flux density [MJ m-2 d^{-1}]
	T	mean daily air temperature at 2 m height [°C]
	v_{2m}	wind speed at 2 m height [m s^{-1}]
	e_s	saturation vapour pressure [kPa]
	e_a	actual vapour pressure [kPa]
	s_a	slope of vapour pressure [kPa °C^{-1}]
	γ	psychrometric constant [kPa °C^{-1}].

The equation (3.9) is used for the calculation of the reference evapotranspiration in this study.

The missing soil heat flux can be calculated according to SNYDER (2000) by:

$$G \approx C_V\, (T_{i+1} - T_i)\, V \tag{3.10}$$

18 ALLEN et al. (1998)
19 e. g.: DOORENBROS and PRUITT (1977), SHUTTLEWORTH (1992), ALLEN et al. (1998)

where G soil heat flux [J]

C_V heat capacity of soil [J m^{-3} K^{-1}]

T_{i+1} temperature at the end of the considered time interval [°C]

T_i temperature at the beginning of the considered time interval [°C]

V considered volume [m^3]

$$C_V = 837\rho_s + 4.19\times10^6\Theta_V \qquad (3.11)$$

where ρ_s soil density [kg m^{-3}]

(estimated at 1300 kg m^{-3})

Θ_V volumetric water content [m^3 m^{-3}]

The gradient of the temperature profile was calculated by linear regression and the estimated temperature at 10 cm depth was considered representative for the upper cubic meter soil. In average the soil heat flux is 9.7 % of the net radiation which was found in good agreement with other sources. VENTURA (1999) estimated the soil heat flux at approximately 10 %.

3.3.2 The Concept of Crop Evapotranspiration Coefficients

The reference evapotranspiration is, as mentioned above, a concept to determine the conversion of energy into millimeters of vaporised water under standardised conditions. The advantage is a spatially comparable computation of reference values, but no adaptation to the local conditions. It was DOORENBROS's and PRUITT 's (1977) achievement to bring up a generalised concept of correcting reference evapotranspiration (ET_0) to specific crops and climatic conditions by introducing the crop coefficient k_c.

$$ET_c = k_c \cdot ET_0 \qquad (3.12)$$

The crop evapotranspiration ET_c describes the crop water requirements defined as the water consumption under optimal agricultural conditions for the particular crop.[20] The coefficient k_c depends on the crop type and changes with the time due to the crop growing stages. With respect to the environmental and climatological influences of where this optimal conditions are not available, ALLEN et al. (1998) improved the empirical relation of k_c by various environmental and management conditions. In particular, he introduced a more physical approach by splitting of the crop coefficient k_c into a transpiration component and an evaporation component to distinguish between the different processes:

$$k_c = k_{cb} + k_e \tag{3.13}$$

The coefficient k_{cb} represents the transpiration component (basal crop coefficient) while the coefficient k_e represents the evaporation coefficient. The product of the basal crop coefficient with the reference evapotranspiration $k_{cb} \cdot ET_0$ delineates the transpiration component under optimal conditions. It represents the case of the top soil being dry but transpiration not being limited by water supply. Therefore the basal crop coefficient includes a residual evaporation component from the soil evaporation nearest to the vegetation. The product of the evaporation coefficient with the reference evapotranspiration $k_e \cdot ET_0$ describes the evaporation component. The process of soil evaporation from bare soil is generally described in chapter 3.3.3.3. If the surface is partly covered with vegetation, only the non-vegetated proportion has to be taken into account.

The current study follows the concept represented by ALLEN et al. (1998) and DOORENBROS and PRUITT (1977). But while the original concept of the crop evapotranspiration was intended to calculate the irrigation demands, it is modified here. The water harvesting component is added to evaluate the effect of different runoff–runon relations. It is used as a non-calibrated model for the evaluation of the water harvesting effect and other agricultural measures.

20 ALLEN et al.(1998): The crop evapotranspiration under standard conditions, denoted as ET_c, is the *a disease-free crop, well-fertilized crop, grown in large fields, under optimum soil water conditions. and achieving full production under the given climatic contitions.*

The general concept of the crop evapotranspiration is depicted in figure 3.2. It follows a 3-step procedure:

1. Determination of the "reference evapotranspiration" which defines a standard for the evapotranspiration measurement. It makes the evapotranspiration of different regions comparable to each other.
2. The adaptation to different crops under the local climatic conditions with the prerequisite of optimal water supply and soil and fertility conditions.
3. The implementation of restrictions caused by limited water supply (water stress) and other environmental constrains. Incorporation of the water harvesting effects.

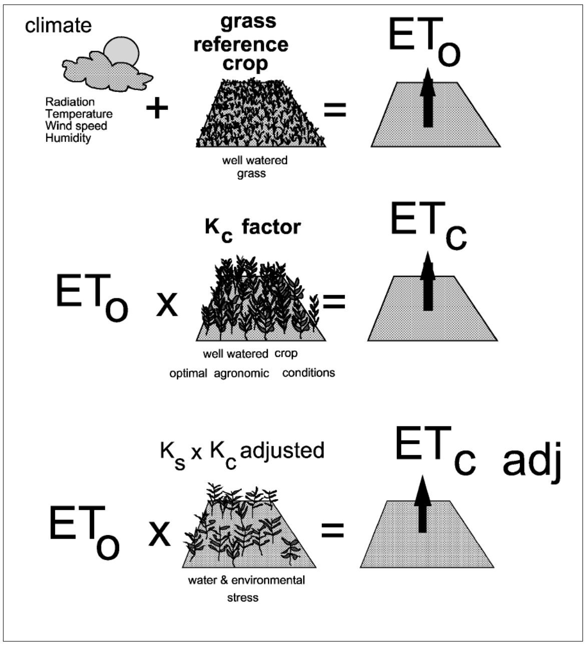

Figure 3.2 Crop evapotranspiration [adapted from A*LLEN et al. (1998)]*

This procedure permits a careful adaptation of the calculation model to the local conditions. The single crop coefficient is used for the general water requirements calculation of sorghum which is compared with the Ta'izz precipitation data. The dual crop coefficient is used on a daily basis to incorporate the effect of individual rainfall events and is applied to model the actual water requirements on the basis of the Mia'amirah data of 1998.

3.3.3 Determination of the Crop Coefficients

The crop coefficient reflects the water requirement of the considered crop species under the given climatic, environmental and management conditions. It covers transpiration as well as evaporation and changes over time due to the crop development during the growing season. The result is in the 1st step a semi-potential water demand function. It reveals the water requirements with respect to the local climatic conditions but ignores the actual supply by rain or irrigation. Hence the result is a time dependent water demand function which can be compared with the actual supply by precipitation with and without water harvesting. This comparison between supply and demand allows to pinpoint the phases of insufficient water supply.

The crop type affects the crop coefficient by differences in the albedo and leaf area as well as in the aerodynamic properties. Sorghum can have a 15-20 % higher ET_c as the reference grass due to the larger leaf area index (LAI).

Further impact on the crop coefficients is given by the agricultural management. Row spacing as well as the local measures thinning and leaf picking described in chapter 4.4 earn special attention. These measures affect the crop coefficient during all growing stages, depending on when they are performed. It is assumed that the impact of the measures is proportional to the biomass/LAI reduction.

3.3.3.1 Crop Growing Stages

The crop growing stages have strong influence on the crop coefficient. They change over time most strongly for annual crops. The annual crop development splits into four stages: initial, crop development, mid-season, late season. For each stage the crop coefficient will be calculated separately. The length should be achieved from local field investigation, but there are also tables available.[21]

Initial Stage

The initial stage starts at planting date and runs until approximately 10 % ground cover. ET_c resembles the evaporation from a bare soil surface (E_S), since the leaf area is not developed and the k_c differs most strongly during this time, depending on the surface wetting conditions.

Development Stage

The crop development stage starts at approximately 10 % ground cover until the leaf area effectively covers the ground. This stage is difficult to detect. For row crops such as sorghum it can be defined when the leaves of adjacent rows overlap entirely and the ground is completely shaded. This occurs with tall crops as sorghum at approximately 75 % of the full plant height. The increase of k_c is linear until the mid-season stage if no intervention like leaf picking or thinning takes place.

21 e. g. Doorenbros and Pruitt (1977), Allen et al. (1998)

Mid-Season Stage

The mid-season stage starts from effectively full ground cover and ends at the beginning of maturity. The crop evapotranspiration is, due to the fully developed crop, constantly high around the reference evapotranspiration. Consequently, k_c is approximately 1. As mentioned before, it can exceed 1 if the crop is significantly larger (like sorghum) than the reference crop.

Late Season

The late season stage starts at the beginning of maturity until the harvest or full maturity. It is assumed that the plants dry out naturally and k_c decreases linearly. This is not the case for robust crops like sorghum which keeps alive if climatic conditions are met.[22] In this case the crop evapotranspiration depends, like in the initial stage, on the water supply.

3.3.3.2 Climate

The values of the crop coefficients (k_c, k_{cb}) tabulated for different crops in DOORENBROS and PRUITT (1977) or ALLEN et al. (1998) refer to a sub-humid ($RH \approx 45$ %) climate with moderate wind speed (≤ 2 m/s). Especially in arid climate with high, strongly variable vapour deficits and higher wind speed the crop evapotranspiration can increase up to 30 %. Oases' effects on irrigated fields can also increase the ET_c considerably. If the standard conditions are not met, they can be adjusted for the mid season by the empirical equation which can be used for the single and the basal crop coefficient.

$$k_{c\,mid} = k_{c\,mid\,(Tab)} + \left[0.04(v_2 - 2) - 0.004(RH_{min} - 45)\right]\left(\frac{h}{3}\right)^{0.3} \tag{3.14}$$

where	$k_{c\,mid\,(Tab)}$	values for $k_{c\,mid}$ and $k_{cb\,end}$ from table 3.1 (can be replaced by the basal crop coefficient k_{cb})
	v_2	daily mean wind speed at 2 m over grass during mid-season or late season growing stage [m s^{-1}],
	RH_{min}	mean value for daily minimum of relative humidity during mid-season or late season growth stage [%],
	h	mean plant height during mid-season stage [m]

22 personal communication: Dr. Hoffmann-Bahnsen Feb. 2000

Table 3.1 Single and basal crop coefficients for sorghum [Doorenbros and Pruitt (1977), Allen et al. (1998)]

	Single crop coefficient			***Basal crop coefficient***		
Stage	***Coefficient***	***Sorghum (sweet)***	***Sorghum (grain)***	***basal coefficient***	***Sorghum (sweet)***	***Sorghum (grain)***
Initial	$k_{c\ ini}$	0.3	0.3	$k_{cb\ ini}$	0.15	0.15
Mid-season	$k_{c\ mid}$	1.2	1.0 – 1.1	$k_{cb\ mid}$	1.15	0.95 – 1.05
Late season	$k_{c\ end}$	1.05	0.55	$k_{cb\ end}$	1.0	0.35

3.3.3.3 Soil Evaporation

The soil evaporation occurs predominantly during the initial phase when the vegetation cover is sparse. Estimating the influence of evaporation from the bare soil requires information on the soil and the soil water balance. Soil water is supplied to the soil surface by capillary rise. This process is affected by the soil texture. Coarse texture reduces capillary forces. Although capillary rise can withdraw water from significant depths, only the upper 0.1 m of soil is normally involved. After rainfall events the top soil is wet, sometimes above field capacity, and the evaporation process is only limited by the available energy until the soil visibly dries up.[23] The evaporation depth at this stage is named “readily evaporable water” (*REW,* see figure 3.3). The value of *REW* depends on texture and bulk density of the top layer. At the turning point, the falling rate starts and evaporation decreases proportionally to the remaining water content in the top soil layer. The total evaporable water *TEW* is the maximum that can be evaporated from the soil. It is defined as the amount of water between field capacity Θ_{FC} and 0.5 Θ_{WP}.[24]

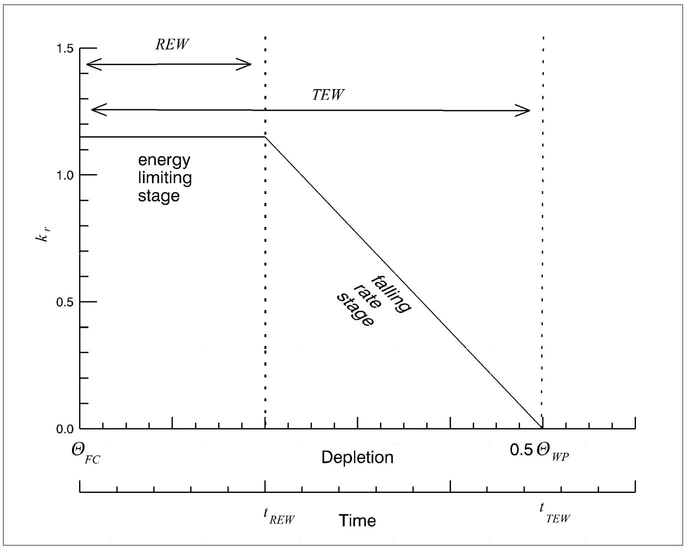

Figure 3.3 Soil evaporation reduction after precipitation events [adapted with changes from Allen et al. (1998)]

23 The evaporation coefficient k_r on bare wet soil is estimated at 1.15 due to the albedo of bare soil being lower than that of the reference grass surface.

24 $0.5\Theta_{WP}$ is halfway between wilting point and oven dry.

$$TEW = 1000(\Theta_{FC} - 0.5\,\Theta_{WP})\,Z_e \qquad (3.15)$$

where TEW total evaporable water [mm]

Θ_{FC}. soil water content at field capacity [1]

Θ_{WP}. soil water content at wilting point [1]

Z_e depth of soil which can be dried by evaporation [m] (approx. 0.2 m)

The linear decline of the k_r for the case $D_e > t_{REW}$ can be derived if REW and TEW are known. k_r can be calculated by transforming the straight line equation into:

$$k_r = \frac{E_S}{E_{SO}} = \frac{TEW - D_{e,i-1}}{TEW - REW} \qquad (3.16)$$

where k_r evaporation reduction coefficient [1]

E_S evaporation from bare soil [mm]

E_{SO} maximum evaporation from soil surface (= 1.15 ET_0) [mm]

TEW total evaporable water [mm]

$D_{e,i-1}$ depletion or cumulative evaporation depth at the beginning of the considered time step [mm]

REW readily evaporable water, maximum amount of water that evaporates at full potential [mm].

For computing purposes it is better to express k_r as a function of time than as a function of the water content. D_e gets replaced by the equivalent t, and the function becomes integrated over time:

$$k_r = \frac{TEW - (TEW - REW)\exp\left(\dfrac{-(t - t_{REW})\,E_{SO}\left(1 + \dfrac{REW}{TEW - REW}\right)}{TEW}\right)}{t\,ET_0} \qquad (3.17)$$

where t time of computed k_r

Equation (3.17) is used with the dual crop coefficient. For the single crop coefficient averaged for decades a generalisation becomes necessary. It is only applied to the initial growing stage where bare soil conditions are most likely. For the energy limiting stage ($t < t_{REW}$) $k_r = k_{c\ ini} = 1.15$, where t_{REW} can be described by

$$t_{REW} = \frac{REW_{cor}}{E_{SO}} \tag{3.18}$$

where REW_{cor} corrected readily evaporable water, explained below.

For $t > t_{REW}$ a modified version of equation (3.17) needs to be applied if the precipitation during the considered stage is not sufficient to completely wet the top soil layer. This is the case if the average time between rainfall events $t_{P\ gs}$ during the considered growing stage is larger than the potential of t_{REW}. Then the evaporation process stops sooner. For this case REW and TEW need to be corrected by using the expressions REW_{cor} and TEW_{cor}. which reflect also the case of $P_{mean} < REW$.

$$TEW_{cor} = min\left(TEW\,, P_{mean} + \frac{W_{gs}}{n_{P\,gs}}\right) \tag{3.19}$$

$$REW_{cor} = REW\left[\min\left(1\ ,\ \ P_{mean} + \frac{W_{gs}}{n_{P\,gs}}\right)\right] \tag{3.20}$$

where P_{mean} mean precipitation for the considered growing stage [mm]

W_{gs} initial water content in the beginning of the growing stage gs [mm]

$n_{P\ gs}$ number of rainfall events during growing stage gs [1]

Using the modified values from equation (3.19) and (3.20) the condition $t_{REW} \geqslant t_{P\,gs}$ will be considered, and $t_{P\ gs}$ is defined as

$$t_{P\,gs} = \frac{L_{gs}}{n_{P\,gs} + 0.5} \tag{3.21}$$

where: t_P average time between precipitation events

L_{gs} length of growing stage period

n_P number of rainfalls during period

3.3.3.4 Water Stress Conditions

The crop coefficient k_c computed above assumes optimal or standard growing conditions which are not always available. Soil fertility can be limited and salinity affects crop development and yield. None of these factors are considered in the current study. Another constrain is water stress which limits crop development. This is the common case under the given conditions and the reason why measures like water harvesting are established. Water stress is expressed by the water stress coefficient k_s.

$$ET_{c\,adj} = k_s \cdot k_c\, ET_0 \tag{3.22a}$$

$$ET_{c\,adj} = (k_s \cdot k_{cb} + k_e)\, ET_0 \tag{3.22b}$$

The use of the dual crop coefficient should be preferred because water stress is only related to the transpiration process. Therefore equation (3.22b) is more precise than equation (3.22a).

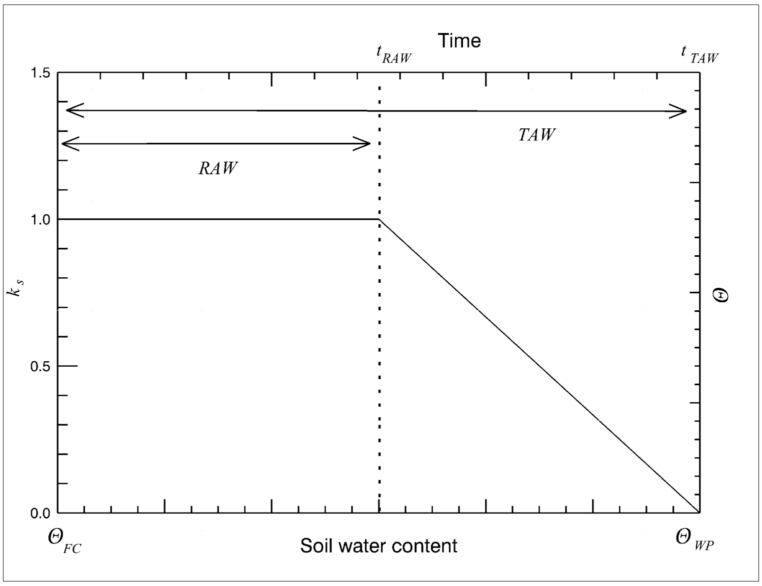

Figure 3.4 Water stress coefficient ks [adapted with changes from A*LLEN* *(1998)]*

The concept is similar to the soil evaporation described in chapter 3.3.3.3 and confusion with the terminology should be avoided. The water uptake by the root system is at full potential if the water content of the soil is close to field capacity. If the water content falls below a certain plant specific threshold Θ_{RAW}, water withdrawal by the plant decreases until the water content drops below the wilting point Θ_{WP}. Below the wilting point no extraction by plants is possible (see figure 3.4).

Hence the water stress coefficient k_s is 1 for $D_r < RAW$ and decreases if $D_r > RAW$:

$$k_s = \frac{TAW - D_{r,i}}{TAW - RAW} = \frac{TAW - D_{r,i}}{(1 - p_{RAW})TAW} \tag{3.23}$$

where k_s water stress coefficient [1],

TAW total available water (defined below) [mm],

$D_{r,\,i}$ depletion of the root zone at a certain time i (defined below) [mm]

RAW readily available water (defined below) [mm]

p_{RAW} proportion of TAW that can be extracted from the root zone without water stress [1].

The total available water (TAW) is defined as the amount between field capacity and wilting point:

$$TAW = 1000(\Theta_{FC} - \Theta_{WP}) Z_r \tag{3.24}$$

where TAW total available water [mm],

Θ_{FC} water content at field capacity [m^3/m^{-3}]

Θ_{WP} water content at wilting point [m^3/m^{-3}]

Zr rooting depth [m]

The readily available water (RAW) is defined as the proportion which can be withdrawn by the plants at full transpiration rate:

$$RAW = p_{RAW}\, TAW \tag{3.25}$$

Values for p_{RAW} can be found tabulated in ALLEN et al. (1998), sorghum is estimated at 0.5 (sweet) – 0.55 (grain).

For the determination of $D_{r,i}$ the soil water balance must be calculated from the in and out flows:

$$D_{r,i} \;=\; D_{r,i-1} - (P_i + P_{WH,i} - Q_i) - CR_i + ET_{c,i} + DP_i \tag{3.26}$$

where $D_{r,i}$ depletion of the root zone at the end of time step[25] i [mm],

$D_{r,i-1}$ depletion of the root zone at the end of the previous time step i-1 [mm],

P_i precipitation during time step i [mm],

25 time step used : days

P_{WHi}	additional precipitation from water harvesting during time step i [mm],
Q_i	runoff during time step i [mm]
CR_i	capillary rise during time step i [mm]
$ET_{c,i}$	crop evapotranspiration during time step i [mm]
DP_i	deep percolation during time step i [mm]

3.3.4 Construction of the Crop Coefficient Curve

The construction of crop coefficients follows the scheme in figure 3.6. First the the length of growing stages will be determined. If the single crop coefficient is used, the k_c-values for initial growing season, mid-growing season and late growing season will be selected from k_c-tables and then adjusted to the local growing conditions. And finally the k_c-curve will be constructed.

For the dual crop coefficient the procedure is somewhat different. After the selection of the length of the growing stages the k_{cb}-values for initial growing season,mid-growing season and late growing season will be selected from the k_{cb}-tables. The adjustment to the local growing conditions is based on the field investigations.

After determination and computation of the k_c values the crop coefficient curve can be constructed by linking the k_c-values of the different growing stages as shown in figure 3.5. The curve represents the change of k_c over time reflecting the effects of the different growing stages. For the dual crop coefficient the k_{cb}-curve will be constructed instead of k_c. Then the course of the k_{cb}-curve will be modified by modulating (adding) the k_e-values to it.

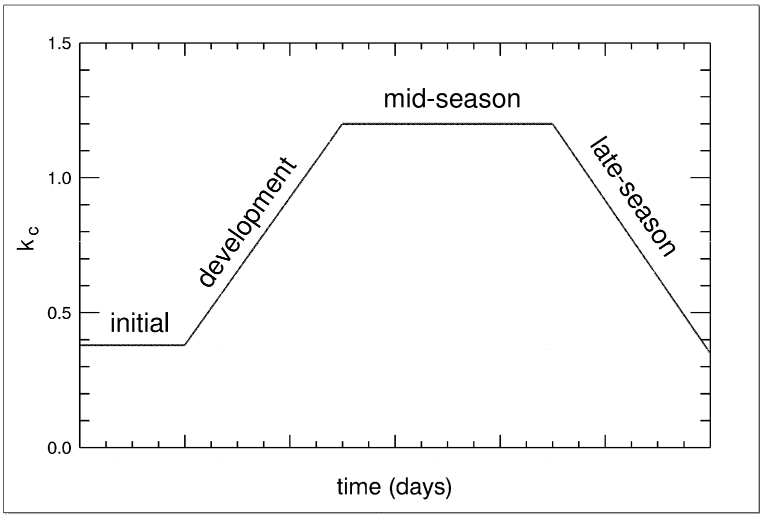

Figure 3.5 Scheme of the k_c-course in different gowing stages

The differences between k_c and k_{cb} are significant mainly in the initial phase where the evaporation is the dominant process. It decreases during the development stage and became little in the mid- and late season.

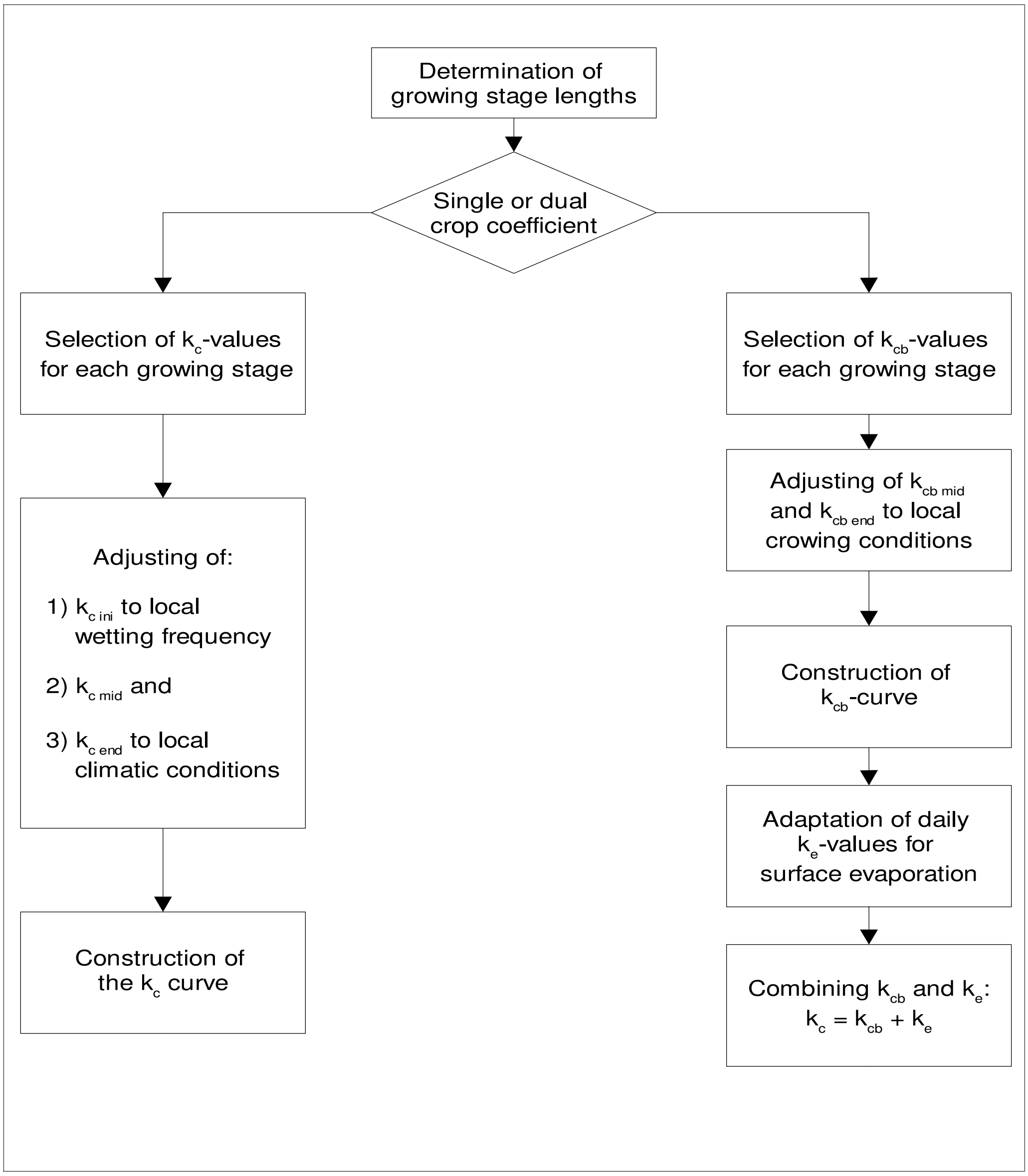

Figure 3.6 Workflow for the determination of ET_0