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

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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 slige 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 (Ee) and transpiration (Tc) components. An empirical equation was developed to determine the daily Kc values based on the estimated Ee 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 ± 59 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 m; 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 Kc 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-saturation 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 (Ee) and plant transpiration (Tc), referred to collectively as crop evapotranspiration (ETc). ETc is calculated by multiplying evapotranspiration from a reference crop (ETr) such as grass or alfalfa by an empirically derived crop specific coefficient (Kc).

ETc 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 ETc [16,17], the FAO Penman-Monteith approach is now accepted as a standard method [18,19]. Basic principles, common errors and biases endemic to ETc measuring systems as well as recommended documentation in reporting ETc are reviewed by Allen et al. [20, 21]. However, Kc is needed to be known to characterize the difference between the cropped (ETc) and reference grass surface (ETr) 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 Kc, 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 Kc [33]. Using the WCL, Ko et al. [29] and Piccini et al. [34] developed a simple method to determine the daily Kc.
for cotton, wheat and summer maize as a function of days after planting (DAP) [so called a crop curve [32]:

\[ K_c = 0.35 - 2.01 \times 10^{-3} \cdot DAP + 2.85 \times 10^{-4} \cdot DAP^2 - 1.67 \times 10^{-6} \cdot DAP^3 \]

for cotton (1)

\[ K_c = 0.75 - 0.02 \cdot DAP + 3.66 \times 10^{-4} \cdot DAP^2 - 1.54 \times 10^{-6} \cdot DAP^3 \]

for wheat (2)

\[ K_c = 0.36 - 8.89 \times 10^{-3} \cdot DAP + 4.02 \times 10^{-4} \cdot DAP^2 - 2.42 \times 10^{-6} \cdot DAP^3 \]

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. (e.g. \( ET_a = \frac{K_c \cdot ET_o}{1 + K_c} \)). 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, (e.g. \( ET_a = \frac{K_c \cdot ET_o}{1 + K_c} \)) 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 decreases crop yield quality.

Reported single \( K_c \) values for different crops [12] are generally used in Uzbekistan [8, 37, 38] and elsewhere due to the lack of local data. Although the tabulated mean \( K_c \) for the 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. [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 (ETc) 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 (Kc) for these crops based on evaporation (E0) and transpiration (Tc).

**MATERIALS AND METHODS**

**Location and description of study sites**

Field trials were conducted during 2009 - 2011 at two sites, namely Akbarabad (40°32' - 40°53' N; 71°56' E) and Azizbek (40°28'N; 71°32'E) in Central plain part of the Fergana valley (Figure 1).

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 m² in Akbarabad and 4 - 6 cm, 90 cm and 9 - 12 plants per m² 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 m². Collector-drainage water (with electrical conductivity, ECw of 1.1 ± 0.1 dS m⁻¹) and canal water (ECw=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

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**Figure 1. Location of the study sites in Fergana valley (a) and experimental set up in the fields of Akbarabad (b) and Azizbek (c).**
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 maximum and minimum temperatures, minimum relative humidity, precipitation and reference evapotranspiration (ET₀) are presented in Figure 2 [69]. The ET₀ was calculated using ET₀ 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 (CaSO₄·2H₂O, 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 2](image_url)

**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. Soil 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 (Kₑ). 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 ET₀ 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 obtained from 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 (Kₑ), salinity tolerance values (Sₑ) and yield response factors (Kₑ) for cotton, wheat and maize were derived from indicative values presented by [12, 44, 45]. The range of the Kₑ for the selected crops was adjusted in the model according to the soil water content, e.g., smaller Kₑ when the soil surface is dry and higher value when the soil surface is wet from rainfall or irrigation [42]. The Kₑ 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 (CARI), 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 (Sₑ) over the crop roots were
selected assuming the greatest root water uptake near the soil surface and decline with increase of the depth. The $S_{\text{sat}}$ at the top and at the bottom of the soil profile was assumed to be as 4.35 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 ($K_c$) 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 BUDGET model default crop parameters. The soil water depletion fraction for no stress was taken from Table 22 of the BUDGET is presented in Table 3.

Calibrated soil input data for the BUDGET is given in Table 3. In this table weighted average values of soil water content at saturation ($\theta_s$), field capacity ($\theta_{FC}$) and wilting point ($\theta_{WP}$) and effective saturated hydraulic conductivity ($K_{sat}$) and corresponding $\tau$ 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 ($\theta_s$, $\theta_{FC}$ and $\theta_{WP}$) were calculated using “Hydraulic properties calculator” developed by [49]. The ($K_{sat}$) was calculated using ROSETTA (WR5, [50,51]). The drainage characteristic ($\tau$) 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)   | Kc$^\dagger$ | p$^*$ | Leng. (day) | Kc$^\dagger$ | p$^*$ | Leng. (day) | Kc$^\dagger$ | p$^*$ |
| Initial       | 35     | 1.14-0.96 | 0.3 | 39      | 3.17-1.10 | 0.3 | 55      | 1.18-1.03 | 0.3 |
| Dev.          | 60     | 0.96-1.18 | 0.3-1.2 | 60 | 1.10-1.11 | 0.3-1.0 | 10 | 0.13-1.12 | 0.3-0.75 |
| Mid sea.      | 45     | 1.18     | 1.2 | 45 | 1.11     | 0.0 | 35 | 1.12     | 0.75 |
| Late sea.     | 40     | 1.18-0.6 | 1.2 | 50 | 1.11-0.23 | 0.0 | 25 | 1.12-0.45 | 0.75 |
| Total         | 180    | 0.2      | - | 250    | 0.5      | - | 100   | 1.0      | - |

Note: $^\dagger$ according to phenological observations; $^\ddagger$ from Tables 17 (for $K_c$) and 22 (for p) of the FAO 56 [12]; $^\natural$ assumed and used values by [46], [42] and [52]. Note: range of $K_c$ for the initial stage depends on crop cover intensity (eig, LAI).

### Table 2. $K_c$ 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$^\dagger$ (day) | Kc$^\dagger$ | S$^\ddagger$ (dS m$^{-1}$) | Length$^\dagger$ (day) | Kc$^\dagger$ | S$^\ddagger$ (dS m$^{-1}$) | Length$^\dagger$ (day) | Kc$^\dagger$ | S$^\ddagger$ (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   | 09    | 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: $^\dagger$ according to phenological observations as well as from reported values by Evett et al. [53], [54], [55]; $^\natural$ Table I.5 of the BUDGET manual [41]; $^\ddagger$ 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$^\natural$ (m) | $d_i$ (m) | Texture class$^\dagger$ | Soil hydraulic parameters | $\tau$ $^\ddagger$ (-) | $K_{sat}$ (mm day$^{-1}$) | CN$^\natural$ (-) |
|----------------------|-----------|-------------------------|---------------------------|-------------------------|--------------------------|-----------------|
| Az_pit1              |           |                         | $\theta_{s}$ $^\natural$ | $\theta_{FC}$ $^\ddagger$ | $\theta_{WP}$ $^\natural$ |
| 0-0.35m              | 0.35      | L                       | 45.8                       | 36.2                    | 21.6                     | 0.47             | 123.3           | 75          |
| 0.35-0.50m           | 0.15      | SL                      | 50.1                       | 36.4                    | 24.5                     | 0.71             | 407.6           |             |
| 0.50-0.76m           | 0.26      | L                       | 48.7                       | 37.8                    | 23.4                     | 0.57             | 213.6           |             |
| 0.76-1.30m           | 0.54      | SL                      | 43.2                       | 37.2                    | 20.1                     | 0.43             | 95.8            |             |
| 1.30-2.00m           | 0.70      | L                       | 40.2                       | 37.3                    | 20.2                     | 0.33             | 46.8            |             |
| Ak_pit1              |           |                         | $\theta_{s}$ $^\natural$ | $\theta_{FC}$ $^\ddagger$ | $\theta_{WP}$ $^\natural$ |
| 0-0.30m              | 0.30      | SL                      | 55.8                       | 33.3                    | 19.6                     | 1.00             | 1126.7          | 65         |
| 0.30-0.57m           | 0.27      | ZL                      | 49.1                       | 41.9                    | 30.8                     | 0.45             | 112.6           |             |
| 0.57-0.73m           | 0.16      | ZL                      | 55.1                       | 48.4                    | 32.6                     | 0.52             | 164.1           |             |
| 0.73-0.98m           | 0.25      | SL                      | 53.3                       | 42.1                    | 24.9                     | 0.66             | 334.3           |             |
| 0.98-1.17m           | 0.19      | L                       | 55.6                       | 49.5                    | 35.0                     | 0.52             | 163.0           |             |
| Ak_pit2              |           |                         | $\theta_{s}$ $^\natural$ | $\theta_{FC}$ $^\ddagger$ | $\theta_{WP}$ $^\natural$ |

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DETERMINATION OF ACTUAL CROP EVAPOTRANSPIRATION (ET\textsubscript{a}) AND DUAL CROP COEFFICIENTS (K\textsubscript{c}) FOR COTTON, WHEAT AND MAIZE IN FERGANA VALLEY: INTEGRATION OF THE FAO-56 APPROACH AND BUDGET

### RESULTS AND DISCUSSIONS

#### Reference (ET\textsubscript{r}) and actual crop evapotranspiration (ET\textsubscript{a})

Results of estimated total ET\textsubscript{r} and ET\textsubscript{a}, as well as observed precipitation (P\textsubscript{n}) and irrigation (I\textsubscript{n}) for the growing period of cotton, wheat and maize are presented in Table 4. The mean P\textsubscript{n} during the growing period of cotton (10 study cases), wheat (5 study cases) and maize (6 study cases) was 592.33, 168 ± 65 and 31 ± 18 mm, respectively. The mean lowest values of 33, 97 and 37 mm in the driest 2010 - 2011. The mean I\textsubscript{n} amounted 390 ± 95, 591 ± 245 and 241 ± 65 mm, respectively. Average ET\textsubscript{r} for the growing period of cotton was 863 ± 50 mm and wheat 541 ± 22 mm, varied less (CV = 5.8 % and 4.1 %), respectively.

### Table 4. Observed precipitation (P\textsubscript{n}) and irrigation (I\textsubscript{n}), calculated potential evapotranspiration (ET\textsubscript{r}) and estimated actual evaporation (E\textsubscript{r}) for the growing period of cotton, wheat and maize

| Field ID | Crops    | Growing period | P\textsubscript{n} (mm) | I\textsubscript{n} (mm) | ET\textsubscript{r} (mm) | ET\textsubscript{a} (mm) |
|----------|----------|----------------|-------------------------|-------------------------|--------------------------|--------------------------|
|          |          | planting      | harvesting              |                         |                          |                          |
| C1-58&16 | cotton   | 19.04.2010    | 15.10.2010              | 33                      | 280                      | 89.8                     | 486                      |
| C-165    |          | 14.04.2010    | 05.10.2010              | 93                      | 357                      | 798                      | 606                      |
| C-174    | cotton   | 06.04.2010    | 17.10.2010              | 33                      | 488                      | 905                      | 597                      |

The differences of ET\textsubscript{r} 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\textsubscript{a} was the main component of ET\textsubscript{r}, during the initial growth stages for cotton (77 ± 5 %), winter wheat (90 ± 3 %) and maize (77 ± 4 %) of ET\textsubscript{r} for that period. The P\textsubscript{n} in the winter wheat and winter maize harvest was cultivated mainly for forage and harvested on various dates within a field.

### Figure 4. Flow chart for estimation of actual crop evapotranspiration and inverse calculation of actual K\textsubscript{c} (adapted from Rosa et al., [14])

Note: 1 Weighted average (indicated by symbol \( \bar{a} \)) of daily observed values; 2 calculated according to USDA classification (I: 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 \( K_{sat} \); 6 computed using ROSETTA (WRPS); 7 based on \( K_{sat} \) at the top layer [41]

### Estimation of crop evaporation (E\textsubscript{a}) and transpiration (T\textsubscript{a}) and crop coefficient (K\textsubscript{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\textsubscript{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\textsubscript{a} and T\textsubscript{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\textsubscript{c}) [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\textsubscript{c}.
The $T_s$ was $24 \pm 3, 5 \pm 2$ and $16 \pm 4 \text{mm}$ for the initial period. The large $E_s$ component resulted from high water content in the upper soil layer ($0 - 20 \text{ cm}$) 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 $E_s$ to $E_T$ decreases as most of the $E_T$ comes from $T_s$. 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 $E_s$ for that period was decreased to about $29, 28$ and $45 \%$ of $E_T$ for cotton, wheat and maize, respectively. During mid-season, because LAI effects were dominant, estimated $E_s/E_T$ values were relatively low (5 - 38\%) when compared to $T_s/E_T$ (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 $E_s$ relative to $E_T$ increases compared to the mid-season period. The ratio of $E_s/E_T$ of $27 \pm 5 \%$ for cotton, are within the range with those previously reported for Uzbekistan for different locations: $36 \pm 4 \%$ for Khorezm region [60], $22 \pm 1 \%$ for Syrdarya region [61], $14 \pm 5 \%$ for Fergana region [15].

Note: Error bars indicate values of standard deviation. \[29, 28 \text{ and } 45 \% \text{ under drip irrigation}\]

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

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| 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 | 493 | 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 | 21.06.2010 | 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: \(\text{calculated using } E_T \text{ calculator} [19]; \text{estimated using BUDGET}\)

Zhao et al. [62], using SIMDualKc model, found seasonal $E_s/E_T$, averaging 29\%, and 41\% \pm 6\% for winter wheat and summer maize, respectively, which are similar with the present study, e.g., 28\% \pm 5\%, and 41\% \pm 8\%, respectively (Figure 5). Sun et al. [63] reported high seasonal $E_s/E_T$ 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 $E_s/E_T$ 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 $E_s/E_T$ was 2 - 3 times higher than those reported by Klocke et al. [65] (e.g., 14 - 18\%). In general, seasonal $E_s/E_T$ 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 $E_s/E_T$ for maize can be decreased when improved irrigation technique was applied [66], e.g., 7 \pm 1\% under sprinkler irrigation and 9 \pm 1\% under drip irrigation.

**Dual crop coefficient (Kc)\)**

Based on the estimated $E_s$ and $T_s$ (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:

$$K_c = \alpha + \frac{\alpha}{2} \left( \frac{T_i}{E_a} \right)$$

(4)

where, $K_c$: dual crop coefficient (-); $\alpha$: shape parameter of $K_c$ that depends on the surface water deficit/surplus ($\sum(\text{Pre}+\text{Irr})$-$\text{ETa}$) in a growing period (n) of crops (Figure 7); $E_a$ and $T_i$ are daily (t) 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 underestimates 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 ($\Delta t$):

$$K_c = -11.66 \cdot (\Delta t)^3 + 15.35 \cdot (\Delta t)^2 - 3.56 \cdot (\Delta t) + 0.32$$

for cotton

$$K_c = -8.22 \cdot (\Delta t)^3 + 11.59 \cdot (\Delta t)^2 - 3.22 \cdot (\Delta t) + 0.41$$

for wheat

$$K_c = -5.90 \cdot (\Delta t)^3 + 6.84 \cdot (\Delta t)^2 - 0.60 \cdot (\Delta t) + 0.09$$

for maize (silage)

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

The determined $K_c$ [Eqs. 5 - 7] includes the $K_o$, $K_i$ and $K_s$ [15, 35, 62] that matches the best estimation of the soil water content as well as crop yield [43].

Note: Error bars indicate values of standard deviation ($\sigma$)

Figure 6. Average values of the $E_a$ and $T_i$ 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 ($\Delta t$, right)

Note: Error bars indicate values of standard deviation ($\sigma$)

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

Note: The absolute value of the ($\sum(\text{Pre}+\text{Irr})$-$\text{ETa}$) 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 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 ($K_c$ in Table 5). The values of $K_c$ at the initial, mid and late season stages of wheat were similar with those ($K_c$) reported by the FAO - 56 [12]. High values of $K_c$ 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 yield and also creates an incentive for workers to grow secondary crops. Liu et al. [67] and Gao et al. [68] reported Kc for winter wheat at the late season stage was 0.72 and 0.41, respectively, thus values obtained in this study (Kc; for wheat, Table 5) in-between these values.

Smaller value of Kc: for maize from those Kc at all stages can be explained by Kc: to consider maize for grain [12] rather than forage. In addition, low Kc from Kc: 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,=283 ± 165 mm and P,=387 ± 89 mm.

In general, the values of Kc: are within the Kc: and Kc: 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 (Kc) for cotton, wheat and maize |
|---------------------------------|-----------------|-----------------|-----------------|
| Growth stages| Cotton | Wheat | Maize |
|------------|-------|-------|-------|
| DAP | Kc1 | Kc2 | Kc3 | DAP | Kc1 | Kc2 | Kc3 | DAP | Kc1 | Kc2 | Kc3 |
| Initial | 0-30 | 0.15 | 0.15 | 0.4 | 0-30 | 0.15 | 0.54 (0.53) | 0-20 | 0.11 | 0.15 | 0.32 (0.4) |
| Dev. | 31-80 | 0.75 | 1.16 | 1.29 | 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 | 0.98 | 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: Kc1 and Kc2 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]; DAP - days after planting; Kc1 - based on present study developed crop coefficients [Eq. 5-7]; Kc: - Table 17 of the FAO-56 [12]; Kc: - from Ko et al. (2009) [69]; Kc: - from Ko et al. (2009) [69].

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 (ETc) and crop coefficients (Kc) 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 (ETc) is calculated from standard weather data using ETc: calculator [19] based on standard FAO Penman-Monteith method [12]. Soil water balance and partitioning ETc: into soil evaporation (Ea) and crop transpiration (Tc) 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 Kc1 [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 Kc, helps water managers and decision makers in enhanced irrigation scheduling and provides precise water applications.

The developed simple approach to estimate daily Kc: for the three main crops grown in the Fergana region was the first attempt to meet this issue. Hence, the developed Kc: combines three coefficients, such as basal (Kbasal), water stress reduction (Kw) and soil evaporation (Ke) (so called dual crop coefficient, [12, 41]). It should permit more accurate estimation of daily crop ETc: thus more reliable calculation of CWR and accurate irrigation scheduling. However, further investigation could improve the estimation of K, 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 Kc.

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