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Review Article

DETERMINATION OF ACTUAL CROP EVAPOTRANSPIRATION (ET_C) AND DUAL CROP COEFFICIENTS (K_C) FOR COTTON, WHEAT AND MAIZE IN FERGANA VALLEY: INTEGRATION OF THE FAO-56 APPROACH AND BUDGET

[1]Shavkat Kenjabaev, [2]Hans Georg Frede, [3]Ilkhom Begmatov, [3]Sabirjan Isaev, [3]Bakhtiyar Matyakubov

[1]Department of Scientific-Research, Scientific Information Centre of Interstate Coordination Water Commission, Tashkent, Uzbekistan.
[2]Institute of Landscape Ecology and Resources Management, Justus-Liebig-University Giessen, Gießen, Germany.
[3]Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, Tashkent, Uzbekistan.
E-mail address: kenjabaev@yahoo.com

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Abstract
Determination of the actual crop evapotranspiration (ETc) during the growing period is important for accurate irrigation scheduling in arid and semi-arid regions. Development of a crop coefficient (Kc) can enhance ETc estimations in relation to specific crop phenological development. This research was conducted to determine ETc values as well as daily and growth-stage-specific Kc for cotton, winter wheat and maize for silage at fields in Fergana Valley (Uzbekistan). The soil water balance model - BUDGET with integration of the dual crop procedure of the FAO - 56 was used to estimate the ETc and separate it into evaporation (Ec) and transpiration (Tc) components. An empirical equation was developed to determine the daily Kc values based on the estimated Ec and Tc. The Kc determination and comparison to existing FAO Kc values were performed based on 10, 5 and 6 study cases for cotton, wheat and maize, respectively. Mean seasonal amounts of crop water requirement in terms of ETc were 560 ± 50, 509 ± 27 and 243 ± 39 mm for cotton, wheat and maize, respectively. Estimated ETc for these crops were 1.10 - fold, 1.09 - fold and 0.73 - fold of recommended irrigation norm according to currently used hydromodule zoning (GMR) under semi-hydromorphic reclamation regime in Fergana province. The growth-stage-specific Kc for cotton, wheat and maize was 0.15, 0.27 and 0.11 at initial; 1.15, 1.03 and 0.56 at mid; and 0.45, 0.89 and 0.53 at late season stages. These Kc values correspond to those reported by the FAO - 56. Development of site specific Kc helps tremendously in irrigation management and furthermore provides precise water applications in the region. The developed simple approach to estimate daily K_c for the three main crops grown in the Fergana region was a first attempt to meet this issue.

Keywords: Actual crop evapotranspiration, evaporation and transpiration, crop coefficient, BUDGET, Fergana Valley.

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INTRODUCTION

Agriculture in Uzbekistan, due to arid climate, relies heavily on irrigation, where about 90 % of the water supply is used by agricultural sector for irrigation on roughly 4.2 Mha of land [1, 2]. About 98% of these irrigated lands are practiced by furrow irrigation [3, 4].

Cotton (Gossypium hirsutum L.) and winter wheat (Triticum aestivum L.) are major crops in the country; occupy about 70 - 80 % of irrigated lands, followed by maize (Zea mays L.), vegetables, and fruits [5, 6]. Indeed, water use in these croplands is hampered due to its inefficient supply and poor management within the irrigation system [7, 8, 9]. Crop specific irrigation norms and application modes including required water for planning and distribution are based on hydromodule zoning (GMR) practiced since 1986 in the region [10, 11].

Although, the GMR is simple and considers hydrogeological-soil-climatic conditions, due to its static nature in terms of the irrigation as well as watering norms within the unit, is lacking to consider variability of climate, crop, groundwater level (GWL) and other land reclamation conditions changed over the years. Hence, water requirements of major crops are not well known contributing to excess water use or aggravating water scarcity situation [5]. Water users tend to adopt high irrigation norms leading high deep percolation and poor use of rainfall [8]. High irrigation norms contributing rise of GWL and fast over-siltation of collector-drainage network. It is therefore important to accurately estimate crop water requirements (CWR) to schedule irrigations properly and improve land reclamation condition.

The most widely used method to estimate CWR is based on the FAO - 56 approach [12, 13, 14, 15]. In the FAO - 56, estimation of the CWR is based upon water lost by soil evaporation (E_c) and plant transpiration (T_c), referred to collectively as crop evapotranspiration (ET_c). ET_c is calculated by multiplying evapotranspiration from a reference crop (ET_o) such as grass or alfalfa by an empirically derived crop specific coefficient (K_c).

ET_o is a climatic parameter, expresses the evaporating power of the atmosphere at a specific location and time of the year and can be computed from weather data [12]. Although, the vast number of empirical or semi-empirical equations was developed and compared to estimate ET_o [16, 17], the FAO Penman-Monteith approach is now accepted as a standard method [18,19]. Basic principles, common errors and biases endemic to ET_o measuring systems as well as recommended documentation in reporting ET_o are reviewed by Allen et al. [20, 21]. However, K_c is needed to be known to characterize the difference between the cropped (ET_c) and reference grass surface (ET_o) due to the difference in crop height (canopy roughness and aerodynamic resistance), crop-soil surface resistance (crop physiology; leaf age, area and condition; light absorption by the canopy and surface wetness) and albedo of the crop-soil surface [12, 14, 22].

Many scientists developed methods to estimate the K_c using: the fraction of ground cover (or leaf area index, LAI) and height [12, 23], crop variety and climatic conditions [12, 24], remotely-sensed vegetation indices [13, 25, 26, 27] and weighing column lysimeters (WCL) [28, 29, 30, 31, 32]. Among these methods, the WCL is considered as a precise approach to estimate the K_c [33]. Using the WCL, Ko et al. [29] and Piccini et al. [34] developed a simple method to determine the daily K_c

for cotton, wheat and summer maize as a function of days after planting (DAP) (so called a crop curve [32]:

$$Kc = 0.35 - 2.01 \cdot 10^{-3} \cdot DAP + 2.85 \cdot 10^{-4} \cdot DAP^2 - 1.67 \cdot 10^{-6} \cdot DAP^3$$

for cotton (1)

$$Kc = 0.75 - 0.02 \cdot DAP + 3.66 \cdot 10^{-4} \cdot DAP^2 - 1.54 \cdot 10^{-6} \cdot DAP^3$$

for wheat(2)

$$Kc = 0.36 - 8.89 \cdot 10^{-3} \cdot DAP + 4.02 \cdot 10^{-4} \cdot DAP^2 - 2.42 \cdot 10^{-6} \cdot DAP^3$$

for maize(3)

The K_c vary during the growing season of crops as well as according to the wetness of the soil surface, especially at the early growth stages when there is little vegetation cover [35]. In past two decades, many researchers were successfully applied time averaged single K_c approach to estimate ET_c (e.g., $ET_c = K_c * ET_o$). However, this approach has difficulty in distinguishing the impacts of irrigation or rainfall frequency on total CWR, especially when water becomes more scarce [14, 36].

Recently, advantages of dual K_c approach in estimating ET_c (e.g., $ET_c = (K_{cb} + K_e) * ET_o$)) over the single K_c approach were reviewed by [14] and tested using SimDualKc software [15].

However, estimation of the dual K_c is more complicated than the single K_c approach and expensive to develop [33]. Therefore, its wide application is still lacking [14]. Moreover, direct using the single K_c (including the K_c for cotton and wheat developed by Ko et al., [29]) or the dual K_c may lead in wrong estimation of the CWR and thereby an accuracy of irrigation scheduling may be diminished. At the same time, over-irrigation is costly (especially for Uzbekistan, as more than 60 % of water is pumped from different sources, [37] and often reduces crop yield quality.

Reported single K_c values for different crops [12] are commonly used in Uzbekistan [8, 37, 38] and elsewhere due to the lack of local data. Although the tabulated mean K_c for the main growth stages of crops are subject to a local calibration that suits given climatic conditions [12], they vary from place to place as well as from season to season and might introduce some errors in estimation of the ET_c [37]. Therefore, it needs to develop or adopt the crop coefficients for local condition, so that irrigation projects can be planned correctly.

The main objectives of this study are: (1) estimation of actual crop evapotranspiration (ET_c) for cotton, winter wheat and maize in Fergana region using model BUDGET integrated with FAO-56 approach and (2) development of the dual crop coefficients (K_c) for these crops based on evaporation (E_a) and transpiration (T_a).

MATERIALS AND METHODS

Location and description of study sites

Field trials were conducted during 2009 - 2011 at two sites, namely Akbarabad (40⁰32' - 40⁰33' N; 71⁰56' E) and Azizbek (40°28'N; 71°32'E) in Central plain part of the Fergana valley (Figure 1).

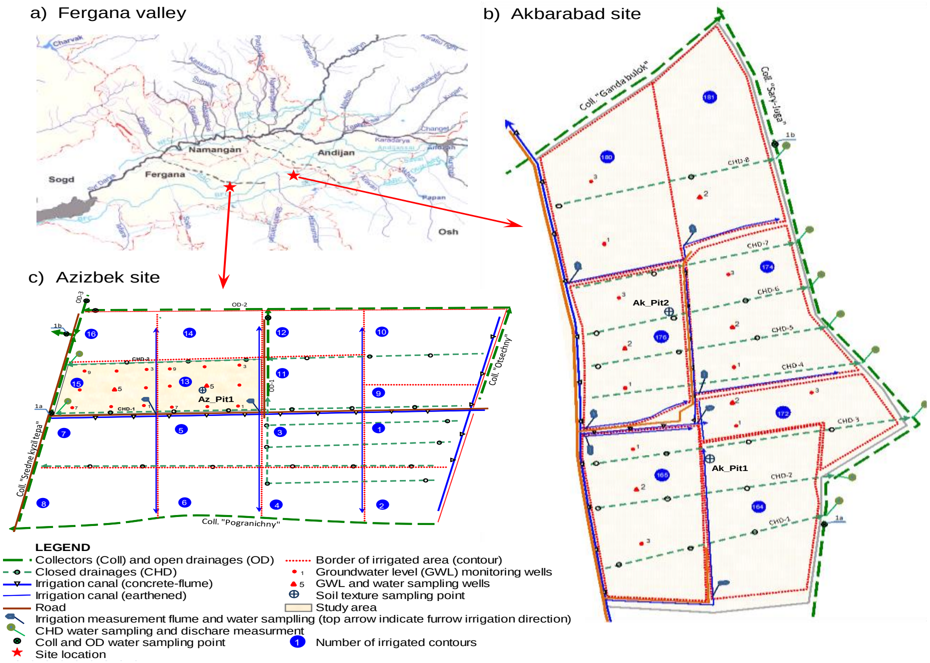

Figure 1. Location of the study sites in Fergana valley (a) and experimental set up in the fields of Akbarabad (b) and Azizbek (c)

Altogether, ten fields with land area ranging from 7 to 26.5 ha were selected for this research [39]. The main crop rotation in the fields comprises cotton and wheat as well as secondary crop - maize following wheat harvest. In 2010 and 2011 the cotton varieties "An-35" and "C-6524" were sown on the beds of the leveled field with sowing depth, beds width and plant density (after thinning) of 3 - 6 cm, 60 cm and 18 - 22 plants per m^2 in Akbarabad and 4 - 6 cm, 90 cm and 9 - 12 plants per m^2 in Azizbek, respectively. Winter wheat variety "Kuma" in Akbarabad and "Kroshka" in Azizbek were broadcast planted incorporated by cultivator into cotton stubble (the common practice in Uzbekistan) in 2009 and 2010 at a seeding rate of 200 - 210 and 220 - 250 kg ha^{-1}, respectively. Plant density of wheat was ranged from 180 to 250 plants m^{-2} at the full canopy cover stage. Maize of local variety was sown for silage with density varying 15 - 40 plants per m^2. Collector-drainage water (with electrical conductivity, EC_w of 1.1 ± 0.1 dS m^{-1}) and canal water (EC_w=0.7±0.1 dS m^{-1}) were used for irrigation of these crops in Akbarabad and Azizbek, respectively. In general, three to four irrigations with gross irrigation amount ranging from 280 to 500 mm, five to seven irrigations from 380 to 960 mm and two to four irrigations from 46 to 110 mm were applied during the growing period of cotton (by alternate furrows), wheat (every furrows) and maize (mixed), respectively during 2009 - 2011. Dates and duration of water application for these crops-fields were decided by farmers. Water was applied when it was available, thus it reflects the actual irrigation delivery rotation among other farms in the region.

Groundwater level (GWL) in both sites was shallow ranging from 0.2 to 2.4 m in Akbarabad and 1.0 - 2.7 m in Azizbek. The upper boundary of the GWL fluctuation reflects the impact of deep percolation associated with excess water applications [15]. On the contrary, the lower boundary of the GWL fluctuation can be explained by existence of tile drainages in both sites [40].

The climatic condition of the sites is characterized by data from meteorological station "Fergana" (40.38° N, 71.75° E and altitude 582 m). The respective monthly average maximum and minimum temperatures, minimum relative humidity, precipitation and reference evapotranspiration (ET_o) are presented in Figure 2 [69]. The ET_o was calculated using ET_o Calculator [19] based on the FAO Penman-Monteith equation [12].

The lands at both sites are mainly flat and slopes are 0.002 - 0.005, northward. Soils, according to FAO and Russian classifications, are Calcic Gleysols and sierozem-meadow with infiltration rate ranging from 0.2 - 3.9 m day^{-1} to 0.2- 2.0 m day^{-1} in Akbarabad and Azizbek, respectively. The primary soils in the experimental sites are loam, sandy loam and silt loam by the texture. These soils are characterized by very high gypsum content ($CaSO_4 \cdot 2H_2O$, 35 - 61%) at 50 - 120 cm soil profile in Akbarabad and 40 - 90 cm in Azizbek, respectively. Principal soil physical characteristics for the two sites are given in Figure 3.

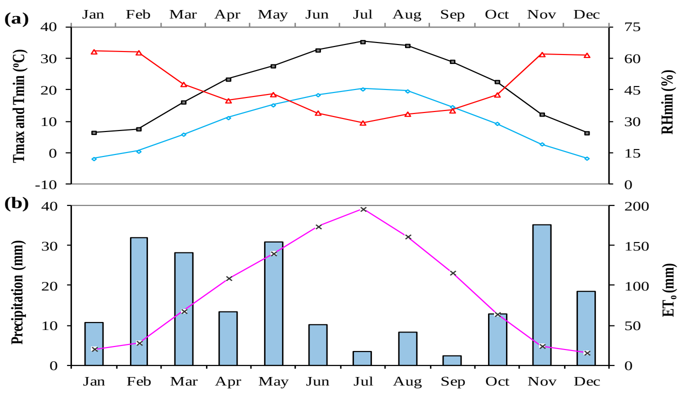

Figure 2. Weather data of the Fergana meteorological station (2009-2011)

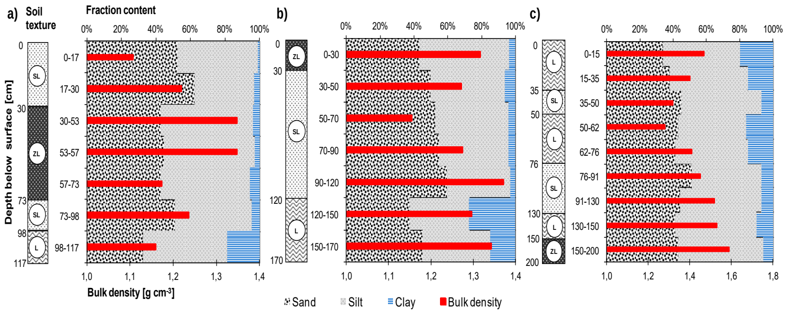

Figure 3. Soil texture, fraction content and bulk density in Akbarabad site – Akpit-1 (a) and Akpit-2 (b) and Azizbek site – Azpit-1 (c)

Model BUDGET

Model description

The BUDGET constitutes a set of subroutines describing various processes involved in water extraction by plant roots and water movement in the soil profile. The model considers water storage in a soil profile affected by infiltration of rain and/or irrigation water including withdrawal of water by crop evapotranspiration and percolation for a given period [41, 42]. The curve number method developed by the US Soil Conservation Service is used to estimate surface runoff originated by rainfall. Finite difference technique is used to solve one-dimensional vertical water flow and root water uptake. Estimation of infiltration and percolation rates is based on exponential drainage function. Sol water balance simulations are performed in a daily time-step. The model considers water stress to yield decline [14]. Relative yield decline, due to water stress during the growing stages, is based on yield response factor (K_y). The minimal approach is used to estimate expected crop yield and soil water balance. Comparison of simulated and observed soil water content and crop yield as well as yield response on altering the model input parameters are discussed by [43].

Model input parameters

Calculated daily ET_o and observed daily rainfall from the weather station 'Fergana' were used as climate input parameters in the BUDGET.

The cropping period (sowing and harvesting dates) and irrigation dates (and amounts) of cotton, wheat and maize were based on field measurements and used as days after planting (DAP) in the BUDGET. The length of crop growing stages (including the sensitivity stages), basal crop coefficients (K_{cb}), salinity tolerance values (S_T) and yield response factors (K_y) for cotton, wheat and maize were derived from indicative values presented by [12, 44, 45]. The range of the Kc_{in} for the selected crops was adjusted in the model according to the soil water content, e.g., smaller Kc_{in} when the soil surface is dry and higher value when the soil surface is wet from rainfall or irrigation [42]. The K_{cb} for the mid and late seasons were adjusted according to FAO - 56. The maximum root depth of cotton and wheat was assumed to be 1.2 and 1.0 m, respectively. The root depth for maize (for silage) was taken from research work conducted in Azizbek site (Central Asian Research Institute of Irrigation (CARII), 2002). The active rooting depth at the beginning of the season for all crops was assumed to be 0.30 m [42, 46]. The 40/30/20/10 percent water extraction pattern (S_{max}) over the crop roots were selected assuming the greatest root water uptake near the soil surface and decline with increase of the depth. The S_{max} at the top and at the bottom of the soil profile was assumed to be as 3.5 and 0.5 mm day^{-1} for cotton, 2.4 and 0.6 mm day^{-1} for wheat and 2.0 and 0.1 mm day^{-1} for maize, which are within the range of model default crop parameters. The soil water content at the anaerobiosis point was taken as 5 volume % below the soil water content at saturation [47].

The length of the growth stages, crop coefficients (K_c), rooting depths (R_d) and soil water depletion factors for no stress (p) used in the BUDGET is presented in Table 1. The length of the sensitivity stages, yield response factors (K_y) and maximum crop salt tolerance threshold (S_T) for cotton, wheat and maize used in the model is presented in Table 2. The soil water depletion fraction for no stress was taken from Table 22 of the FAO - 56 and adjusted depending on soil type and ETc [12, 41].

Calibrated soil input data for the BUDGET is given in Table 3. In this table weighted average values of soil water content at saturation (θ_S), field capacity (θ_{FC}) and wilting point (θ_{WP}) and effective saturated hydraulic conductivity (K_{sat} and corresponding τ values, [48] of 5 layers were aggregated from 8 layers in Azizbek (Az_pit1) and 7 layers in Akbarabad (Ak_pit1 and Ak_pit2) considering model limitation with up to 5 soil compartments input. The soil hydraulic parameters (θ_S, θ_{FC} and θ_{WP}) were calculated using "Hydraulic properties calculator" developed by [49]. The (K_{sat}) was calculated using ROSETTA (WRP5, [50, 51]). The drainage characteristic (τ) was calculated as a function of K_{sat} [41]. Indicative values of the curve number (CN) that is based on the infiltration rate of the top layer was taken from Table 2.4b of the BUDGET user manual [41] and adjusted to the relative wetness of the topsoil during the model simulation run.

Table 1. Crop growth stages and parameters used in BUDGET

Growth stages	Cotton				Wheat				Maize			
	Leng.‡ (day)	Kcξ (-)	Rd† (m)	pώ (-)	Leng.‡ (day)	Kcξ (-)	Rd† (m)	pώ (-)	Leng.‡ (day)	Kcξ (-)	Rd† (m)	pώ (-)
Initial	35	0.14-0.96	0.3	0.65	35	0.17-1.10	0.3	0.55	20	0.18-1.03	0.3	0.55
Dev.	60	0.96-1.18	0.3-1.2		140	1.10-1.11	0.3-1.0		30	1.03-1.12	0.3-0.75	
Mid sea.	45	1.18	1.2		45	1.11	1.0		35	1.12	0.75	
Late sea.	40	1.18-0.6	1.2		30	1.11-0.23	1.0		25	1.12-0.45	0.75	
Total	180				250				110			

Note: ‡ according to phenological observations; ξ, ώ from Tables 17 (for K_c) and 22 (for p) of the FAO - 56 [12]; † assumed and used values by [46], [42] and [52]. Note: range of K_c for the initial stage depends on crop cover intensity (e.g., LAI)

Table 2. K_y values corresponding to the growing stages of cotton, wheat and maize and maximum crop salt tolerance threshold (S_T) used in BUDGET

Growth stages	Cotton			Wheat			Maize		
	Length‡ (day)	Kyξ (-)	S_T† (dS m-1)	Length‡ (day)	Kyξ (-)	S_T† (dS m-1)	Length‡ (day)	Kyξ (-)	S_T† (dS m-1)
Establ.	8	0.5	27	12	1	20	8	0.7	10
Veg. (early)	32	0.2		48	0.2		25	0.4	
Veg. (late)	30	0.2		89	0.4		15	0.4	
Flower.	45	0.5		24	0.6		22	1.5	
Yield form.	40	0.47		48	0.5		30	0.5	
Ripening	25	0.25		29	0.6		10	0.2	
Total	180	0.85		250	1		110	1.25	

Note: ‡ according to phenological observations as well as from reported values by Evett et al. [53], [54], [55]; ξ Table I.5 of the BUDGET manual [41]; † Table 4 of the FAO - 29 [44].

Table 3. Weighted average soil hydraulic parameters for Azizbek (Az_pit1) and Akbarabad (Ak_pit1 and Ak_pit2)

Layer[1] (m)	d_i (m)	Texture class[2]	Soil hydraulic parameters (%vol)			τ [5] (-)	K_{sat}[6] (mm day-1)	CN[7] (-)
			θ_S [3]	θ_{FC} [4]	θ_{WP} [4]			
Az_pit1								
0-0.35¤	0.35	L	45.8	36.2	21.6	0.47	123.3	75
0.35-0.50	0.15	SL	50.1	36.4	24.5	0.71	407.6	
0.50-0.76¤	0.26	L	48.7	37.8	23.4	0.57	213.6	
0.76-1.30¤	0.54	SL	43.2	37.2	20.1	0.43	95.8	
1.30-2.00¤	0.70	L	40.2	37.3	20.2	0.33	46.8	
Ak_pit1								
0-0.30¤	0.30	SL	55.8	33.3	19.6	1.00	1126.7	65
0.30-0.57¤	0.27	ZL	49.1	41.9	30.8	0.45	112.6	
0.57-0.73	0.16	ZL	55.1	48.4	32.6	0.52	164.1	
0.73-0.98	0.25	SL	53.3	42.1	24.9	0.66	334.3	
0.98-1.17	0.19	L	55.6	49.5	35.0	0.52	163.0	
Ak_pit2								

0-0.30	0.30	ZL	50.2	41.7	28.6	0.53	172.8	65
0.30-0.70¤	0.40	SL	54.0	44.1	28.7	0.54	186.9	
0.70-1.20¤	0.50	SL	47.5	42.4	27.3	0.52	166.8	
1.20-1.50	0.30	L	50.8	44.9	30.6	0.43	98.8	
1.50-1.70	0.20	L	49.6	45.0	29.3	0.42	90.5	

Note: [1] Weighted average (indicated by symbol ¤); [2] according to USDA classification (L: loam, SL: sandy loam and ZL: silt loam); [3] calculated using "Hydraulic properties calculator" [49]; [4] laboratory measured values; [5] calculated as a function of K_{sat}[$\tau = 0.0866 * e^{0.8063\log_{10}(K_{sat})}$]; [6] estimated using ROSETTA (WRP5); [7] based on K_{sat} at the top layer [41]

Estimation of crop evaporation (E_a) and transpiration (T_a) and crop coefficient (K_c)

Separate estimation of crop transpiration and soil water evaporation is based on the dual crop coefficient procedure [12, 56]. The actual soil evaporation (E_a) is computed considering soil wetness due to irrigation and precipitation as well as crop cover [41]. The actual water uptake by plant roots is described by means of a sink term that takes into account root distribution and soil water content in the soil profile. Soil water content, mulch (any crop residues) and crop cover (LAI, leaf area index) is needed to estimate E_a and T_a.

The evaporation rate from the wetted soil surface is adjusted depending on wetness of the soil surface due to irrigation method (e.g., alternate or every furrow with wide and narrow beds). This increases accuracy in estimating daily evaporation coefficient (K_e) [57].Wetness of the soil surface of 50-60%, 60 - 90 % and 60 - 70 % was assumed for cotton, wheat and maize, respectively. In order to adjust ground canopy cover, on-site measurements of the LAI (AccuPAR LP80, Decagon Devices, Inc.) at the growth stages of the crops were considered.

Figure 4 gives a summary of the procedures for estimating actual crop evapotranspiration (including actual crop transpiration and soil water evaporation) using the dual crop coefficient approach in BUDGET and reverse calculation of actual K_c.

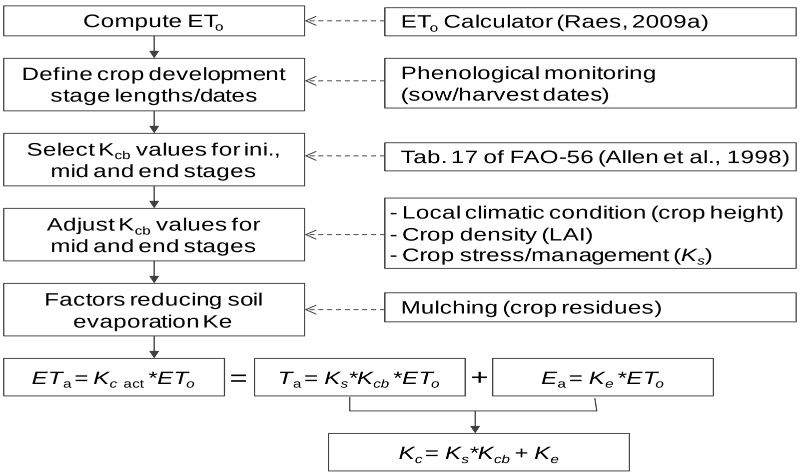

Figure 4. Flow - chart for estimation of actual crop evapotranspiration and inverse calculation of actual K_c (adopted from Rosa et al., [14])

RESULTS AND DISCUSSIONS

Reference (ET_o) and actual crop evapotranspiration (ET_a)

Results of estimated total ET_o and ET_a as well as observed precipitation (P_{re}) and irrigation (I_{rr}) for the growing period of cotton, wheat and maize are presented in Table 4. The mean P_{re} during the growing period of cotton (10 study cases), wheat (5 study cases) and maize (6 study cases) was 59±33, 168 ± 65 and 31 ± 18 mm, respectively, with the mean lowest values of 33, 97 and 37 mm in the driest 2010 - 2011. The mean I_{rr} amounted 390 ± 95, 591 ± 245 and 241 ± 65 mm, respectively. Average ET_o, for the growing period of cotton 863 ± 50 mm and wheat 541 ± 22 mm, varied less (CV = 5.8 % and 4.1%), respectively. Because the state retains control over mechanization [58], growing period for these crops in the sites was more or less the same, e.g., 185 ± 6 and 252 ± 9 days, respectively. Whereas calculated ET_o for the growing period of maize (98 ± 20 days) with 408 ± 95 mm had varied much (CV = 23 %). Maize as a secondary crop after wheat harvest was cultivated mainly for forage and harvested on various dates within a field.

Although the differences of ET_a and its components between the seasons for each crop are apparent, they relate with climatic conditions (Figure 2) and irrigation schedules (Table 4) influencing the wetness of the soil surface. The E_a was the main component of ET_a during the initial growth stages for cotton (77 ± 5 %), winter wheat (90 ± 3 %) and maize (77 ± 4 %) of ET_a for that period (Figure 5, right).

Table 4. Total observed precipitation (P_{re}) and irrigation (I_{rr}), calculated potential evapotranspiration (ET_o) and estimated actual evaporation (E_a) and transpiration (T_a) for the growing period of cotton, wheat and maize

Field ID	Crops	Growing period		P_{re} (mm)	I_{rr} (mm)	ET_o^þ (mm)	ET_a^¥ (mm)
		planting	harvesting				
C-15&16	cotton	19.04.2010	15.10.2010	33	280	889	486
C-165	cotton	14.04.2010	05.10.2010	93	357	798	606
C-174	cotton	06.04.2010	17.10.2010	33	488	905	597

C-180&181	cotton	07.04.2010	15.10.2010	89	332	806	527
C-13&14	cotton	15.04.2011	11.10.2011	33	483	905	606
C-164	cotton	05.04.2011	07.10.2011	33	435	905	576
C-165	cotton	04.04.2011	03.10.2011	98	267	809	513
C-172	cotton	04.04.2011	06.10.2011	33	498	905	611
C-174	cotton	04.04.2011	30.09.2011	33	473	905	586
C-176	cotton	04.04.2011	09.10.2011	107	288	808	488
C-13&14	wheat	14.10.2009	21.06.2010	215	483	516	490
C-172	wheat	05.10.2009	21.06.2010	99	718	576	555
C-176	wheat	05.10.2009	21.06.2010	215	411	542	506
C-15&16	wheat	15.10.2010	21.06.2011	215	382	542	493
C-180&181	wheat	20.10.2010	15.06.2011	96	959	530	500
C-13&14	maize	26.07.2010	17.10.2010	29	187	321	225
C-15&16	maize	29.06.2011	15.10.2011	14	275	513	298
C-164	maize	15.07.2010	02.10.2010	20	281	351	221
C-172	maize	18.07.2010	02.10.2010	20	312	333	231
C-176	maize	19.07.2010	05.11.2010	41	140	391	200
C-180&181	maize	29.06.2011	02.11.2011	61	252	541	283

Note: [b] calculated using "ET_o calculator" [19]; [¥] estimated using BUDGET

The T_a was 24 ± 3, 5 ± 2 and 16 ± 4 mm for the initial period. The large E_a component resulted from high water content in the upper soil layer (0 - 20 cm) due to rainfall and pre-sowing irrigation (moisture charging, for cotton) and after-planting irrigation (germination stimulating, for wheat and maize) as well as a low fraction of soil covered by the crop canopy (LAI) during the initial stage (Figure 5, left). As a crop canopy develops, the ratio of E_a to ET_a decreases as most of the ET_a comes from T_a. This occurs because the light interception by the leaves increases before reaching the soil surface. Therefore during the crop development stage, and when there was no irrigation (except maize), moisture at the upper soil layer was depleted and therefore estimated average E_a for that period was decreased to about 29, 28 and 45 % of ET_a for cotton, wheat and maize, respectively. During midseason, because LAI effects were dominant, estimated E_a/ET_a values were relatively low (5 - 38%) when compared to T_a/ET_a (62 - 95 %) for all crop - fields. During the late season, because LAI decreased as crop starts to dry-up and loose leaves, the proportion of E_a relative to ET_a increases compared to the mid-season period. The ratio of E_a/ET_a of 27 ± 5 % for cotton, are within the range with those previously reported for Uzbekistan for different locations: 36 ± 4% for Khorezm region [60], 22 ± 1 % for Syrdarya region [61], 14 ± 5 % for Fergana region [15].

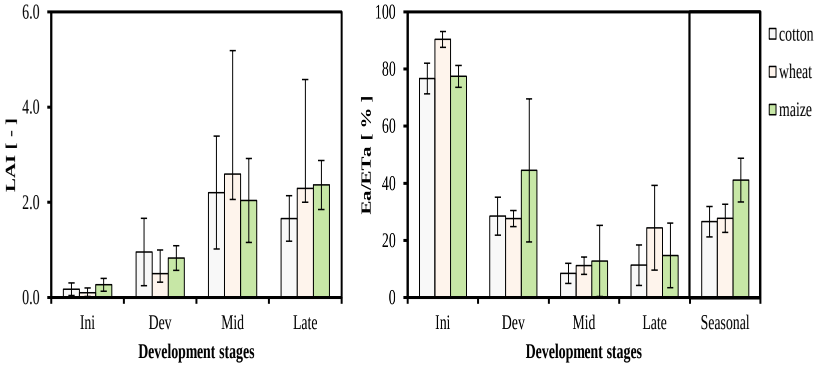

Figure 5. Leaf area index (LAI, left) and ratio of actual evaporation (E_a) into evapotranspiration (ET_a, right) for development stages of cotton, wheat and maize

Note:Error bars indicate values of standard deviation (σ)

Zhao et al. [62], using SIMDualKc model, found seasonal E_a/ET_a averaging 29% and 41 ± 6 % for winter wheat and summer maize, respectively,which are similar with the present study,e.g.,28 ± 5%, and 41±8%, respectively (Figure 5). Sun et al. [63] reported high seasonal E_a/ET_a for the winter wheat (30 - 35 %), were in agreement with the present study, e.g., fields C - 15 & 16 (29 %) and C - 176 (36 %), as the crop was highly stressed, the crop density was low to medium; hence a large amount of energy was available for soil evaporation. Such higher values of E_a/ET_a might also be impact of insufficient irrigation [64] that was practiced at these fields (Table 4). Although summer maize was sown after wheat harvest incorporated with wheat straw, and due to uneven distribution of crop residues, the ratio of E_a/ET_a was 2 - 3 times higher than those reported by Klocke et al. [65] (e.g., 14 - 18 %). In general, seasonal E_a/ET_a for cotton and wheat are comparable while it is high for maize reflecting differences in crop architecture influencing the ground cover fraction as well as irrigation frequency that is smaller in case of cotton and wheat due to their prolonged growing period (Table 1). However, the seasonal E_a/ET_a for maize can be decreased when improved irrigation technique was applied ([66], e.g., 7 ± 1 % under sprinkler irrigation and 9 ± 1 % under drip irrigation.

Dual crop coefficient (Kc)

Based on the estimated E_a and T_a (Figure 6) that consider peculiarity of the climate, crop, soil, agronomic and water management practiced at the sites, the K_c was empirically developed for cotton, wheat and maize using the following relationship:

$$Kc = \varpi + \frac{\varpi}{2} * \left(\frac{T_a}{E_a} \right) \quad (4)$$

where, Kc: dual crop coefficient (-); ϖ : shape parameter of K_c that depends on the surface water deficit/surplus ((∑Pre+Irr)-ETa) in a growing period (n) of crops (Figure 7); E_a and T_a: daily (t_i) actual crop evaporation and transpiration, respectively (mm day^{-1}).

Although simple approaches [29, 34] have been developed to estimate daily K_c [refer to Eqs. 1-3] using the WCL, it under-estimates or falls when total growing period (n) differs from 170, 180 and 148 days for cotton, wheat and maize, respectively. Therefore, in this study, a new approach was proposed to estimate the K_c that is a function of a relative growing period after planting (Δt):

$Kc = -11.66 \cdot (\Delta t)^3 + 15.35 \cdot (\Delta t)^2 - 3.56 \cdot (\Delta t) + 0.32$	for cotton	(5)
$Kc = -8.22 \cdot (\Delta t)^3 + 11.59 \cdot (\Delta t)^2 - 3.22 \cdot (\Delta t) + 0.41$	for wheat	(6)
$Kc = -5.90 \cdot (\Delta t)^3 + 6.84 \cdot (\Delta t)^2 - 0.60 \cdot (\Delta t) + 0.09$	for maize (silage)	(7)

where, Δt: relative growing period of crops after planting ($\Delta t = t_i/n$); i=1, 2, ..., n: the index of day t throughout the growing period n).

The determined K_c [Eqs. 5 - 7] includes the K_{cb}, K_e and K_s [15, 35, 62] that matches the best estimation of the soil water content as well as crop yield [43].

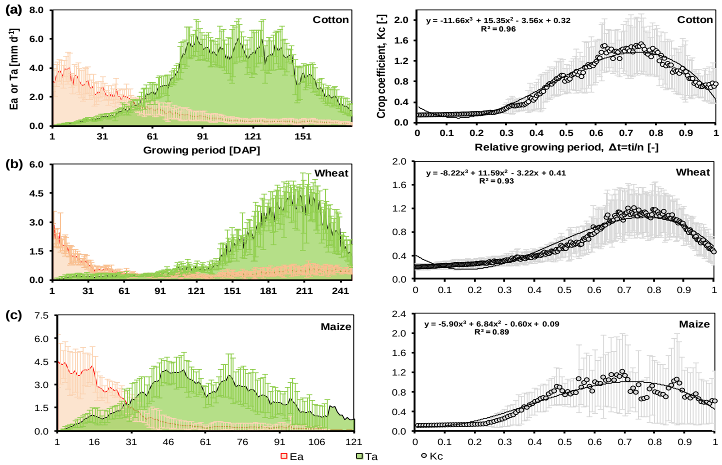

Figure 6. Average values of the E_a and Ta for the growing period (DAP, left): (a) cotton for ten case studies, (b) wheat for five case studies and (c) maize for six case studies, and their respective crop coefficients as a function of the relative growing period (Δt, right)

Note: Error bars indicate values of standard deviation (σ)

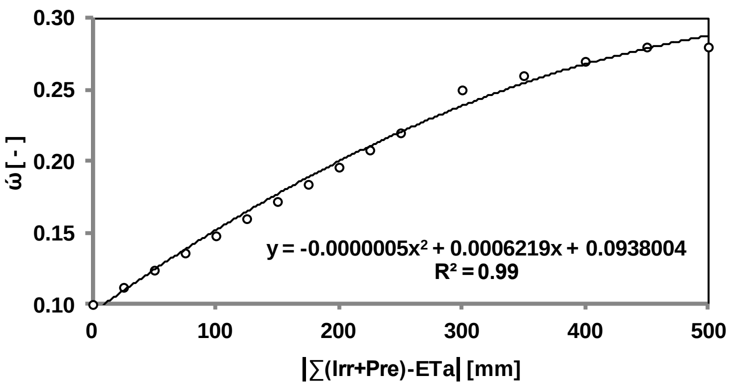

Figure 7. Relationship between the shape parameter of K_c (ϖ) and surface water deficit/surplus during the growing period of crops

Note: The absolute value of the ((∑Pre + Irr) - ETa) considers water deficit as well (opposite to this curve)

Daily K_c values of cotton, wheat and maize were also plotted (results are not shown) using third order polynomial curves [Eqs. 1-3 and 5-7] and growth-stage-specific K_c was compared with those reported by FAO - 56 (Table 5). The growth-stage-specific K_c for cotton, wheat and maize was 0.15, 0.26 and 0.11 at the initial; 1.15, 1.03 and 0.89 at the mid; and 0.45, 0.56 and 0.43 at the late season stages, respectively (Kc_1 in Table 5). The values of Kc_1 at the initial, mid and late season stages of cotton were similar with those (Kc_2) reported by the FAO - 56 [12]. High values of Kc_1 at the late stage of wheat can be explained by the application of last irrigation on average 33 days before the harvest (whereas for cotton, it is 51 days). This might create a high leaf area index (LAI), thus larger Ta (Figure 6 b). One also needs to note that farmers at the sites try to harvest wheat early that according to them makes heavier grain yield and also creates an incentive for workers to grow secondary crops. Liu et al. [67] and Gao et al. [68] reported K_c for winter wheat at the late season stage was 0.72 and 0.41, respectively, thus values obtained in this study (Kc_1 for wheat, Table 5) in-between these values.

Smaller value of Kc_1 for maize from those Kc_2 at all stages can be explained by Kc_2 to consider maize for grain [12] rather than forage. In addition, low Kc_1 from Kc_3 for maize for all growth stages could be explained as scarce rainfall (14 - 61 mm) as well as small irrigation water supply (140-312 mm) for the growing period (Table 4) compared to those observed by Piccinni et al. [34], e.g., I_{rr}=283 ± 165 mm and P_{re}=387 ± 89 mm.

In general, the values of Kc_1 are within the Kc_2 and Kc_3 range (Table 5) that make the Equations [5-7] applicable for Fergana condition. In addition, the results of crop coefficients estimated for the main growth stages in this study were consistent with those reported in literature.

Table 5 Growth stage crop coefficients (K_c) for cotton, wheat and maize

Growth stages‡	Cotton				Wheat				Maize			
	DAP^ξ	Kc_1	Kc_2	Kc_3	DAP	Kc_1	Kc_2	Kc_3	DAP	Kc_1	Kc_2	Kc_3
Initial	0-30	0.15	0.15	0.4	0-30	0.26	0.15	0.54 (0.53)	0-20	0.11	0.15	0.32 (0.4)
Dev.	31-80	0.75		1.16	31-170	1.02		0.36 (0.7)	21-55	0.65		0.68 (1.0)
Mid sea.	81-135	1.15	1.1-1.15	1.29	171-210	1.03	1.1	0.03† (1.1)	56-95	0.89	1.15	0.92 (1.2)
Late sea.	136-180	0.45	0.5-0.4	0.04†	211-240	0.56	0.15	<0 (0.4)	96-125	0.43	0.5	0.8 (0.9)
Total	**180**				**240**				**125**			

Note: ‡Kc_1 and Kc_3 are averaged at the initial and mid-season stages for the period (DAP), and the last day of the period (DAP) are used at the development and late season stages considering the shape of Kc curve presented by [12]; ^{ξ}DAP - days after planting; Kc_1 -based on present study developed crop coefficients [Eqs. 5-7], Kc_2 - Table 17 of the FAO-56 [12], and Kc_3 - from Ko et al. (2009) [Eqs. 1-2] and [34][Eq. 3]; †Kc_3<0 when total growing period (n) is >170 days for cotton and n>180 days for wheat. Values in parenthesis (Kc_3 for 180 days maturing wheat variety) indicate average growth-stage values reported by [29].

SUMMARY AND CONCLUSION

In Fergana region (in other regions as well), the use of irrigation scheduling based on GMR will not meet accurate crop water requirement (CWR) and result in either increased production costs due to over-irrigation or reduced profits owing to deficit irrigation. This research was aimed for determination of accurate CWR or crop evapotranspiration (ET_a) and crop coefficients (K_c) for cotton, winter wheat and maize grown in the Fergana province of Uzbekistan. Irrigation scheduling can then be improved for extension service providers and farmers to avoid water over or under-use and to more precisely meet the CWR to produce greater yields, crop quality, enhanced water use efficiency and reduced surface/subsurface drainage outflow.

Estimated in this study, reference evapotranspiration (ET_o) is calculated from standard weather data using ET_o calculator [19] based on standard FAO Penman-Monteith method [12]. Soil water balance and partitioning ET_a into soil evaporation (E_a) and crop transpiration (T_a) components was performed using BUDGET model [42] after validation of model results for soil moisture and crop yield [43]. Based on results of the BUDGET, Kc was developed, expressed as a function of relative days after planting (DAP) using non-linear regression [69]. The modified Kc_2 [12] values for the cotton, winter wheat and summer maize in this region during the initial, mid-season, development and late stages are obtained. In conclusion, the development of regionally based K_c helps water managers and decision makers in enhanced irrigation scheduling and provides precise water applications.

The developed simple approach to estimate daily Kc_1 for the three main crops grown in the Fergana region was the first attempt to meet this issue. Hence, the developed Kc_1 combines three coefficients, such as basal (K_{cb}), water stress reduction (K_s) and soil evaporation K_e (so called dual crop coefficient, [12, 41]. It should permit more accurate estimation of daily crop ET_a, thus more reliable calculation of CWR and accurate irrigation scheduling. However, further investigation could improve the estimation of K_c considering different agro-climatic zones, crop varieties (that have different growing periods) and groundwater contribution [28] through the combined use of lysimeters to validate the developed K_c.

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