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Upgrading Maize Cultivation in Bosnia and Herzegovina from Rainfed to Irrigated Systems: Use of Remote Sensing Data and the Dual Crop Coefficient Approach to Estimate Evapotranspiration

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Abstract: A two-year experiment was conducted with a local maize hybrid under full irrigation (F), deficit irrigation (D) and rainfed conditions (R) to estimate maize evapotranspiration in Bosnia and Herzegovina. Three approaches (Allen & Pereira (A&P), SIMDualKc (SD), and Vegetation Index (VI)) were used to estimate actual crop coefficient ($K_{c\ act}$), actual basal crop coefficient ($K_{cb\ act}$), and actual crop evapotranspiration ($ET_{c\ act}$) were applied with the dual crop coefficient method and remote sensing (RS) data. While $K_{cb\ act}$ from all approaches matched FAO56 tabulated values, SD showed differences, in comparison to A&P, of up to 0.24 in D and R conditions, especially in initial and mid-season stages. VI demonstrated very good performance in all treatments. In F, the obtained $K_{c\ act}$ for all approaches during the initial and end stages were higher than the tabulated values, ranging from 0.71-0.87 for $K_{c\ ini\ act}$ and from 0.80-1.06 for $K_{c\ end\ act}$, while the mid-season period showed very good agreement with the literature. Maize crop evapotranspiration range is 769-813 mm, 480-752 mm, and 332-618 mm for F, D and R, respectively. The results confirmed the suitability of both approaches (SD and VI) to estimates maize crop evapotranspiration under F, with the VI approach demonstrating an advantage in calculating $K_{cb\ act}$, $K_{c\ act}$, and $ET_{c\ act}$ values under water stress conditions. The 67.6% increase in grain yields with irrigation emphasizes the need to transition from rainfed to irrigation-dependent agriculture, even for drought-resistant crops like maize.

Keywords: maize evapotranspiration; dual-K_c approach; crop coefficient; satellite data; irrigation; Sentinel-2

1. Introduction

Climate change impacts agriculture in Bosnia-Herzegovina (BiH), both in a positive and a negative way [1]. Longer growing seasons benefit multi-cropping, while high air temperatures and prolonged water shortages threaten spring and summer crops [2,3]. There is an increased variability of weather conditions observed in all seasons, with rapid changes occurring over short periods from extremely cold to warm weather, or from periods of extremely high rainfall to extremely dry periods [3]. Climate change analyses of the RCP8.5 scenario for BiH indicate significant climate shifts. These include an increase of annual temperatures by 5 °C and a decrease of annual precipitation of up to 30%, particularly during the summer months. Furthermore, a decrease of the number of days with snowfall is anticipated [4]. These changes can have a serious impact on the problem of drought and water deficit [5]. In terms of agricultural production, the greatest risks are droughts, followed by spring frosts, autumn frosts, hail, and floods [6]. In BiH, the most vulnerable regions to climate change are primarily situated in the north, with vulnerability gradually decreasing towards the central, southern, and eastern parts of the country [7,8].

Agriculture is based on small-scale, subsistence-oriented production, usually with a low level of agricultural technology implementation, such as irrigation systems or application of smart agriculture solutions [9]. Such cropping systems are highly sensitive to climate change, as they heavily rely on weather conditions [8]. Although agriculture is an important economic sector in BiH [10], the water management sector in agriculture is often neglected, both in terms of research and implementation activities funded by the government [11]. According to the BiH Statistical Institutes, from 2000 to 2020 [12], the most cultivated crop was maize for grain, yet with low productivity [13]. The cultivation of maize and winter cereals, crops that possess a certain resilience to climate change, has led to a low level of adoption of precision irrigation technologies. However, climate change and ratified agreements such as the Sofia Declaration on Green Agenda for the Western Balkans [14] will soon change this situation.

Various crop biophysical parameters (Leaf Area Index - LAI, Fraction of Ground Cover - f_c, Canopy Cover - CC) are directly related to crop coefficients, and they can be used to predict single (K_c) or basal crop coefficient (K_{cb}) for various vegetable, field and fruit crops [15]. The density coefficient (K_d) was developed to facilitate this calculation from parameters such as f_c and crop height (h), or LAI [16]. This method of determining crop coefficients in the literature is recognized as the A&P approach [15–17] and has been validated by comparing it with the values of K_{cb} and K_c obtained from field measurements for different crops [17,18].

Remote sensing has become a very popular technique for monitoring agricultural farms because of its ability to acquire synoptic information at temporal and spatial scales [19,20]. Remote sensing imagery has been emerging as a robust approach to monitor actual crop physiological development and evapotranspiration (ET) [21,22], because of the relationship between crop vegetative growth and crop coefficient (K_c), being increasingly used for computing crop water requirements [23,24]. There is a close correlation between several vegetation indices (VI) and different biophysical characteristics of the plants (e.g., LAI, f_c, biomass, and processes depending on light absorption by the canopy, including ET) [25–28]. Spectral images obtained through Earth observation can be transformed into K_{cb} maps using vegetation indices (VI). This approach is based on determined relationship between VIs and canopy cover biophysical variables such as LAI [29,30]. Through the integration of these maps with stress coefficient (K_s) and evaporation coefficient (K_e) values computed using the soil water balance (SWB) model, it becomes feasible to generate actual basal crop coefficients ($K_{cb\ act}$) or actual crop coefficients ($K_{c\ act}$). This approach is referred to as the vegetation indices and SWB combination method, as outlined by Pôças and Calera [18].

Normalized Difference Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI) are the most used VI for the estimation of actual basal crop coefficient (K_{cb}) and K_c. The formulation of both VI combines the reflected light in the red and near-infrared (NIR) bands, thus providing an indirect measure of the absorption of red light by chlorophylls and reflectance of NIR by the mesophyll structure in leaves [25,31]. Choudhury and Ahmed [30] suggest that using SAVI instead of NDVI allows extending the range over which the VI responds to the increase in vegetation amount/density beyond a LAI value of around 3, which is related to NDVI saturation problems for high LAI values. In addition, the NDVI is considered more sensitive than SAVI to soil background reflectance changes due to the moisture of the soil surface [32].

The most widely used method for calculating crop evapotranspiration (ET_c) involves multiplying the reference evapotranspiration (ET_o) by a K_c, commonly known as the FAO56 approach [33]. Depending on data availability and the required accuracy, K_c can be determined as a single crop coefficient, considering differences in evapotranspiration between field crops and the reference grass surface. Otherwise, it can be calculated as a dual coefficient, based on two factors: a K_{cb} representing plant transpiration and, a soil evaporation coefficient (K_e) [33,34]. The standard values for these coefficients for various crops have been extensively documented by numerous researchers [35,36], including for maize [36–39]. The FAO56 approach also considers non-standard or non-optimal

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conditions, accounting for deviations in management and environmental factors. These non-optimal conditions, when referring to water stress are incorporated in the stress coefficient (K_s).

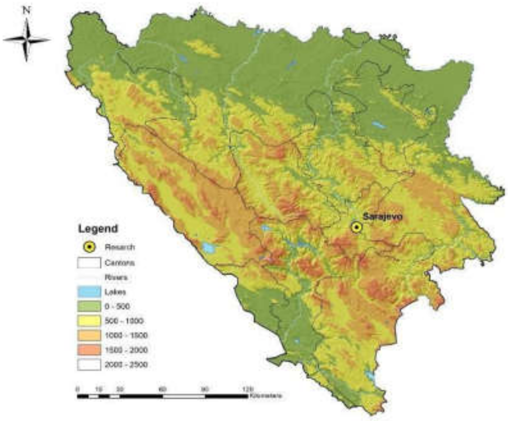
Most of the research related to specific crop growth and crop irrigation requirements considers the single crop coefficient approach and tabulated values of K_c via specific software models such as *CROPWAT* [40], *SPAW* [41], *AquaCrop* [42], *ISAREG* [43]. In BiH, the dual crop coefficient (dual-K_c) approach has had limited application. Recently, the use of other models has been improved, with the *AquaCrop* model [44] seeing greater utilization. Through the implementation of activities within the SMARTWATER project [45], Crljenković [46] presented the capabilities of three models, including the application of the dual-K_c approach for the first time (AquaCrop, CROPWAT and SIMDualKc). SIMDualKc is a soil water balance model that uses a dual-K_c approach for the calculation of daily evapotranspiration at the field level. Therefore, the model provides estimates of evapotranspiration and, consequently, soil water balance (SWB) especially in crops covering partially the soil, i.e., row crops [47]. The possibility of using locally calibrated software models and other techniques to calculate crop coefficients (K_{cb} or K_c), ET_c, or irrigation water requirements (IWR) is becoming relevant [18] due to the continuous need for updates and the potentially extensive time and expenses associated with direct field measurements of biophysical parameters [48]. Using the VI approach, the estimated K_c or K_{cb} may represent the actual crop coefficient ($K_{c\ act}$) or basal crop coefficient ($K_{cb\ act}$) when accounting for variations in plant development due to non-optimal conditions, such as frost or high temperatures, as well as obtaining spatial variation within fields [34]. In addition, VI allow obtaining the spatial variation of $K_{c\ act}$ or $K_{cb\ act}$ within fields and provide information for field-to-field differences in planting dates, plant spacing and cultivars [35]. When applying the VI approach to calculate $K_{c\ act}$ or $K_{cb\ act}$, adjustment is required for stress conditions. Since it is not feasible to achieve this directly through the VI approach, a daily soil water balance (SWB) for the plant root zone is commonly performed to determine the water stress coefficients (K_s).

The present study aims to establish a foundation for future applications of the dual crop coefficient approach using SIMDualKc model (SD) and remote sensing (RS) methodologies, for irrigation management of maize, the most significant crop in the region. The research evaluates three distinct approaches to estimate actual crop coefficient ($K_{c\ act}$), actual basal crop coefficient ($K_{cb\ act}$) and actual crop evapotranspiration ($ET_{c\ act}$) using: i) Allen & Pereira approach, ii) SIMDualKc approach and iii) Vegetation indices approach, under different water availability conditions (full irrigation - F, deficit irrigation - D, and rainfed agriculture - R). Combining the dual-Kc and RS methodologies is an innovative approach for monitoring ET_c under specific pedo-climatic conditions of BiH. Given the pressure that climate change has on BiH agriculture and the advancement of remote sensing procedures, it is important to provide practical methodologies at regional and farm level, to optimize irrigation scheduling precision and cope with future climate uncertainties.

2. Materials and Methods

2.1. Study Location and Its Pedo-Climatic Characteristics

This research was conducted at the experimental field of the University of Sarajevo, the Faculty of Agriculture and Food Science, (43°49'34"N, 18°19'20"E), which is in Butmir (Figure 1) near Sarajevo, at about 512 m a.s.l.. According to Köppen climate classification [49] the climate in this region is Cfb x”s (temperate warm and humid climates), with long term average air temperature of 9.9 ^{o}C and annual average precipitation of 940 mm [50].



(a) (b)

Figure 1. Study location, Butmir experimental field (a), with the location of Full (F), Deficit (D) and Rainfed (R) irrigation treatments (b).

The area of Butmir is characterized by Fluvial soil type [51] or Fluvisol, based on the World Reference Base for Soil Resources [52], with a heavy texture (clay content of up to 43.3%) and depth of up to 1.20 m. The soil has four layers, where the first two layers have a clay loam texture. The total available water (TAW) of the soil is 182 mm (Table 1). Regarding chemical characteristics, the soil at Butmir has a slightly acidic pH reaction in H_2O (6.13 - 6.35). It has an average humus content in the surface layer (2.3%), but the content of humus decreases drastically with depth and in the fourth layer it amounts to only 0.6%. The content of easily accessible phosphorus is low, especially in the thin second layer (0.30-0.40 m). The content of easily accessible potassium is medium.

Table 1. Basic physical and water-related characteristics of the soil profiles at the Butmir experimental location.

Location	Soil layer	Soil texture	Soil layer thickness (m)	Sand 2-0.02 (%)	Silt 0.02-0.002 (%)	Clay <0.002 (%)	FC Vol (%)	PWP Vol (%)	TAW (mm)
Butmir	I	clay loam	0.0-0.30	37.4	29.1	33.5	43.73	19.98	71.23
	II	clay loam	0.30-0.40	36.0	31.6	32.4	43.60	20.41	23.19
	III	clay	0.40-0.60	31.1	25.6	43.3	44.60	28.07	33.05
	IV	clay loam	0.60-1.20	42.8	19.2	38.0	39.75	30.66	54.53

Note: FC is the soil water content at field capacity; PWP is the soil water content at permanent wilting point; and TAW is the total available water.

Weather data were collected at an agrometeorological station placed at the Butmir experimental site, near the experimental field. In Table 2, are presented average monthly maximum (T_{max}) and minimum (T_{min}) air temperatures, rainfall (P), and Hargreaves and Samani reference evapotranspiration (ET_o) for the maize growing period in two years, along with the long-term (30 years) averages for reference period (1991-2020) provided by the Federal Hydrometeorological Institute of Sarajevo (FHMZ).

Table 2. Average monthly maximum (T_{max}), minimum (T_{min}) air temperature, rainfall (P) and reference evapotranspiration (ET_o) as average for reference period 1991 – 2020 and 2021 and 2022.

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Period	Parameter	May	June	July	August	September	Maize vegetation Average	Maize vegetation Sum
1991 – 2020	T_{max}	21.38	25.39	27.35	28.27	22.45	24.97	124.84
	T_{min}	9.06	12.64	14.10	14.32	10.39	12.10	60.50
	P	86.02	87.24	75.03	61.74	89.99	80.01	400.03
	ET_o	104.02	120.96	131.55	123.02	83.29	112.57	562.84
2021	T_{max}	22.55	29.61	32.57	30.89	25.61	28.25	141.23
	T_{min}	9.92	11.95	14.34	12.47	8.16	11.37	56.83
	P	25.00	27.40	62.00	45.40	35.60	39.08	195.40
	ET_o	113.78	157.42	170.42	147.62	100.02	137.85	689.27
2022	T_{max}	26.08	30.95	31.89	29.85	23.62	28.48	142.39
	T_{min}	8.25	13.33	13.13	14.76	9.38	11.77	58.85
	P	49.80	40.40	68.20	99.50	115.56	74.69	373.46
	ET_o	142.49	162.07	169.85	132.84	88.48	139.15	695.73

At Butmir, July and August are the warmest months, with average T_{max} around 28 °C and T_{min} around 14 °C. Compared to the reference period, in 2021 and 2022, a higher T_{max} were observed in every month, with an average difference during the maize vegetation period of 3.28 °C in 2021 and 3.51 °C in 2022 compared to the reference period. The highest difference was in July, when the temperature in 2021 was higher by 5.22 °C. In contrast, T_{min} were lower in the years of the experiment compared to the reference period, for vegetation period they are 3.67 °C lower in 2021 and 1.65 °C lower in 2022. This indicates greater temperature variations in recent years as the result of climate change in BiH [1,53].

In terms of precipitation, 2021 had characteristics of a dry year with 195 mm of rainfall during the maize growing season (May-September), which is 204 mm less than the average for the reference period (400 mm). On the other hand, 2022 experienced normal levels of precipitation, with 373 mm of rainfall, which is slightly lower (26 mm) than the reference period average. The distribution of rainfall during 2021 shows the highest amounts in July (62 mm), but overall, there were lower rainfall values compared to the reference values throughout all months of the vegetation period. In 2022, there was a lower amount of rainfall at the beginning of the vegetation period, ranging from 36 to 46 mm less than the reference values, while higher rainfall was recorded in August and September. Based on these data, we can conclude that 2021 was a dry year, while 2022 can be considered a normal hydrological year.

There were no substantial differences in the ET_o values between the experimental years. The total ET_o for 2021 is 689 mm, while for 2022 it is 695 mm, both higher by 130 mm compared to the reference values (562 mm). ET_o in 2021 and 2022 is higher in every month of the maize vegetation period. This also indicates effect of climate changes, which have been confirmed by other studies conducted in BiH [5,54].

Figure 2 displays daily data, including T_{max} and T_{min}, as well as rainfall (P), for both experimental years at the Butmir location.

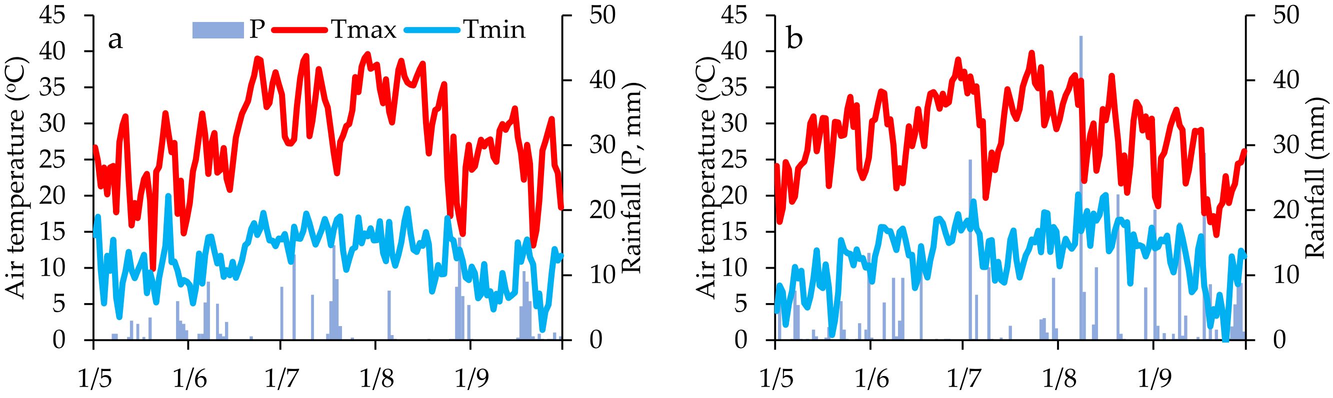

Figure 2. Daily maximum (T_{max}), minimum (T_{min}) air temperature and rainfall (P) for year 2021 (a) and 2022 (b) at Butmir.

In 2021, more pronounced temperature fluctuations were recorded compared to 2022, especially at the beginning and end of the maize growing season. During 2021, high maximum temperatures (T_{max}) exceeding 38 °C were recorded nine times from the end of June until the end of August, with the highest temperature of 39.6 °C recorded on July 29th, 2021. This is significant as the maximum temperature threshold for heat stress in maize is considered to be 40 °C [36], and during 2021, it was near this value on several occasions. Unusually lower temperatures (T_{max} < 25 °C) followed by rainfall were recorded from July 17th to 19th, 2021. In 2022, temperatures exceeding 38 °C were recorded only twice, on June 29th (38.9 °C) and July 29th (39.8°C). Like 2021, there was a short period of lower T_{max} and higher rainfall during July, lasting for two days from July 8th to 9th, 2022.

In 2021, during the maize vegetation period, 19 rain events with rainfall greater than 1 mm were recorded. These events were almost evenly distributed across the analyzed months. On average, each event brought 5.38 mm of rain. The highest amount of rainfall occurred on August 28th, 2021, with 15.8 mm. In 2022, from the beginning of May to the end of September, there were 45 rainy days with rainfall greater than 1 mm. September had the highest number of rainy days (14). The average amount of rain per event in 2022 was 8.15 mm. The largest recorded rainfall was 46.8 mm, which happened on August 8th, 2022. From the daily rainfall data, the issue of the very dry conditions in 2021 becomes even more apparent.

Findings from Popov and Gnjatoand [55] support a significant increase in the occurrence of warm extremes alongside a declining trend in cold extremes, indicating that 2021 is not an exception and that such conditions of high temperatures and low precipitation levels will become more frequent in BiH.

2.2. Experimental Design and On-Field Measurements

A domestic hybrid BL-43 of maize (*Zea mays* L.) was grown at nine plots (20 m x 20 m, summing up 400 m2 per plot) under three water regimes (full irrigation (F), deficit irrigation (D), and rainfed (R)). Each irrigation treatment had three replicates. Plant spacing was 0.2 m x 0.7 m and maize was grown in the South-North direction, following the path of Sentinel-2 satellite's' orbit, and adjusting plots to fit into 10 m x 10 m pixels – grid points. In this way, it was ensured that each plot had four grid cell values which amounts to 12 values per treatment, per sensing date (4 grid cell x 3 plots per treatment) (Figure 3).

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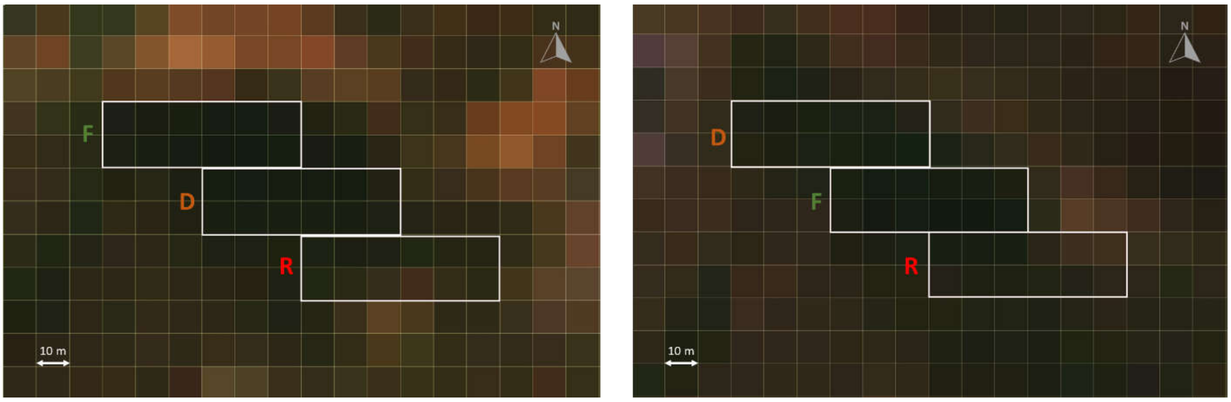

(a) (b)

Figure 3. Irrigation treatments Full (F), Deficit (D) and Rainfed (R) for both crop cycles 2021 (a) and 2022 (b).

The experiment was set up following the procedure already applied for maize in Colovic and Yuand [56] and Piscitelli and Colovicand [57].

Maize sowing, emergence and harvesting days for both years are shown in Table 3. The sowing and harvesting dates were the same for all three treatments.

Table 3. Dates and the number of days after sowing (DAS) for maize growing stages for full irrigation (F), deficit irrigation (D), and rainfed (R) water treatments.

	2021			2022		
	Date (DAS)					
	F	D	R	F	D	R
Sowing		07.05			05.05	
Emergence	17.05 (10)	17.05 (10)	17.05 (10)	17.05 (12)	17.05 (12)	17.05 (12)
Beg. of tasseling	15.07 (69)	15.07 (69)	15.07 (69)	18.07 (74)	18.07 (74)	18.07 (74)
Full silk	29.07 (83)	29.07 (83)	15.07 (69)	25.07 (81)	25.07 (81)	25.07 (81)
Milk maturity	03.09 (119)	03.09 (119)	23.08 (108)	22.08 (109)	22.08 (109)	15.08 (102)
Wax maturity	13.09 (129)	13.09 (129)	27.08 (112)	05.09 (123)	05.09 (123)	22.08 (110)
Full maturity	10.10 (156)	10.10 (156)	30.09 (146)	15.10 (163)	15.10 (163)	05.10 (153)
Harvesting		23.10 (169)			22.10 (170)	

The growing stages and length of the vegetation period were the same for both full (F) and deficit (D) treatments. Full maturity was achieved 156 and 163 days after sowing (DAS) for 2021 and 2022, respectively. The rainfed (R) treatment had a shorter vegetation period in both years, reaching full maturity 146 and 153 DAS, in 2021 and in 2022, respectively.

The daily climate data for the two years of the experiment were collected using the iMETOS agro-meteorological station located within the Butmir experimental station. Reference evapotranspiration (ET_o) was calculated by using Hargreaves-Samani equation [58,59] with locally calibrated and validated kR_s values. The following equation was used:

$$ET_o = 0.0135\ kR_s\ 0.408R_a\ (T_{mean} + 17.8)\ TD^{0.5} \quad (1)$$

where ET_o is the reference evapotranspiration (mm day^{-1}), Ra is extraterrestrial radiation (MJ m^{-2} day^{-1}), kR_s – empirical coefficient (0.14), TD is temperature difference between the maximum (T_{max}) and minimum (T_{min}) air temperature (°C), and T_{mean} the mean daily air temperature at 2 m height (°C).

where ET_o is the reference evapotranspiration (mm/day), R_a is extraterrestrial radiation (MJ/m^2/day), kR_s – empirical coefficient (0.14), TD is temperature difference between the maximum

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(T_{max}) and minimum (T_{min}) air temperature (°C), and T_{mean} the mean daily air temperature at 2 m height (°C).

Hargreaves [60] recommended using kR_s = 0.162 for "interior" regions and kR_s = 0.19 for "coastal" regions, while Allen et al. (1998) and many authors suggested the use of local kR_s [61,62]. Based on this, kR_s = 0.14 was used as that value was recommended by Čadro and Uzunović [59] for the local conditions of central BiH [50]. Hargreaves and Samani [58] equation was selected because only T_{max}, T_{min} and wind speed (u_2) daily data were available continuously during 2021 and 2022, but not radiation and humidity data. To analyze and compare climate conditions in 2021 and 2022, with average conditions, daily climate data for the period 1991 – 2020 was collected from the nearest weather station (Bjelave, Sarajevo). These data refer to: maximum and minimum air temperature (T_{max} and T_{min}, °C) and sum of rainfall (P, mm), data ware provided by the Federal Hydrometeorological Institute of Sarajevo (FHMZ). The data from this weather station could not be used during the experiment because they were not available for every day, but only at the end of each year.

Soil fertility inputs were based on the chemical analyses of soil were the same in all treatments. The length of growing stages, plant height during the mid-season (h), leaf area index (LAI) and grain yield were measured during both growing seasons. The mean plant height during the mid-season and LAI were measured each seven days. The average values of these parameters, per plot and treatment, were calculated based on five plants per plot, 15 plants per repetition, or 45 plants in total per treatment. For 2021, h was 2.69 m for F treatment, 2.55 m for D treatment, and 1.82 m for R treatment. In the year 2022, the heights were 2.57 m for F, 2.44 m for D, and 1.99 m for R treatments.

LAI was calculated as the ratio between the sum of physiologically active leaf area (LA) to the soil area occupied by the plant. Individual leaf LA (LA_{leaf}) was calculated as suggested by [63,64] using the Equation 2:

$$LA_{leaf} = LL \times LW \times 0.75 \quad (2)$$

where LL represents the length of the leaf lamina, LW represents the maximum leaf lamina width and 0.75 is the correction factor as proposed by the afore-mentioned authors. Only green parts of the leaf lamina were taken into consideration. Measurements were taken each seven days, during the whole vegetation period, for five representative plants from each plot and presented as an average value for each treatment.

Grain yield was calculated by multiplying the average kernel weight of five plants per plot by the plots' average number of plants per ha. The results were later corrected for the kernel moisture content of 14% (Table 4).

Table 4. The maize grain yield (t ha^{-1}) in 2021 and 2022 for full irrigation (F), deficit irrigation (D), and rainfed (R) water treatments.

Year	Full irrigation	Deficit irrigation	Rainfed
2021	12.65	13.83	4.48
2022	14.20	12.30	8.75

The average grain yields varied between irrigation treatments and years. The yield of F and D treatments were two times higher than the average maize yield of 6.0 t ha^{-1} reported by the Statistical Agency of BiH [12]. The average yield of R treatment was 6.6 t ha^{-1} which is in the range of the statistical data confirming that in BiH maize is cultivated mainly under rainfed conditions. During 2021, the yield of treatment D was higher than F by 12.4%, while the yield of R was lower by as much as 64.6%. In 2022, the maize yield in F treatment was 13.4% higher than in D, and 38.4% higher than in R. When comparing 2022 to 2021, the yield of F treatment increased by 10.9%. However, the yield of D decreased by 12.4%, and drastically decreased by 48.8% for R.

During the experiments, the irrigation water requirements (IWR) were calculated based on soil water balance (SWB) MS Excel-based irrigation tool EXCEL_IRR [65], that applies standard FAO56 single crop coefficient approach [33]. Tabulated values of crop coefficient were applied for initial, mid-season and end-season as $K_{c\ ini}$ = 0.3, $K_{c\ mid}$ = 1.2 and $K_{c\ end}$ = 0.35, respectively. The irrigation norm was set at 30 mm, via drip irrigation system with one lateral line per row of plants and emitter

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spacing of 0.2 m. The minimum rainfall amount to be considered in effective rainfall estimation was 2 mm. The efficiency of irrigation was 95% and the number of days to stop irrigation before harvesting was 25. For the water balance calculation and estimation of soil water depletion, a maximum root depth of 1.0 m was used.

The depletion fraction threshold (p) for no-stress (full irrigation treatment – F) was fixed to 0.55 (Allen et al., 1998) of total available water (TAW). Deficit irrigation treatment was irrigated on the same dates as the full irrigation treatment, but with 50% of the water amount applied in F treatment.

Irrigation amounts applied for F and D treatments and rainfall (P) are illustrated in Figure 4 for 2021 and 2022.

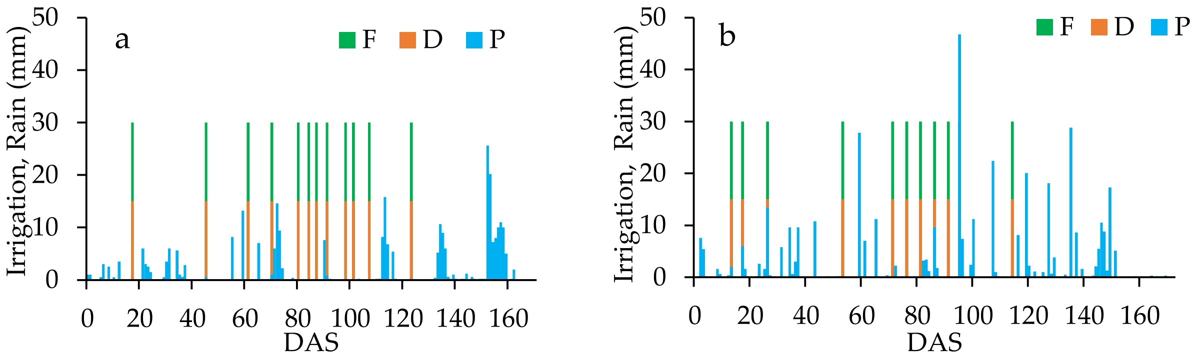

Figure 4. Irrigation for full (F) and deficit (D) treatments, and amount of rainfall (P) in 2021 (a) and 2022 (b).

In 2021, irrigation was applied 12 times on the following DAS: 17, 45, 61, 70, 80, 84, 87, 91, 98, 101, 107, and 123. The total water applied was 360 mm and 180 mm, for the F and D treatments, respectively. In 2022, there were 11 irrigation events on the following DAS: 11, 15, 24, 51, 69, 74, 79, 84, 89, 93, and 112. The water applied for the F treatment was 330 mm, and for the D treatment, it was 50% of that amount, or 165 mm.

2.3. Remote Sensing Data and the Dual Crop Coefficient Approach

In order to explore the potential use of vegetation indices (VI) obtained from remote sensing via satellite, as well as the modeling of maize crop growth and development, in the central BiH region, the values of the basal crop coefficient (K_{cb}) were determined based on three approaches (Figure 5):

i) Allen & Pereira approach (A&P) – which is the reference approach, involving the use of ground data: leaf area index (LAI) measurements, each 7 days during the maize crop season, in both years under study (2021 and 2022). This approach uses the A&P equation [16] to obtain the density coefficient (K_d), and then, the basal crop coefficient ($K_{cb\ A\&P}$) according to the methodology defined by [33];

ii) SIMDualKc approach (SD) – Involving the use of the SIMDualKc model following the recommendations from the FAO56 document [35] to calculate basal crop coefficient ($K_{cb\ SD}$). Through calibration and validation of the soil water balance model (SWB), using a set of statistical "goodness of fit" indicators, calibrated values for all conservative parameters were determined. The year of 2022 served as the calibration year, while 2021 was used for validation;

iii) Vegetation indices approach (VI) – involving the calculation of the basal crop coefficient ($K_{cb\ VI}$) based on the Soil Adjusted Vegetation Index (SAVI) obtained from Sentinel-2 satellite imagery [66]. Calibration of this method was conducted using the trial-and-error method by adjusting η exponent representing relationship between SAVI and a transpiration coefficient (T_c) within the initial K_{cb} formula. The observed values considered were the AP K_{cb} values, along with the same set of statistical indicators as in SD approach. In this case as well, the year 2022 was used for calibration, and 2021 for validation.

Figure 5. Methodology flow chart for the three approaches considered for the determination of basal crop coefficients (K_{cb}): SIMDualKc model (SD), Ground truth A&P (A&P) and Remote sensing vegetation indices (VI).

After calibrating and validating procedures for the SD and VI approaches, the daily SWB was employed to identify water stress conditions within the three irrigation treatments/water stress conditions: F, D and R.

The dual crop coefficient approach implies the separation of the plant and soil effects on the crop coefficient (K_c) and, under non-stressed conditions, is computed as:

$$K_c = K_{cb} + K_e \quad (3)$$

For water stress conditions, Kc is a result of the following equation:

$$K_c = K_s\, K_{cb} + K_e \quad (4)$$

In such instances, the terms actual evapotranspiration ($ET_{c\ act}$), actual crop coefficient ($K_{c\ act}$), and actual basal crop coefficient ($K_{cb\ act}$) are used [35]. The stress coefficient (K_s), evaporation coefficient (K_e), actual basal crop coefficient ($K_{cb\ act}$), crop coefficient (K_c), and actual crop evapotranspiration ($ET_{c\ adj}$) were computed for each treatment, for each year of the experiment (2021 and 2022), and for each approach applied (A&P, SD, and VI). The complete methodology is presented in Figure 5.

2.4. Basal Crop Coefficient ($K_{cb\ A\&P}$) Calculation Based On-Ground LAI Observations - Allen & Pereira Approach (A&P)

The reference value of K_{cb} was calculated following the method proposed by Allen and Pereira [16] and known as A&P approach [17]. This method is based on the plant density coefficient (K_d) that was calculated based on ground measurements, mainly LAI (Equation 2) [16,34,67]. The following equations were used:

$$K_{cb\ A\&P} = K_{c\ min} + K_d\left(K_{cb\ full} - K_{c\ min}\right) \quad (5)$$

where K_d is crop density coefficient, $K_{cb\ full}$ is the estimated basal K_{cb} for peak plant growth conditions having nearly full ground cover (LAI > 3), and $K_{c\ min}$ is the minimum K_c for bare soil (K_c = 0.15 for standard agricultural conditions) [68,69]. K_d presented in Equation (5) is calculated with following equation [16]:

$$K_d = 1 - e^{[-0.7LAI]} \quad (6)$$

where LAI is defined as the area of leaves per area of ground surface ($m^2\ m^{-2}$) and it was calculated based on measured ground data (Equation 2), for each 7 days, during both years. The K_{cb}

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full in Equation 5 represents an upper limit on K_{cb} for vegetation under an adequate water supply having a full ground cover and a LAI > 3. The $K_{cb\ full}$ value was calculated as a function of mean plant height during the mid-season (h) and adjusted for climate conditions as:

$$K_{cb\ full} = F_r \left(min(1.0 + k_h h, 1.20) + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3} \right) \quad (7)$$

where F_r is resistance correction factor that takes into consideration stomatal control by vegetation [33], u_2 is the average daily wind speed (m s^{-1}) at a height of 2 m above ground level, during the growth period, RH_{min} (%) is the average daily minimum relative humidity during the growth period, and h is the mean plant height (m) during the mid-season. The effect of the crop height is considered through the sum (1 + k_h h), with k_h = 0.1 for tree, vine and tall field crops [15]. The upper limit for $K_{cb\ full}$ was 1.20, because according to local climatic adjustment there was no need to change $K_{cb\ full}$ value which remain equal to the standard value. A value F_r = 1 was used, because this is the standard value for most agricultural crops [70].

Since RH_{min} was not recorded during maize growing period in 2021 and 2022, it was estimated based on T_{max} and T_{min}, using the following equation [33]:

$$RH_{min} = \frac{e^0(T_{min})}{e^0(T_{max})} 100 \quad (8)$$

2.5. SIMDualKc Model for Estimating Basal Crop Coefficient ($K_{cb\ SD}$) Using Dual Crop Coefficient Approach (SD)

SIMDualKc software is a soil water balance model that calculates daily crop evapotranspiration, by considering a dual crop coefficient approach [33,71–73]. The SIMDualKc model calibration consisted of adjusting the standard parameters for crop (such as K_{cb} - $K_{cb\ ini}$, $K_{cb\ mid}$, $K_{cb\ end}$ - and p - p_{ini}, p_{dev}, p_{mid}, $p_{maturity}$ for each crop growth stage) and soil (TEW - totally evaporable water, REW - readily evaporable water, and effective depth of the surface soil layer subject to drying - Z_e) as presented in several studies such as [74,75] in order to minimize the differences between the simulated K_{cb} and observed ones (from A&P approach). Calibration was performed for the F treatment during 2022, while 2021 data was used for validation procedure. In the beginning of the calibration, the standard values proposed by Pereira and Paredes [37] were considered. Crop data included dates for the start of each crop development stages (Table 5) as well as the corresponding root depth, plant height and p-fraction. The maximum root depth was set to 1.0 m [36] and maximum observed plant height was 2.69 m.

Table 5. Dates, days after sowing (DAS) and length of the maize crop growth stages in 2021 and 2022.

Crop growth stages	2021		2022	
	Date (DAS)	Length	Date (DAS)	Length
Planting/Initiation (Initial)	07.05.2021 (1)	30	05.05.2022 (1)	25
Start rapid growth (Development)	06.06.2021 (30)	40	30.05.2022 (25)	45
Start midseason (Mid-Season)	16.07.2021 (70)	61	14.07.2022 (70)	64
Start senescence/Maturity	15.09.2021 (131)	-	16.09.2022 (134)	-
End season/harvesting (End)	23.10.2021 (170)	40	22.10.2022 (172)	39

Irrigation method was set to trickle irrigation (drip) with a fraction of soil surface wetted by irrigation (f_w) of 0.3, for both F and D irrigation treatments. Irrigation schedule was set to "User specified" and all irrigation events were provided to the model, with dates of the event and corresponding irrigation depth (mm) (Figure 5).

To identify the optimal set of non-measured parameters and assess their goodness-of-fit, a graphical comparison of simulated and observed K_{cb} values was created. Subsequently, linear regression was calculated, and when the regression coefficient (b_0) and determination coefficient (R^2) were close to 1, the predicted values were considered close to the observed ones. Finally, a set of

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indicators commonly used in hydrology and crop modeling for residual error estimation was applied [17,59,76–78].

2.6. Basal Crop Coefficient Derived from Remote Sensing Data ($K_{cb\ VI}$) – Vegetation Indices Approach (VI)

Free Sentinel-2 images were acquired directly from the Copernicus Open Access Hub (available at: https://scihub.copernicus.eu). Sentinel-2 data provided 12 bands with channels ranging from 443 to 2190 nm and a spatial resolution of 10 to 60 m. The European Space Agency (ESA) provides different types of images as Level-1C (L1C), Level-2A (L2A) etc. L1C images were geometrically corrected with the top-of-atmosphere (TOA) reflectance, but L2A images were geometrically and atmospherically corrected with top-of-canopy (TOC) reflectance. L2A images were used for analyses because of their TOC correctness (L1C images need to be atmospherically corrected using the Sen2Cor processor available in the SNAP toolbox).

For image processing and VI computing, ESA SNAP software (version 9.0.0) was used. In SNAP, the analyzed plots are located on the images using geographic coordinates and the pixels of importance are marked (Figure 2). The sensing period was from 9th May to 1st October in 2021, and from 19th May to 6th October in 2022. In 2021, 41 images over the study area in Butmir were available but only 20 images were usable (cloud-free). In 2022, 39 images were available and 16 of them were usable (Table 6). This is a consequence of the humid climate at the research location, thus the frequent presence of clouds and fog, over Butmir, which prevents ground visibility from a satellite perspective. Table 6 presents the summary of usable image dates considered for each year. They were resampled to 10 m pixel size and clipped to the region of interest.

Table 6. Satellite image dates and days after sowing (DAS) considered for each year.

Year	May	June	July	August	September	October	Total number of images
	Date (DAS)						
2021	09.05 (2)	03.06 (27)	08.07 (62)	02.08 (57)	01.09 (117)	01.10 (146)	20
	29.05 (22)	08.06 (32)	13.07 (67)	07.08 (92)	06.09 (122)		
		18.06 (42)	28.07 (82)	12.08 (97)	11.09 (127)		
		23.06 (47)		17.08 (102)	26.09 (142)		
		28.06 (52)		22.08 (107)			
2022	19.05 (14)	03.06 (29)	03.07 (59)	02.08 (89)	06.09 (124)	06.10 (154)	16
	24.05 (19)	13.06 (39)	13.07 (69)	07.08 (94)			
		23.06 (49)	18.07 (74)	17.08 (104)			
			23.07 (79)	27.08 (114)			
			28.07 (84)				

Using downloaded images (Table 6), SAVI [79] and $K_{cb\ VI}$ were calculated on a pixel-by-pixel basis and an averaged for each plot in the study area. SAVI was selected as suggested in previous research for maize crop [66].

Each treatment comprised three repetitions (plot) and each plot had four pixels, in total 12 values per sensing date, for each treatment. SAVI was calculated using the SAVI Processor command in SNAP software based on the surface spectral reflectance (ϱ) on the red (RED) and near-infrared (NIR) domains, following equation:

$$SAVI = \frac{(\rho NIR - \rho RED)}{(\rho NIR + \rho RED + L)}(1 + L) \quad (9)$$

where index L is the soil conditioning index varying between 0 and 1, with a value of L close to 1 representing a high degree of vegetation coverage and thus soil background has no effect on the retrieval of vegetation information. A value of L equal to 0.5 is considered for the most common environmental conditions and was found to minimize the effects of soil brightness variation and eliminate the need for calibration under different soil conditions [18,80].

Basal crop coefficient from vegetation indices ($K_{cb\ VI}$) was calculated using the modified approach introduced by Campos and Neale [66], that is based on Choudhury and Ahmed [30]. This approach includes residual evaporation factor (0.15) for bare soil that reflects evaporation occurrence several days after irrigation or rain event [16,18,33]. To calculate $K_{cb\ VI}$ the following equation was used:

$$K_{cb\ VI} = K_{cb\ max}\left[1 + \left(\frac{SAVI_{max} - SAVI}{SAVI_{max} - SAVI_{min}}\right)^{\eta}\left(\frac{0.15}{K_{cb\ max}} - 1'\right)\right] \quad (10)$$

where, η or (k/k') is representative of the non-linear relationship between SAVI and a transpiration coefficient T_c, $K_{cb\ max}$ is the basal crop coefficient at effective full crop cover, $SAVI_{max}$ and $SAVI_{min}$ represent the maximum and minimum values of SAVI corresponding to dense vegetation and bare soil, respectively.

Since it was determined that η approaches 1 when using SAVI [30,81], many studies propose using linear relationship between SAVI and K_{cb} [30,66,82]. Since the validity of these equations is restricted to the conditions for which they are developed, Equation 10 was utilized and calibrated for crop, climate, and management conditions in the present study.

To calculate the initial values of $K_{cb\ VI}$, the reference values of these parameters for maize, $SAVI_{min}$ and $SAVI_{max}$, are derived from Equation 9, and $K_{cb\ max}$ from Equation 5, following a two-year experiment conducted in this study (2021 and 2022), considering the F irrigation treatment. However, for initial calculation the η = 0.96 value was used as reported value for maize in scientific literature (Campos et al., 2017; Pôças et al., 2020).

Like the process already presented for SIMDualKc, the simulated basal crop coefficient values calculated with Equation 10 from vegetation indices ($K_{cb\ VI}$) were calibrated for 2022 and validated for 2021, by comparing them with the observed values of the basal crop coefficient ($K_{cb\ A\&P}$). The trial-and-error procedure was initially used with the original Equation 10, with a value of η = 0.96 (Campos et al., 2017), and then this value was adjusted until the difference measured with goodness-of-fit indicators (b_0, R^2, RMSE, AAE, ARE, E_{max}, EF, and d_{IA}) between observed ($K_{cb\ A\&P}$) and predicted ($K_{cb\ VI}$) values was minimized.

2.7. Actual Basal Crop Coefficient ($K_{cb\ act}$), Crop Coefficient (K_c) and Actual Crop Evapotranspiration ($ET_{c\ act}$) Estimation

After calibrating and validating the SIMDualKc and vegetation indices, the K_{cb} values were computed for each approach (A&P, SD, and VI) and experimental year. As a result, three sets of K_{cb} values—Allen and Pereira ($K_{cb\ A\&P}$), SIMDualKc ($K_{cb\ SD}$), and SAVI-based vegetation indices approach ($K_{cb\ VI}$)—were generated for each year of the experiment (Figure 1). These K_{cb} values represent full irrigation treatments, signifying a situation without stress. To calculate the actual crop (maize) evapotranspiration ($ET_{c\ adj}$) and include stress conditions, the stress factor (K_s) at the crop root zone was estimated using the daily soil water balance (SWB) method [18,34,83] of the SIMDualKc model. Therefore, the following equation was employed to introduce water stress in the estimates:

$$ET_{c\ act} = (K_s\, K_{cb} + K_e)\, ET_o \quad \text{or} \quad ET_{c\ act} = K_{c\ act} ET_o \quad (11)$$

where the term K_s K_{cb} represents the actual basal crop coefficient ($K_{cb\ act}$), which is the result of actual stress conditions. Meanwhile, K_s K_{cb} + K_e represents the actual crop coefficient ($K_{c\ act}$) and ET_o is reference evapotranspiration calculated based on Equation 1.

To present water stress conditions, K_s was calculated following the procedures explained in FAO56 [18,33] and based on initial soil conditions (Table 1) for every treatment and year:

$$K_s = \frac{TAW - D_r}{(1-\rho)TAW} \; for\ D_r > RAW \qquad (12)$$
$$K_s = 1\ for\ D_r \le RAW$$

where TAW is totally available water, RAW is readily available water, Dr is root zone depletion, and p is the depletion fraction threshold. The soil dataset was prepared to represent the soil characteristics, so that TAW was calculated by the model, using provided data on the soil layer thickness, root depth and FC and WP fractions in volume for each soil layer (Table 1).

Evaporation coefficient (K_e) was calculated with the following equation [33]:

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$$K_e = K_r(K_{c\,max} - K_{cb\,act}) \leq f_{ew}K_{c\,max} \quad (13)$$

where K_r is the soil evaporation reduction coefficient, $K_{c\,max}$ is the maximum value of crop coefficient, f_{ew} is the fraction of the soil that is wetted and exposed. The evaporable soil layer, which is subject to soil evaporation, was defined to have a thickness of 0.15 m, according to the soil characteristics, as proposed by [84]. The SIMDualKc SWB model was employed to compute K_s and K_e separately for each treatment (F, D, and R) and year of the experiment (2021 and 2022).

To avoid confusion in results section, specific prefixes were assigned to each calculated parameter (K_{cb}, $K_{cb\,act}$, $K_{c\,act}$, K_s, K_e, and $ET_{c\,act}$) for each treatment (F, D, and R), year (2021 and 2022), and calculation approach (A&P, SD, and VI). For the year 2021, the prefixes are F21, D21, and R21, corresponding to Full, Deficit, and Rainfed treatments, respectively. Similarly, for the year 2022, the prefixes are F22, D22, and R22.

Finally, two sets of modeled $ET_{c\,adj}$, from $K_{cb\,VI}$ ($ET_{c\,adj\,VI}$) and $K_{cb\,SD}$ ($ET_{c\,adj\,SD}$) approaches, are compared with observed ones ($ET_{c\,adj\,A\&P}$), computed following the A&P approach.

2.8. Statistical Analysis

In the statistical equations, observed values (X_i) were represented by $K_{cb\,A\&P}$ calculated using the Allen & Pereira approach with ground measurement of LAI, while predicted values (Y_i) were K_{cb} values calculated by SIMDualKc approach ($K_{cb\,SD}$) or by an approach based on vegetation indices ($K_{cb\,VI}$). X represents the mean value for observed, and Y represents the mean value for predicted K_{cb}. The applied statistical methods are expressed as:

$$b_0 = \frac{\sum_{i=1}^{n}(X_i - X)(Y_i - Y)}{\sum_{i=1}^{n}(X_i - X)^2} \quad (14)$$

$$R^2 = \left\{\frac{\sum_{i=1}^{n}(X_i - X)(Y_i - Y)}{[\sum_{i=1}^{n}(X_i - X)^2]^{0.5}\,[\sum_{i=1}^{n}(Y_i - Y)^2]^{0.5}}\right\}^2 \quad (15)$$

$$RMSE = \left[\frac{\sum_{i=1}^{n}(Y_i - X_i)^2}{n}\right]^{0.5} \quad (16)$$

$$AAE = \frac{1}{n}\sum_{i=1}^{n}|X_i - Y_i| \quad (17)$$

$$ARE = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{X_i - Y_i}{X_i}\right| \quad (18)$$

$$E_{max} = max|Y_i - X_i|_{i=1}^{n} \quad (19)$$

$$EF = 1.0 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=1}^{n}(X_i - X)^2} \quad (20)$$

$$d_{IA} = 1 - \frac{\sum_{i=1}^{N}(X_i - Y_i)^2}{\sum_{i=1}^{N}(|Y_i - X| + |X_i - X|)^2} \quad (21)$$

RMSE is the root mean square error, providing insight into the variance of the errors. AAE serves as an alternative to RMSE, indicating the magnitude of estimated errors. ARE is the average relative error presented as a percentage. Emax denotes the maximum absolute error. EF stands for model efficiency, and d_{IA} is the index of agreement.

After selection of best fitting values, same values were applied on second year of experiment and again tested with same statistical indicators.

3. Results and Discussion

3.1. Leaf Area Index (LAI) Through the Crop Seasons

The average values of leaf area index (LAI) measured on a seven-days basis for each treatment (F, D and R) are presented in Figure 6. LAI data was used to calculate K_{cb} in A&P approach.

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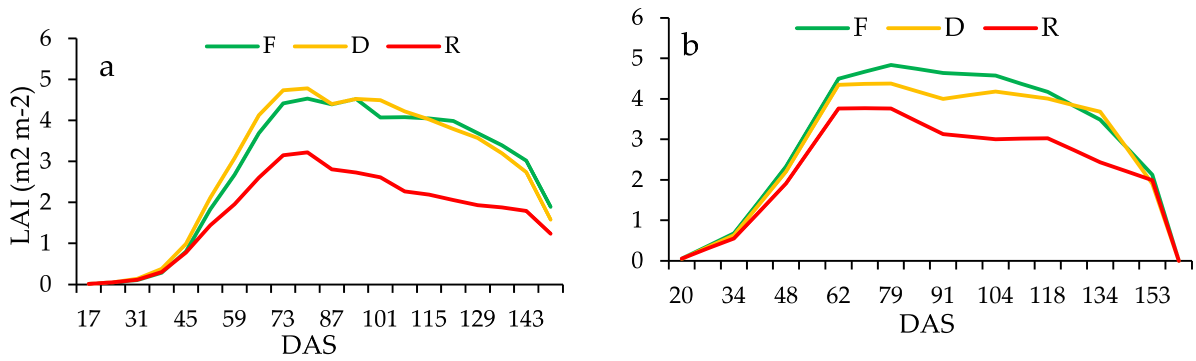

Figure 6. Average LAI (m^2 m^{-2}) for full (F), deficit (D) and rainfed (R) treatments during maize growth seasons 2021 (a) and 2022 (b) in Butmir, Sarajevo, Bosnia and Herzegovina.

During 2021, the maximum average value of LAI was observed in 80 DAS, for all treatments: 4.53 m^2m^{-2} for F, 4.78 m^2 m^{-2} for D, and 3.22 m^2 m^{-2} for R treatments. In general, the D treatment showed the highest values of LAI from 52 to 108 DAS. Similarly, in 2022, 79 days after sowing, the highest LAI was achieved: 4.84 m^2 m^{-2} for F, 4.38 m^2 m^{-2} for D, and 3.76 m^2 m^{-2} for R treatments. These values are in line with LAI values reported in other studies on maize [63,85–87]. Campos and Neale [66] reported even higher maximum LAI for maize, reaching 5.50 m^2 m^{-2}.

3.2. Estimation of basal crop coefficient with SIMDualKc ($K_{cb\ SD}$) model

The year 2022 was utilized for calibration, and 2021 for validation of the prediction models (SD and VI).

The calibration and validation of the SIMDualKc (SD) approach for maize in central BiH were conducted using truly independent datasets of basal crop coefficients (K_{cb}), with the A&P approach serving as the ground truth reference dataset. All calibrated values ($K_{cb\ ini}$, $K_{cb\ mid}$, $K_{cb\ end}$, p_{ini}, p_{dev}, p_{mid}, $p_{maturity}$, TEW, REW and Z_e) for SD approach are presented in Table 7.

Table 7. Initial and calibrated parameter values used in the SIMDualKc model for maize.

	Maize basal crop coefficients (K_{cb})			Depletion factors for no stress conditions (p)					Soil evaporation parameters		
	$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$	p_{ini}	p_{dev}	p_{mid}	$p_{maturity}$	p_{end}	TEW (mm)	REW (mm)	Z_e (m)
Initial	0.15	1.15	0.50	0.50	0.50	0.50	0.50	0.50	51	11	0.15
Calibrated	0.30	1.15	0.45	0.55	0.55	0.55	0.55	0.55	51	11	0.15

Based on the review and update of the FAO56 conducted by Pereira and Paredes [37], which considered only high-quality research conducted on maize in various locations, including Brazil, Portugal, Uruguay, China, and Pakistan, the observed values of $K_{cb\ mid}$ ranged between 1.00 and 1.15, while $K_{cb\ end}$ ranged from 0.20 to 0.64. The calibrated values for central BiH fall within the same range. The same authors also provided values for depletion factors for no stress conditions (p), ranging between 0.40 and 0.80. In this research (Table 7), the calibrated values of p remain consistent across all crop stages and are slightly higher than those originally proposed by updated FAO56. This may be attributed to the robust root system of the maize hybrid (BL-43), indicating high drought resistance, as stated by the developer. Initial values considering soil evaporation parameters (TEW, REW and Z_e) estimated based on soil physical and water-related characteristics (Table 1) did not change after calibration.

Figure 7 depicts a graphical relationship between observed K_{cb} values ($K_{cb\ A\&P}$) and calibrated SIMDualKc ($K_{cb\ SD}$) for 2021 and 2022. The results show very good alignment both in the calibration year and in the validation year.

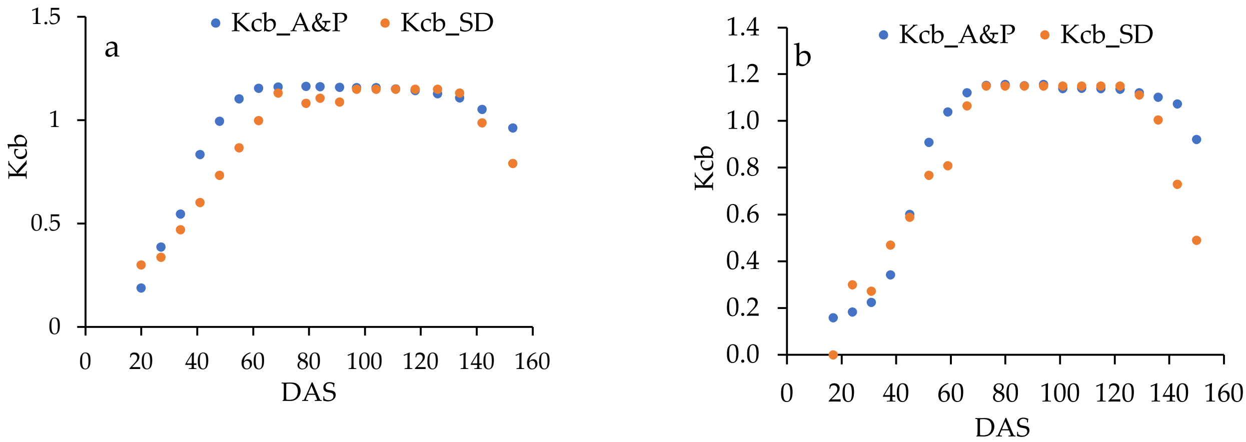

Figure 7. Basal crop coefficient (K_{cb}) based on Allen and Pereira approach ($K_{cb\ A\&P}$) and simulated by SIMDualKc ($K_{cb\ SD}$) after model calibration in 2022 (a) and validation in 2021 (b).

These results are confirmed by a set of goodness-of-fit indicators (Table 8).

Table 8. Goodness-of-fit indicator for SIMDualKc (SD) model calibration and validation.

	n	b_0	R^2	RMSE	AAE	ARE	E_{max}	EF	d_{AI}
Calibration	20	0.93	0.89	0.12	0.08	11.82	0.26	0.82	0.95
Validation	19	0.95	0.91	0.11	0.07	15.68	0.34	0.89	0.97

Note: b_0 - regression coefficient; R^2 - determination coefficients; RMSE - the root mean square error; AAE - the magnitude of estimated errors; ARE - the average relative error in percentages; E_{max} - the maximum absolute error; EF - model efficiency, d_{IA} - the index of agreement.

The regression coefficient (b_0) is very close to 1 (0.93 – 0.95) indicating very similar results between $K_{cb\ A\&P}$ and $K_{cb\ SD}$. Also, R^2 is high (0.89 - 0.91) indicating that simulated values ($K_{cb\ SD}$) explained most of the total variance of observed values ($K_{cb\ A\&P}$). Estimated errors are small, RMSE is less than 0.12, AAE is below 0.08 and ARE is below 15.68%, while maximum absolute error is less than 0.34. Since the target value for EF and d_{IA} is 1.00, in this research EF can be considered good, ranging from 0.82 to 0.89, while d_{IA} is very high, ranging from 0.95 to 0.97. These values indicate very good results of K_{cb} prediction by the calibrated SIMDualKc model.

3.3. Estimation of Basal Crop Coefficient with Vegetation Indices Approach ($K_{cb\ VI}$)

To calculate the initial values of $K_{cb\ VI}$, the reference values of following parameters for maize $K_{cb\ max}$ = 0.95, $SAVI_{min}$ = 0.68 and $SAVI_{max}$ = 0.09 and η = 0.96 (Equation 10) [18,34,66] were used considering only non-stress (F) conditions, in 2021 and 2022 crop cycles.

The calibration (2022) and validation (2021) of the Vegetation indices (VI) approach for maize in central BiH followed trial-and-error procedure until observed ($K_{cb\ A\&P}$) and predicted ($K_{cb\ VI}$) values was minimized.

All calibrated values ($K_{cb\ max}$, $SAVI_{max}$, $SAVI_{min}$, η) for VI approach are presented in Table 9.

Table 9. Initial and calibrated values used in the $K_{cb\ VI}$ equation (18) for the Vegetation indices approach, for maize.

	$K_{cb\ max}$	$SAVI_{max}$	$SAVI_{min}$	η	Coefficient
Initial values	0.95	0.68	0.09	0.96	0.15
Calibrated values	1.17	0.64	0.14	2.40	0.15

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All the newly obtained values closely match those previously reported in the literature, with one notable exception: the damping coefficient η (2.40). The damping coefficient (η) was introduced by Choudhury and Ahmed [30] to illustrate the nonlinear relationship between vegetation indices (such as SAVI and NDVI) and transpiration coefficients (T_c). In their study, Choudhury and Ahmed [30] reported a η value close to 1 when using SAVI in Equation 10. This η value applies to various crops and corresponds to the period of full transpiration—prior to senescence or seed development. In our case, the SAVI data are covering the entire maize growing period and indicate a nonlinear relationship between SAVI and T_c.

As explained by González-Dugo and Mateos [83], subsequent to Choudhury and Ahmed [30] some authors [88,89] have employed a linear K_{cb} – VI relationship despite the underlying nonlinear relationship, while others have examined and validated Equation 10 for local conditions. For instance, Er-Raki and Chehbouniand [90] found value of η = 1.55 for wheat in Marocco, while Campos and Neale [66] found η = 1.11 when $K_{cb\ min}$ = 0, and η = 0.96 when $K_{cb\ min}$ = 0.12 for maize in eastern Nebraska.

As noted by Pôças and Calera [18], the comparison of various K_{cb}-VI relationships across different crops, based on published research using empirical and conceptual approaches, is valid for assessing ET_c and irrigation requirements. However, the primary challenge arises from the variability of this relationship, influenced by factors like crop type, irrigation management, soil conditions, and climate.

Figure 8 shows a graphical relationship between observed ($K_{cb\ A\&P}$) and based on VI estimated basal crop coefficient ($K_{cb\ VI}$) value for 2021 and 2022. These findings demonstrate excellent consistency, both during the calibration and validation years.

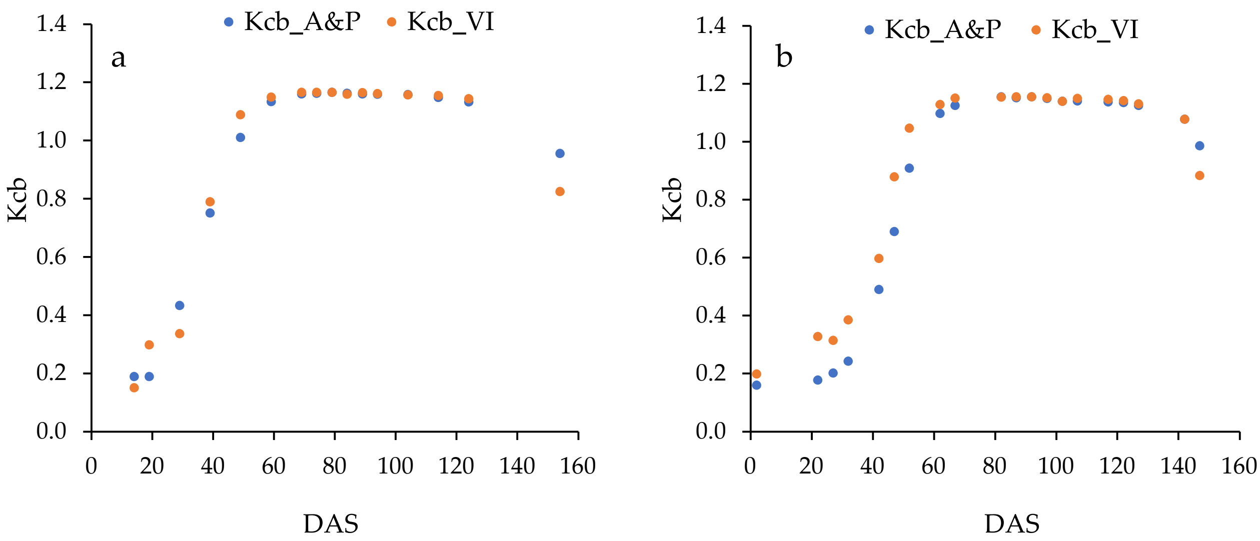

Figure 8. Basal crop coefficient (K_{cb}) based on Allen and Pereira approach ($K_{cb\ A\&P}$) and simulated by Vegetation Indices ($K_{cb\ VI}$) after equation calibration in 2022 (a) and validation in 2021 (b).

These results are confirmed by a set of goodness-of-fit indicators (Table 10).

Table 10. Goodness-of-fit indicator for Vegetation Indices (VI) approach for calibration and validation.

	n	b_0	R^2	RMSE	AAE	ARE	E_{max}	EF	d_{AI}
Calibration	16	1.00	0.97	0.05	0.03	8.19	0.13	0.97	0.99
Validation	20	1.02	0.97	0.08	0.05	15.40	0.19	0.95	0.99

Note: b_0 - regression coefficient; R^2 - determination coefficients; RMSE - the root mean square error; AAE - the magnitude of estimated errors; ARE - the average relative error in percentages; E_{max} - the maximum absolute error; EF - model efficiency, d_{IA} - the index of agreement.

The regression coefficient (b_0) remains consistent at 1 during calibration and slightly increases to 1.02 during validation, suggesting a close match between $K_{cb\ A\&P}$ and $K_{cb\ VI}$. High R^2 values of 0.97 for data sets indicate that the simulated values ($K_{cb\ VI}$) effectively capture most of the observed variance ($K_{cb\ A\&P}$). Error metrics such as RMSE (< 0.08), AAE (< 0.05), and ARE (< 15.40%) are all very low, with the maximum absolute error below 0.19. Both EF and d_{IA}, with values exceeding 0.97 and approaching the target of 1.00, signify excellent performance. Overall, these findings confirmed the precision of the calibrated VI approach in estimating maize basal crop coefficients using vegetation indices. Moreover, compared to the statistical parameters for the SD approach (Table 8), the VI method emerges as a more precise and preferable option.

3.4. Estimated Values of Average Basal Crop Coefficient (K_{cb}) and Crop Coefficient (K_c) for Maize

The comparison between the actual crop coefficient ($K_{cb\ act}$) and the calculated crop coefficient ($K_{c\ act}$) for maize using three different approaches (A&P, SD, and VI) across three irrigation treatments (F, D, and R) and tabulated K_{cb} and K_c values is presented in Table 11.

Table 11. Comparison between actual K_{cb} and K_c calculated for three approaches (A&P, SD, and VI) and three irrigation treatments and tabulated values.

Irrigation treatment	Year	Approach	K_{cb}			K_c		
			$K_{cb\ ini}$	$K_{cb\ mid}$	$K_{cb\ end}$	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
No stress	-	Tabulated	0.15	1.15	0.50 – 0.15*	0.30	1.20	0.60 – 0.35*
			$K_{cb\ ini\ act}$	$K_{cb\ mid\ act}$	$K_{cb\ end\ act}$	$K_{c\ ini\ act}$	$K_{c\ mid\ act}$	$K_{c\ end\ act}$
Full irrigation	2021	A&P	0.16	1.13	0.45	0.71	1.22	1.05
		SD	0.29	1.13	0.45	0.83	1.22	1.05
		VI	0.26	1.14	0.45	0.81	1.23	1.05
	2022	A&P	0.19	1.13	0.45	0.77	1.22	0.80
		SD	0.29	1.12	0.45	0.86	1.20	0.80
		VI	0.19	1.13	0.45	0.76	1.21	0.80
Deficit irrigation	2021	A&P	0.12	0.56	0.40	0.68	0.90	1.01
		SD	0.07	0.32	0.37	0.63	0.66	0.98
		VI	0.21	0.55	0.40	0.77	0.89	1.01
	2022	A&P	0.16	0.70	0.15	0.78	1.08	0.54
		SD	0.14	0.46	0.05	0.76	0.85	0.44
		VI	0.17	0.69	0.15	0.78	1.08	0.54
Rainfed	2021	A&P	0.11	0.26	0.37	0.59	0.44	0.99
		SD	0.06	0.13	0.32	0.54	0.32	0.94
		VI	0.26	0.27	0.37	0.74	0.45	0.99
	2022	A&P	0.15	0.40	0.10	0.74	0.79	0.45
		SD	0.04	0.18	0.03	0.63	0.58	0.37
		VI	0.15	0.40	0.10	0.74	0.80	0.50

Note: *First value is for harvest at high grain moisture and the second is for harvest after filed dying of the grain (Allen et al., 1998). Note: $K_{cb\ ini\ act}$ is the actual initial basal crop coefficient, $K_{cb\ mid\ act}$ is the actual mid-season basal crop coefficient, $K_{cb\ end\ act}$ is the actual end basal crop coefficient; $K_{c\ ini\ act}$ is the

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actual initial crop coefficient, $K_{c\ mid\ act}$ is the actual mid-season crop coefficient; $K_{c\ end\ act}$ is the actual end crop coefficient.

Comparison with tabulated crop coefficient (K_{cb}) values defined by FAO56 [33] can only be applied to non-stress conditions, which in this research correspond to the data for the F irrigation treatment. For the A&P approach, the values of basal crop coefficient for initial ($K_{cb\ ini\ act}$: 0.16 - 0.20), mid-season ($K_{cb\ mid\ act}$: 1.13 - 1.14), and end stage ($K_{cb\ end\ act}$: 0.45) are almost identical to tabulated values (0.15, 1.15 and 0.50). The SD approach shows slightly higher values for the initial basal crop coefficient ($K_{cb\ ini\ act}$: 0.29 - 0.30), as does the VI approach ($K_{cb\ ini\ act}$: 0.20 - 0.26), while other values of the basal crop coefficient are similar to tabulated ones (Table 11). These values meet the condition outlined in the FAO56 paper, which specifies that local values of K_{cb} should not deviate by more than 0.2 [33]. Within the updated tabulated FAO56 K_{cb} values, Pereira and Paredes [37] provided an overview of $K_{cb\ min}$ and $K_{cb\ end}$ values for maize obtained from a large number of studies, varying in irrigation methods, climate conditions, study locations, and methods of determining ET_c (SIMDualKc, SWB-TDR, ISAREG). The $K_{cb\ mid}$ values range from 1.00 to 1.15, which aligns with our findings. Similarly, the $K_{cb\ end}$ values fall within the range of 0.20 to 0.64.

Under conditions of certain stress, such as deficit irrigation treatment (D) in this study, the $K_{cb\ act}$ values determined by the A&P approach are lower than those in the F treatment, especially during the mid-season crop development stage when they range from 0.56 to 0.70. Particularly noticeable is the very low value of $K_{cb\ end\ act}$ (0.15) during the 2022 growing season, which can be interpreted as a faster completion of maize vegetation under deficit irrigation conditions. In our case, since harvesting was done simultaneously (DAS 169 in 2021 and DAS 170 in 2022) for all irrigation treatments (F, D and R), this resulted in different moisture levels of maize grains at the time of harvest, which could affect the values of $K_{cb\ end\ act}$ and $K_{c\ end\ act}$ values. This issue is also related to the last LAI measurement taken on October 4, 2021, and October 5, 2022, respectively, or the last available image from Sentinel-2 captured on October 1, 2021, and October 6, 2022, which occurred before the final day of vegetation on October 23, 2021, and October 22, 2022, respectively. Compared to the A&P values as reference, the SD approach underestimates K_{cb} values, especially during the initial and mid-seasonal stages of maize development. The values of the basal crop coefficient differ by up to 0.24. On the other hand, the VI approach showed excellent alignment of K_{cb} values in all three development stages, with differences of only 0.01. An exception is observed during the initial phase of maize in 2022 (normal hydrological year) when a slightly higher value of $K_{cb\ ini\ act}$ (0.21) was obtained using the VI approach.

Under non-irrigated conditions (R treatment), which represents the typical conditions for maize cultivation in BiH, the values of the basal crop coefficient are even lower. This is particularly evident during the mid-season stage in the dry year of 2021, when $K_{cb\ mid\ act}$ was only 0.26. Such low K_{cb} values indicate the inability of this crop to achieve its genetic potential and highlight the importance of introducing irrigation into regular maize cultivation practices in BiH. In rainfed agriculture, both SD and VI approaches yield similar results as in deficit irrigation conditions. The SD approach underestimates K_{cb} values, whereas the VI approach, particularly in 2022, shows the same values as A&P. The poor performance of the SD approach can be attributed to the fact that its calculation of K_{cb} does not account for real-time changes in the crop due to specific stress related to current weather conditions. On the other hand, A&P, through LAI, and VI, through SAVI images, adjust these values to actual conditions in the field. Overall, we can conclude that the SD approach should be used with caution for monitoring maize under stress conditions, and its use should be preferred to estimating K_{cb} for stress-free conditions. Furthermore, considering that VI is dependent on the number of available cloud-free images, which in our conditions amounted to 20 for 2021 and 16 for 2022 (Table 6), a smaller number of images would certainly affect the accuracy of K_{cb} estimation. This is particularly important for humid conditions like those in BiH, where there is a high number of cloudy days.

Many authors [18,23,34,81,83,91] have previously reported that the combined utilization of VI approaches and SWB models enables the spatial representation of $K_{c\ act}$ and $ET_{c\ act}$ for crops cultivated under both stress and non-stress conditions. The advantage of the VI approach lies in its ability to consider variations in crop growth due to weather conditions [34,92] such as frost, low or high

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temperatures, variations in air moisture or wind speed. Except for that, this approach can demonstrate variations between different fields [35], as evidenced by this research comparing results for no stress (F) and stress (D and R) conditions.

The influence of evaporation is reflected in the K_c, and in this study its values ($K_{c\ act}$) are obtained by adding $K_{cb\ act}$ to the evaporation coefficient (K_e) calculated in the SIMDualKc model using Equation 13. Since the same K_e data were used for all calculation approaches (A&P, SD, and VI), the interpretation of differences between the approaches remains the same as in the case of $K_{cb\ act}$. Therefore, we will focus here on the differences between the tabulated FAO56 [33] values and the $K_{c\ act}$ values obtained in this study. In stress-free conditions (F), the obtained $K_{c\ act}$ values (A&P, SD and VI) for both years of the study (2021 and 2022) during the initial and end stages of maize development are higher than the tabulated values, ranging from $K_{c\ ini\ act}$ of 0.71 to 0.87 compared to $K_{c\ ini}$ of 0.3, and for $K_{c\ end\ act}$ from 0.80 to 1.06 compared to $K_{c\ end}$ of 0.35 to 0.60 (Table 11). On the other hand, the mid-season period ($K_{c\ mid\ act}$: 1.20 – 1.23) shows very good agreement with the tabulated values ($K_{c\ mid}$: 1.20). It is evident that the tabulated K_c values do not adequately cover the evaporation that occurs when the maize is not fully covering the soil, i.e., during periods of maize growth and senescence. Also, maize was harvested earlier with high grain moisture, especially in 2021, as indicated by Pereira and Paredes [37], where $K_{c\ end}$ values under high grain moisture conditions can reach up to 0.95 [93].

3.5. Estimating Actual Evapotranspiration ($ET_{c\ act}$) for Maize

After calibration and validation, the actual evapotranspiration of maize ($ET_{c\ act}$) was calculated using Equation 19 for all three approaches (A&P, SD, and VI), all irrigation treatments (F, D and R) and both years of experiment (2021 and 2022). The daily $ET_{c\ act}$ for 2021 is shown in Figure 9.

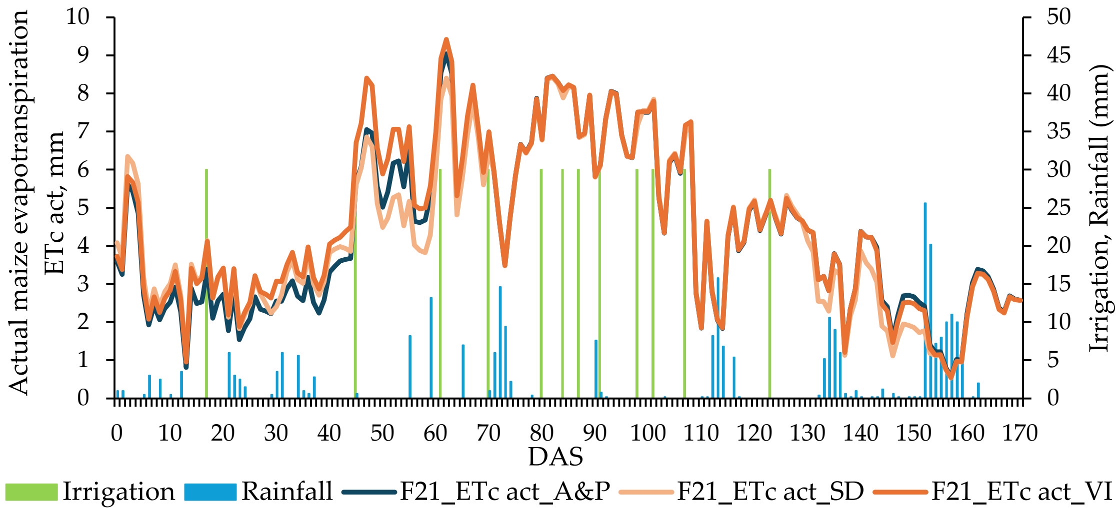

Figure 9. Actual maize evapotranspiration ($ET_{c\ act}$) as a result of Allen and Pereira approach (A&P), SIMDualKc approach (SD) and Vegetation indices approach (VI) for full irrigation treatment in 2021.

The daily evapotranspiration values obtained using different approaches during 2021 align closely, particularly from 60 DAS until the end of the vegetation period. Larger differences are present during the initial development stage, up to the tasseling stage. During this period, $ET_{c\ VI}$ is slightly higher, as indicated by the regression coefficient value in Table 10 (b_0 = 1.02). On the other hand, $ET_{c\ SD}$ values show slightly lower values compared to the reference level ($ET_{c\ A\&P}$), especially during the period from DAS 54 to 58, and period DAS 134 - 153.

The discrepancies during the initial stages of vegetation arise from variations in the $K_{cb\ act}$ values (Table 11) for each approach, or more precisely, from the capability of the SIMDualKc model and vegetation indices to accurately calculate these values during a period of intense biophysical changes in plants. However, these errors are negligible, as previously determined by statistical indicators (Tables 8 and 10).

The highest value of $ET_{c\ act}$, 9.05 mm day^{-1}, was found for 62 DAS (July 8, 2021), while the lowest value, 0.57 mm day^{-1}, was found for 157 DAS (October 11, 2021). During the mid-season growth stage (70 – 130 DAS), there were several noticeable declines in daily $ET_{c\ act}$ values. These declines were recorded during 73, 103, 110, and 114 DAS. Comparing these results with atmospheric conditions, it is evident that during these periods, there were lower air temperatures and increased rainfall, resulting in higher relative humidity and lower evapotranspiration rates.

The daily $ET_{c\ act}$ values for the second year of the experiment (2022) are presented in Figure 10.

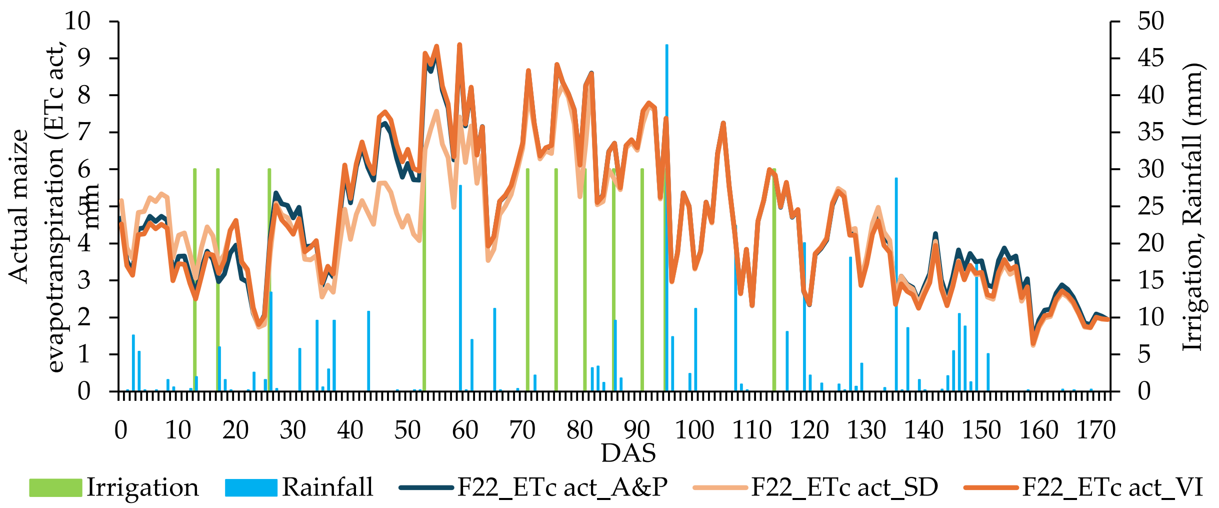

Figure 10. Actual maize evapotranspiration ($ET_{c\ act}$) as a result of Allen and Pereira approach (A&P), SIMDualKc approach (SD) and Vegetation indices approach (VI) for full irrigation treatment in 2022.

As in the first year of the study, the results show very good agreement during the mid-season growth stage (DAS: 69 - 133). However, during the development stage (DAS: 25 – 69), there are some differences, indicating lower $ET_{c\ act}$ values using the SD approach, and slightly higher by the VI approach. The highest value of $ET_{c\ act}$, 9.27 mm day^{-1}, was recorded on 59 DAS (July 3rd, 2022), while the lowest value, 1.41 mm day^{-1}, was recorded on 159 DAS (October 5th, 2022). The higher maximum and minimum values of $ET_{c\ act}$ in 2022 compared to 2021 indicate better conditions for maize development in the second year of the experiment. This is further confirmed by the 10.9% higher yields achieved in the second year (Table 4).

Similarly to the previous year, in 2022, there was also a decline in $ET_{c\ act}$ due to periods of lower air temperature and higher rainfall. This is evident for 64, 96, 100, 110, and 120 DAS.

Since the study also covered water stress conditions, namely deficit irrigation - D (50% of water requirements) and rainfed cultivation - R, the $ET_{c\ act}$ values were calculated for these conditions as well. These values, expressed as the sum of $ET_{c\ act}$ in mm for each growth stage, are provided in Table 12.

Table 12. Sum of actual evapotranspiration ($ET_{c\ act}$, mm) for different maize development stages as a result of different calculation approaches (A&P, SD and VI) and different irrigation treatments.

Irrigation treatment	Year	Approach	Initial	Development	Mid-season	End	Vegetation period
Full irrigation	2021	A&P	81	202	355	104	742
		SD	95	194	355	90	734
		VI	92	226	356	101	776
	2022	A&P	90	261	351	111	813
		SD	101	219	345	104	769
		VI	90	263	351	103	807

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Deficit irrigation	2021	A&P	77	188	257	80	601
		SD	73	155	188	66	482
		VI	87	206	256	78	627
	2022	A&P	91	253	305	102	752
		SD	88	205	236	81	610
		VI	92	247	304	97	740
Rainfed	2021	A&P	66	146	120	71	403
		SD	62	125	83	63	332
		VI	82	168	123	71	444
	2022	A&P	85	224	212	94	616
		SD	71	170	151	75	467
		VI	85	228	214	91	618

Note: A&P - Allen and Pereira approach; SD - SIMDualKc approach; VI - Vegetation indices approach.

The highest values of $ET_{c\ act}$ were calculated for 2022 and irrigation treatment which implied no stress conditions (full irrigation - F), ranging from 769 to 813 mm depending on the calculation model. The lowest values were recorded in 2021 under non-irrigated conditions, with $ET_{c\ act}$ values ranging from 332 to 444 mm.

Since the approach of calculating ET_c using dual crop coefficient or remote sensing has not been previously applied in BiH and the region (Serbia and Croatia), it is difficult to find studies that estimated the ET_c values of maize for Balkan region in nonstress conditions.

Since the approach of calculating ET_c using dual crop coefficient or remote sensing has not been previously applied in BiH and the wider region (including Serbia and Croatia), it is challenging to find studies that have estimated the ET_c values of maize for the Balkan region under non-stress conditions. For the Vojvodina region in Serbia, Pejić and Rajićand [94] reported maize ET_c values of around 530 mm, while Gregorić and Počučaand [95] obtained an average value for the period from 1975 to 2000 of 511 mm. Using the FAO56 methodology and tabulated K_c values, Kresovic and Matovicand [96] obtained an average ET_c value for maize for the period from 2002 to 2010 of 530 mm, while Šimunić and Liksoand [97] obtained 561 mm for wet, and 514 mm for dry year in Croatia. For continental part of BiH, there have been certain studies on maize involving the use of FAO56 tabulated single crop coefficient values and the AquaCrop model. According to these studies, the long-term (1961 – 1990) average maize ET_c for the Banja Luka region (north BiH) is 635 mm [98], while for 2018 and locations in central BiH (Srebrenik, Kalesija, and Kakanj), it ranges between 432 - 531 mm [44]. In other studies, conducted worldwide in continental climates, maize ET_c values ranging from 663 to 803 mm have been obtained [99,100].

During the mid-season, the highest sum of $ET_{c\ act}$ under the F (345 – 356 mm) and D (188 – 305 mm) irrigation treatments (Table 12) was observed. Interestingly, this is not the case in the R irrigation treatment, where $ET_{c\ act}$ has the highest sum in the developmental stage (125 – 228 mm), which among other is the result of available soil moisture at the beginning of the vegetation and lower air temperature during this period (Table 2).

By comparing the two years of research, it can be seen that during 2022, when normal climatic conditions prevailed, the values of $ET_{c\ act}$ were higher in all stages of maize development, and for the entire vegetation period, they were 10% (71 mm) higher in the F treatment, 25% (150 mm) higher in the D treatment, and even 54% (212 mm) higher in the R treatment. The results indicate that even under well-wetted crop conditions (F), there are certain differences in $ET_{c\ act}$ between dry and normal years.

4. Conclusions

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Agriculture in BiH is highly sensitive to climate change, especially in the water sector, highlighting the critical need for the implementation of sustainable water management approaches. However, an additional challenge arises from the insufficient level of research and innovation in this sector. Agricultural producers frequently overlook the actual water requirements of plants, instead relying on subjective judgments to determine when to irrigate. Data related to agriculture, including crop type, field management, irrigation practices, and crop water requirements, are often either unmeasured, unavailable, or estimated through certain approximations. Within the water management sector, research in BiH commonly relies on straightforward methodologies, such as using monthly water balances and evapotranspiration calculation methods, which typically require a limited set of input parameters. Furthermore, the evaluation of crop water needs and irrigation requirements often involves the application of a single crop coefficient (K_c) or FAO56 tabulated values for continental or Mediterranean conditions. In BiH, there has been no research conducted so far that has explored the application of dual crop coefficient or remote sensing for determining crop evapotranspiration, crop water requirements, and irrigation needs. A similar situation is in the region (Croatia, Serbia, and Montenegro). Therefore, the findings of this study can be recognized as a foundation for future utilization of RS methodologies and the dual crop coefficient approach, for irrigation management in the region. This is particularly crucial for adapting to climate change, specifically drought conditions, and advancing sustainable agriculture practices in BiH.

By utilizing measured data on soil characteristics, climate, and agricultural crops during a two years (2021 and 2022) real-case study on maize in the continental climate of BiH, calibration and validation of the SIMDualKc software model (SD) and equation used to determine the basal crop coefficient based on satellite imagery (VI) was performed. The obtained results suggest the potential use of both approaches for a more precise estimation of ET_c and crop water requirements, which could lead to improvements in water management in the region and ease the process of changing the rainfed production to irrigation use.

The SD approach, with defined criteria and parameters for maize, can be used with high precision for analyzing maize crops that are not under water stress, or for those that are supplementary irrigated under continental climate conditions, such as those in the research area. Its application, due to estimated lower $K_{cb\ act}$ values, is questionable under conditions of deficit irrigation or rainfed maize cultivation, which is a common practice in BiH. These results may be attributed to fixed point values of basal crop coefficients that do not adapt to current stress conditions. On the other hand, the VI approach showed a slightly higher $K_{cb\ act}$ values but satisfactory results during both years of research and in all production conditions (F, D, and R). Unlike the soil water balance (SWB) approach and the SIMDualKc model, this approach considers the current state of the crop, based on the processing of satellite imagery and the calculation of $K_{cb\ act}$ through the SAVI vegetation index. The complicating factor for the application of this approach is the need to include stress and evaporation parameters (K_s and K_e), which are the result of the SWB and must be calculated separately.

The obtained results indicated the high accuracy of the VI approach, even in humid climatic conditions characterized by a large number of cloudy days when satellite imagery is not available.

Both approaches for calculating K_{cb}, K_c, and ET_c have their advantages and disadvantages. Therefore, it is necessary to continue such research, especially for each crop and specific local conditions, with the goal of better utilizing natural resources, especially water, and more accurately determining plant water and irrigation requirements to minimize the negative impact of agriculture on the environment.

This research also demonstrates that by irrigating maize, even when applying deficit irrigation, higher yields can be achieved in the humid climate conditions typical of central BiH. Evidence for this is the difference in yield between the rainfed and the deficit irrigation treatment, where the yield in the deficit irrigation treatment was 67.6% higher, as well as the differences in the values of obtained $K_{cb\ act}$ during the dry 2021 year, where during the mid-season, the $K_{cb\ act}$ in the rainfed treatment was only 0.26 compared to 1.13 in the non-stressed conditions. This is also evidence of the ongoing transition in BiH from rain-fed agriculture to irrigation-dependent systems, particularly evident in the fact that this applies to crops that are relatively drought-resistant, such as maize.

The approach followed in the experimental irrigation scheduling (the water balance method with a single crop coefficient and FAO56 tabulated K_c values) may lead to discrepancies in the results of water balance and stress presence due to differences between the actual K_c and tabulated K_c values during certain periods and under full irrigation conditions. However, this was not observed in this study, and such an approach did not affect the obtained data.

Considering all the advantages of remote sensing approaches, future modeling software such as SIMDualKc, AquaCrop, and others may move towards integrating remote sensing into crop growth and development modeling processes. Additionally, the development of artificial intelligence also opens significant opportunities.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization, S.Č., M.T., and T.A.P.; methodology, S.Č., Z.O., D.S., B.C., W.S.A., M.Š., M.M., M.T., and T.A.P.; software, S.Č., Z.O., D.S., B.C., W.S.A., M.Š., and T.A.P.; validation, S.Č. Z.O. D.S. B.C. W.S.A. and T.A.P.; formal analysis, S.Č., Z.O., D.S., B.C., W.S.A., M.Š., M.M., M.T., and T.A.P.; investigation, S.Č., Z.O., D.S., B.C., W.S.A., M.Š., M.M., M.T., and T.A.P.; resources, S.Č., Z.O., D.S., B.C., W.S.A., M.Š., M.M., M.T., and T.A.P.; data curation, S.Č., Z.O., D.S., B.C., W.S.A., M.Š., M.M., M.T., and T.A.P.; writing—original draft preparation, S.Č., Z.O., D.S., B.C., W.S.A., M.Š., M.M., M.T., and T.A.P.; writing—review and editing, S.Č., Z.O., D.S., B.C., W.S.A., M.Š., M.M., M.T., and T.A.P.; visualization, S.Č., Z.O., D.S., B.C., W.S.A., M.Š., M.M., M.T., and T.A.P.; supervision, S.Č., M.T., and T.A.P.; project administration, S.Č., M.T., and T.A.P.; funding acquisition, S.Č., M.T., and T.A.P. All authors have read and agreed to the published version of the manuscript.".

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