Crop Water Requirement Assessment and Annual Planning of Water Allocation

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Crop Water Requirement Assessment and Annual Planning of Water Allocation

By

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Abstract

The potential of remote sensing data in water resource and in particular in irrigation management has been widely acknowledged. However, in reality, operational applications of remote sensing in irrigation management are few. In this study, the applicability of the main available remote sensing based techniques of irrigation management was evaluated in a pilot area in Iran. The evaluated techniques include so called Crop Water Requirement "CWR" methods for the planning of annual water allocation in irrigated agriculture.

A total of 45 years of historical weather data were classified into wet, normal, and dry years using a Standardised Precipitation Index (SPI). For each of these three classes the average reference evapotranspiration was calculated. Next, by applying Markov Chain Process to the time series of precipitation, the expected CWR for the forthcoming planning year was estimated. Using proper interpolation techniques the expected reference evapotranspiration at each station was converted to reference evapotranspiration maps of the area, which were then used for annual water allocation planning.

To estimate the crop water requirement, methods developed for the DEMETER project (DEMonstration of Earth observation Technologies in Routine irrigation advisory services) and Surface Energy Balance System "SEBS" algorithm were used, and their results were compared with conventional methods, including FAO-56 and lysimeter data amongst others. Use was made of both ASTER and MODIS images to determine crop water requirement at local and regional scales. Four methods of estimating crop coefficients were used: DEMETER K_c-NDVI, DEMETER K_c-analytical, FAO-56 and SEBS algorithm.

Results showed that DEMETER (analytical approach) and FAO methods with lowest RMSE are more suitable methods for determination of crop coefficient than SEBS, which gives actual rather than potential evapotranspiration. The use of ASTER and MODIS images did not result in significantly different crop coefficients in the pilot area for the DEMETER analytical approach ($\alpha=0.05$). This is promising, as it implies that MODIS can be used for determination of CWR at regional "water user association" level. Sensitivity analysis of crop coefficient to crop height, leaf area index, incoming shortwave radiation, wind speed, relative humidity and temperature was carried out as well. The results showed that the crop coefficient is sensitive to (in order of most to least sensitive), temperature, leaf area index, incoming shortwave radiation and relative humidity, wind speed and crop height. Comparison between the planned values of crop water requirement and the realised values in 2004 were not significantly different ($\alpha=0.05$).

Key words: Water allocation planning, Crop coefficient, DEMETER, SEBS, SPI drought index, Irrigation management

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1. Introduction

The continuing growth of world population places new demands on water resources every day. Improved management and planning of water resources are needed to ensure proper use and distribution of water among competing users. Fortunately, there are opportunities for conservation and significantly more effective use of water use by the world's largest user, agriculture. Accurate planning and delivery of the necessary amount of water in time and space can conserve water (Bos et al., 2009). In this context, methods to quantify accurate irrigation water requirement play a key role in the conservation and management of water resources. Planning and management of water use by agriculture are especially important in an arid and a semi-arid climate. Understanding the crop water requirement, use and consumption in irrigated agriculture is a prerequisite for better management and conservation of agricultural water.

1.1. General problem statement

Iran is an arid country and lack of proper planning and management on water resources has caused the country to face water crises. Agriculture is the main user of water in Iran. One of the most important component in the water balance is evapotranspiration (ET) (Dingman, 2002). In 1996 the Iranian government developed the Iranian Water Directive "IWD" (NETwat) for all basins in the Iranian territory. In this document has calculation of ET is based on the average meteorological data and some standard FAO parameters (Alizadeh and Kamali, 2007). The implementation of this method has not been successful due to a number of major shortcomings, including:

- Lack of adaptation of some parameters in CWR, such as crop coefficient (Kc), to local conditions
- Using fixed amount of crop water requirement for every year (dry, wet & normal years)
- No consideration of CWR distribution in space all over the basin
- Using one meteorological station as a reference station for the whole basin

As Iran is a large country (632 basins) also in practice (on farm) correction and improving accuracy of IWD is difficult and expensive. Remote sensing technology is a promising tool to overcome these problems. However, timely access to high resolution images in this country is difficult and expensive.

1.2. Research objective and questions

1.3. General objective

The aim of the research is to develop a method to determine crop water requirement based on remote sensing for water allocation planning.

1.4. Specific objectives

The primary objectives will be achieved through the following sub-objectives:

- To generate climatic scenarios (categorize years in wet, normal and dry years)
- To calculate and analyze crop factors (K_c) derived with different methods & at different scales (FAO and remote sensing based)
- To calculate and analyze crop water requirement for different scenarios
- To explore the applicability of remotely sensed based crop K_c for practical water allocation planning.

1.5. Research questions

The following research questions are formulated to achieve the above objectives:

- What are the climatic scenarios and how can they be defined?
- Which method of crop coefficient estimation is most appropriate for determining crop water requirements?
- Are there differences between crop water requirements in different scenarios?
- What are the relations between K_c calculated at different scales (MODIS and ASTER)?
- Could remote sensing technology improve the processes of planning for annual water allocation at each delivery points (gates)?

1.6. Hypothesis

In order to accomplish the objectives and research questions, the following hypotheses have been formulated:

- The existing assessment of crop water requirement can be improved through remote sensing technology.
- Low resolution satellite data can be used for estimation of CWR.
- Crop coefficient is trait of crops (Figure 1.1)

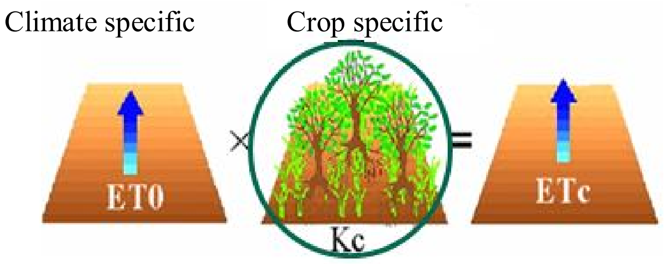


Figure 1.1 Process of crop water requirement

- Determination of crop water requirement based on average historical meteorological data is far from reality of each year and, derivation of CWR for wet, normal and dry year will improve the estimates of CWR.

1.7. Organization of the thesis

This thesis is organized in seven chapters. The overview of chapters is as follows:

Chapter 1 contains introduction, problems, objectives and research questions.
Chapter 2 includes literature review and on the background of crop water requirement planning in Europe.
Chapter 3 describes the study area in detail, including climate, land cover and topography of the pilot area.
Chapter 4 includes material and applied methods.
Chapter 5 illustrates the results of applying different methods of calculating K_C and ET at different scales and scenarios.
Chapter 6 presents conclusions, recommendations and limitations of the study.

2. Literature review

2.1. Introduction

The potential application of remote sensing in water resource and in particular in irrigation management has been widely acknowledged by several authors, and several algorithms for deriving various related biophysical and climatic parameters have been successfully tested in different environments (Baret et al., 2007,; Bausch, 1995; Choudhury et al., 1994, ; Neale et al., 1989). However, the real applications of remote sensing in the actual operation of irrigation management are few. In this line one of the examples is the project DEMETER (DEMonstration of Earth observation Technologies in Routine irrigation advisory services) which has been dedicated to assess introduction of remote sensing and information technology in the actual irrigation management. Several other algorithms have been developed to estimate the crop water requirements in time and space based on remotely sensed data too. In this line one of the advanced and more referenced is Surface Energy Balance System “SEBS” algorithm developed by Su (2002). In this research the applicability of these two models (DEMETRE & SEBS) have been evaluated and tested for the actual planning of irrigation management in a pilot area. In this chapter the two above mentioned models are described.

2.2. DEMETER

The DEMETER project was carried out to demonstrate the applicability of earth observation data in routine irrigation management at field level. The project, funded by European Union, was carried-out from 2003 to 2005 in three irrigated areas in Spain, Italy and Portugal and further extended to other areas within the PLEIADS project (D’Urso et al., 2007). During 2006 and 2007, the procedure has been implemented operationally in two irrigation district in Campania Region in Italy. In this project crop water requirement under non-stressed conditions has been calculated in time and space based on crop coefficient, K_c values which have been derived through application of the following two procedures.

Crop coefficient is a ratio between the specific crop actual ET under standard condition and a reference crop ET. Crop type, climate, soil evaporation and crop growth stages are factors that affect K_c. The crop coeffiecient K_c can be calculated in two forms: single K_c and dual K_c. In a single K_c-approach, a single, constant value for the crop factor is used for crop and soil together. In the dual K_c approach, separate factors are used for the soil, K_e, and the crop, K_{cb}. The basal crop coefficient K_{cb} is defined for different stages of growth ($K_{cb\ ini}$, $K_{cb\ mid}$, $K_{cb\ end}$). Crop coefficients can be estimated applying different types of method, mainly: conventional and remote sensing based methods.

2.2.1. “K_c-NDVI” approach

The foundations of this procedure are:

- NDVI and green fractional cover have a linear relationship (Calera et al., 2001)
- NDVI and the basal crop coefficient have linear relationship(K_{cb}) (Bausch and Neale, 1987)

In the DEMETER project crop coefficients has been calculated in dual ($K_c = K_{cb} + K_e$) and single forms.
Where K_{cb} is basal crop coefficient and K_e is soil water evaporation coefficient.

2.2.1.1. Dual crop coefficient NDVI approach

In the dual crop coefficient approach, the effects of crop transpiration (K_{cb}) and soil evaporation (K_e) are estimated separately. K_{cb} is estimated based on the assumed linear relationship between normalized NDVI and K_{cb}. The normalized NDVI is the NDVI scaled by the range between the maximum and minimum NDVI, derived from satellite images. The corresponding minimum and maximum K_c–values are taken from standard FAO tables, and stretched over the normalized NDVI range.

Soil evaporation is strongly varies with the soil moisture content. The irrigation system (gravity, sprinkler, drip, etc), the irrigation frequency, and the exposure of the soil to sunlight (which depends on the type and growth stage of crop) also affect soil evaporation (Calera and Jochum, 2005). In this procedure, K_e is estimated based on equation 2.1. Calera et al. (2001) use NDVI as a proxy for ground fractional cover, f_c, and therefore for the bare soil fraction, $1-f_c$. The other fractions are parameterized by β, which is crop and development stage dependent:

$$K_e = (1-f_c)*\beta \qquad (2.1)$$

β is crop dependent and empirically estimated from K_c of a crop and usually is taken as 0.25. Furthermore, a relationship between NDVI derived satellite and f_c is used (Calera and Jochum, 2005).

2.2.1.2. Single crop coefficient NDVI approach

This method is similar to the dual crop NDVI approach, but with a single crop coefficient for crops and soil together. A linear relationship between NDVI derived from remote sensing and K_c derived from a field experiment or from FAO tables is established. The maximum and minimum K_c values are attributed to the maximum and minimum NDVI, and K_c for intermediate values of NDVI are interpolated between these two points (Gilabert et al., 1996).

2.2.2. “K_c-analytical” approach

The second procedure, named “Kc-analytical”, is based on the direct application of the Penman-Monteith equation with crop characteristics estimated from satellite images, in analogy to the direct calculation proposed by FAO (D’Urso et al., 2007).

$$K_c = \frac{E_p\left(r_c = r_{c\min}\right)}{E_{ref}} = \frac{\left[s\left(Q^* - G\right) + c_p \rho_a \frac{\left(e_s - e_a\right)}{r_{a,H}}\right]\left[s + \gamma\left(1 + 0.34U\right)\right]}{\left[s\left(0.77K\downarrow + L^* - G\right)\right) + \gamma \frac{0.014\gamma\lambda}{Ta + 273.3} U\left(e_s - e_a\right)\right]\left[s + \gamma\left(1 + \frac{r_c}{r_{a,H}}\right)\right]} \tag{2.2}$$

Q^*	net radiation flux density (MJ m^{-2} day^{-1}),
L^*	net long-wave radiation flux density
G	soil heat flux density (MJ m^{-2} day^{-1}),
e_s	saturation vapour pressure (kPa),
e_a	actual vapour pressure (kPa),
e_s - e_a	saturation vapour pressure deficit (kPa),
c_p	air specific heat (J $kg^{-1}K^{-1}$)
ρ_a	air density (kg m^{-3})
s	slope vapour pressure curve (kPa $°C^{-1}$),
γ	Psychometric constant (kPa $°C^{-1}$)
$r_{a,H}$	aerodynamic resistance for heat transport (s m^{-1})
r_c	canopy resistance (s m^{-1})
U	wind speed (m s^{-1})
λ	evaporation heat of water (J kg^{-1})
K	incoming shortwave radiation (MJ m^{-2} day^{-1})
Ta	air temperature (°C)

In this equation the canopy characteristics are crop height, h_c, leaf area index, LAI, and surface albedo, r, that are derived from satellite images. Climatic data are wind speed, U, relative humidity, RH, air temperature, T_a and incoming shortwave radiation, $K\downarrow$.

The procedure for deriving the K_c map is based on the concept presented in Figure 2.1 and includes the following steps:

1. Deriving canopy geometrical characteristics from at-surface spectral data.

- Deriving LAI by using formula 2.3:

$$LAI = -\frac{1}{0.42}\ln(1 - \frac{WDVI}{0.51}) \tag{2.3}$$

LAI is used later for the calculation of G (Eq 2.8)

Weighted Difference Vegetation Index (WDVI)

$$WDVI = \rho_i - \rho_r \frac{\rho_{si}}{\rho_{sr}} \tag{2.4}$$

ρ_i, ρ_r: are reflectance's of canopy in the infrared and red bands

ρ_{si}, ρ_{sr} : are reflectance's of bare soil in the infrared and red bands

- Deriving aerodynamic resistance from crop high

$$r_{a,H} = \frac{In\left(\frac{Z_U - 0.667h_c}{0.123h_c}\right) In\left(\frac{Z_T - 0.667h_c}{0.0123h_c}\right)}{0.168U_Z} \quad (2.5)$$

- Z_U,Z_T: are the measurement heights for wind-speed and temperature, and U_Z is the wind speed
- Deriving canopy resistance

$$r_{c,\min} = \frac{r_{leaf\,\min}}{LAI_{eff}} \quad (2.6)$$

$r_{leaf,min}$: minimum stomata resistance based on Allen et al. (1998) it is assumed to be 100 sm^{-1} and effective LAI, “LAI_{eff}”, is assumed to be equal to 0.5 LAI_{max} .

2. Deriving net radiation

After deriving albedo with using proportionate formula with satellite images, net radiation is derived from equation 2.7 (Jensen et al., 1990). In this equations L^* is calculated from $K\downarrow$, T_a and e_a.(Allen et al., 1998):

$$Q^* = (1-r)K \downarrow + L^* \quad (2.7)$$

r is surface albedo,

Choudhury et al. (1987) found empirical following formula:

$$G = C_G(-\beta LAI)Q^* \quad (2.8)$$

Where the parameter $C_G \in [0.3; 0.4]$ represents the ratio G/Q* for bare soil surfaces; β is an extinction coefficient that can be taken equal to 0.5. (Calera and Jochum, 2005) state that its value varies with canopy geometry and solar zenith angle.

3. Climatic data gathering

Finally, K_c is calculated using equation (2.2) for a map, which is assumed to be valid for 10 days around the date of image acquisition.

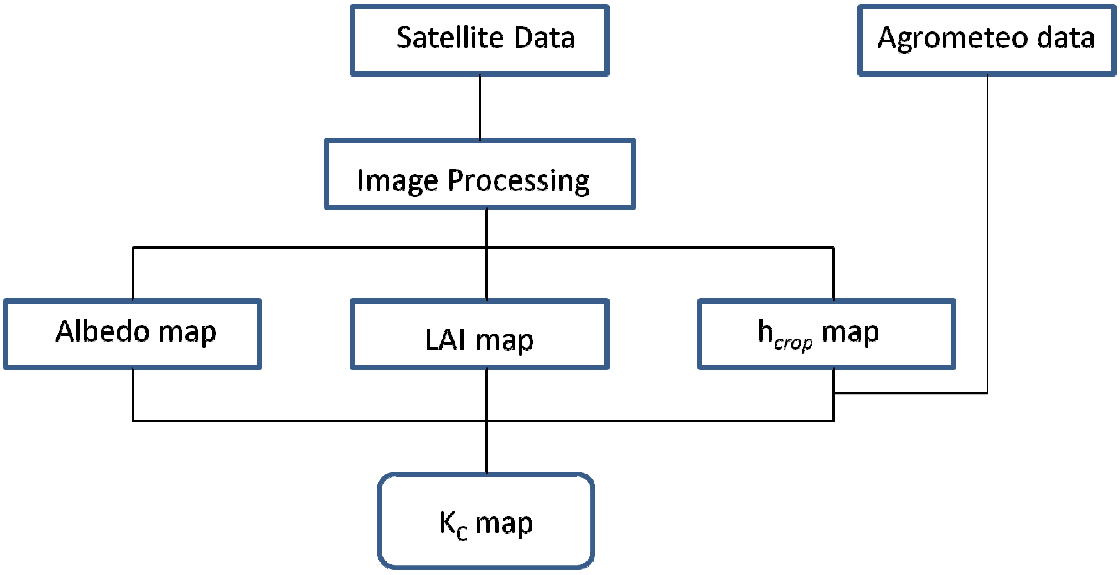


Figure 2.1 Conceptual model of the analytical approach crop coefficients

2.3. SEBS algorithm

(Oke, 1987) defined surface energy balance models as models that "simulate micro scale energy exchange processes between the ground surface and the atmospheric layer near the ground level". The general surface energy balance can be summarized as:

$$R_n = G + H + \lambda E \tag{2.8}$$

Where R_n is net radiation at the surface (W m^{-2}), λE is Latent heat flux (energy consumed by evapotranspiration, i.e. energy used in a phase change of water) (W m^{-2}), G is ground heat flux (W m^{-2}) is the energy used to warm the subsurface of the Earth, H is sensible heat flux (W m^{-2}), the heat transferred between the surface and air by turbulence. The Surface Energy Balance System (SEBS) is one of several surface energy balance remote sensing based models for determination of pixel wise evapotranspiration (Su, 2002). SEBS was developed for the estimation of surface heat fluxes using satellite earth observation data in combination with routinely available meteorological data. SEBS requires as inputs three sets of data:

1. Remote sensing data: albedo, emissivity, NDVI and land surface temperature.
2. Ground meteorological data: Air pressure, temperature, humidity and wind speed at the reference height.
3. Downward solar radiation and long wave radiation

2.3.1.1. Net radiation

Net radiation on any point of earth surface calculated from the following formula:

$$R_n = (1-\alpha)\,k\downarrow + \varepsilon.L\downarrow - L\uparrow \qquad (2.9)$$

Where: α is albedo, $K\downarrow$ is downward solar radiation (W m^{-2}) measured, ε is surface emissivity, $L\downarrow$ is downward long wave radiation (Wm^{-2})

$L\downarrow = \sigma.\varepsilon_a.Ta^4$

Where

σ is the the Stefan Boltzmann constant ($5.67x10^{-8}$ $Wm^{-2}K^{-4}$), T_a is air temperature at reference height (K), and ε_a the emissivity of the standard atmosphere (Champbell and Norman, 1998):

$$\varepsilon_a = 9.2 * 10^{-6}(T_a + 273.15)^2 \qquad (2.10)$$

$L\uparrow$is outgoing long wave radiation

$$L\uparrow = \varepsilon_s.\sigma.T_S^{\ 4} \qquad (2.11)$$

ε_s is surface emissivity and T_S is surface temperature (K).

2.3.1.2. Surface albedo

Liang (2002) developed an empirical equation to convert narrow bands to broad bands albedo. The empirical relationships for ASTER and MODIS are shown in the following equations:

$$Albedo_{ASTER}=0.484r_1+0.335r_3-0.324r_5+0.551r_6+0.305r_8-0.367r_9-0.0015 \qquad (2.12)$$

$$Albedo_{MODIS}=0.160r_1+0.291r_2+0.243r_3+0.116r_4+0.112r_5+0.018r_7-0.0015 \qquad (2.13)$$

r_x : Reflectance corresponding different bands

2.3.1.3. Soil heat flux

Su (2002) assumed there is linear relationship between soil heat flax and net radiation. In the model SEBS calculation of soil heat flux is carried out based on fractional vegetation cover and net radiation.

$$G = R_n[\Gamma_c + (1-f_c)\times(\Gamma_s - \Gamma_c)] \qquad (2.14)$$

were

f_c is the fractional vegetation cover, Γ_c is an empirical constant related the ratio of soil heat flux to net radiation for fully vegetation cover (Γ_c=0.05) and for bare soil (Γ_s=0.135).

2.3.1.4. Sensible heat flux

Sensible heat flux is heat energy transferred between the surface and air. In the SEBS model the Monin-Obukhov Similarity (Brutsaert, 1982) is applied for calculation of sensible heat flux:

$$u = \frac{u*}{k}\left[Ln\left(\frac{z-d_0}{z_{om}}\right) - \psi_m\left(\frac{z-d_0}{L}\right) + \psi_m\left(\frac{z_{om}}{L}\right)\right] \qquad (2.15)$$

$$\theta_0 - \theta_a = \frac{H}{ku*\rho cp}\left[Ln\left(\frac{z-d_0}{z_{oh}}\right) - \psi_h\left(\frac{z-d_0}{L}\right) + \psi_h\left(\frac{z_{oh}}{L}\right)\right] \qquad (2.16)$$

Where z is reference height (m), u is the wind speed and $u*$ the friction velocity (both in ms^{-1}), d_0 is the displacement height (m), z_{om} and z_{oh} are the roughness height for momentum and heat transfer (m), k=0.4 von Kármán's constant, c_p is heat capacity of dry air (J kg^{-1}), ρ is air density (kg m^{-3}), θ_0 and θ_a are potential temperature (K) at surface and air temperature at height z, L is Obukhov length (m), defined as:

$$L = -\frac{\theta_v \rho u*^3 c_p}{KgH} \qquad (2.17)$$

In above equation g is the acceleration due to gravity (m s^{-2}) and θ_v is the virtual temperature near the surface (K).

2.3.1.5. Roughness length for heat and momentum transfer

Su (2002) in SEBS model estimated z_{oh} from z_{om} using KB^{-1}. Su and Jacobs (2001) derived z_{om} from NDVI, as in the following equations:

$$Z_{om} = 0.005 + 0.5*(\frac{NDVI}{NDVI_{max}})^{2.5} \qquad (2.18)$$

$$Z_{om} = \exp(-5.2 + 5.3*NDVI) \qquad (2.19)$$

In this model z_{oh} is calculated as:

$$z_{oh} = \frac{z_{om}}{\exp\left(KB^{-1}\right)} \qquad (2.20)$$

Where KB^{-1} is Stanton number, representing the excess resistance for heat transfer. For estimation of the value of KB^{-1} (Su and Jacobs, 2001) an extended physical based model is used:

$$KB^{-1} = \frac{kC_d}{4C_t\frac{u*}{u(h)}\left(1-e^{-n_{ec}/2}\right)}f_c^2 + 2f_cf_s\frac{k.\frac{u*}{u(h)}.(z_{om}/h)}{C_t*} + KB_s^{-1}fs^2 \qquad (2.21)$$

In equation (2.21) c_d is the drag coefficient of the foliage that assumed as constant (0.2), f_c and f_s are the fractional vegetation cover and its complement. C_t is heat transfer coefficient of the leaf; for most canopies and environmental conditions Su and Jacobs (2001) assumed the C_t-value is between $0.005N \leq C_t \leq 0.075N$, N is the number of sides of a leaf for heat exchange, and KB_s^{-1} is for bare soil that can be determined with following formula:

$$KB_S^{-1} = 2.46(R_e^*)\ 1/4 - \ln(7.4) \qquad (2.22)$$

Where: R_e, is roughness Reynolds number for soil.

2.3.1.6. Evaporative fraction and actual evapotranspiration

Evaporative fraction in SEBS has been estimated with sensible heat flux under dry and wet limited condition. As under dry condition latent heat flux is minimum it could be neglected then surface energy
balance equation could be summarized as following:

$$H_{dry} = R_n - G_0 \qquad (2.23)$$

Under the wet limit, actual evapotranspiration reaches to potential evapotranspiration and surface energy balance could be written as:

$$H_{wet} = R_n - G_0 - \lambda E_{wet} \approx 0 \qquad (2.24)$$

Using equation 2.24 in Penman-Monteith's equation, Su (2002) estimated H_{wet} as follows:

$$H_{wet} = \left[(R_n - G_0) - \left(\frac{\rho c_p}{r_{ew}} \right) . \left(\frac{e_s - e}{\gamma} \right) \right] / \left(1 + \frac{\Delta}{\gamma} \right) \qquad (2.25)$$

Under wet limit aerodynamic resistance is estimated as:

$$r_{ew} = \frac{1}{ku^*} \left[Ln\left(\frac{z - d_0}{z_{oh}} \right) - \psi_h \left(\frac{z - d_0}{L} \right) + \psi_h \left(\frac{z_{oh}}{L} \right) \right] \qquad (2.26)$$

Where λ is latent heat of vaporization (2.45MJ kg^{-1})
The Obukhov length under wet limit can be estimated as:

$$L_w = \frac{\rho u^{*3}}{0.61 . kg . (R_n - G_0) / \lambda} \qquad (2.27)$$

Relative evaporative fraction (Λ_r) is derived from 2.8, 2.23 and 2.24 equations as follows:

$$\Lambda_r = \frac{\lambda E}{\lambda E_{wet}} = 1 - \frac{\lambda E_{wet} - \lambda E}{\lambda E_{wet}} = 1 - \frac{H - H_{wet}}{H_{dry} - H_{wet}} \qquad (2.28)$$

Finally evapotrative fraction is given by:

$$\Lambda = \frac{\lambda E}{R_n - G} = \frac{\Lambda_r \lambda E_{wet}}{R_n - G} \qquad (2.29)$$

Then the daily evaporanspiration is calculated by assuming that the evaporative fraction (derived at satellite overpas) remains constant throughout the day:

$$ET_a = 8.64 * 10^7 * \frac{\Lambda . R_{nday}}{\lambda \rho_w} \qquad (2.30)$$

Where ρ_w is the density of water (kgm^{-3}) and R_{nday} is daily net radiation (Wm^{-2}).

3. Study area

3.1. Location

The study area is the Ghazvin basin in the Ghazvin province in Iran. It covers an area of 5031 km^2. The area is located between 49°,18′ E – 50° ,41′E and 35°,57′N – 36°, 22′N with maximum altitude of 2033 m and minimum altitude 1141 m. Figure 3.1 shows the irrigation network, the stations and the dam in the study area.

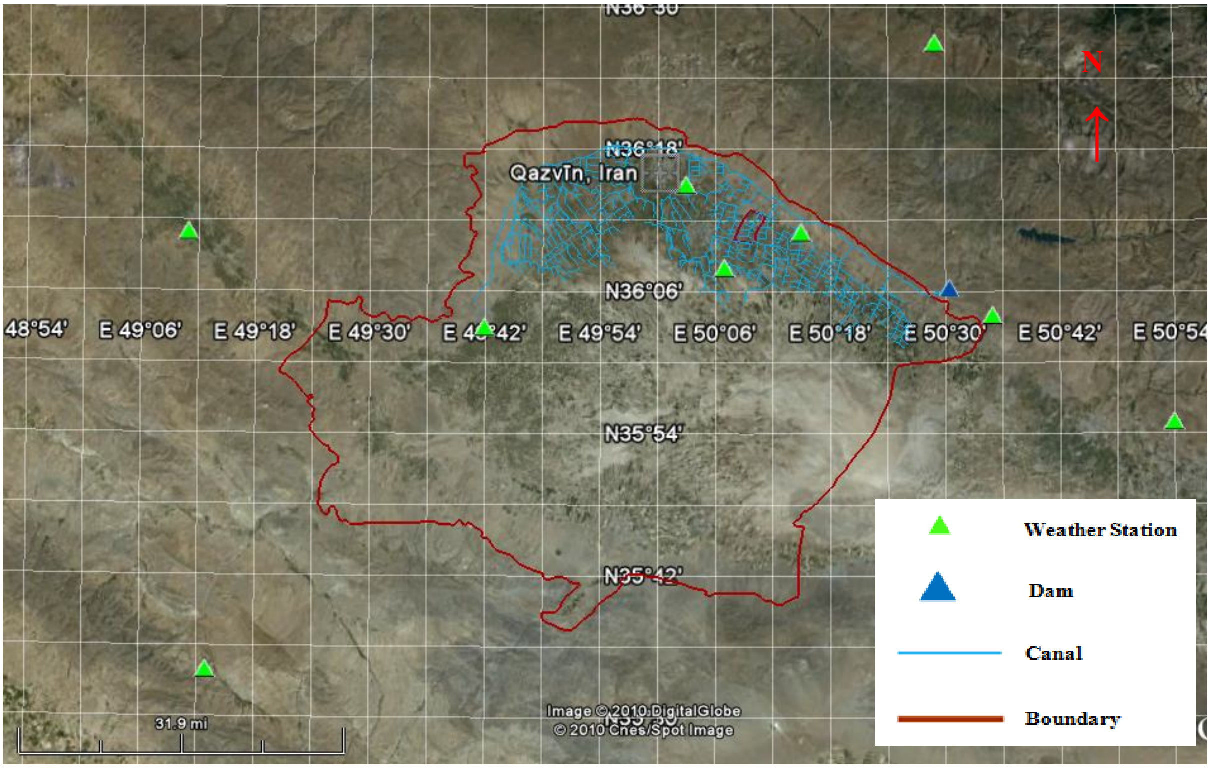


Figure 3.1 Locations of Ghazvin basin, irrigation network, weather stations and Ziaran dam

3.2. Climate

The study area has a semi arid climate. The daily average climatological parameters are presented in Table3.1.

Table 3.1 Climatological variables in the Ghazvin basin

Temperature	Temperature	Humidity	Wind Speed	Sunshine	Radiation	Rainfall	ETo	ETo
Max	Min	%	Km/day	hour	MJ/m2/d	mm/year	mm/year	mm/day
20.7	6.3	52.9	156.2	8.2	17.5	342	1358	3.7

3.3. Irrigation

The Ghazvin irrigation network is a medium-sized irrigation system. The system is about 60,000 ha and is composed of 170 gate-units “water user associations” (WUA). There is one dam as surface water resource; there are 3577 agricultural wells and 38 agricultural Qants as ground water resources in this basin. Water productivity in the system is generally low and due to limited supply (in particular from the Ziaran dam) shortages occur in the system. The current practices to calculate the crop water requirement is outdated and does not take into account the specific local conditions (soil & water quality, canal network efficiency, cropping pattern). Moreover, the system is rather bureaucratic and water is not always delivered on time. A major other issue in the area is the excessive groundwater extraction by farmers, leading to a lowering of the groundwater table at a rate of 1 meter per year. This strong lowering of the groundwater table is unsustainable and the question is how to reduce these groundwater extractions (Sharifi and Gieske, 2008).

Current annual crop water planning in Ghazvin basin based on average of 30 years ET_0 and FAO K_c table for crop pattern in water user associations in the beginning of the year for coming year. Table 3.2 shows the planning for crop water requirement.

Table 3.2 Annual crop water requirement planning in Ghazvin basin

Date:

Ir.Systems:

Village:

Gate:

WUA:

Crop pattern:

Crops	**Wheat**	**Alfalfa**	**Barely**	**Corn**	**Sorgum**	**Onion**	**Tomato**	**Potato**	**Grape**	**Canola**	**Been**	**Fallow land**
Area(ha)												

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
CWR												

Total (m^3):

This study is taking one of the WUAs as an example. Figures 3.2 and 3.3 shows the structure and of the irrigation network as well as the location if the selected WUA (Sharif Abad).

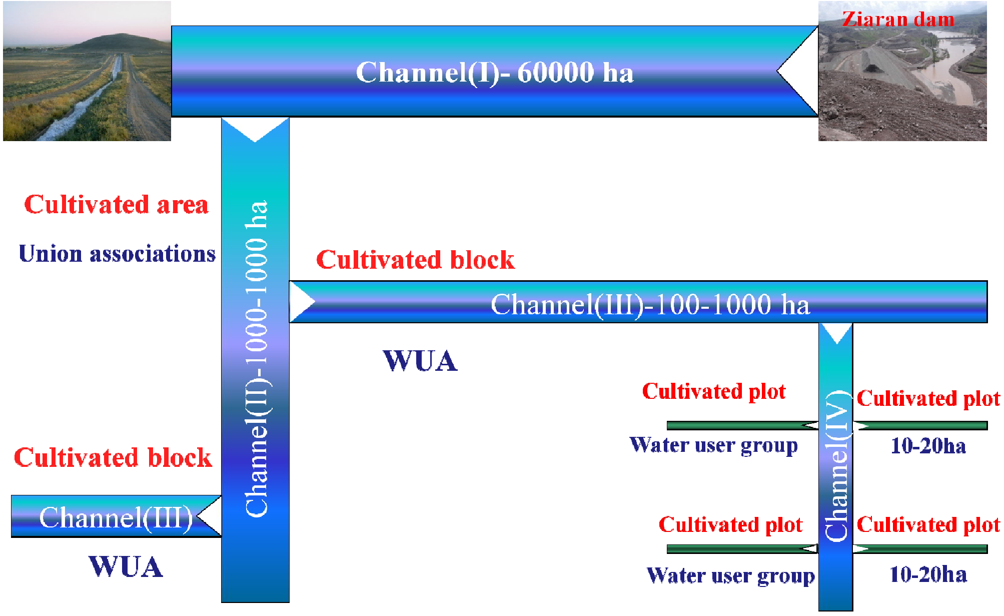


Figure 3.2 Dstribution of water in irrigation network

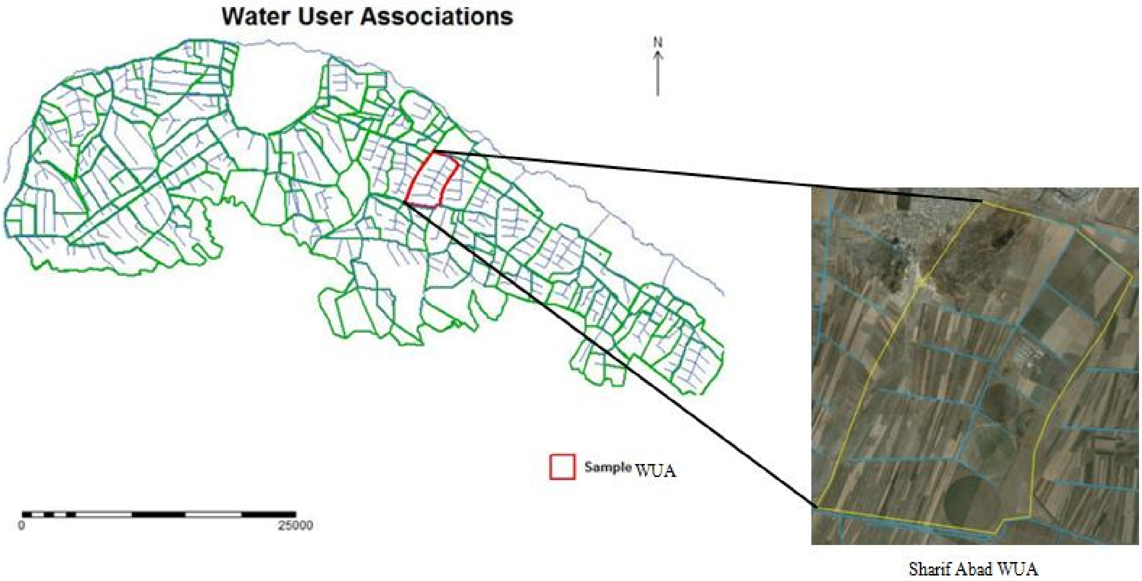


Figure 3.3 Map showing the irrigation network and, the selected sample water user association "WUA"

3.4. Land Use

The agricultural land use in the basin is presented in Table 3.3. The main crops in this basin are wheat and barley, grape and sorghum. There are wheat, canola, alfalfa and, sorghum In Sharif Abad WUA.

Table 3.3 Agricultural Land use in the Ghazvin basin

Land use type	percentage
wheat & barley	18.9
Autumn farming(wheat, barley& canola)	18.8
canola	3.5
alfalfa	1.5
spring crops(corn, vegetables& alfalfa)	8.3
sorghum	10.5
Fallow land	22.8
dry farming land	1.6
artificial nutrition pools	0.1
trees of around roads	0.1
river bed	0.2
saline soil	0.8
residential area	3.6
industrial area	0.3
garden of village side	5.9
garden& autumn farming(mix)	2.4
garden& vineyard(mix)	0.9

4. Materials and methods

4.1. Materials

The materials which were collected and used in this study include meteorological data, low, medium and high spatial resolution satellite data, and crop types and their phonological information. In the following, these are briefly presented.

4.1.1. Meteorological data

Meteorological data which were collected (Table 4.1) and used in this research include: maximum and minimum air temperature, maximum and minimum relative humidity, wind speed and pressure as input for SEBS(hourly) and DEMETER (daily) models and reference evapotranspiration with the FAO-56 method (daily, for 45 years). In addition 45 years of daily precipitation has been collected and used for calculation of drought index (SPI).

Table 4.1 Weather stations and meteorological data

Station	Name	Latitude	Longitude	Elevation	years	Meorological Parameter
Synoptic (3 hours by 3 hours)	Qazvin	36.02	50.05	1279.2	1961-2005	Max&Min temperature, Max&Min Relative Humidity, wind speed, sunshine hour, precipitation, pan evaporation
	Karaj	36.05	50.90	1312.5	1976-2005	
	Moalem	36.45	50.48	1629.2	1976-2005	
Climatology (6 hours by 6 hours)	Magsal	36.13	50.12	1265.0	1976-2005	Max&Min temperature , Max&Min Relative Humidity, wind speed, precipitation
	Khoramdareh	36.18	49.18	1575.0	1976-2005	
	Baghkosar	36.07	50.58	1225.0	1976-2005	
	Nirougah	36.18	50.25	1285.0	1976-2005	
	Avaj	35.57	49.22	2034.9	1976-2005	
	Takestan	33.92	49.70	1283.4	1976-2005	

4.1.2. Crop data

Crop information includes phonological and management information, and canopy characteristics such as development stage (FAO-56), crop height, crop calendar, crop area and cropping pattern, and irrigation practises. Figure 4.1 and Table 4.2 show various crop development stages (Allen et al., 1998) and their corresponding height information.

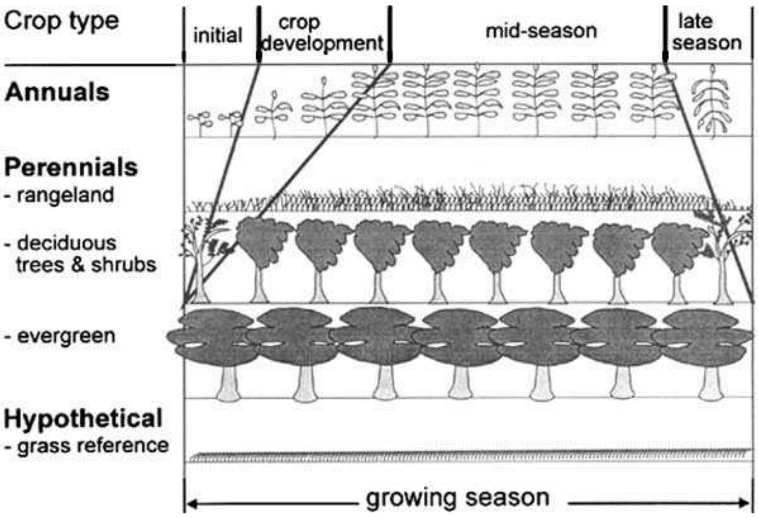


Figure 4.1 Growth stages of different crops (Allen et al., 1998)

Table 4.2 Crop development stages of various crops in the pilot area (this information were collected through personal communications with experts in the region)

Crop	Stage	Period(day)	Height(cm)
Wheat	**1**	110	15
	2	59	50
	3	63	85
	4	31	90-100
Canola	**1**	130	15
	2	58	60
	3	46	110
	4	40	140
Sorghum	**1**	21	50
	2	35	150-200
	3	44	220-260
	4	30	270-340
Alfalfa	**1**	10	10
	2	25	15-20
	3	25	40
	4	10	50

4.1.3. Lysimeter data

Weekly lysimeter data of alfalfa for three years (2001-2004) has been collected and used for validation of different methods of crop coefficient(Ebrahimipak, 2002). Three-year average Lysimeter data for wheat, grass and, canola in weekly form has been collected(Ebrahimipak, 2002).

4.1.4. ASTER images

In this study, high resolution images were used to identify the field sizes, shapes and crop types. For this purpose, ASTER images were used. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is one of advanced multispectral imager with high resolution and covers 14 spectral bands raging from visible to thermal infrared. In this study, ASTER level 1B products have been used. Table 4.3 summarizes obtained level 1B ASTER products. ASTER level 1B contains radiometrically calibrated and geometrically co-registered data for all the ASTER channels. Table 4.4 shows acquisition date of available ASTER and MODIS images based on crop growth stages of Sharif Abad WUA in Ghazvin irrigation network.

Table 4.3 description ASTER spectral bands

Subsystem	Band No.	Spectral range (µm)	Spatial Resolution
VNIR	1	0.52-0.60	15 m
	2	0.63-0.69	
	3N	0.78-0.86	
	3B	0.78-0.86	
SWIR	4	1.600-1.70	30 m
	5	2.145-2.185	
	6	2.185-2.225	
	7	2.235-2.285	
	8	2.295-2.365	
	9	2.360-2.430	
TIR	10	8.125-8.475	90 m
	11	8.475-8.825	
	12	8.925-9.275	
	13	10.25-10.95	
	14	10.95-11-65	

Table 4.4 Acquisition date of ASTER and MODIS images

Date	DOY	Wheat	Alfalfa	Canola	Sorghum
24-May	145	stage3	stage2	stage3,4	***
27-May	147	stage3	stage2	stage3,4	***
13-Jun	165	stage4	stage4	stage4	stage1
13-Jul	194	***	stage3	***	stage2,3
26-Aug	238	***	stage3	***	stage3
06-Sep	249	***	stage1	***	stage3,4
08-Sep	252	***	stage1	***	stage3,4
27-Sep	271	***	stage3	stage1	stage4

4.1.5. MODIS images

Moderate Resolution Imaging Spectroradiometer (MODIS) refers to two instruments carried onboard NASA's Earth Observing System (EOS) satellites, Terra and Aqua. MODIS covers 36 spectral bands raging from 0.4 µm to 14.4 µm. MODIS spatial resolutions of different bands include: 250 m (bands 1 and 2), 500 m (bands 3-7), and 1000 m (bands 8-36). In this research some of MODIS data and products related to various crop development stages have been used (Table 4.5).

Table 4.5 MODIS products that have been used

Short name	Platform Product	MODIS product	Raster TYPE	Resolution (m)	Temporal Granularity
MOD09GA	Terra	Surface Reflectance Bands 1–7	Tile	500/1000m	Daily
MOD11A1	Terra	Land Surface Temperature & Emissivity	Tile	1000m	Daily
MYD15A2	Aqua	Leaf Area Index - FPAR	Tile	1000m	8 Day

4.2. Methodology

This research aims at developing a method to estimate accurately the CWR of various crops in Ghazvin basin, which is suitable for annual water allocation planning. To achieve this, it intends to make use of the state of the arts technology in the application of remote sensing for assessment of CWR. Figure 4.2 presents overall structure of the methodology.

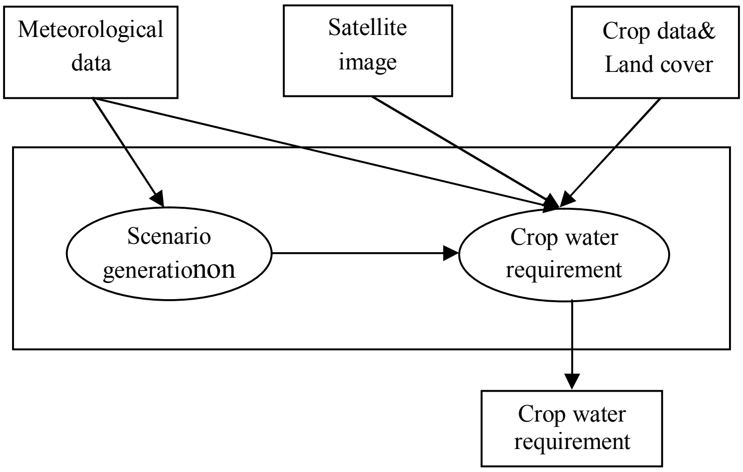


Figure 4.2 Overall structure of the methodology

4.2.1. Scenario generation

Crop water requirement in drought conditions is different from normal conditions. This implies that in a dry year a crop will require more water than in a wet year. To cope with this variation, years have been classified into three classes, notably: dry, wet and normal years. For each year a corresponding CWR is determined. Further using the Markov Chain Process (Ochola and Kerkides, 2003) the probability of each year associated with each class is determined and is used to estimate the expected crop water requirement of the next year given the conditions in previous years. For classification of years a Drought Index "DI" is used. In this study, the Standardised Precipitation Index "SPI" was used for categorizing years in wet, dry and normal classes (Table 4.6). The years 1961 to 2005 were classified in three categories (wet, normal & dry) in annual periods using SPI index. Most water supply planners are using SPI in their decision making process, as this index indicates the occurrence of drought quite well (Hayes, 2006). SPI is a probability index that only considers precipitation (McKee et al., 1995). SPI is calculated for several time scales, ranging from 1-24 months.

Table 4.6 SPI index values related to scenarios

SPI Values	Condition
1 and more	wet
-.99 to .99	normal
-1 and less	dry

4.2.2. Crop Water Requirement

ICID-CIID (2000) defines the CWR as "the total water needed for evapotranspiration, from planting to harvest for a given crop in a specific climate regime, when adequate soil water is maintained by rainfall and/or irrigation so that it does not limit plant growth and crop yield". Considering this definition and FAO approach, the crop water requirement was determined as the following formula:

$$ET_c = K_c * ET_0 \quad (4.1)$$

Where ET_c or ET_p is crop potential evapotranspiration, K_c is crop coefficient and ET_0 is reference evapotranspiration. Average monthly ET_0 was calculated using daily weather data with FAO-56 Penman-Monteith or Modified-Hargreaves methods in all climatic stations and considering different scenarios (Section 4.2.2.1). In the next step, the average monthly ET_0 was interpolated between stations for all fields using an appropriate interpolation method. Crop water requirement was calculated using Eq. (4.1), and related crop specific K_c. For planning purposes using proper remote sensing based method a regional K_c for each WUA (further explained in Section 4.2.2.2) was calculated and used for determination of CWR at each WUA. Figure 4.3 presents various stages of crop water requirement determination.

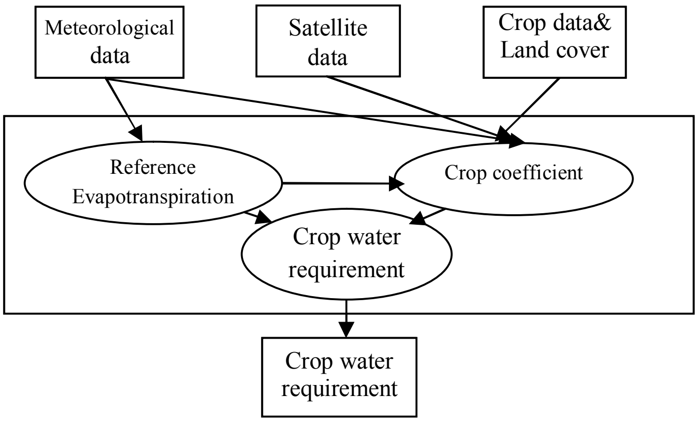


Figure 4.3 Stages of crop water requirement determination

4.2.2.1. Reference crop evapotranspiration (ET_0)

The standardized Penman-Monteith (PM) ET of FAO-56 has been used in the design of irrigation systems as well as applications under a wide range of conditions and climates (Bos et al., 2009).

The FAO-56 Penman-Monteith method requires radiation, air temperature, air humidity and wind speed data. The FAO-56 Penman-Monteith equation has three advantages over many other methods. First of all, it is a physically based approach that has been tested using several lysimeters. Second, it does not need other parameters than those routinely measured at most weather stations. Third, it has been made available through a large number of software packages (Allen et al., 1998).

In data limited situations when only radiation, wind speed and humidity are available, Hargreaves model provides a good alternative estimate for ET_0 (Allen et al., 1998). Hargreaves method is one of the simplest models for practical use, since it requires only two easily accessible parameters, temperature and solar energy. The Hargreaves and Samani (1985) model has been applied in a wide range of climatic conditions. Droogers and Allen (2002) modified Hargreaves method by adding precipitation to improve estimation of ET0 especially for arid area.

The average monthly ET_0 will be calculated, applying FAO-56 Penman-Monthieth method and daily weather data for all synoptic stations. In the climatology stations Modified-Hargreaves (MH) or Hargreaves-Samani (HS) with available meteorology data will be used to estimate ET_0. The ET_0 derived from MH and HS will be tested to find the method which is closer to FAO-56 PM. Next, the point ET_0 data will be interpolated using proper interpolation method (the lowest error) to derive the ET_0 map of the basin. Average ET_0 at each point will be calculated for each of the three scenarios, and together with its related crop coefficient is used to estimate the crop water requirement. The mean ET_0 per scenario also presents the variation of evapotranspiration in time and space at different scenarios.

4.2.2.2. Crop coefficient (K_c)

As defined in Section 2.2, K_c is a ratio between the actual crop ET under standard conditions (potential evapotraspiration) and a reference crop ET. It is formulated in two forms: single K_c and dual K_c for different stages of growth. In single K_c form, the combination of crop transpiration and soil evaporation are integrated. In this study single K_c was used, as the energy balance approaches (DEMETER and SEBS) are unable to separate evaporation from transpiration (Tasumi and Allen, 2006). Moreover, for normal irrigation planning and management purposes, basic irrigation scheduling, and also for most hydrologic water balance studies, average crop coefficients are more relevant and convenient than the K_C computed on a daily time step using a separate crop and soil coefficient (Allen et al., 1998).

Figure 4.4 shows stages of single crop coefficient determination. Crop coefficient will be calculated in two ways as follows:

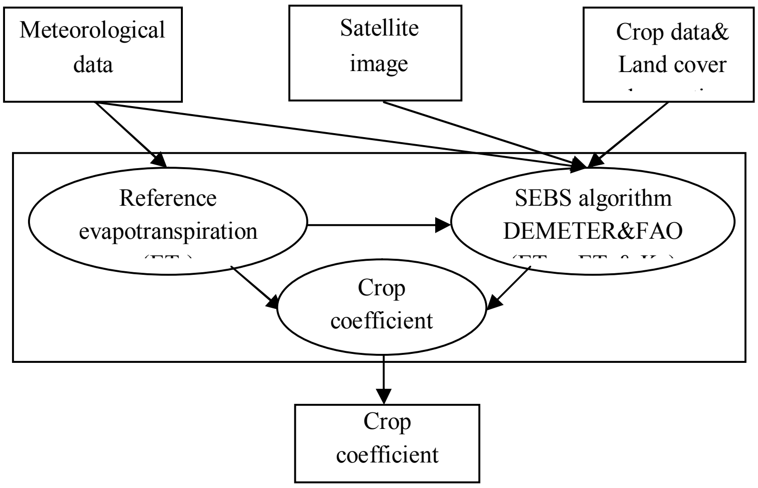


Figure 4.4 Stages of Crop coefficient estimation

1) **Crop specific coefficient:**

For this purpose the following three methods will be tested and evaluated:

- **Analytical remote sensing based K_c (DEMETER)**

As it was mentioned in the second chapter, the procedure for deriving the K_c map is four steps:

- ***Deriving canopy geometrical characteristics***

Deriving canopy geometrical characteristics from spectral data includes: LAI, roughness length, vegetation height aerodynamic resistance.

- Deriving LAI, using formula (4.2) that has been proposed by Su and Jacobs (2001):

$$LAI = NDVI\left(\frac{1+NDVI}{1-NDVI+\Delta NDVI}\right)^{0.5} \tag{4.2}$$

- Deriving roughness length by using formula (4.3) that has been proposed by Su and Jacobs (2001):

$$Z_{om} = \exp(-5.2 + 5.3 * \mathrm{NDVI}) \tag{4.3}$$

- Brutsaert (1982) proposed two formulas for estimation of the vegetation height (h) and displacement height (d):

$$h = \frac{z_{om}}{0.123} \qquad d = \frac{2}{3}h \tag{4.4}$$

- Deriving aerodynamic resistance from crop high

$$r_{a,H} = \frac{In\left(\frac{Z_U - 0.667h_c}{0.123h_c}\right) In\left(\frac{Z_T - 0.667h_c}{0.0123h_c}\right)}{0.168U_Z} \tag{4.5}$$

Z_U,Z_T : the measurement heights for wind-speed and temperature, U_Z : wind speed

- Deriving canopy resistance

$$r_{c,\min} = \frac{r_{leaf,\min}}{LAI_{eff}} \tag{4.6}$$

$r_{leaf,min}$: minimum stomata resistance that Allen et al., (1998) assumed it to be 100 sm^{-1} and LAI_{eff} is equal o.5 LAI_{max}.

- ***Deriving net radiation***

  As it was mentioned in Chapter 2, Eq. (2.7) , (2.10), (2.11), (2.13) and (2.14) were used to derive the net radiation .

- ***Weather data preparation***

  Parameters that were used for calculation of in 2.2 equation using FAO-56 (Allen et al., 1998)standards had been used.

- ***deriving K_c map***
  Using (2.2) formula for deriving K_c map for around date of image acquisition as an average K_c in this period.

- **K_c- NDVI remote sensing based K_c (DEMETER)**

In several studies, NDVI has been directly used to predict K_c ((Bausch, 1995; Bausch and Neale, 1987; Choudhury et al., 1994, ; Neale et al., 1989). In this method two points were identified with maximum NDVI (deriving from ASTER images) with related K_c and minimum NDVI with related K_c (bare soil) then regression equation (linear equation) between these two points shows K_c-NDVI relationship.

- **Adjusted KC from FAO-56 table**

The FAO-56 tabular crop coefficient for the mid-season and the end of growing stages assumes a relative humidity of 45% and a wind speed at 2 meters over the ground of 2 m/s. For other climatic conditions, the K_c values should be corrected for RH and wind speed. FAO-56 recommends equation 4.7 for this type of corrections:

$$K_{C\,stage} = K_{C\,stage\ (Tab)} + [0.04(U_2-2)-0.004(RH_{min}-45)](h/3)^{0.3} \qquad (4.7)$$

Where: K_c stage is adjusted K_c in the mid season and the end of growth stage, K_c stage (Tab) is K_c for different growth stages based on FAO-56 tables.

- **K_c from SEBS algorithm**

Crop coefficient images based on the SEBS remote sensing method were estimated by dividing the maximum values SEBS-derived ET for different crops by reference ET. About 8 ASTER images during growing season of year were used to define the temporal evolution of crops K_c for the study area (sample gate in the irrigation network “Sharif-Abad”). Here, it is assumed that the largest value of actual evapotranspiration “ET_{act}” is equal to potential evapotranspiration for different crops. K_c was determined by dividing potential (ET_{act}) evapotranspiration by reference evapotranspiration.

2) Regional crop coefficient

An average crop coefficient of the pilot area based on remote sensing techniques was estimated based on using DEMETER method and SEBS algorithm using MODIS and ASTER images. Average K_c of a mixture of crops in Sharif-Abad was defined here as regional crop coefficient. The derived regional K_c using MODIS and ASTER images were then compared (Figure 4.5). This approach deserves more attention because indications are growing that tabulated K_c values give biased crop potential evapotranspiration estimates for large areas, such as heterogeneous areas (Bastiaanssen, 1998). Michael and Bastiaanssen (2000) investigated calculation of regional scale K_c from remote sensing data based on the Priestly and Taylor equation for ET_c.

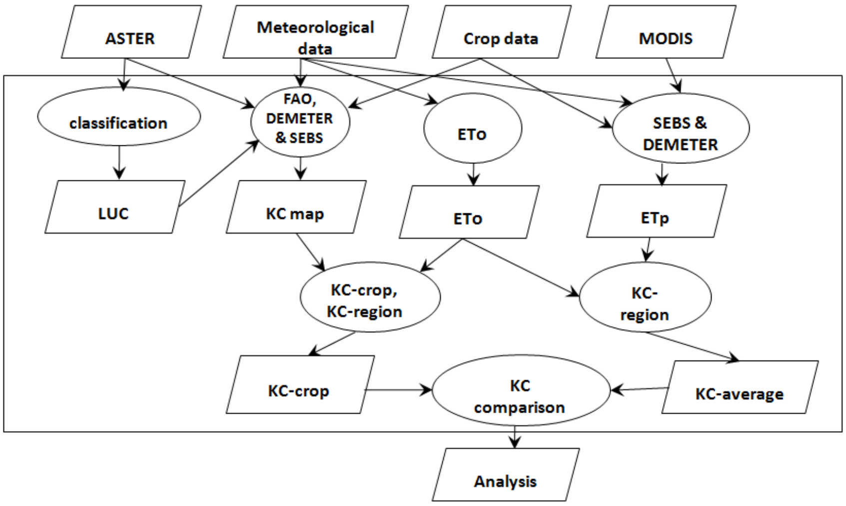


Figure 4.5 crop coefficient analyzing

4.2.2.3. Potential crop evapotranspiration (ET_p)

ET_p is the evapotranspiration if enough water is available to meet the sum of evaporation and transpiration. There are several methods for estimation of ET_p, including ground based and remote sensing based methods. In this research the SEBS algorithm as remote sensing based group and FAO-56 PM method as ground based group were used.

4.2.2.4. Crop coefficient sensitivity analysis

The sensitivity of ET_0 with respect to various crop and climatic variables such crop height, Leaf Area Index, Relative Humidity, temperature, incoming short wave radiation, and wind speed was determined. These parameters and variables were varied one by one in Eq (2.2) while other parameters were kept constant, and the effect on the values of K_c was examined.

4.2.2.5. Annual crop water requirement planning

Currently, in the actual operation as was mentioned in Section 3.3, every year at the beginning of the season the crop water requirement of the irrigation network is estimated and sent to the water supply agency (Regional Water and Energy authorities, within the Iranian Ministry of Energy). This estimate was carried out using a standard table which provides a fixed monthly crop water requirement for the whole basin and in any type of year (Table 4.7). The full table is given in the appendix.

In this study an attempt will be made to improve the situation through improved method of estimation of crop water requirement (localized crop coefficient) and considering probability of having different scenarios (wet, normal and dry year). A Markov Chain Process will be used for estimating the expected ET_0 at each forthcoming year. Figure 4.6 shows the process of annual crop water requirement planning.

Table 4.7 Current Crop water requirement in Ghazvin plain

Crops	Irri. Times	Apr.	May	Jun	Jul	Aug	Sep	Oct	Nov	CWR (M^3)
Wheat	5	1000	2000	1000				2000	1000	7000
		1000	2000	2000				2000	2000	9000
Sorghum	6		1500	1200	1200	2200	1400			7500
Alfalfa	16	1500	2000	3000	3000	3000	2000	2000		16500
Canola	5	1500	2000				2000	1500		7000

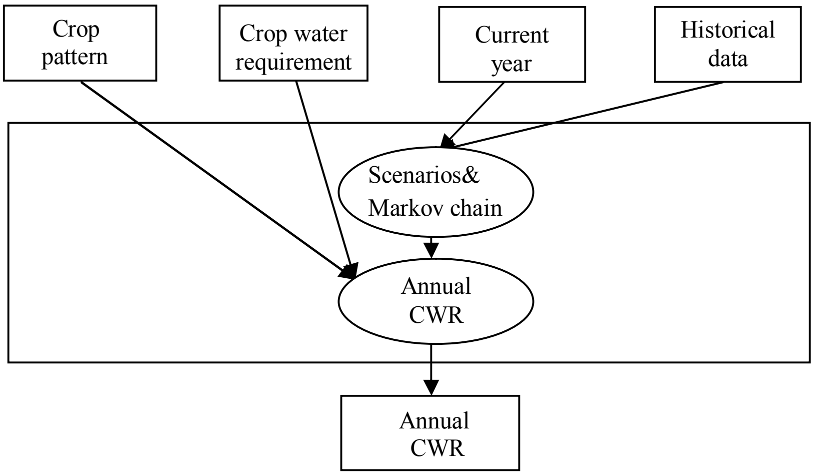


Figure 4.6 Process of planning for annual crop water requirement

5. Results and Discussion

5.1. Drought analysis (Scenario generation)

SPI drought indexes have been calculated for 45 years considering monthly precipitation. The result has been used to classify the years into wet, dry and normal (Figure 5.1 and Table 4.5).

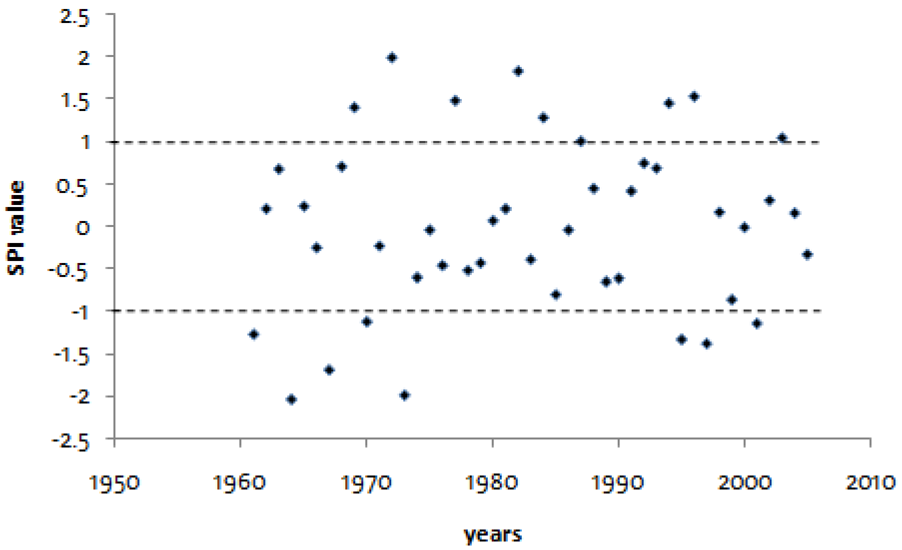


Figure 5.1 categorized years in three classes

The average reference evapotranspiration and evaporation values of pan class “A” for different scenarios are shown in the Table 5.1. This table shows that in different conditions (scenarios) evapotranspiration is different; in dry years reference evapotranspiration is higher than in average and normal years.

Table 5.1 Average E_{pan} and ET_0 (mm) for different classes

Class	Dry	Normal	Wet
Ave.ET_0 (mm)	1420.0	1366.0	1315.6
Ave.E_{pan} (mm)	1667.5	1498.9	1468.6

The evaporation values of pan class A versus SPI is shown in Figure 5.2., From the table it can be seen that in dry conditions evaporation is more than average; in normal conditions evaporation is around average value and in the wet conditions evaporation is less than average values. That implies, that ET_0 and crop water requirement will be different in different years and especially different scenarios. On this basis, the forth hypothesis of the research “ET_0 varies from year to year, especially from scenario to scenarios” will be accepted.

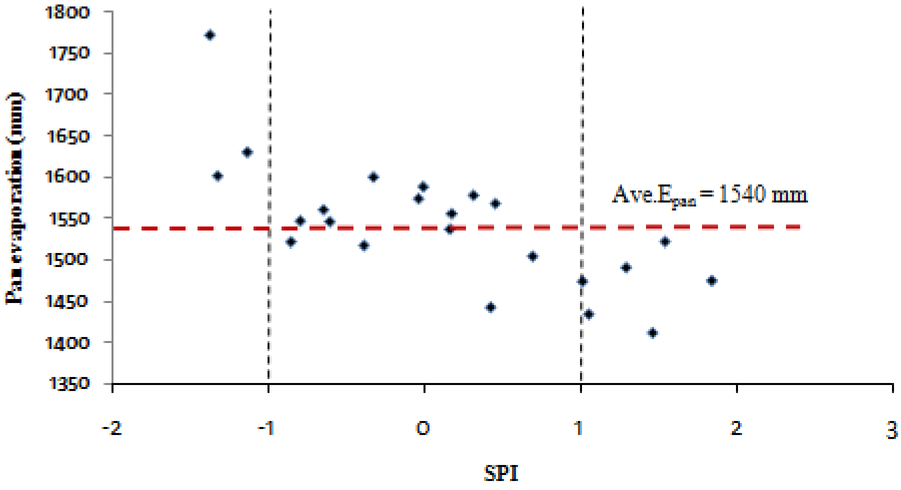


Figure 5.2 Evaporation of pan class A in different classes

5.2. Reference crop evapotranspiration (ET_0)

The reference evapotranspiration was calculated for 45 years of daily weather data of the meteorological stations. In synoptic stations, ET_0 was calculated with FAO-56 Penman-Monteith and in climatological stations determined with Hargreaves-Samani. For 11 years daily ET_0 Modified Hargreaves “M-H” and Hargreaves-Samani “H-S” has been compared with ET_0 Penman-Monteith. As it can be seen from Table 5.2, the Root Mean Square Error “RMSE” for H-S is less than M-H. This is due to the fact that the pilot area is semi arid and quantity of precipitation is low, therefore less influence compared to the influence of meteorological parameters like relative humidity that has strong effect on ET_0. Figure 5.3 shows good correlation between ET_0 derived from Penman-Monteith and ET_0 derived from Hargreaves-Samani. Correlation equation was tested with t-student test. The result showed that H-S and P-M were not significantly different at (α=0.01). This result was different with the Droogers and Allen (2002) result for determination of ET_0 in semi arid area.

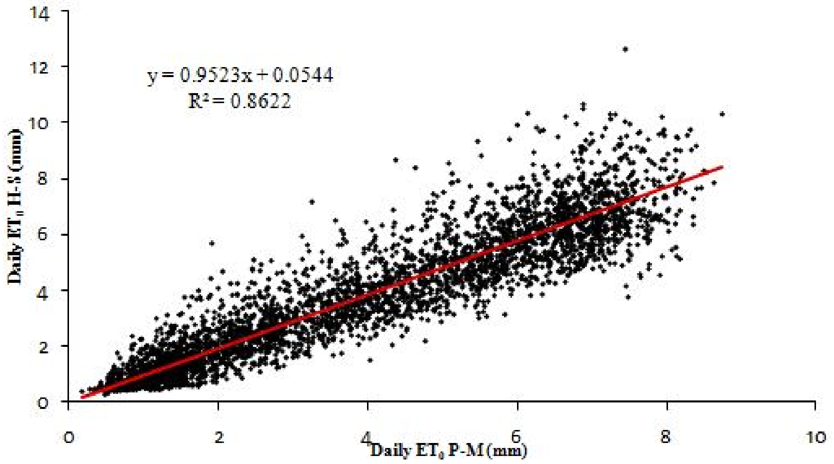


Figure 5.3 Correlation of ET_0 Penman-Monteith with ET_0 Hargreaves-Samani

Table 5.2ET$_0$ estimated by Penman-Monteith, Modified Hargreaves and Hrgreaves-Samani

Year	Method		
	M-Hargreaves	Hargreaves-Samani	Penman-Monteith
2005	1588.8	1396.3	1416.5
2004	1558.1	1374.3	1402.4
2003	1534.9	1354.3	1328.9
2002	1584.6	1390.1	1339.5
2001	1646.5	1435.7	1313.8
2000	1614.6	1411.7	1369.6
1999	1627.5	1424.4	1299.8
1998	1531.7	1360.3	1300.5
1997	1568.2	1382	1343.1
1996	1489.3	1324.7	1257.3
1995	1580.4	1388.4	1355.4
RMSE	241.8	65.5	

Average daily, monthly, and annual ET$_0$ of the 45 years for the study area were calculated and presented in Appendix-2 Average monthly and annual ET$_0$ were interpolated between meteorological stations with different methods in order to find the proper method with the lowest RMSE. Table 5.3 shows that moving surface interpolation method has the lowest error for annual ET$_0$. In the table, the May ET$_0$ has been used as instance for the analysis.

Table 5.3 Different interpolation methods` RMSE of annual and May ET$_0$

Methods	RMSE$_{\text{Annual ET0}}$	RMSE$_{\text{May ET0}}$
Kriging	0.24	0.04
Universal Kriging	0.25	0.04
Moving Average	0.8	0.18
Moving Surface	**0.14**	**0.01**
Trend Surface	27	5

Kriging did not produce a good result, may be due to not finding proper variogram which reflects the fact that there is no clear spatial structure for ET$_0$ in the area. One other reason could be the low number of stations in the area (few stations and large distances between them). In addition to the feasibility of using height as a variable related auxiliary regression correlation between ET$_0$ stations and height was pluviometry. Correlation coefficient obtained was less than 0.5 therefore the height cannot be used as auxiliary variable. In other words Co-Kriging approach will not increase the estimation accuracy (Aghdasi, 2004). Moving surface model produced good result. Aghdasi (2004) interpolated rainfall (daily, 10 days, monthly and, annual) using different geostatistical models and found that moving surface as the proper method. Figure 5.4 shows interpolation of annual ET$_0$ using moving surface method in Ghazvin basin. The result presents that over the different parts of basin ET$_0$ has different values.

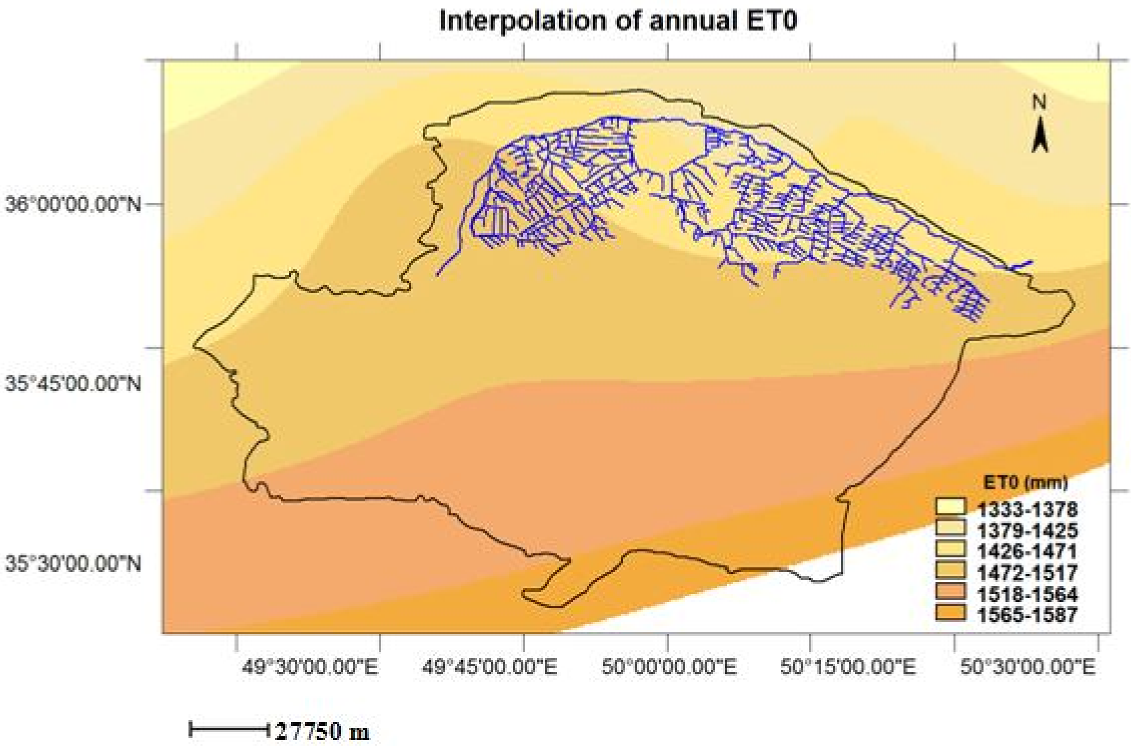


Figure 5.4Interpolation of annual ET$_0$ with moving surface method

Daily ET$_0$ for selected days over growth period has shown in Table5.4.

Table 5.4 ET$_0$ (mm) in selected days

Date	ET$_0$(mm)
24-May	5.42
27-May	6.35
13-Jun	6.53
13-Jul	6.24
26-Aug	6.45
06-Sep	5.36
08-Sep	5.91
27-Sep	5.15

5.3. Crop coefficient

5.3.1. Crop specific K$_c$

5.3.1.1. Lysimeter method

Three years weekly lysimeter data (2001-2004) was collected for alfalfa (Ebrahimipak, 2002). The quality of the result was checked using this lysimeter. The K_c lysimeter has been calculated by dividing the measured actual evapotranspiration "ET$_a$" by the reference evapotranspiration "ET$_0$". Since crop had been given enough water (no stress), ET$_a$ had been assumed to be equal the potential evapotranspiration "ET$_p$". ET$_a$ had been measured through accounting of the water balance in the lysimeter. Table 5.5 shows the alfalfa K_c derived through lysimeter for three years. Lysimeter data for wheat, grass and, canola in three-year average was available, so this information to evaluate the accuracy of results in the daily scale were not used.

Table 5.5 lysimeter K_c of alfalfa

K_c	Init	Mid	End
Ave. K_c	0.75	1.1	1.07
K_c	0.8	1.21	1.17

5.3.1.2. FAO-56 method

Table 5.6 shows the crop K_c extracted from FAO-56 standard table values versus the FAO standard K_c value adjusted for relative humidity, wind speed and, crop height as proposed by Allen et al. (1998) for all crops in Sharif Abad WUA. The result shows that adjusted crop K_c is larger than non-adjusted. This is consistent with the fact that in more dry area and higher wind speed, K_c values will be higher (Allen et al., 1998).

Table 5.6Table versus adjusted FAO-56 k_c

Crop	Stage	$K_{C\ FA0\text{-}56\ Table}$	$K_{C\ FAO\text{-}56\ adj}$
Wheat	**Initial**	0.4	***
	Mid	1.15	1.23
	End	0.4	0.48
Canola	**Initial**	0.35	***
	Mid	1.15	1.26
	End	0.35	0.60
Sorghum	**Initial**	0.3	***
	Mid	1.2	1.41
	End	1.05	1.15
Alfalfa	**Initial**	0.4	***
	Mid	1.2	1.25
	End	1.15	1.19

5.3.1.3. DEMETER method

Crop coefficients were calculated with the DEMETER method (analytical and NDVI-based) at two different spatial scales, notably crop specific K_c (ASTER) and regional K_c (ASTER&MODIS) for different growing stages.

-Analytical approach

Specific K_c-values for different crops and development stages were calculated using ASTER (30 m) images and land use map. A land use map was used to identify crops. Figure 5.5 shows the resulting

K_c map of the pilot area at 27th of May 2007. Figure 5.6 presents process of calculation K_c for canola as an example.

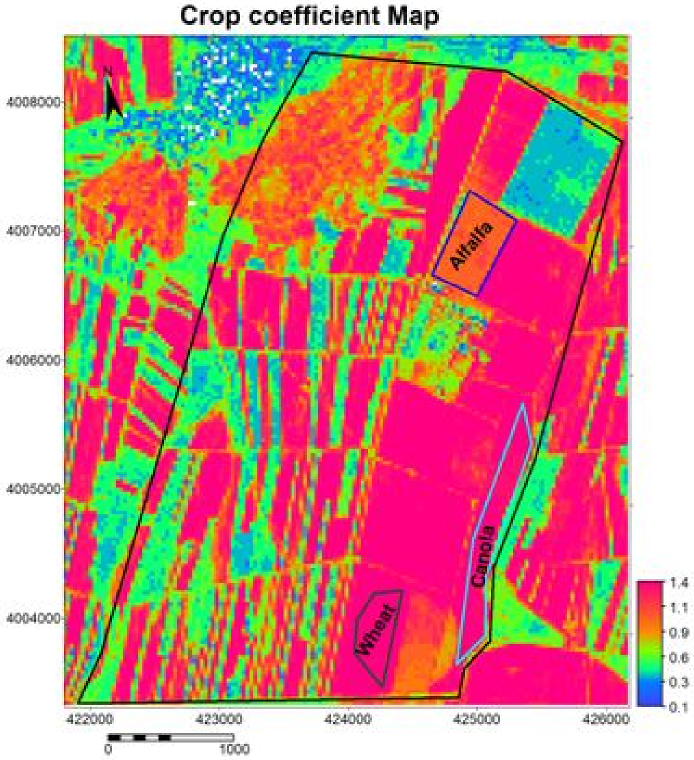
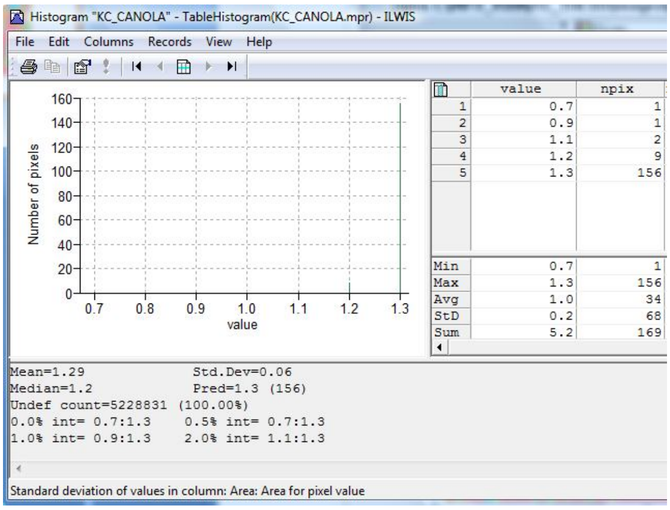


Figure 5.5 K_c map for different crops in 27.05.2005



	value	npix
1	0.7	1
2	0.9	1
3	1.1	2
4	1.2	9
5	1.3	156
Min	0.7	1
Max	1.3	156
Avg	1.0	34
StD	0.2	68
Sum	5.2	169

```
Mean=1.29                Std.Dev=0.06
Median=1.2               Pred=1.3 (156)
Undef count=5228831 (100.00%)
0.0% int= 0.7:1.3    0.5% int= 0.7:1.3
1.0% int= 0.9:1.3    2.0% int= 1.1:1.3
```

Standard deviation of values in column: Area: Area for pixel value

Figure 5.6 K_c value of canola

Figure 5.6 shows hyetograph of K_c values at 27th of May 2007. K_c values in different growing stages for all crops that there are growing in Sharif Abad were calculated. Table 5.7 shows the K_c values of crops in Sharif Abad WUA.

Table 5.7 K_c value of crops in Sharif Abad WUA (analytical DEMETER)

ASTER	DOY	Wheat	Alfalfa	Canola	Sorghum
24-May	145	1.25	0.79	1.29	***
27-May	147	1.29	***	1.32	***
13-Jun	165	0.47	1	0.57	***
13-Jul	194	***	1.21	***	0.91
26-Aug	238	***	***	***	1.41
06-Sep	249	***	0.82	***	1.44
27-Sep	271	***	1.16	***	1.14

- K_c-NDVI approach

In this method two points (derived from ASTER images) were identified: point one with maximum NDVI and related K_c and point two with minimum NDVI and related K_c (bare soil). Next equation connecting these two pints is derived and used for interpolation of other points. Equation (5.1) shows the derived linear relationship derived between NDVI and K_c:

$$y = 1.78x + 0.0864 \qquad 5.1$$

Table5.8 shows K_c of crops in Sharif Abad WUA using this linear equation. Figure 5.7 shows K_c of sorghum in different growth stages using the K_c -NDVI relationship as an example. The solid line shows the interpolation over time between the satellite images, using the dates of the crop growing calendar.

Table 5.8 K_c-NDVI relationship

Crop	$NDVI_{Init}$	$NDVI_{mid}$	$NDVI_{end}$	$K_{c\ Init}$	$K_{c\ mid}$	$K_{c\ end}$
Wheat	***	0.64	0.388	***	1.23	0.78
Alfalfa	0.16	0.6	0.34	0.37	1.16	0.69
Canola	***	0.62	0.289	***	1.19	0.6
Sorghum	0.3	0.7	0.31	0.62	1.34	0.64

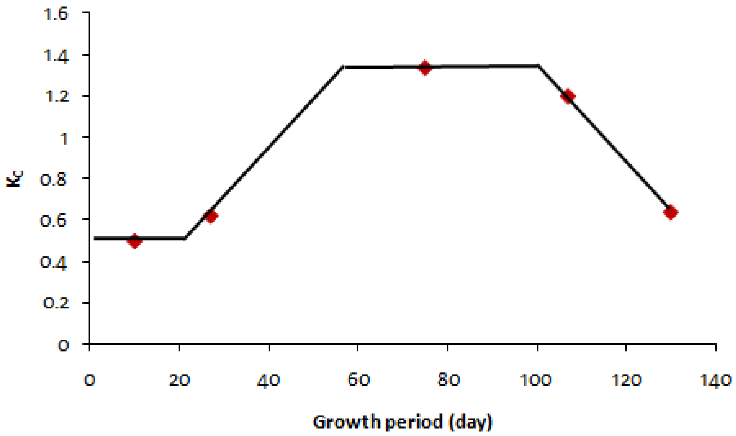


Figure 5.7Sorghum K_c-NDVI Points refer to remote-sensing derived K_c values; the line is an interpolation using the dates of the growing calendar of Sorghum

5.3.1.4. K_c from SEBS algorithm

Here, crop K_c is derived for Sharif Abad WUA using SEBS algorithm. The maximum value of ET_a in each field was assumed as potential evapotranspiration and K_c extract via dividing maximum of ET_a by ET_0. Table 5.9 shows the crop coefficient for crops.

Table 5.9 K_c value of crops in Sharif Abad WUA (SEBS algorithm)

ASTER	DOY	Wheat	Alfalfa	Canola	Sorghum
24-May	145	1.35	1.61	1.45	***
27-May	147	1.27	1.46	1.56	***
13-Jun	165	1.23	1.39	1.31	***
13-Jul	194	***	1.23	***	1.1
26-Aug	238	***	***	***	1.25
06-Sep	249	***	1.2	***	1.83
27-Sep	271	***	1.45	***	1.36

5.3.2. Discussion crop specific K_c

Table 5.10 shows derived crop coefficient using different methods. Lysimeter data were used for validation of results. Table 5.11 shows Root Mean Square Error as error index for the different methods just for alfalfa.

$K_{c\ \text{FAO-56 adj}}$ and $K_{c\ \text{DEMETER (Analytical)}}$ had the lowest error among methods. K_c-NDVI method showed the highest error. $K_{c\ \text{FA0-56 Table}}$ and $K_{c\ \text{SEBS}}$ showed almost the same error. Although RMSE nearly the same for FAO-56 (adjusting K_c) and DEMETER (Analytical approach) methods, but DEMETER (Analytical approach) method is introduced as proper method in this study due to in the sensitivity analysis (Section 5.4) it will be mentioned that the crop coefficient is very sensitive to temperature and leaf area index but these variables do not appear in FAO-56 (adjusting K_c) *Eq* (4.7). To apply surface energy balance methods (in this study SEBS algorithm) to calculate K_c information about the irrigation status of the study area is necessary because in well irrigated and proper irrigation management could be assumed that actual evapotranspiration rate is equal to potential evapotranspiration rate(Tasumi and Allen, 2006).Unfortunately, in this study there was not enough information about irrigation status at the time of image acquisition. K_c values derived by the SEBS algorithm were overestimated and this result shows that maximum value for actual evapotranspiration values were more than potential evapotranspiration values then to considering the maximum of actual evapotranspiration values are equal to potential evapotranspiration value for crops were not proper assumption.

Derived K_c values using DEMETER $_{K\text{c-NDVI approach}}$ had not proper accuracy in comparison with derived $K_{c\ \text{FAO-56 adj}}$ that this achievement is against to the results of DEMETER project in Barrax site (Calera and Jochum, 2005) that is shown in Table 5.12. After these words the proper method for estimation of crop coefficient DEMETER (analytical approach) is introduced.

Table 5.10 Crop coefficient in different methods

Crop	Stage	$K_{C\ \text{FAO-56 Table}}$	$K_{C\ \text{FAO-56 adj}}$	$K_{C\ \text{DEMETER}}$		$K_{C\ \text{SEBS}}$	K_C
				Analytical	K_C-NDVI		Lysimeter
Wheat	Init	0.40	***	***	***	***	***
	Mid	1.15	1.23	1.27	1.23	1.27	***
	End	0.40	0.48	0.47	0.78	1.23	***
Canola	Init	0.35	***	***	***	***	***
	Mid	1.15	1.26	1.30	1.19	1.45	***
	End	0.35	0.60	0.57	0.60	1.31	***
Sorghum	Init	0.30	***	0.60	0.62	1.10	***
	Mid	1.20	1.41	1.42	1.34	1.50	***
	End	1.05	1.15	1.14	0.64	1.36	***
Alfalfa	Init	0.40	0.87	0.82	0.37	1.20	0.80
	Mid	1.20	1.25	1.09	1.16	1.23	1.21
	End	1.15	1.19	1.00	0.69	139.00	1.17

Table 5.11 Root Mean Square Error of different method

Method	RMSE
$K_{c\ \text{FA0-56 Table}}$	0.23
$K_{c\ \text{FAO-56 adj}}$	0.12
DEMETER (Analytical)	0.12
DEMETER(K_c-NDVI)	0.37
SEBS algorithm	0.26

Table 5.12 Crop coefficient Derived NDVI in Barrax(Calera and Jochum, 2005)

Crop	$K_{c,\ ini}$	$K_{c,\ ini}$	$K_{c,\ Mid}$	$K_{c,Mid}$
	(K_c-NDVI)	**FAO-56**	**(K_c-NDVI)**	**FAO-56**
Alfalfa	0.4	0.4	1.2	1.2
Wheat	0.4	0.3	1.2	1.15
Maize	0.4	0.4	0.75	1

5.3.3. Regional K_c

5.3.3.1. DEMETER method

The regional Kc based on DEMETER (analytical and NDVI –based) is calculated and presented.

- **Analytical approach**

Average K_c values were calculated and considered as a 'regional K_c' of Sharif Abad WUA using two ASTER (30m) and MODIS (1km, 500m) images. Figures 5.8-5.13 show regional K_c on 27th May 2004 for ASTER and MODIS.

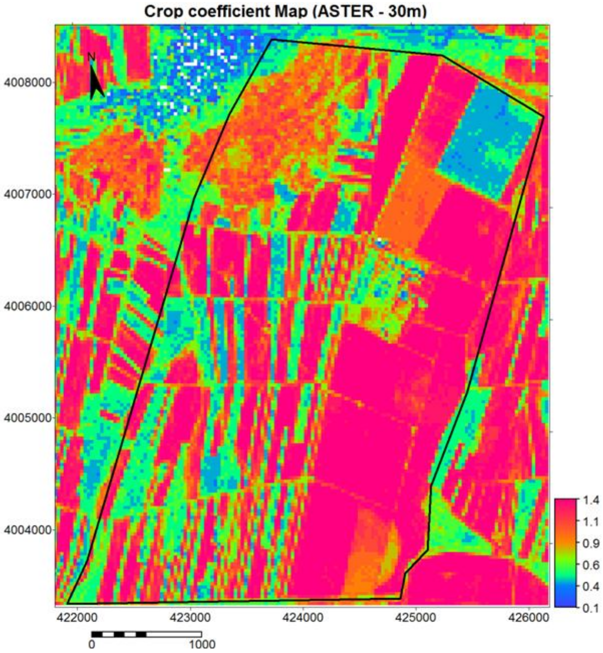
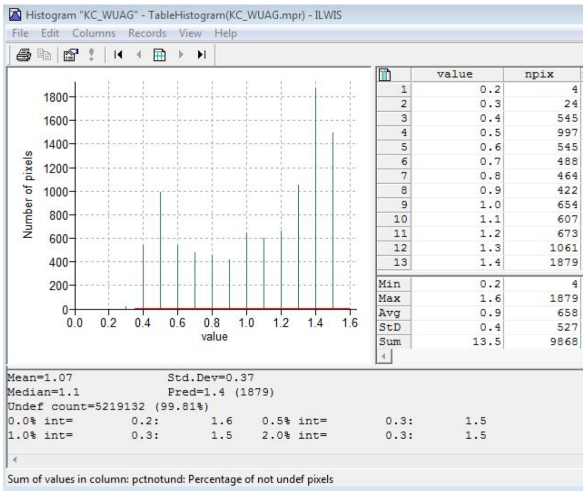


Figure 5.8 Regional K_c map on 27.05.2004



	value	npix
1	0.2	4
2	0.3	24
3	0.4	545
4	0.5	997
5	0.6	545
6	0.7	488
7	0.8	464
8	0.9	422
9	1.0	654
10	1.1	607
11	1.2	673
12	1.3	1061
13	1.4	1879
Min	0.2	4
Max	1.6	1879
Avg	0.9	658
StD	0.4	527
Sum	13.5	9868

```
Mean=1.07              Std.Dev=0.37
Median=1.1             Pred=1.4 (1879)
Undef count=5219132 (99.81%)
0.0% int=       0.2:       1.6    0.5% int=       0.3:       1.5
1.0% int=       0.3:       1.5    2.0% int=       0.3:       1.5
```

Sum of values in column: pctnotund: Percentage of not undef pixels

Figure 5.9 Regional K_c on 27.05.2004

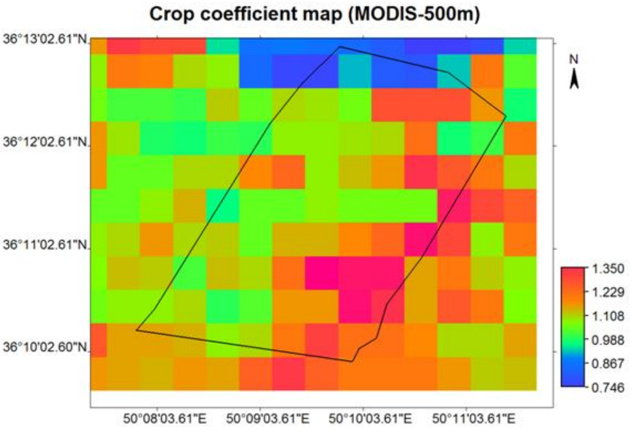
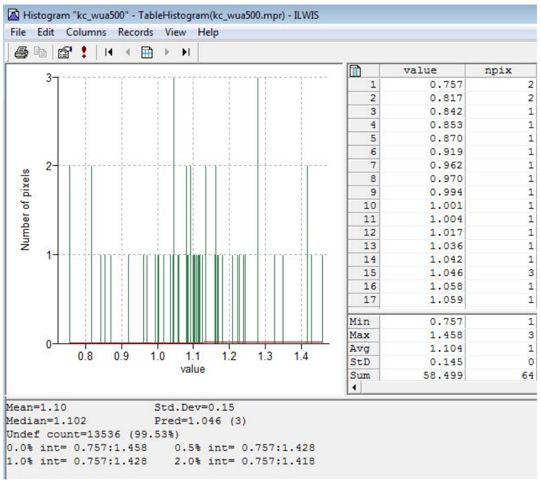


Figure 5.10 Regional K_c map on 27.05.2004



	value	npix
1	0.757	2
2	0.817	2
3	0.842	1
4	0.853	1
5	0.870	1
6	0.919	1
7	0.962	1
8	0.970	1
9	0.994	1
10	1.001	1
11	1.004	1
12	1.017	1
13	1.036	1
14	1.042	1
15	1.046	3
16	1.058	1
17	1.059	1
Min	0.757	1
Max	1.458	3
Avg	1.104	1
StD	0.145	0
Sum	58.499	64

```
Mean=1.10              Std.Dev=0.15
Median=1.102           Pred=1.046 (3)
Undef count=13536 (99.53%)
0.0% int= 0.757:1.458    0.5% int= 0.757:1.428
1.0% int= 0.757:1.428    2.0% int= 0.757:1.418
```

Figure 5.11 Regional K_c on 27.05.2004

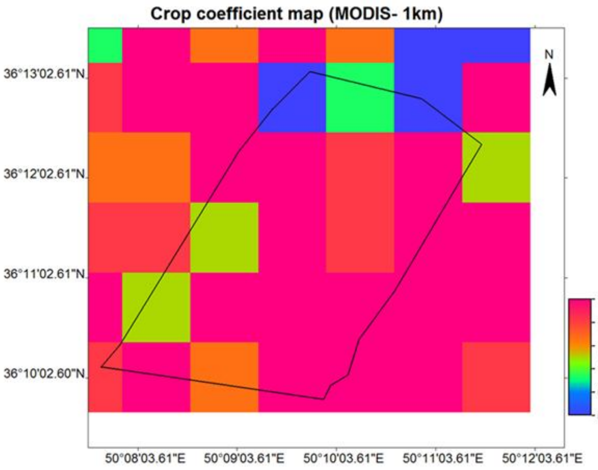
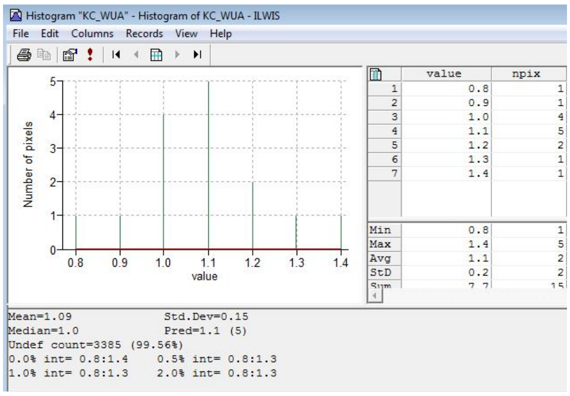


Figure 5.12 Regional *Kc* map on 27.05.2004



	value	npix
1	0.8	1
2	0.9	1
3	1.0	4
4	1.1	5
5	1.2	2
6	1.3	1
7	1.4	1
Min	0.8	1
Max	1.4	5
Avg	1.1	2
StD	0.2	2
Sum	7.7	15

```
Mean=1.09              Std.Dev=0.15
Median=1.0             Pred=1.1 (5)
Undef count=3385 (99.56%)
0.0% int= 0.8:1.4    0.5% int= 0.8:1.3
1.0% int= 0.8:1.3    2.0% int= 0.8:1.3
```

Figure 5.13 Regional *Kc* on 27.05.2004

The regional K_c values are shown in the Table 5.12. The regional K_c values for ASTER and MODIS images were tested with a t-student test (Paired Two Sample for Means). The result showed that ASTER regional K_c and MODIS regional K_c were not significantly different at (α=0.05). Also correlation equation (Y=A*X+B) between regional K_c values for ASTER and MODIS images (ASTER=A*MODIS+B) was tested. The result showed that ASTER regional K_c and MODIS regional K_c were not significantly different at (α=0.05) (Figure 5.14). Results of this test showed if ASTER regional K_c values equals MODIS regional K_c values with noel hypothesis (H_0 A=1, H_0 B=0) that there is no significant difference between regional ASTER and MODID crop coefficient. Since ET_0 map for WUS is constant for acquisition time MODIS and ASTER images and there was no significant difference between regional derived K_c values using ASTER and MODIS images, therefore the regional K_c derived from low resolution images could be used for CWR in the planning process.

Table 5.13 Regional K_c value of Sharif Abad WUA (DEMETER-Analytical)

Date	Regional K_c Sharif Abad WUA		
	ASTER (30m)	MODIS (1km)	MODIS (500m)
24-May	0.85	0.92	0.89
27-May	1.07	1.09	1.06
13-Jul	0.96	1.07	1.06
26-Aug	1.03	1.18	1.05
27-Sep	0.96	1.08	1.02

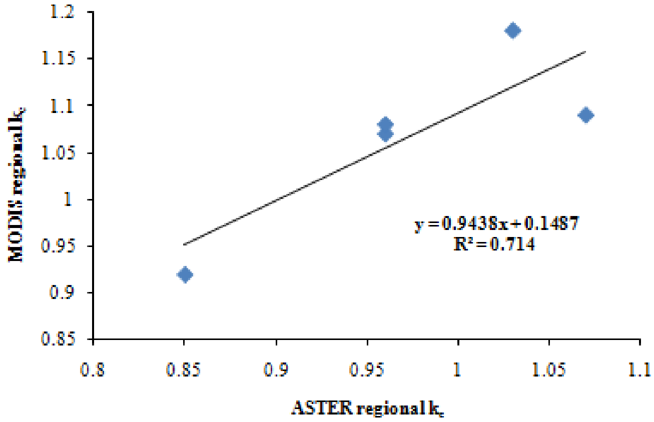


Figure 5.14 Correlation of ASTER regional K_c and MODIS regional K_c

K_c-NDVI approach

Linear relationship that derived between NDVI and K_c has been used for making K_c map using ASTER images.

Average of K_c values for Sharif Abad was calculated as regional K_c. Table 5.13 shows regional K_c of Sharif Abad WUA.

Table 5.14 Regional K_c value of Sharif Abad WUA (K_c-NDVI)

Date	K_c (30 m)
24-May	0.76
27-May	1
13-Jul	0.91
26-Aug	0.97
27-Sep	0.84

For day 27th May 2005 the relationship between NDVI map and K_c map was found for MODIS (500 m) image (Figures5.15 and 5.16). This regression equation was tested with t-Student. This relation at level (α=0.01) was significant. Figure 5.17 shows the relationship and regression equation. This regression equation could be used for disaggregation of K_c map of 500m to 250m pixel scale using the 250m NDVI information.

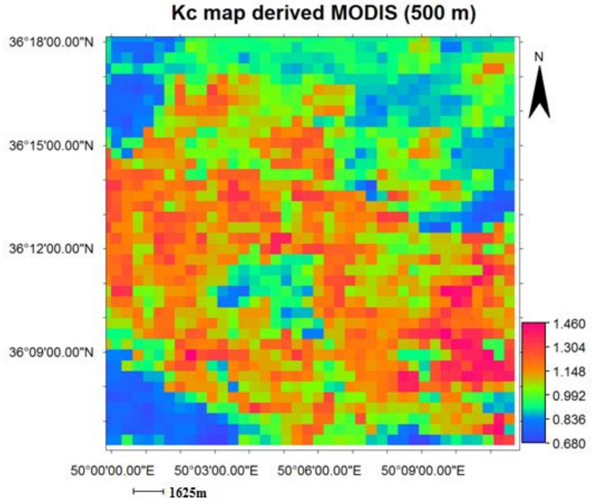


Figure 5.15K_c map derived of MODIS (500m)

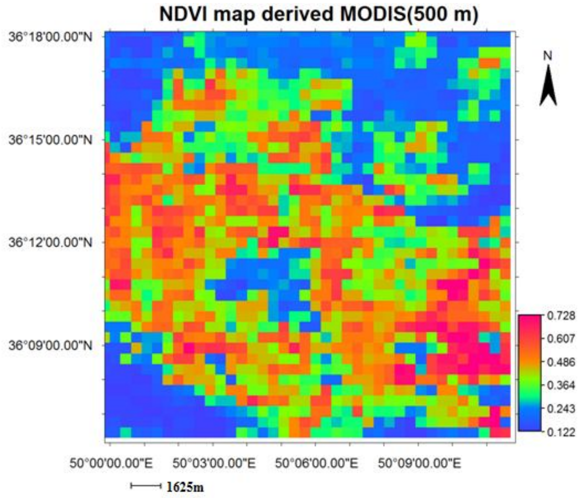


Figure 5.16 NDVI map derived of MODIS (500m)

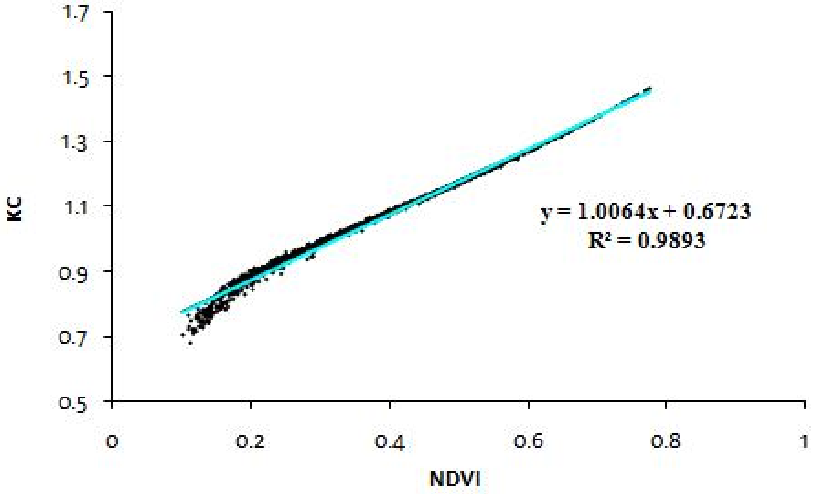


Figure 5.17 Correlation between K_c and NDVI (MODIS)

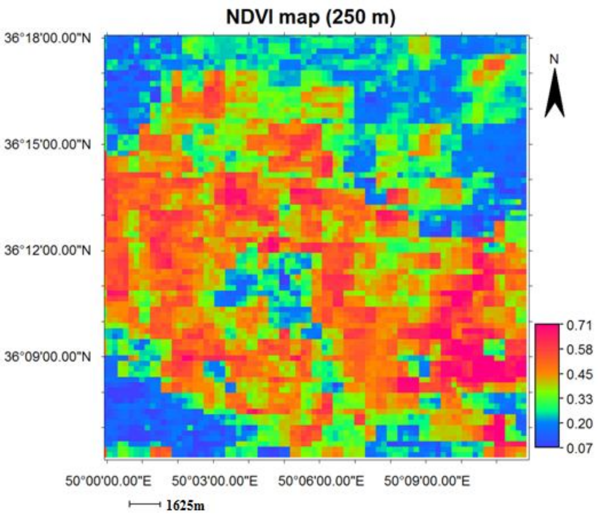


Figure 5.18 K_c map derived of MODIS (250m)

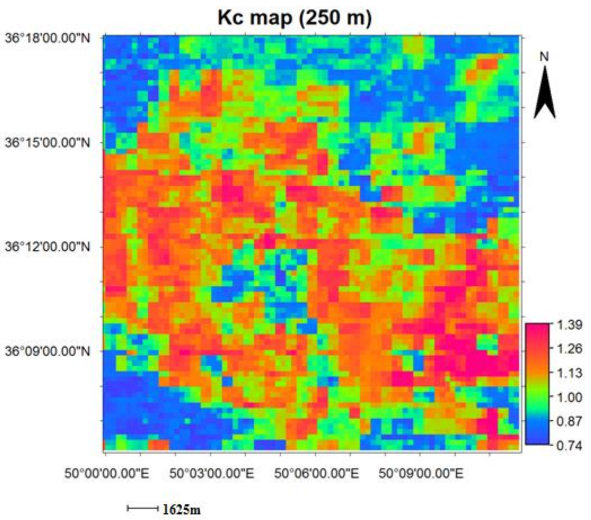


Figure 5.19 NDVI map derived of MODIS (250m)

5.3.3.2. K_c from SEBS algorithm

SEBS algorithm was carried out to estimate the actual crop evapotranspiration. It was assumed that the area is well irrigated and therefore, the average actual evapotranspiration can be equal to the potential evapotranspiration. Average K_c for Sharif Abad WUA was estimated. Table 5.14 shows the regional K_c derive using SEBS algorithm.

Table 5.15 Regional K_c value of Sharif Abad WUA (SEBS algorithm)

Date	Regional K_c Sharif Abad WUA	
	ASTER (90 m)	**MODIS (1 Km)**
24-May	1.37	1.4
27-May	1.32	1.45
13-Jul	1.06	1.15
26-Aug	1.18	1.21
27-Sep	1.03	0.95

Regression equation between regional K_c MODIS and ASTER was tested. Figure 5.20 shows correlation between ASTER regional K_c and MODIS regional K_c. Correlation coefficient (r) value showed that there is significance relationship between variables (regional K_c MODIS and ASTER). Null hypothesis (H_0 A=1 and H_0= B=0) for regression coefficient was rejected.

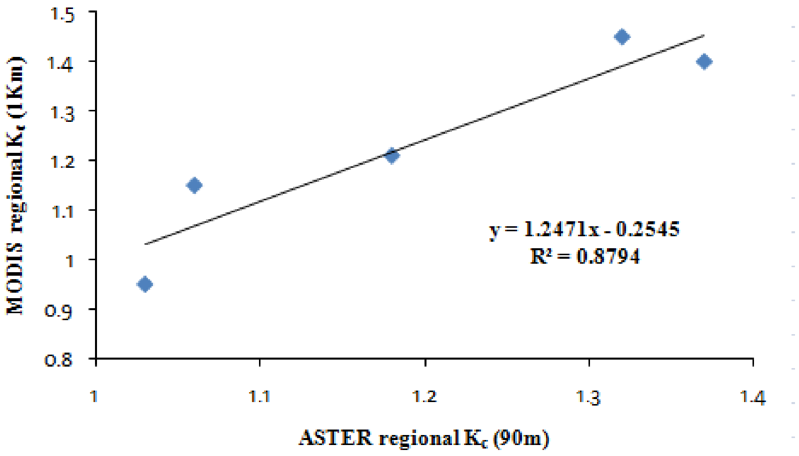


Figure 5.20 Correlation between ASTER regional K_c and MODIS regional K_c (SEBS algorithm)

5.4. Sensitivity analysis

The sensitivity of the K_c to Relative Humidity “RH”, Temperature “T”, Wind speed “U”, Leaf Area Index “LAI”, crop height “h_c”, downward solar radiation and, canopy resistance carried out using equation 2.1. The sensitivity of the K_c has been tested for inputs used in DEMETER method. The result showed that K_c according to seniority is sensitive to temperature, LAI, K↓, RH, wind speed and then crop height. Figures 5.21 to 5.26 show the variation of K_c to variations of each individual variable.

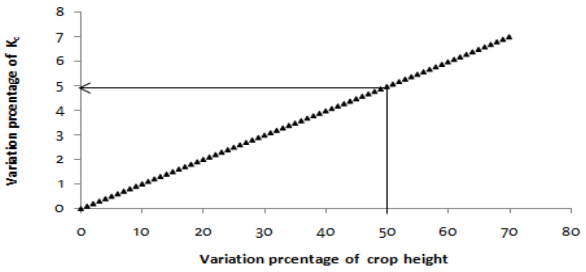


Figure 5.21 Variation fraction of K_c to h_c

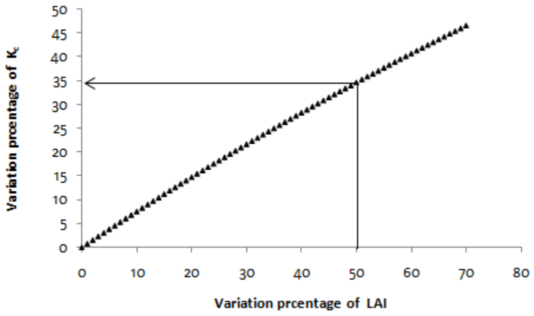


Figure 5.22 Variation of K_c with respect to LAI

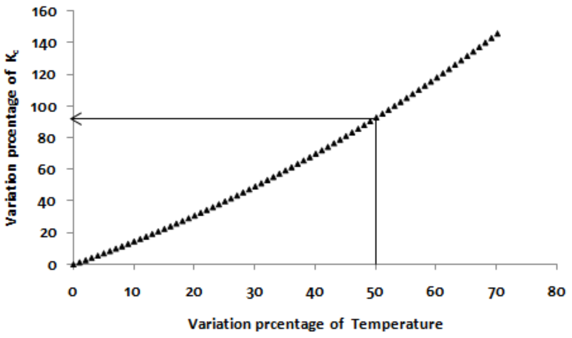


Figure 5.23 Variation of K_c with respect to T

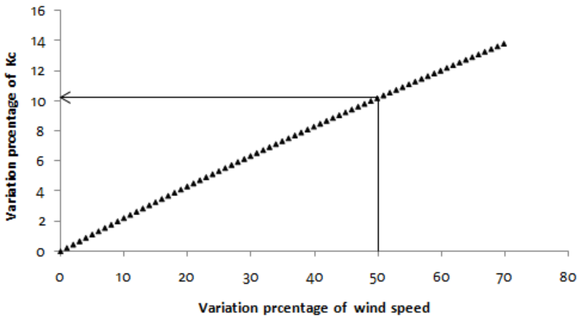


Figure 5.24 Variation of K_c with respect to U

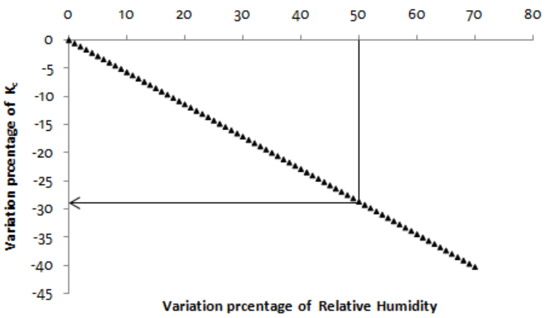


Figure 5.25 Variation of K_c with respect to *RH*

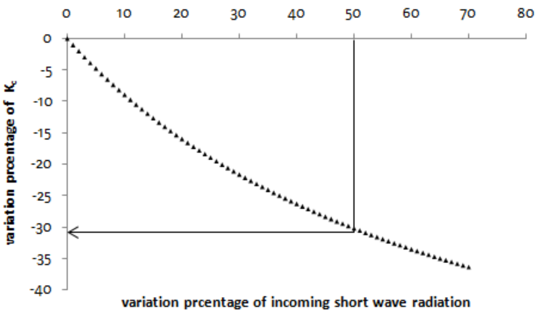


Figure 5.26 Variation of K_c with respect to $K\downarrow$

Results showed that besides crop characteristics climatological parameter have also affecting crop coefficients. This results show that the third hypothesis which was "crop coefficient is trait of crops" was rejected.

5.5. CWR annual planning

As was mentioned earlier, the objective here is to estimate to the best of our knowledge the crop water requirement of all the crops in each individual gate or water user association. In this process, the probability of occurrences of various climatic scenarios should be considered as well as a proper methodology for crop water requirements for each crop at various stages of its development. This requires estimation of crop water requirements in time and space, as well as the probability of occurrence of each climatic state.

Analyzing the 45 years rainfall data probability of various climatic states (dry, normal and wet) was determined using SPI index. Table 5.15 and Table 5.16 show occurrence probability of each state.

Table 5.16 Occurrence time of states

State	Dry	Normal	Wet
Dry	0	7	1
Normal	4	18	7
Wet	4	4	0

Table 5.17 Occurrence probability of states

State	Dry	Normal	Wet
Dry	0	0.88	0.12
Normal	0.14	0.62	0.24
Wet	0.5	0.5	0

Year 2004 was considered as a target year in which planning for water allocation should be performed. Initial climatic state (2003 year) was wet, Markov Chain Process was carried out to identify the probability of occurrences various climatic states in 2004 (Table 5.17). Using these probabilities, the expected crop water requirement for the pilot area in the course of 2004 growing period was determined.

Table 5.18 Probability of occurrence of different climatic state in year 2004

State	Initial State Probability	Result State Probability
Dry(1)	0	0.5
Normal(2)	0	0.5
Wet(3)	1	0
The number of time periods from initial:		1
Expected cost or return:		1393.02 (mm)

Average daily reference evapotranspiration for different climatic states were calculated, in all stations. Considering the analysis of the various methods of calculating K_c, the K_c derived through DEMETER analytical approach was selected as the proper crop coefficient. Considering the climatic state at 2003(wet), and the probability of having wet, normal and dry in 2004 (Table 5.18), the expected ET_0 was calculated. Next, considering the expected ET_0 and the crop coefficient the crop water requirement for each crop was calculated. Finally considering the cropping pattern in the WUA the monthly and annual required water is estimated and presented in Table 5.19 (monthly in appendix: A). This table also includes the crop water requirement as estimated by different conventional methods calculated by various institutions. Comparison of planning values with the actual crop water requirement determined using the 2004 weather data showed no significant difference at (α=0.05) between planning and the actual crop water requirement (RMSE 14.2 mm). Table 5.20 shows the percentage difference of various crop water requirement estimates from the actual crop water requirement in year 2004. The result showed that quality of annual CWR planning according to seniority is CWR planning (based on results of this research), soil and water research institute, current planning, consultants Pandam and, the Iranian water directive. The annual amount of water allocated based on the results of this research showed very little difference with what occurred in reality (around 1% difference). Figure 5.27 shows the regression level between the CWR as determined in this research and what occurred in 2004.

Table 5.19 Crop water requirement values in different documents

	Crop Water Requirement values (mm/ha)					
Crop	**CWR planning**	**Iranian Water directive a***	**Soil and water research institute b***	**Consultants PANDAM c***	**Current planning**	**Actual 2004 CWR**
Canola	648	***	***	466	700	645
Wheat	696	421	587	546	700	695
Alfalfa	1302	990	1230	1357	1650	1283
Sorghum	858	689	772	650	1100	880

a* (Alizadeh and Kamali, 2007)

b*(Farshi et al., 1997)

c*(PANDAM, 2005)

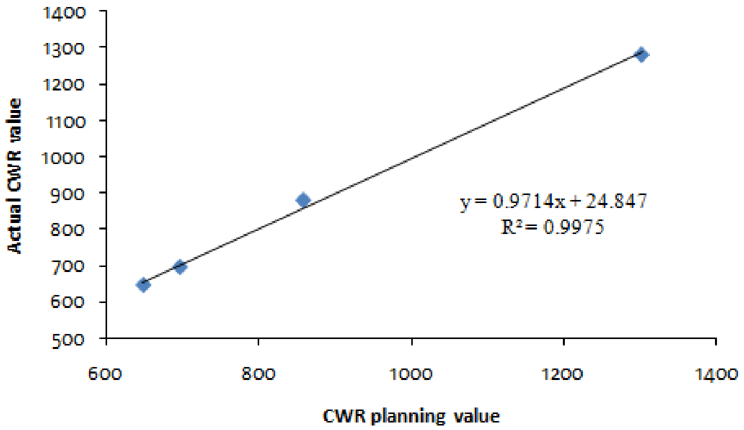


Figure 5.27 regression between CWR planning and actual CWR

Table 5.20 Percentage of differences between the annual amounts of CWR based on various methods and the actual CWR in 2004

Name	Error%
CWR planning (ITC)	1.1
Iranian Water directive	28
Soil and water research institute	10.6
Consultants PANDAM	17.4
Current planning	15.7

6. Conclusions and recommendations

This chapter is designed to answer the research questions as was formulated in the research (Chapter1). First the answers to the research questions will be given and considered as conclusions. Next, the limitation of the research will be presented, and finally based on the finding of the research some recommendation for further research will be presented.

6.1. Conclusions

In this section the research questions and their corresponding answers are presented.

1. What are the climatic scenarios and how can they be defined?
   Climatic scenarios were defined by classification of years in wet, dry and, normal classes using SPI drought indexes. Each class forms one climatic scenario with different crop water requirement characteristic.

2. Which method of crop coefficient estimation is most appropriate for determining crop water requirements?
   Out of the four methods tested for crop coefficient estimation, the FAO-56 method when it was adjusted to local conditions, and crop coefficient derived from DEMETER analytical approach were proved to be most suitable method for determining crop water requirement. Using surface energy balance methods has to be applied cautiously. This method needs the support of enough information about irrigation situation and field data.

3. Are there differences between crop water requirements in different scenarios?
   Average daily reference evapotranspiration was proved to be different in various scenarios. Moreover, crop water requirement in dry conditions (dry year) was higher than normal and the wet year. This implies that the irrigation requirements should be differentiated according to scenarios, which is currently not done.

4. What are the relations between K_c calculated at different scales (MODIS and ASTER)?
   There was no significant difference at level ($\alpha=0.05$) between the average crop coefficient maps derived from using ASTER and MODIS images with DEMETER analytical approach (proper method for K_c estimation). This was an important finding that implies public domain available MODIS data can be successfully and effectively be applied in water allocation process in irrigation networks.

5. Could remote sensing technology improve the processes of planning for annual water allocation at each delivery points (gates)?
   The finding of this research proved that advanced remotely sensed based methods such as DEMETER has great potential and application in water allocation planning. This was proved to be the case by using the high resolution as well as the medium and low resolution satellite

data. In particular this research proved that MODIS data and products which are publicly available can operationally be applied in water allocation planning in irrigation networks. This can be implemented at each individual gates (water user association) as well as large networks.

In this part hypothesis and their corresponding assessment is presented.

- The existing assessment of crop water requirement can be improved through remote sensing technology.
  Using remote sensing technology in different methods like DEMETER and SEBS algorithm in to locally estimate crop coefficient improved CWR planning. This technology could be used real time CWR planning.

- Low resolution satellite data can be used for estimation of CWR.
  In this study it has been shown that there were no significant difference at level ($\alpha = 0.05$) between MODIS and ASTER images for making crop coefficient map and determining CWR. Therefore low resolution satellite images can be used for estimation of CWR.

- Crop coefficient is trait of crops
  Results showed that besides crop characteristics climatological parameter have also affecting crop coefficients. This rejected the third hypothesis which was “crop coefficient is trait of crops”.

- Determination of crop water requirement based on average historical meteorological data is far from reality of each year and, derivation of CWR for wet, normal and dry year will improve the estimates of CWR.
  The crop water requirements in different year proved to be different from the average year. Annual crop water planning using Marcov chain, which considering probability of occurrence of different climatic states proved to produce results very close to reality (2004 year).

6.2. Limitation of the research

This research like many others was not implemented in an ideal environment, and suffered from several shortcomings as follows:

- No possibility for field work for data collection and field test, observations and evaluation. A number of parameters which could have been taken from fields observation were estimated using empirical relations
- Lack of lysimeter data for all crops for validating the results
- Lack of ASTER images in the initial growth stages of some of the crops
- Lack of ASTER images of study area in one explicit year
- Lack of station near the study area for atmospheric correction
- Difficulties of contact with experts in study area for checking some information in different way

6.3. Recommendations

This research presented some of the potential applications and the role of remotely sensing data and methods in irrigation management. Especially with the current trends in the availability and accessibility of the high, medium and low temporal and spatial resolution satellite data, more opportunities will be created. To improve the applicability of this data and method the following applications and line of research are recommended.

- To utilize remote sensing images to obtain real-time and cost-effective spatial information and crop coefficient maps. Such system can then support annual and short period time planning of agricultural water allocation.

- Sensitivity analysis of crop coefficient with respect to different variables using DEMERER analytical approach showed that the crop coefficient is most sensitive to leaf area index and temperature. It is recommended that these variables are considered in the adjustment procedure of standard FAO-56 KC table.

- Comparisons of the average K_c derived from high and low resolution satellite data in irrigation network did not show significant differences. This shows that low resolution satellite data can be applied in irrigation management. Its application is therefore highly recommended.

- Current research, due to its limitations has used satellite data of different years to calculate K_c of various crops in various development stages. To further highlight the applicability of satellite data it is highly recommended that the exercise being repeated with satellite data of one growing period.

- Using satellite images in one explicit year in order to specify peak volume of water consumption for water user associations is recommended.

- Using real time meteorological data at acquisition time of satellite images in order to determination of CWR for water user association is suggested to gain more accurate result. Range of effluence estimate between meteorological stations (ET_0) in order to allot meteorological information of stations to specific water user association instead of several times interpolation of data is recommended.

- Estimation of crop water stress through comparisons of the actual crop evapotranspiration and the crop water requirements based on remote sensing is another recommended area of interest.

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Appendices

Appendix A: Crop water requirement in different reference

Current CWR estimation in Ghaznin network

Crops	Irri. times	Apr.	May	Jun	Jul	Aug	Sep	Oct	Nov	CWR (m^3)
Wheat	5	1000	2000	1000				2000	1000	7000
		1000	2000	2000				2000	2000	9000
Barley	4	1000	2000					2000	1000	6000
Sugar beet	14	2000	2000	2500	3500	3500	2000	1000		16500
Pea & Lentil	4	1500	1000	2000	1000					5500
Maize	8			2000	2500	2500	2000	1000		10000
Sorghum	9		2000	2000	2500	2500	2000			11000
Potato	11		2500	2000	3500	2500	2000			12500
Tomato(seed)	14	1000	3000	2000	3000	3000	2000	2000		16000
Tomato	13		3000	3000	2000	3000	2000	2000		15000
Onion and carrot	13	1500	3000	3000	3000	2500	2000			15000
Sun flower	5		2000	1500	2500	1000				7000
Been	7		1000	2000	2500	2500	1000			9000
Corn	6		1500	1200	1200	2200	1400			7500
Cotton	8		2000	1000	2500	2500	2000			10000
Water melon	5		1000	2000	1500	1500	1000			7000
Alfalfa	16	1500	2000	3000	3000	3000	2000	2000		16500
Canola	5	1500	2000				2000	1500		7000
Cucumber	6		2000	1500	2000	1500				7000
Young fruit	19	1000	1000	1500	2000	2000	2000	1500	1000	12000
Fruit	19	1500	1500	2000	3000	3000	3000	3000	1500	18500
Grape	6		1500		1500	1500				4500
Grape(traditional)	2		3000	2000						5000

CWR estimation for Ghazvin network based on water directive document

Crops	Apr.	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	CWR (mm)
Wheat	115	133	52				7	16	13	8	20	57	421
Alfalfa	80	101	142	161	155	128	80	43	22	15	22	41	990
Sorghum		13	85	222	233	136							689

CWR estimation for Ghazvin network based on water research institute book

Crops	Apr.	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	CWR (mm)
Wheat	134	188	93.7				11.2	21.8	15.1	14	27.4	81.9	586.6
Alfalfa	116	170	209	225	207	144	76.7					82.6	1230.3
Sorghum		53.7	151	231	219	68.3							722.3

CWR estimation for Ghazvin network based on PANDAM report

Crops	Apr.	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	CWR (mm)
Wheat	79.8	145	78.6				13.3	16.2				24.9	357.69
Alfalfa	55.9	112	177	204.7	197.2	167.2	138	53.3				17.9	1123.32
Sorghum			100.2	187.3	217.8	140.6							645.9
Canola	87.0	93.1					45.8	15.2				37.1	278.2

CWR estimation (planning for 2004 year) for Sharif Abad WUA in this study

Crops	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	CWR (mm)
Wheat	142.6	202.7	169.6	3.4			20.8	20.5	11.8	11.7	28.2	84.7	696.1
canola	146.1	191.5	116.2			12.1	32.0	18.0	10.3	10.2	26.6	85.5	648.3
Alfalfa	129.3	170.7	234.2	278.9	228.1	183.9	39.9					37.8	1302.8
Sorghum		5.4	103.2	255.6	288.2	205.8							858.1

CWR (2004 year) for Sharif Abad WUA in this study

Crops	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	CWR (mm)
Wheat	132	176	178	3.35			21.3	19.6	10.6	11.4	39.5	103	695.3
canola	135	166	120			12.5	32.2	17.3	9.4	9.98	37.2	104	644.5
Alfalfa	119	148	248	255	248	185	35.4					45	1283.5
Sorghum		4.3	109	234	302	204	26.2						880.0

Appendix B: Average daily reference evapotranspiration in different classes

Julian day	Dry	Normal	Wet	Julian day	Dry	Normal	Wet	Julian day	Dry	Normal	Wet
1	1.03	0.83	0.79	**61**	2.34	1.94	1.87	**121**	4.50	4.42	4.65
2	1.01	0.84	0.74	**62**	1.99	1.88	2.02	**122**	4.43	4.17	4.55
3	0.93	0.90	0.86	**63**	2.54	2.00	1.82	**123**	4.31	4.13	4.46
4	0.93	0.84	0.84	**64**	2.30	2.15	1.87	**124**	4.65	4.40	4.09
5	0.96	0.87	0.93	**65**	2.79	2.27	2.83	**125**	4.50	4.40	4.11
6	0.92	0.84	0.78	**66**	2.76	2.17	2.81	**126**	4.55	4.47	4.31
7	0.80	0.80	0.72	**67**	2.60	2.04	2.07	**127**	4.70	4.51	4.03
8	0.97	0.86	0.89	**68**	2.42	2.23	2.57	**128**	4.93	4.69	4.64
9	0.94	0.76	0.73	**69**	2.40	2.36	2.43	**129**	5.33	4.84	4.42
10	1.02	0.77	0.82	**70**	2.37	2.40	2.14	**130**	5.00	4.97	4.37
11	0.84	0.76	0.76	**71**	2.70	2.22	2.56	**131**	5.00	4.90	4.46
12	0.90	0.79	0.76	**72**	2.46	2.13	2.51	**132**	5.18	4.56	4.47
13	0.90	0.79	0.99	**73**	2.55	2.51	2.06	**133**	5.43	4.62	5.13
14	0.97	0.85	1.00	**74**	2.30	2.24	2.50	**134**	5.16	4.98	4.93
15	1.12	0.82	0.79	**75**	2.50	2.19	2.48	**135**	5.32	4.90	4.89
16	1.11	0.77	0.72	**76**	2.63	2.17	2.30	**136**	5.60	5.24	4.56
17	1.40	0.78	0.94	**77**	2.70	2.26	1.90	**137**	5.22	5.12	5.04
18	1.21	0.87	1.01	**78**	2.66	2.56	2.36	**138**	5.16	4.90	4.70
19	0.94	0.90	0.68	**79**	2.38	2.64	2.61	**139**	5.08	5.34	4.88
20	0.93	0.86	0.97	**80**	2.72	2.78	2.55	**140**	5.59	5.36	4.31
21	1.04	0.88	0.86	**81**	2.67	2.71	2.43	**141**	5.34	5.31	4.50
22	0.99	0.85	0.68	**82**	2.61	2.79	2.36	**142**	6.15	5.53	4.66
23	0.84	0.94	0.75	**83**	2.89	2.84	2.50	**143**	6.00	5.47	5.14
24	1.07	0.97	0.86	**84**	3.10	3.00	2.92	**144**	6.51	5.35	5.06
25	1.08	1.00	0.81	**85**	3.04	3.08	2.40	**145**	6.20	6.03	5.25
26	1.03	0.90	0.88	**86**	3.31	3.18	2.20	**146**	6.00	5.93	5.57
27	0.88	1.00	0.95	**87**	2.80	3.00	2.64	**147**	6.00	5.92	4.85
28	1.25	0.94	0.79	**88**	2.81	3.15	2.54	**148**	6.00	6.13	5.22
29	1.05	0.99	0.97	**89**	3.11	3.22	2.76	**149**	6.00	5.77	4.66
30	0.93	0.99	0.82	**90**	3.01	2.99	3.05	**150**	6.00	5.97	4.94
31	1.16	1.08	1.19	**91**	3.58	3.31	2.97	**151**	6.22	5.89	5.75
32	1.16	1.08	0.99	**92**	3.01	3.23	3.28	**152**	6.00	5.96	6.12
33	1.17	1.07	0.82	**93**	3.97	3.37	3.48	**153**	6.70	6.02	6.12
34	1.14	1.12	1.36	**94**	2.92	3.41	3.53	**154**	6.70	6.20	5.93
35	1.42	1.23	1.10	**95**	3.37	3.20	3.25	**155**	6.40	6.17	6.58
36	1.33	1.30	0.93	**96**	3.58	3.34	3.68	**156**	6.35	6.70	6.03
37	1.26	1.23	1.02	**97**	3.29	3.50	3.56	**157**	7.00	6.78	6.17
38	1.34	1.21	1.14	**98**	3.15	3.52	3.23	**158**	7.00	6.73	6.54
39	1.41	1.35	1.20	**99**	3.80	3.69	3.60	**159**	6.66	6.51	6.68
40	1.38	1.21	1.46	**100**	3.58	3.51	4.13	**160**	6.46	6.40	6.05
41	1.33	1.18	1.23	**101**	3.35	3.64	3.84	**161**	6.26	6.51	6.76
42	1.30	1.38	1.48	**102**	3.42	3.75	4.00	**162**	6.63	6.79	6.61
43	1.39	1.33	1.39	**103**	3.41	3.76	3.62	**163**	7.00	6.69	7.35
44	1.46	1.32	1.29	**104**	3.36	3.93	3.39	**164**	7.00	6.75	6.57
45	1.61	1.44	1.29	**105**	4.05	4.03	3.72	**165**	7.00	6.87	6.58
46	1.65	1.67	1.32	**106**	4.00	4.01	3.83	**166**	6.20	6.48	6.94
47	1.70	1.48	1.21	**107**	4.00	3.98	3.90	**167**	6.50	6.84	6.53
48	1.65	1.37	1.37	**108**	3.74	3.86	4.24	**168**	7.05	6.88	7.14
49	1.43	1.43	1.15	**109**	4.00	4.17	4.05	**169**	7.00	6.90	6.67
50	1.66	1.57	1.33	**110**	4.20	4.11	4.53	**170**	6.80	6.47	7.07
51	1.90	1.70	1.30	**111**	4.00	3.84	4.55	**171**	7.50	7.07	7.22
52	2.05	1.71	1.40	**112**	4.20	4.06	4.14	**172**	7.20	6.94	7.06
53	2.07	1.76	1.44	**113**	4.10	4.06	4.22	**173**	7.01	6.76	7.60
54	1.64	1.72	1.38	**114**	4.30	4.03	3.80	**174**	7.24	7.05	6.89
55	1.79	1.87	1.59	**115**	4.33	3.86	3.55	**175**	6.46	7.02	6.50
56	2.11	2.00	1.67	**116**	4.34	4.03	4.30	**176**	7.22	6.60	6.88
57	2.10	1.93	1.66	**117**	4.61	4.25	4.15	**177**	7.40	7.13	6.31
58	2.15	1.88	1.51	**118**	4.42	3.98	4.10	**178**	8.00	7.75	6.94
59	2.07	1.81	1.58	**119**	4.12	4.03	3.79	**179**	7.50	7.02	6.39
60	2.05	1.94	1.48	**120**	4.29	4.26	4.31	**180**	8.00	7.29	6.92

Julian day	Dry	Normal	Wet	Julian day	Dry	Normal	Wet	Julian day	Dry	Normal	Wet
181	7.90	7.42	6.97	**243**	5.62	5.97	5.43	**305**	2.10	2.14	1.99
182	7.80	7.59	6.96	**244**	7.00	6.16	5.37	**306**	2.13	2.09	1.79
183	7.50	7.30	6.77	**245**	6.50	5.78	5.06	**307**	2.12	2.08	2.08
184	7.80	7.35	6.68	**246**	5.67	5.76	5.90	**308**	1.90	1.91	1.96
185	7.80	7.30	6.99	**247**	5.70	5.96	5.55	**309**	2.16	2.06	1.67
186	7.70	7.46	6.97	**248**	6.03	5.51	5.38	**310**	2.01	1.92	1.77
187	7.40	7.07	7.68	**249**	6.50	5.86	5.05	**311**	2.04	1.88	1.75
188	7.50	7.13	6.91	**250**	6.00	5.76	5.09	**312**	1.90	1.88	1.76
189	7.50	7.33	7.08	**251**	5.59	5.36	5.05	**313**	1.64	1.98	1.53
190	7.50	7.23	7.07	**252**	5.61	5.39	5.48	**314**	2.02	1.78	1.53
191	7.50	7.34	7.03	**253**	6.00	5.57	5.12	**315**	2.23	1.66	1.60
192	7.50	7.48	6.94	**254**	5.70	5.25	4.80	**316**	1.72	1.75	1.45
193	8.00	7.33	6.81	**255**	5.01	5.24	4.86	**317**	1.67	1.80	1.35
194	6.72	7.15	7.07	**256**	6.00	5.16	4.92	**318**	1.63	1.59	1.80
195	7.50	7.14	7.70	**257**	5.10	4.93	4.81	**319**	1.60	1.53	1.38
196	7.50	7.13	7.32	**258**	5.00	4.78	4.96	**320**	1.61	1.40	1.42
197	7.90	7.61	7.62	**259**	5.11	4.74	5.11	**321**	1.76	1.50	1.17
198	7.70	7.55	7.53	**260**	5.00	4.67	5.21	**322**	1.44	1.48	1.26
199	7.50	7.22	6.64	**261**	5.30	5.12	4.51	**323**	1.55	1.46	1.47
200	7.50	7.23	7.23	**262**	5.30	4.98	4.71	**324**	1.30	1.53	1.21
201	7.40	7.15	7.01	**263**	5.00	4.79	4.11	**325**	1.60	1.46	1.44
202	7.20	6.93	6.69	**264**	5.00	4.76	4.48	**326**	1.58	1.31	1.38
203	7.50	7.22	6.71	**265**	5.00	5.03	4.23	**327**	1.81	1.58	1.24
204	7.70	7.11	6.99	**266**	5.00	4.70	4.58	**328**	1.78	1.36	1.31
205	7.60	7.05	7.04	**267**	4.50	4.41	3.83	**329**	1.42	1.39	1.16
206	7.20	6.81	6.67	**268**	4.03	4.45	4.01	**330**	1.39	1.36	1.42
207	7.70	7.06	6.83	**269**	4.48	4.53	4.05	**331**	1.29	1.33	1.29
208	7.50	6.85	6.87	**270**	3.79	4.29	3.96	**332**	1.52	1.28	1.28
209	6.97	6.96	5.92	**271**	4.30	4.12	4.29	**333**	1.27	1.19	1.27
210	7.63	6.95	6.26	**272**	4.07	4.04	4.18	**334**	1.23	1.18	1.03
211	7.00	6.82	7.44	**273**	3.91	4.26	3.93	**335**	1.18	1.14	0.86
212	7.00	6.90	7.10	**274**	3.70	4.07	3.73	**336**	1.24	1.11	1.02
213	6.47	6.52	7.25	**275**	3.93	3.92	3.62	**337**	1.34	1.14	0.97
214	7.00	7.01	6.76	**276**	4.12	3.73	3.59	**338**	1.06	1.12	0.94
215	7.50	6.99	6.48	**277**	3.79	3.78	3.56	**339**	1.29	1.16	0.88
216	7.50	6.94	6.35	**278**	3.76	3.45	3.14	**340**	1.24	1.12	1.01
217	7.70	7.28	6.90	**279**	4.30	3.57	3.36	**341**	1.16	1.00	0.95
218	7.20	6.97	6.31	**280**	3.55	3.23	3.19	**342**	1.07	0.93	0.92
219	7.30	6.72	6.60	**281**	3.31	3.17	3.12	**343**	1.05	0.86	0.85
220	7.00	6.76	6.65	**282**	2.91	3.41	2.97	**344**	1.04	1.05	0.67
221	6.50	6.32	6.44	**283**	3.12	3.18	2.99	**345**	1.02	0.79	1.02
222	7.00	6.77	6.98	**284**	3.52	3.25	2.79	**346**	0.87	0.99	0.63
223	7.00	6.61	6.78	**285**	3.11	3.42	2.73	**347**	0.92	0.86	0.65
224	7.00	6.65	6.80	**286**	3.07	3.28	2.86	**348**	0.97	0.81	0.99
225	7.20	6.83	6.83	**287**	2.85	3.10	2.63	**349**	1.01	0.95	0.75
226	7.50	7.18	6.54	**288**	2.75	2.88	2.88	**350**	0.98	0.91	0.70
227	7.40	6.95	6.28	**289**	2.79	2.95	2.89	**351**	0.95	0.90	0.80
228	6.90	6.46	6.61	**290**	2.83	2.76	3.54	**352**	1.06	0.88	1.06
229	7.50	6.55	6.18	**291**	2.50	2.68	2.91	**353**	1.03	0.88	1.16
230	7.06	6.25	5.79	**292**	2.49	2.92	2.70	**354**	1.02	0.81	0.84
231	6.59	6.44	6.37	**293**	2.67	3.13	2.78	**355**	0.96	0.86	0.84
232	6.38	6.23	6.29	**294**	2.86	2.72	2.51	**356**	0.99	0.98	0.74
233	6.31	6.31	6.96	**295**	2.34	2.59	2.29	**357**	0.93	0.96	0.63
234	6.33	6.66	6.55	**296**	2.30	2.51	2.28	**358**	0.79	0.91	0.60
235	6.08	6.30	6.08	**297**	2.44	2.27	2.51	**359**	0.98	0.86	0.59
236	6.01	6.18	6.35	**298**	2.10	2.45	2.78	**360**	1.00	0.87	0.69
237	6.50	6.13	6.03	**299**	2.10	2.48	2.79	**361**	0.96	0.77	0.72
238	6.50	5.89	6.39	**300**	2.03	2.66	2.84	**362**	0.96	0.79	0.87
239	6.00	5.84	6.34	**301**	2.24	2.44	2.54	**363**	1.24	0.88	1.04
240	6.50	5.93	6.20	**302**	1.99	2.23	2.55	**364**	1.10	0.87	0.75
241	6.50	5.97	5.48	**303**	2.41	2.43	2.28	**365**	0.89	0.80	0.65
242	6.70	5.84	5.57	**304**	2.18	2.23	2.08	**SUM**	**1420.00**	**1366.40**	**1315.58**

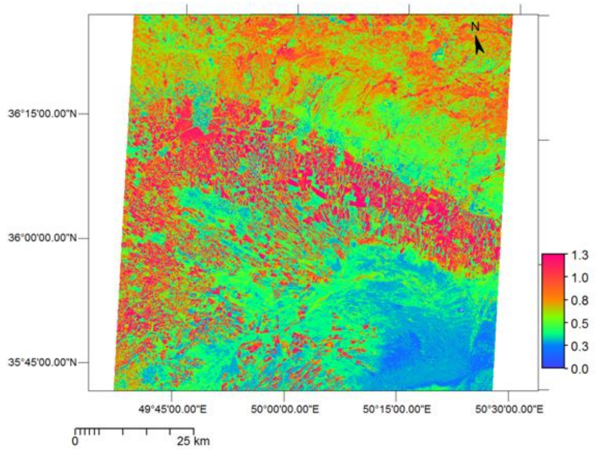
Appendix c: Classified years using SPI index

Year	SPI
1961	-1.27
1962	0.21
1963	0.68
1964	-2.04
1965	0.24
1966	-0.25
1967	-1.69
1968	0.71
1969	1.41
1970	-1.12
1971	-0.23
1972	2
1973	-1.99
1974	-0.6
1975	-0.04
1976	-0.46
1977	1.49
1978	-0.52
1979	-0.43
1980	0.07
1981	0.21
1982	1.84
1983	-0.39
1984	1.29
1985	-0.8
1986	-0.04
1987	1.01
1988	0.45
1989	-0.65
1990	-0.61
1991	0.42
1992	0.75
1993	0.69
1994	1.46
1995	-1.33
1996	1.54
1997	-1.38
1998	0.17
1999	-0.86
2000	-0.01
2001	-1.14
2002	0.31
2003	1.05
2004	0.16
2005	-0.33

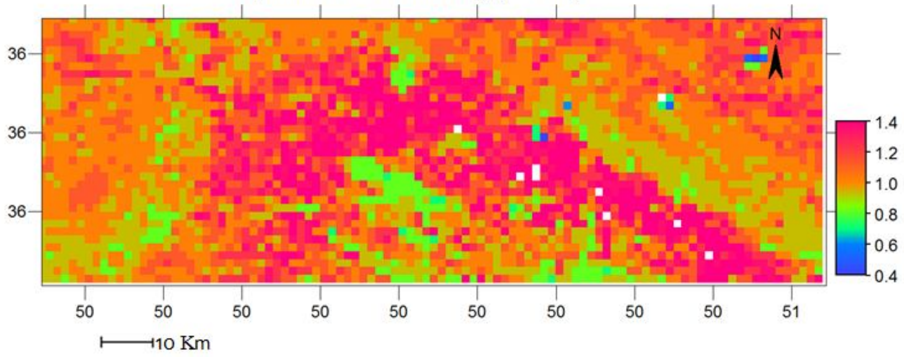
Classified year		
Dry	Normal	Wet
1961	1962	1969
1964	1963	1972
1967	1965	1977
1970	1966	1982
1973	1968	1984
1995	1971	1994
1997	1974	1996
2001	1975	2003
	1976	
	1978	
	1979	
	1980	
	1981	
	1983	
	1985	
	1986	
	1987	
	1988	
	1989	
	1990	
	1991	
	1992	
	1993	
	1998	
	1999	
	2000	
	2002	
	2004	
	2005	

Appendix D: K_c maps using DEMETER analytical approach

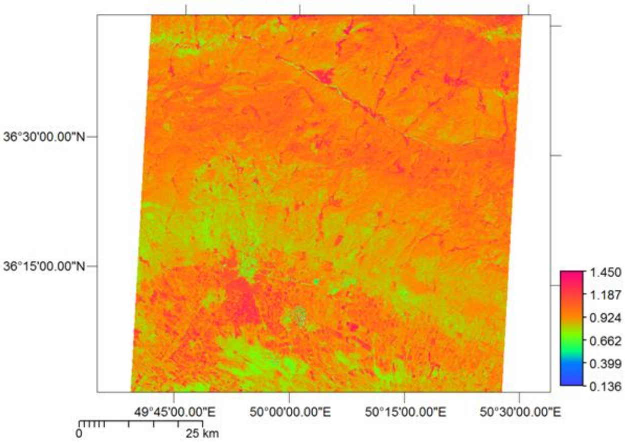
Crop coefficient man on 24th of may (ASTER)



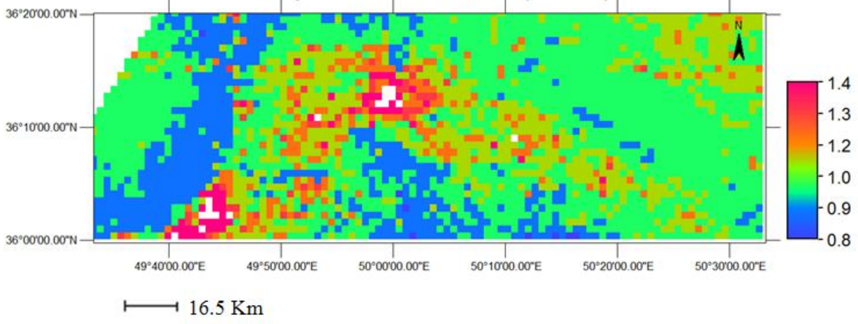
Crop coefficient 24 th May (MODIS)

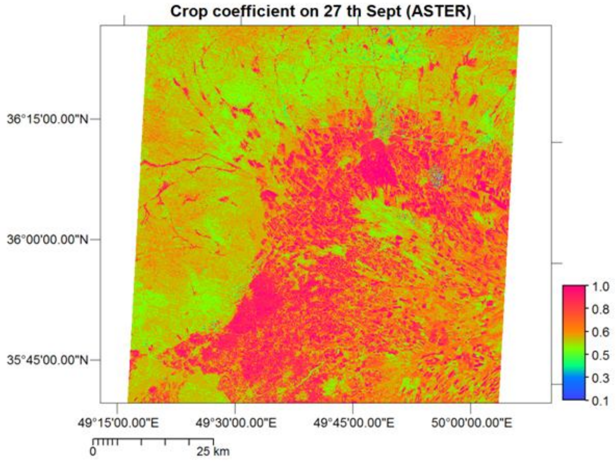


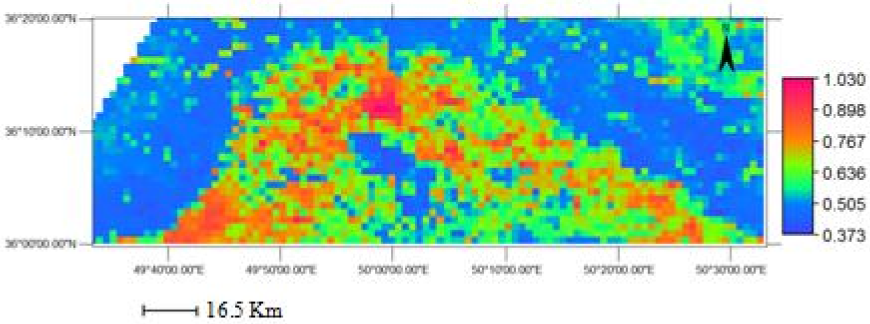
Crop coefficient on 13 th Jul (ASTER)

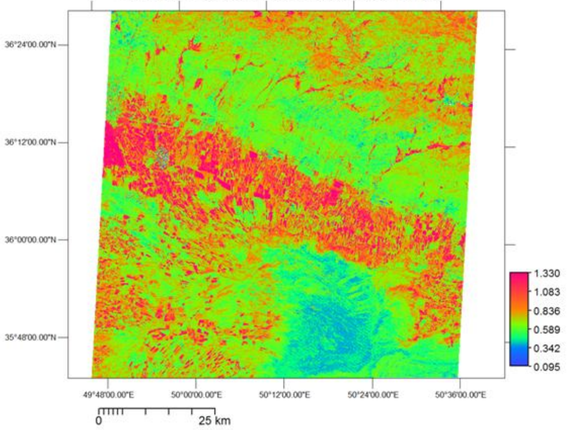


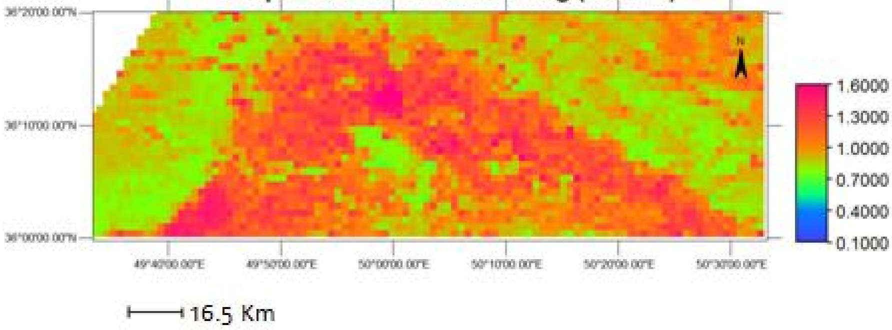
Crop coefficient 13th Jul (MODIS)




Crop coefficient on 27 th Sept (ASTER)

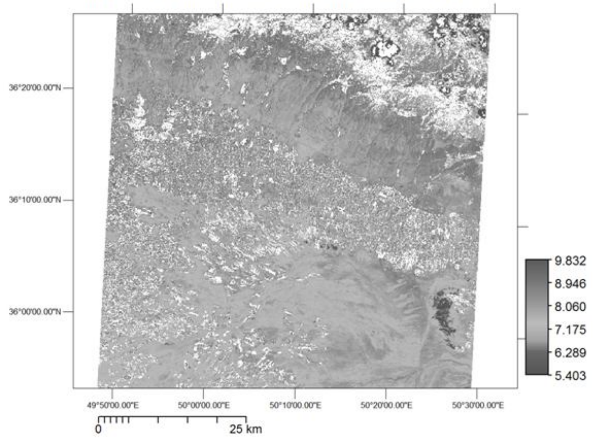

Crop coefficient 27th Sept (MODIS)


Crop coefficient map on 26th Aug (ASTER)

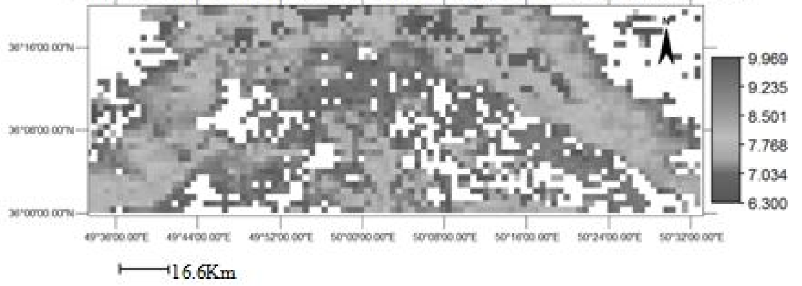

Crop coefficient on 26th Aug (MODIS)

Appendix E: Actual daily evapotranspiration using SEBS algorithm

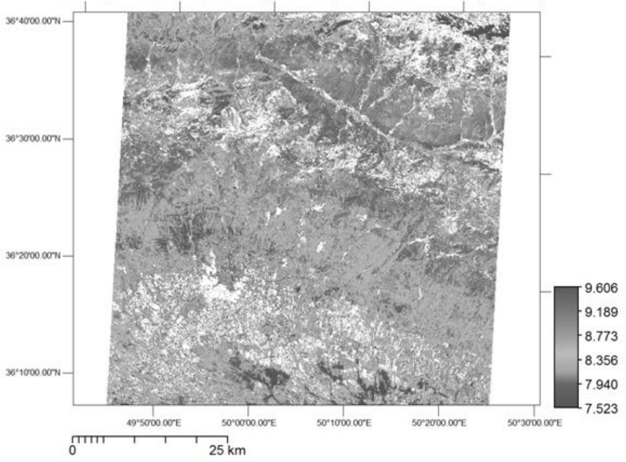
Daily actual evapotranspiration (mm) on 27th May (Aster)



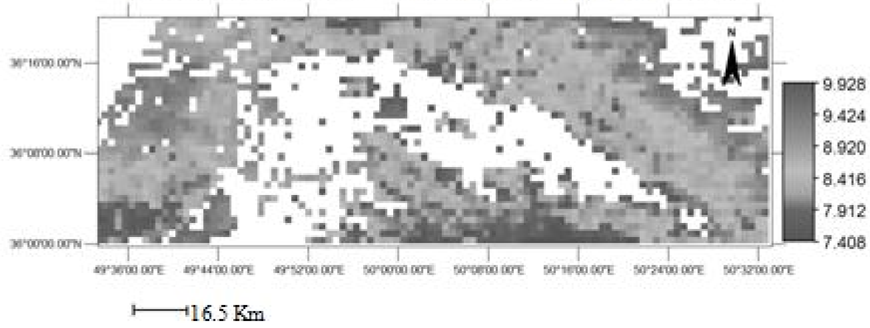
Daily actual evapotranspiration (mm) on 27th May (MODIS)

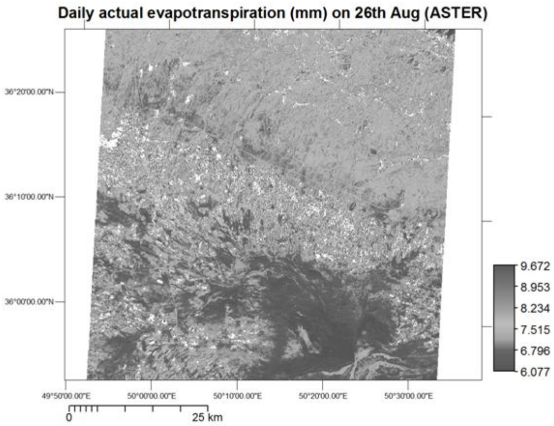


Daily actual evapotranspiration (mm) on 13th Jul (ASTER)

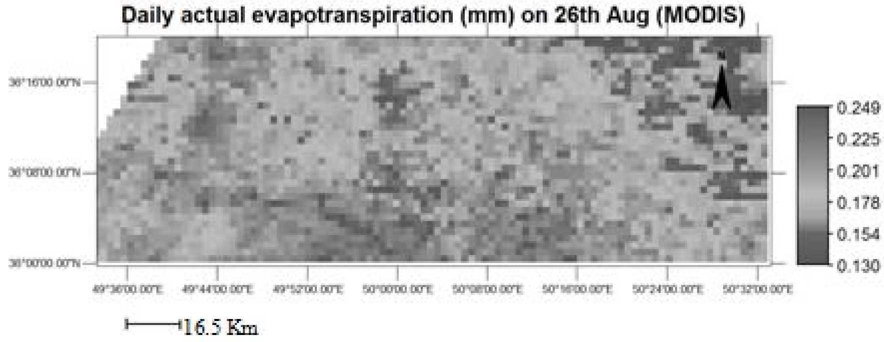


Daily actual evapotranspiration (mm) on 13th Jul (MODIS)

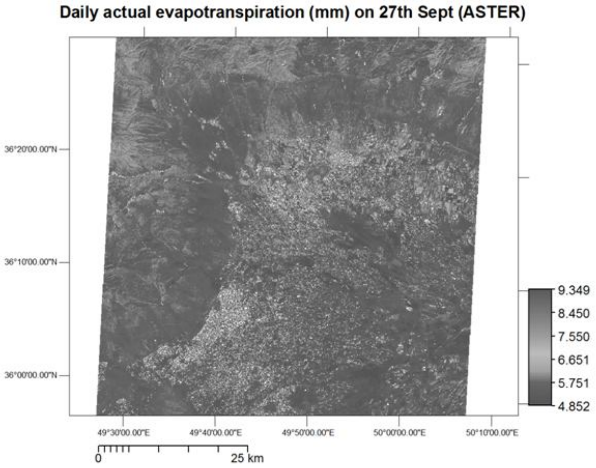




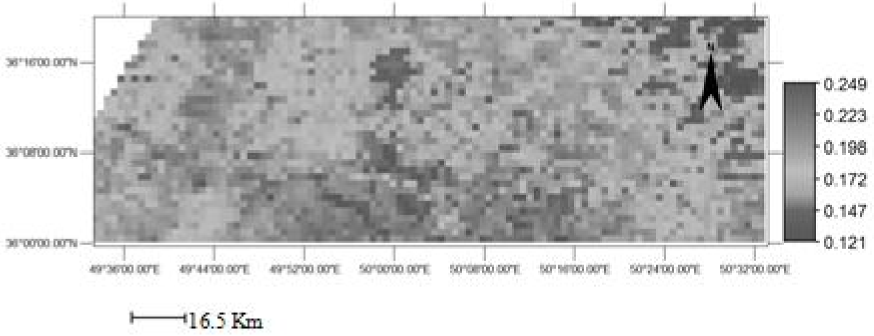
Daily actual evapotranspiration (mm) on 26th Aug (ASTER)



Daily actual evapotranspiration (mm) on 26th Aug (MODIS)



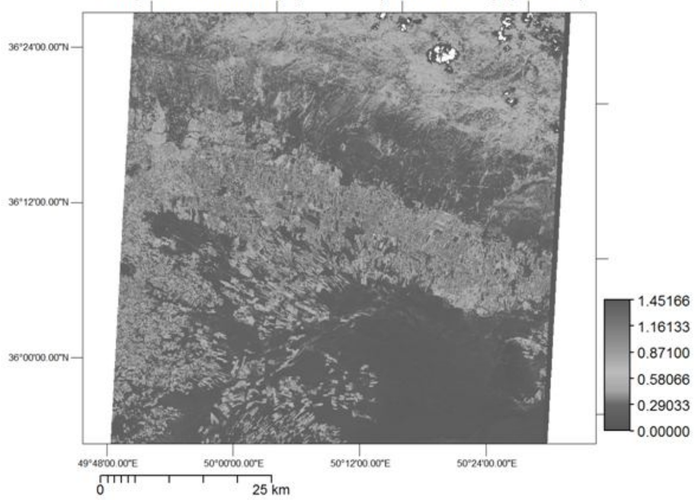
Daily actual evapotranspiration (mm) on 27th Sept (ASTER)



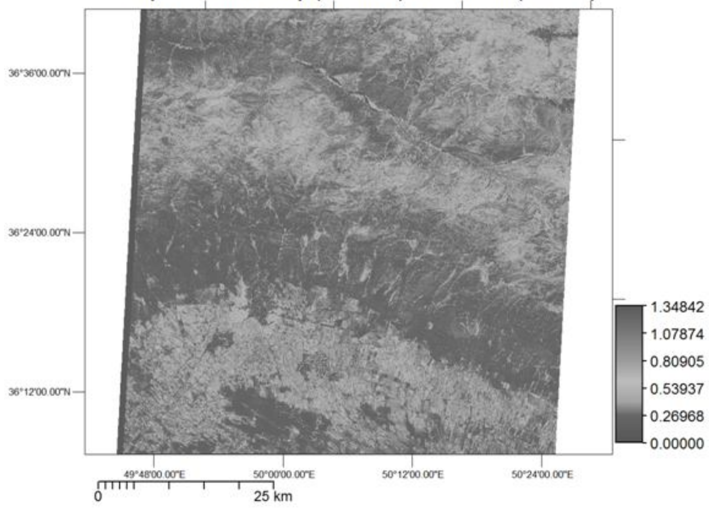
Daily actual evapotranspiration (mm) on 27th sept (MODIS)

Appendix F: Crop coefficient maps using K_c-NDVI

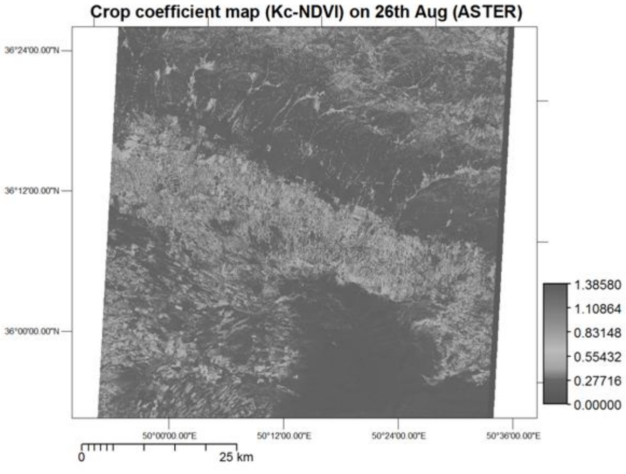
Crop coefficient map (Kc- NDVI) on 27th May (ASTER)

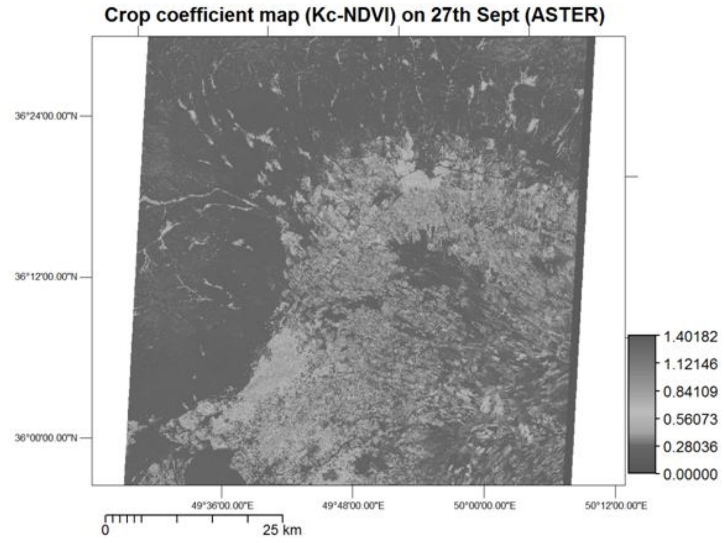


Crop coefficient map (Kc-NDVI)ON 13th Jul (ASTER)



Crop coefficient map (Kc-NDVI) on 26th Aug (ASTER)




Crop coefficient map (Kc-NDVI) on 27th Sept (ASTER)
36°24'00.00"N
36°12'00.00"N
36°00'00.00"N
49°36'00.00"E
49°48'00.00"E
50°00'00.00"E
50°12'00.00"E
1.40182
1.12146
0.84109
0.56073
0.28036
0.00000
0
25 km

Appendix G: Marcov Chain Total expected return/cost

Starting time period:	1
Ending time period:	10
Step:	1

State Name	**State Probability**	**Recurrence Time**
Dry	0.1785	5.6031
Normal	0.6452	1.5498
Wet	0.1763	5.6729
Expected	Cost/Return=	1366.772

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