

Prairie View A&M University

Digital Commons @PVAMU

Agriculture and Human Science Faculty
Publications

Faculty Publications

3-1-2021

Performance of spring and summer-sown maize under different irrigation strategies in Pakistan

Abdul Ghaffar Khan

University of Agriculture, Faisalabad

Muhammad Imran

University of Agriculture, Faisalabad

Anwar Ul Hassan Khan

University of Agriculture, Faisalabad

Ali Fares

Prairie View A & M University

Jiří Šimůnek

University of California, Riverside

See next page for additional authors

Follow this and additional works at: <https://digitalcommons.pvamu.edu/agriculture-facpubs>

Recommended Citation

Khan, A., Imran, M., Khan, A., Fares, A., Šimůnek, J., Ul-Haq, T., Alsahli, A., Alyemeni, M., & Ali, S. (2021). Performance of spring and summer-sown maize under different irrigation strategies in Pakistan. *Sustainability (Switzerland)*, 13, 1-13. <https://doi.org/10.3390/su13052757>

This Article is brought to you for free and open access by the Faculty Publications at Digital Commons @PVAMU. It has been accepted for inclusion in Agriculture and Human Science Faculty Publications by an authorized administrator of Digital Commons @PVAMU. For more information, please contact hvkoshy@pvamu.edu.

Authors

Abdul Ghaffar Khan, Muhammad Imran, Anwar Ul Hassan Khan, Ali Fares, Jiří Šimůnek, Tanveer Ul-Haq, Abdulaziz Abdullah Alsahli, Mohammed Nasser Alyemeni, and Shafaqat Ali

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/350003537>

Performance of Spring and Summer–Sown Maize under Different Irrigation Strategies in Pakistan

Article in *Sustainability* · March 2021

DOI: 10.3390/su13052757

CITATIONS

0

READS

89

9 authors, including:



Abdul Ghaffar Khan

Ayub Agricultural Research Institute

12 PUBLICATIONS 75 CITATIONS

[SEE PROFILE](#)



Muhammad Imran

University of Veterinary and Animal Sciences

552 PUBLICATIONS 5,635 CITATIONS

[SEE PROFILE](#)



Ali Fares

Prairie View A&M University

134 PUBLICATIONS 2,464 CITATIONS

[SEE PROFILE](#)



Jiri, Jirka Simunek

University of California, Riverside

584 PUBLICATIONS 30,709 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Soils sustain life: measuring and modelling water flow and chemical transport [View project](#)



crop management under stressfull environment [View project](#)

Article

Performance of Spring and Summer-Sown Maize under Different Irrigation Strategies in Pakistan

Abdul Ghaffar Khan ^{1,2,3}, Muhammad Imran ^{1,4,5,*}, Anwar-ul-Hassan Khan ¹, Ali Fares ³, Jiří Šimůnek ⁵, Tanveer Ul-Haq ⁴, Abdulaziz Abdullah Alsahli ⁶, Mohammed Nasser Alyemeni ⁶ and Shafaqat Ali ^{7,8,*}

- ¹ Institute of Soil & Environmental Sciences, University of Agriculture, Faisalabad 03802, Pakistan; ghaffarniazi@gmail.com (A.G.K.); drauhkhan@yahoo.com (A.-u.-H.K.)
- ² Senior Scientist (Soil Science) Directorate of Rapid Soil Fertility Survey & Soil Testing Institute Punjab, Lahore 54000, Pakistan
- ³ College of Agriculture and Human Sciences, Prairie View A&M University, Prairie View, TX 77446, USA; alfares@pvamu.edu
- ⁴ Department of Soil and Environmental Sciences, MNS-University of Agriculture, Multan 60000, Pakistan; tanveer.ulhaq@mnsuam.edu.pk
- ⁵ Department of Environmental Sciences, University of California Riverside, Riverside, CA 92521, USA; jiri.simunek@ucr.edu
- ⁶ Department of Botany and Microbiology, College of Science, King Saud University, Riyadh 11451, Saudi Arabia; aalshenaifi@ksu.edu.sa (A.A.A.); mnyemeni@ksu.edu.sa (M.N.A.)
- ⁷ Department of Environmental Sciences, Government College University, Faisalabad 38000, Pakistan
- ⁸ Department of Biological Sciences and Technology, China Medical University, Taichung 40402, Taiwan
- * Correspondence: m.imran@mnsuam.edu.pk (M.I.); shafaqataligill@gcuf.edu.pk (S.A.)



Citation: Khan, A.G.; Imran, M.; Khan, A.-u.-H.; Fares, A.; Šimůnek, J.; Ul-Haq, T.; Alsahli, A.A.; Alyemeni, M.N.; Ali, S. Performance of Spring and Summer-Sown Maize under Different Irrigation Strategies in Pakistan. *Sustainability* **2021**, *13*, 2757. <https://doi.org/10.3390/su13052757>

Academic Editors:
Mohammad Valipour and José Manuel Mirás-Avalos

Received: 8 December 2020
Accepted: 23 February 2021
Published: 4 March 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Abstract: Pakistan is facing severe water shortages, so using the available water efficiently is essential for maximizing crop production. This can be achieved through efficient irrigation practices. Field studies were carried out to determine the dynamics of soil water and the efficiency of water utilization for maize grown under five irrigation techniques (flood-irrigated flatbed, furrow-irrigated ridge, furrow-irrigated raised bed, furrow-irrigated raised bed with plastic mulch, and sprinkler-irrigated flatbed). Spring and summer maize was grown for two years. The Irrigation Management System (IManSys) was used to estimate the irrigation requirements, evapotranspiration, and other water balance components for this study's different experimental treatments based on site-specific crop, soil, and weather parameters. The results showed that the flood irrigation flatbed (FIF) treatment produced the highest evapotranspiration, leaf area index (*LAI*), and biomass yield compared to other treatments. However, this treatment did not produce the highest grain yield and had the lowest water use efficiency (*WUE*) and irrigation water use efficiency (*WUE_i*) compared to the furrow-irrigated raised-bed treatment. The furrow-irrigated raised bed with plastic mulch (FIRBM) treatment improved grain yield, *WUE*, *WUE_i*, and harvest index compared to the flood irrigation flatbed (FIF) treatment. The results showed a strong correlation between measured and estimated net irrigation requirements and evapotranspiration, with high *r*² values (0.93, 0.99, 0.98, and 0.98) for the spring- and summer-sown maize. It was concluded that the FIRBM treatments improved the grain yield, *WUE*, and *WUE_i*, which ultimately enhanced sustainable crop production. The growing of summer-sown maize in Pakistan has the potential for sustainable maize production under the semiarid and arid climate.

Keywords: sprinkler irrigation; furrow-irrigated raised bed; irrigation management software; evapotranspiration; water use efficiency

1. Introduction

In recent decades, increasing water shortages have begun threatening food security for millions of people because more than 80% of freshwater is used by agriculture [1]. According to the International Water Management Institute (IWMI), one-third of developing

countries' population lives in regions where water supplies are inadequate to meet their agricultural, domestic, and industrial needs [2]. With over 220 million people, if sufficient water supplies are not available for crop production, Pakistan cannot meet its demand for food. The per capita water supply decreased from 5600 m³ in 1947 to only about 1000 m³ in 2004 [3]. With the rising demand for irrigation water for agriculture, the world is now facing the challenge of producing more food with less water. Realistically, this goal can be achieved only when irrigation water utilization is more efficient. Moreover, water scarcity can be managed through optimal planning [4]. The highest (55.5 USD m⁻³) agriculture water use efficiency in the world was reported in the Netherlands, whereas in Pakistan, it was only 0.2 USD m⁻³ [5].

Water and its movement across the soil–plant–atmosphere continuum are some of the most important core factors influencing crop productivity [6]. Efficient irrigation technologies and water management practices moderate the negative impacts of higher water use on farm incomes and environmental effects on soils and groundwater tables [7]. Many agricultural management practices have been used to increase agricultural production for many years [8]. Irrigation scheduled at different growth stages can significantly improve water use efficiency [9]. Similarly, Ref. [10] also reported that grain yield and water use efficiency (*WUE*) were strongly affected by soil water contents and irrigation scheduling. Furrow-irrigated raised-bed planting, furrow-irrigated raised bed with plastic mulch planting, and sprinkler irrigation have been proposed as three of the most significant strategies to minimize the cost of cultivation, improve *WUE*, and maximize crop yield. In bed sowing, 24% [11] and 34% [12] of water was saved compared to flat sowing. The sprinkler irrigation method has a higher potential for application efficiency than flood irrigation [13]. In the Indian subcontinent, sprinkler irrigation has increased on-farm irrigation efficiencies by up to 80% under the prevailing climatic conditions [14]. It was also found that water savings with sprinkler irrigation were 30% higher than with flatbed sowing [15]. The pivot central sprinkler irrigation practice also improved the water use efficiency, ranging from 1.07 kg m⁻³ to 2.2 kg m⁻³ [16]. There were also reports that the water use efficiency decreased when irrigation systems ignored soil variability and applied water uniformly [16].

Soil covers, such as different mulching materials, can significantly reduce evaporation and improve soil temperature and crop yield. The cost of plastic mulch is lower compared to gravel or sand, and it is easily managed. Thus, it has been widely reported that both grain yield and *WUE* can be increased under mulches [17,18]. It was observed that the soil and water conservation techniques played a significant role in decreasing water losses and increasing water infiltration [18]. It was also reported that the high moisture content was recorded in areas where conservation practices have been adapted compared to other areas where farmers ignore these practices. It was also reported that soil and water conservation practices improved soil health by increasing soil organic matter, ultimately improving water conservation [19]. These practices also improved the crop yield.

To forecast environmental parameters of interest [20], simulation models usually integrate theoretical principles, scientific information, computational algorithms, and statistical considerations. The Irrigation Management System (IManSys) [21,22] was used to estimate the irrigation requirements for this study's different experimental treatments based on site-specific crop, soil, and weather parameters.

Maize is the third most important cereal crop in Pakistan after wheat and rice, and its production increased by 6% during 2019–2020. Its contribution in value addition of agriculture is 2.9%, and it contributes 0.6% to the gross domestic production (GDP) of Pakistan. The increase in production was mainly due to the increase in cultivated area, which increases the water demand in the agriculture sector [23]. Thus, it is vital to improve the water use efficiency of maize in order to reduce agriculture's water requirement.

This study has two objectives. The first objective is to evaluate the effects of different irrigation techniques and growing seasons (spring and summer) on water use efficiency, crop yield, evapotranspiration, and soil water dynamics within and below the root zone in

Pakistan. The second objective is to evaluate the performance of IMaySys in estimating the irrigation requirements, evapotranspiration, and the rest of the water budget components of this study using site-specific weather conditions of Pakistan.

2. Materials and Methods

2.1. Experimental Site and Setup

The field experiment was conducted at the experimental farm of the Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad, Pakistan (latitude, 31°26' N and 73°06' E, 184 m ASL) during the spring and summer growing seasons of 2011 and 2012. The study area's climate is semi-subtropical, arid, with more than 70% of the annual rainfall occurring from June to September. An automated weather station was installed about 500 m away from the experimental field. Reference evapotranspiration (ET_0) was calculated using the Penman–Monteith equation from meteorological variables (Figure 1).

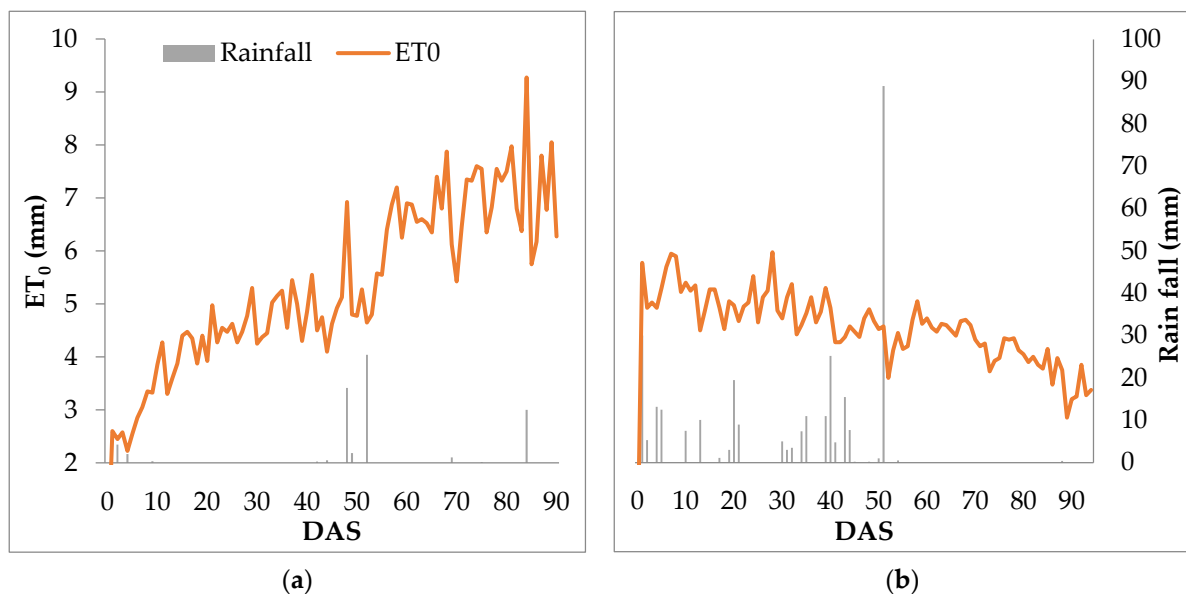


Figure 1. Daily reference evapotranspiration (ET_0) and rainfall during the (a) spring (average of 25 February to 29 May, 2011 and 2012) (b) summer (27 July to 7 November, 2011 and 2012) seasons. DAS stands for days after sowing.

The experimental site's soil type is well-drained Hafizabad loam, mixed, semiactive, isohyperthermic Typic Calcargids (Table 1). The three composite soil samples were collected from each soil layer and then analyzed for soil texture [24], soil organic matter [25], and water retention curves [26]. The soil bulk density was also determined using the core method [27] for each major soil layer at three randomly selected locations. At the same time, the saturated hydraulic conductivity (K_{fs}) was also measured at three randomly selected sites using the Guelph permeameter method (Model 2800 KI) [27].

Table 1. Measured soil physical and hydraulic parameters of the four main horizons at the experimental site.

Depth (cm)	Particle Fractions (%)			B.D. (Mg m ⁻³)	θ_s	θ_{FC}	θ_{PWP}	θ_{AWC}	K_{fs} cm Day ⁻¹	SOC (%)
	Sand	Silt	Clay							
0–20	40.07 ± 0.12	37.41 ± 0.13	22.52 ± 0.10	1.45 ± 0.10	0.44 ± 0.03	0.29 ± 0.01	0.13 ± 0.01	0.16 ± 0.01	28.31 ± 1.55	0.50 ± 0.37
20–40	43.47 ± 0.15	34.08 ± 0.12	22.45 ± 0.14	1.48 ± 0.03	0.44 ± 0.02	0.27 ± 0.01	0.12 ± 0.01	0.15 ± 0.01	27.27 ± 3.01	0.34 ± 0.45
40–60	45.24 ± 0.22	32.30 ± 0.23	22.46 ± 0.12	1.55 ± 0.02	0.43 ± 0.02	0.27 ± 0.01	0.12 ± 0.01	0.15 ± 0.01	19.52 ± 4.25	0.28 ± 0.18
60–100	46.38 ± 0.19	31.21 ± 0.14	22.41 ± 0.14	1.59 ± 0.02	0.42 ± 0.01	0.27 ± 0.013	0.12 ± 0.01	0.15 ± 0.01	20.00 ± 2.35	0.22 ± 0.28

B.D = soil bulk density, θ_s = saturated water content, θ_{FC} = water content at field capacity, θ_{PWP} = water content at the permanent wilting point, θ_{AWC} = available water content, K_{fs} = field-saturated hydraulic conductivity, SOC = soil organic carbon, $n = 3$.

2.2. Experimental Treatments

The experimental design was a randomized complete block design with four replications, with irrigation techniques as the main treatments. Plot sizes were 4 m² each, separated by a 1 m crop-free buffer strip. The local high-yielding maize hybrid (DK 919) was planted. The spring sowing time was on 27 February, 2011, and 25 February, 2012. However, the summer sowing was on 27 July, 2011, and 29 July, 2012. The seeding rate was 25 kg ha⁻¹, with a 65 cm row spacing and a 22.5 cm plant to plant distance. Fields were irrigated uniformly (101.6 mm) before sowing to ensure optimum germination. Urea was applied at a rate of 250 kg N ha⁻¹ in two splits. Phosphorous and potassium were applied at sowing at 150 kg ha⁻¹ of single super phosphate and 105 kg ha⁻¹ of potassium sulfate. The spring-sown maize was harvested on 29 May, 2011, and 27 May, 2012, whereas the summer-sown maize was harvested on 5 November, 2011, and 7 November, 2012.

The individual experimental treatments consisted of five different irrigation techniques (i.e., flood-irrigated flatbed (FIF), furrow-irrigated ridge (FIR), furrow-irrigated raised bed (FIRB), furrow-irrigated raised bed with plastic mulch (FIRBM), and sprinkler-irrigated flat sowing (SIF)). Readily available water (RAW) was maintained at adequate levels in all irrigation techniques so that there were no water stresses in either growing season.

2.3. Plant Measurements

From a harvested area of 1 m² at the center of each plot, the total aboveground biomass and grain yield were recorded. The ratio of grain yield to total biomass was calculated as the harvest index. A digital leaf area meter (YMG-A/YMG-B) was used to calculate the leaf area (LA) from the three randomly selected leaves (top, middle, and bottom leaves) from three randomly selected plants per replication per treatment. After the LA meter calibration, the Leaf Area Index (LAI) was calculated by dividing the total leaf area by the land area. However, in the absence of the leaf area meter, LA was calculated using the following formula [28]:

$$\text{Leaf area} = L \times W \times A \quad (1)$$

where L is the leaf length (m), W (m) is the greatest leaf width, and A is a factor, which has a value of 0.75 for maize. Leaf area index was measured 7, 15, 30, 60, 75, and 90 days after sowing (DAS) and at harvest.

2.4. Soil Water Content and Actual Evapotranspiration

Based on weekly measured water content readings, the amount of irrigation water needed to sustain the soil water status at RAW (mm) was determined and applied when required. Readily available water (RAW) was determined according to the formula below:

$$RAW = pTAW \quad (2)$$

where the “threshold value for readily available water” (*TAW*) for maize ($p = 0.55$) was taken from the FAO Irrigation and Drainage Paper No. 33 and adjusted using the following formula [29]:

$$p_{adj} = 0.55 + 0.04(5 - ET_c) \quad (3)$$

where p_{adj} is the adjusted fraction of the total available water depleted from the root zone before any moisture stress, and ET_c is the crop evapotranspiration in mm/day.

The soil water content in the top 100 cm of the soil profile was measured weekly using the Time Domain Reflectometry (Triaxial Cables Manufacturer MODEL 6050X3) form at the following soil profile sections: 0–20, 20–40, 40–60, 60–100 cm depth. The soil water content monitoring sensor was calibrated before starting the experiment using gravimetric reference samples from the corresponding depths [30]. Water contents at field capacity and a permanent wilting point (Table 1) were determined for each depth with a pressure plate apparatus at pressures of -33 and -1500 kPa, respectively [30]. Based on soil water measurements, actual evapotranspiration was calculated using the water balance equation:

$$ET_a = (I + P) - \Delta S \quad (4)$$

where ET_a is actual evapotranspiration (mm), I (mm) is irrigation, P (mm) is rainfall, and ΔS (mm) is the change in the root zone water storage. Drainage was assumed to be negligible because irrigation amounts were adequately delivered to replace depleted water based on measured soil water contents in the root zone and the optimum water-holding capacity of the soil.

2.5. Water Use Efficiency and Irrigation Water Use Efficiency

The water use efficiency (*WUE*) is defined as follows [31]:

$$WUE = \frac{GY}{ET_a} \quad (5)$$

where *WUE* ($\text{kg ha}^{-1} \text{mm}^{-1}$) is the water use efficiency for grain yield (kg ha^{-1}), *GY* is the grain yield (kg ha^{-1}), and ET_a (mm) is the actual evapotranspiration.

Irrigation water use efficiency (WUE_i) is calculated as follows:

$$WUE_i = \frac{GY}{I} \quad (6)$$

where I (mm) is the applied irrigation depth.

2.6. IManSys Model Simulation

The Irrigation Management System (IManSys) software was used to calculate irrigation requirements for maize, based on the site-specific data [32]. IManSys solves the following water balance equation:

$$STO = RAIN + NIR - DRAIN - RUNOFF - CANOPY INTERCEPTION - ET_a \quad (7)$$

where STO is the change in the soil water storage (mm), $RAIN$ is rainfall (mm), NIR is the net irrigation requirement (mm), $DRAIN$ is the drainage below the root zone (mm), $RUNOFF$ is surface runoff (mm), the $CANOPY INTERCEPTION$ is the rainfall interception by the crop (mm), and ET_a is the actual evapotranspiration (mm).

Equation (7) is rearranged, and then the gross irrigation requirements are calculated as follows:

$$NIR = (STO - NET\ RAIN + DRAIN + ET_a)/f \quad (8)$$

where f is the irrigation system efficiency accounting for irrigation losses ($f < 1$). The input data for IManSys are meteorological data (rainfall, maximum and minimum air temperatures, wind speed, and solar radiation), crop data (the initial and maximum crop root zone depths, and the initial, mid-season, and end-season crop coefficients), and the soil water-holding capacity for each soil layer. The output data include net irrigation requirement (NIR), effective rainfall, potential evapotranspiration (ET_0), actual evapotranspiration (ET_a), and runoff. More details about IManSys can be found in [32]. The model uses the measured gross rainfall to determine net rainfall/effective rainfall based on the crop's LAI and plant height.

2.7. Model Performance

IManSys model was calibrated for the net irrigation requirement (NIR) and ET_a using a data set of the 1st year of all treatments for both seasons. Soil physical and hydraulic parameters (Table 1), climatic data, rooting depth of crop, and LAI were used for calibration to achieve a goodness of fit between predicted and observed values of the water balance component. The model was then validated with the data of the second year of all treatments for both seasons. Model efficiency was calculated using the Nash and Sutcliffe method [33]:

$$NSE = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - O)^2} \quad (9)$$

Here an EF value of 1 indicates that the model predicted and observed values are an exact match, and an EF value of 0 indicates that the mean of observed data would be a similarly accurate prediction of observed data as the model predicted values. EF value from $-\infty$ to 0 occurred when observed means were a better predictor than the model.

2.8. Statistical Analysis

The collected data were subjected to normality and homogeneity tests and statistically analyzed using the analysis of variance (ANOVA) techniques according to the randomized complete block design (RCBD) for both field trials. The mean values were compared using the LSD (a least-significant difference) test at $p \leq 0.05$ [34]. The software package STATISTIX 8.1 [35] was used for the statistical analysis.

3. Results and Discussion

3.1. Soil Water Dynamics

The water content in the top 20 cm (0–20 cm) showed clear differences between different treatments (Figures 2 and 3) in both growing seasons. In contrast, the water contents in lower layers showed insignificant variations due to more upward movement and negligible drainage. The water content in the upper 20 cm soil layer was highest in the FIRBM treatment than the other treatments during both growing seasons. The extent of measured water contents was as follows: FIRBM > FIRB > FIR > FIF > SIF. Both evaporation and transpiration affected the upper 20 cm soil layer. A high proportion of root water absorption normally occurs in the near-surface layers due to higher root densities near the plant base [36]. Earlier researchers reported that the plastic mulch conserved more water than other mulch materials [37]. Similarly, the highest soil water storage and low evaporation were recorded for the plastic mulch with furrow irrigation [38].

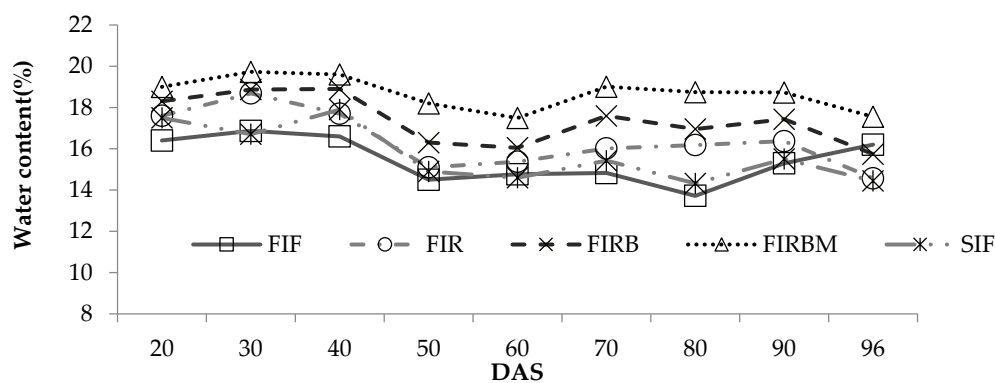


Figure 2. Measured soil water contents in the top 20 cm soil layer during the spring season.

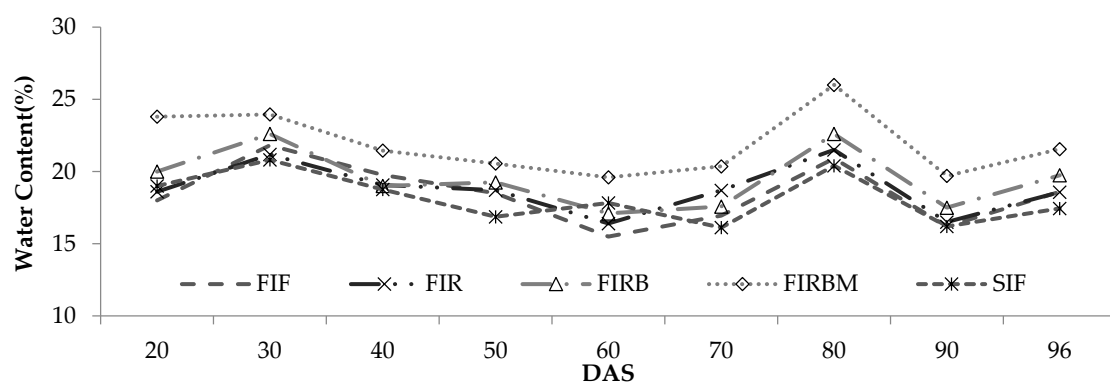


Figure 3. Measured soil water contents in the top 20 cm soil layer during the summer season.

3.2. Seasonal Water Balance among Different Irrigation Practices

The highest (420–410.5 mm) and lowest (340–290.5 mm) *NIR* amounts were recorded for the FIF and SIF treatments during the spring and summer growing seasons (Table 2). The highest seasonal evapotranspiration (475–407.5 mm) was recorded for the FIF treatment, whereas the lowest seasonal evapotranspiration (390.2–280 mm) was recorded for the SIF treatment during the spring and summer growing seasons (Table 2). There is a reasonable correlation between seasonal water evapotranspiration and the amount of net irrigation requirement (*NIR*) (Figure 4). However, the ET_a of the spring season was slightly higher than that of the summer season across all treatments. This might be attributed to differences in climatic conditions, changes in soil water storage, and a total growing season irrigation depth.

Table 2. Comparison of measured and simulated water balance components *NIR* (net amount of irrigation (irrigation (*I*) + rainfall (*RF*))), ET_a (actual evapotranspiration), and ΔS (change in soil water storage within the root zone) during the spring and summer seasons.

Treatments	Spring						Summer					
	Measured (mm)			Estimated (mm)			Measured (mm)			Estimated (mm)		
	<i>NIR</i>	ET_a	ΔS	<i>NIR</i>	ET_a	ΔS	<i>NIR</i>	ET_a	ΔS	<i>NIR</i>	ET_a	ΔS
* FIF	420 a ⁺	475 a	−55 d	428 a	480 a	−52 c	410.5 a	407.5 a	3.0 d	415 a	412.3 a	2.7 d
FIR	410 b	457.5 b	−47.5 c	414.5 b	460 b	−55.5 d	385.5 b	374.2 b	11.3 c	395.5 b	386.4 b	9.1 b
FIRB	390.8 c	437.8 c	−47.0 bc	395.5 c	442 c	−46.5 bc	345.5 c	332.7 c	12.8 b	350.3 c	340 c	10.3 a
FIRBM	370.8 d	405.3 d	−34.5 a	372 d	410 d	−38 a	327.5 d	311.2 d	16.3 a	325 d	315 d	10.0 a
SIF	340 d	390.2 e	−50.2 b	347.5 d	392 e	−44.5 b	290.5 e	280 e	10.5 c	300.2 e	292.2 e	8.0 c

* FIF = flood-irrigated flat (conventional farmer practice); FIR = furrow-irrigated ridge; FIRB = furrow-irrigated raised bed; FIRBM = furrow-irrigated raised bed with plastic mulch; SIF = sprinkler-irrigated flat. ⁺ Values sharing the same letter(s) in the column do not differ significantly at $p < 0.05$ according to the least-significance difference (LSD) test.

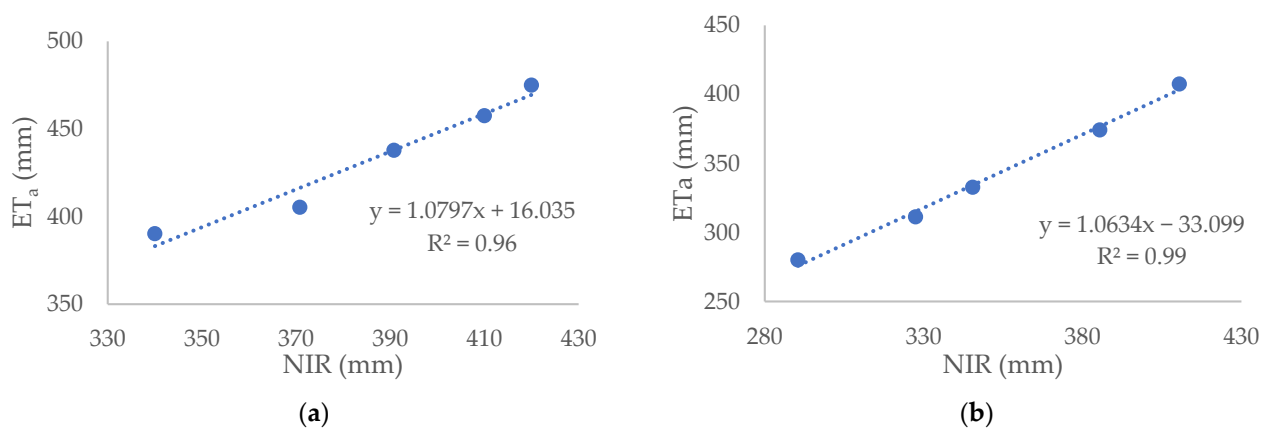


Figure 4. Correlation between ET_a and NIR during the (a) spring and (b) summer growing seasons.

The extent of water depletion followed the following order FIF > SIF > FIR > FIRB > FIRBM during the spring growing season. Soil water storage depletion variations across treatments impacted the crop's evapotranspiration during the growing season. Maximum soil water storage values were recorded for the furrow-irrigated raised bed with plastic mulch treatment (FIRBM) during the summer growing season. A plastic film may reduce surface water evaporation and improve soil temperatures and increase yield [39,40]. Additionally, its cost is lower than that of gravel and sand, and its operation is more straightforward. Consequently, the plastic-mulching technique is widely adopted.

3.3. Crop Growth and Yield

Crop growth and yield varied among different irrigation treatments and growing seasons (Table 3). Grain yield was the highest in the furrow-irrigated raised bed with plastic mulch (FIRBM) treatment. An increase in grain yield by 11.5 and 8.9% for the FIRB with plastic mulch was observed over FIF during the two growing seasons. This increase was likely due to higher water use efficiencies in this treatment during the two growing seasons. This treatment reduces evaporation from the soil surface due to the minimum soil exposure to direct sunlight. An increase in yield was likely due to reduced drainage from furrows and enhanced lateral water movement. These results concur with those reported by [41]. The key contributing factors of mulch in increasing grain yield include improved soil physical and chemical properties and enhanced soil biological activity [42]. Our results agree with [43], who reported that furrow irrigation significantly increased the grain yield of maize. The raised-bed treatment saved water and increased yield in the wheat–maize rotation compared to the flood-irrigated flat field [37].

Table 3. Measured plant parameters during the spring and summer seasons.

Treatments	Spring			Summer		
	Grain Yield (Mg ha ⁻¹)	Biomass (Mg ha ⁻¹)	Harvest Index	Grain Yield (Mg ha ⁻¹)	Biomass (Mg ha ⁻¹)	Harvest Index
FIF	5.67 c ⁺	14.2 a	0.39 c	6.04 bc	16.1 a	0.37 c
FIR	6.06 abc	13.6 abc	0.44 b	6.16 bc	15.1 bc	0.40 b
FIRB	6.16 ab	13.9 ab	0.44 b	6.26 ab	15.3 ab	0.40 b
FIRBM	6.32 a	12.8 c	0.45 a	6.58 a	14.8 bc	0.44 a
SIF	5.80 bc	13.1 bc	0.44 b	5.87 c	14.3 c	0.40 b
LSD ($p \leq 0.05$)	0.48	1.10	0.01	0.37	0.91	0.01

FIF = flood-irrigated flat (conventional farmer practice); FIR = furrow-irrigated ridge; FIRB = furrow-irrigated raised bed; FIRBM = furrow-irrigated raised bed with plastic mulch; SIF = sprinkler-irrigated flat. ⁺ Values sharing the same letter(s) in the column do not differ significantly at $p < 0.05$ according to the least-significant difference (LSD) test.

The biomass (grain + straw) under different irrigation practices varied between 13.1 and 14.2 Mg ha⁻¹ in spring and between 14.3 and 16.1 Mg ha⁻¹ in summer. The higher biomass in the flood irrigation treatment (Table 3) was achieved due to higher vegetative growth as a result of higher water applications. The plant height and vegetative growth increased with higher water applications, which ultimately increased the biomass. Our results agree with [17,37], who reported that the plastic film enhanced crop yield by 21–92%. Similar to our observations, Sun et al. [39] studied the relationship between irrigation and yield and concluded that increased irrigation increased ET_c and soil evaporation and, consequently, the biomass. However, excessive irrigation was not cost effective and decreased the grain yield [41]. The highest harvest index for the FIRBM treatment was likely due to the higher total dry matter and higher grain yield in this treatment. The polythene mulch resulted in a better microenvironment and better retention of soil moisture, ultimately leading to a higher grain yield and harvest index (HI). Similar results were obtained by [42], who reported that raised-bed planting enhanced the harvest index significantly due to lessened weed infestation and lodging. The highest harvest index in the FIRBM treatment could be due to the better germination rate, higher total dry matter accumulation, and grain yield. The lowest harvest index for flood irrigation was likely due to higher plant height and biomass. These findings are validated by another researcher's observations, who also recorded the maximum HI for the raised-bed treatment [40].

The leaf area index (LAI) is influenced by different irrigation practices and growing seasons (Figure 5) after 45, 60, 75, and 90 days of sowing. Crop grown under the flood-irrigated flat sowing treatment during the spring season had a significantly higher leaf area index (i.e., 2.08, 3.94, 4.40, and 4.04 at 45, 60, 75, and 90 DAS, respectively). The lowest LAI values were obtained for the sprinkler-irrigated flatbed treatment (1.75, 2.97, 3.74, and 3.40 at 45, 60, 75, and 90 DAS, respectively). A similar trend was observed during the summer season (Figure 5b). The high LAI under flood irrigation may be due to the ample water availability in the root zone. These results concur with the results reported by [44].

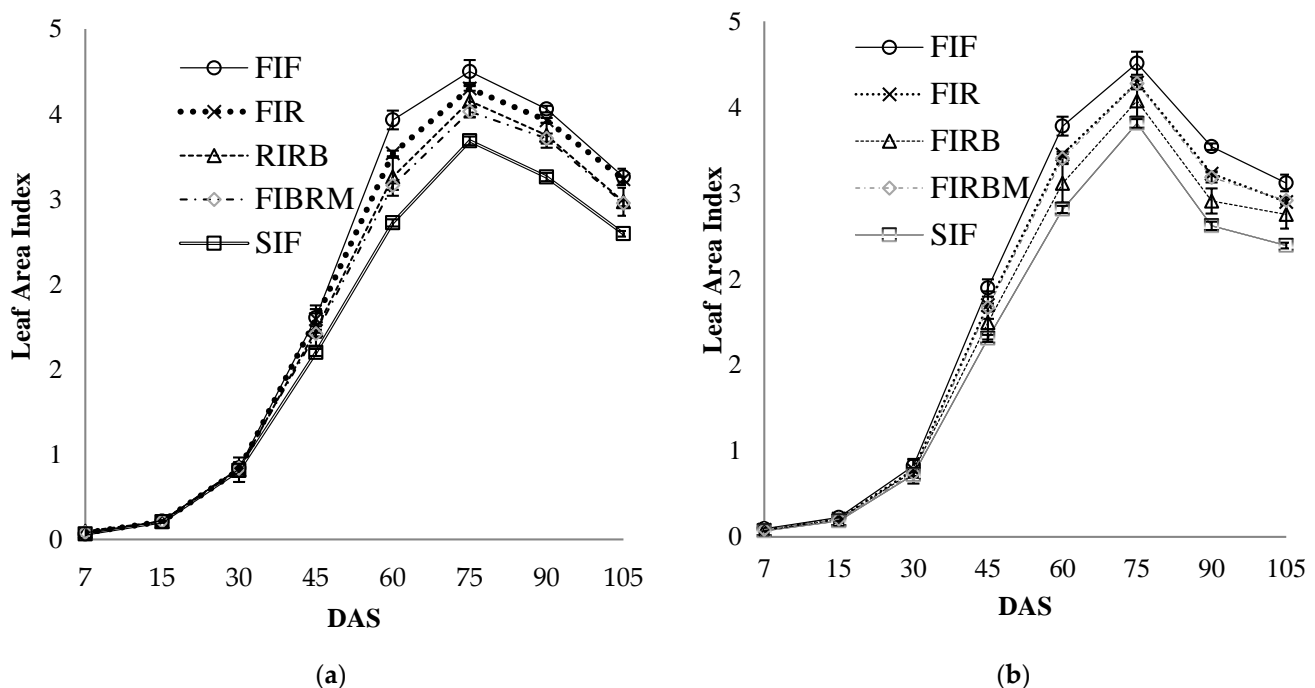


Figure 5. Leaf area index (LAI) during the (a) spring and (b) summer seasons (DAS—days after sowing).

3.4. Water Use Efficiency (WUE) and Irrigation Water Use Efficiency (WUE_i)

The average WUE varied between 11.9 and 15.2 and 14.8 and 21.1 kg ha⁻¹mm⁻¹ during the spring and summer growing seasons (Table 4), respectively. The water use

efficiency was highest for the FIRBM treatment and lowest for the FIF treatment during both growing seasons. However, it was statistically similar to SIF, which has an additional cost of the sprinkler system and is more expensive than plastic mulch in Pakistan. In general, WUE values decreased with increasing amounts of irrigation water. Reference [45] reported values of WUE of 5.90–7.45 kg m⁻³ from their experiments with maize in the same region of Pakistan.

Table 4. Measured water use efficiency (WUE) and irrigation water use efficiency (WUE_i) during the spring and summer seasons.

Treatments	Spring		Summer	
	WUE (kg ha ⁻¹ mm ⁻¹)	WUE_i (kg ha ⁻¹ mm ⁻¹)	WUE (kg ha ⁻¹ mm ⁻¹)	WUE_i (kg ha ⁻¹ mm ⁻¹)
FIF	11.9 d +	13.5 d	14.8 c	14.7 c
FIR	13.3 c	14.7 c	16.4 c	15.9 b
FIRB	14.0 b	15.7 b	18.8 b	18.1 ab
FIRBM	15.2 a	17.2 a	21.1 a	20.2 a
SIF	14.8 ab	17 ab	20.9 ab	20.0 a

FIF = flood-irrigated flat (conventional farmer practice); FIR = furrow-irrigated ridge; FIRB = furrow-irrigated raised bed; FIRBM = furrow-irrigated raised bed with plastic mulch; SIF = sprinkler-irrigated flat. + Values sharing the same letter(s) in the column do not differ significantly at $p < 0.05$ according to the least-significant difference (LSD) test.

Similarly, [36] reported WUE s of 1.96–1.99 kg grain m⁻³ for maize with the FIRB irrigation practice. One scientist also found that bed planting resulted in 34% water savings and 32 and 19% higher yields for maize and wheat crops, respectively [12]. The WUE_i in the summer season was higher in all treatments than WUE_i in the spring season (Table 4). This could be attributed to water use from the soil water storage due to higher temperatures, higher wind speeds, and lower relative humidity levels in April and May. The maximum mean WUE_i was observed for the FIRBM treatment (17.2 kg ha⁻¹mm⁻¹), while the minimum WUE_i was observed for the FIF treatment (12.1 kg ha⁻¹mm⁻¹) during spring. The WUE_i recorded for all treatments is ranked from high to low: FIRBM > SIF > FIRB > FIR > FIF. During the summer season, the water use efficiency was more significant than the irrigation water use efficiency due to the ample supply of water and rainfall (Table 4). The maximum mean WUE_i was observed for the FIRBM treatment (20.2 kg ha⁻¹mm⁻¹), and the minimum WUE_i for the FIF treatment (14.7 kg ha⁻¹ mm⁻¹). Plastic mulch significantly enhanced WUE due to reduced evaporation water loss and an increase in transpiration. Similar results are noted by [46,47] under arid to semiarid conditions. Similarly, Reference [36] found that WUE_i generally increased with a decline in irrigation quantity.

3.5. Performance of the IManSys Model

There is a strong linear correlation between measured and estimated ET_a for both growing seasons (Figure 6). IManSys-simulated ET_a values fitted measured values well, with correlation coefficients of 0.99 in both spring and summer seasons. Similarly, there were also linear relationships between measured and estimated NIR values (Figure 7). IManSys fitted the NIR values well, with r^2 values of 0.99 and 0.98 in the spring and summer seasons, respectively. Strong correlations were thus obtained between measured and estimated values of both NIR and ET_a . Our results are in line with a previous study in which the model performed well under similar environmental conditions [22].

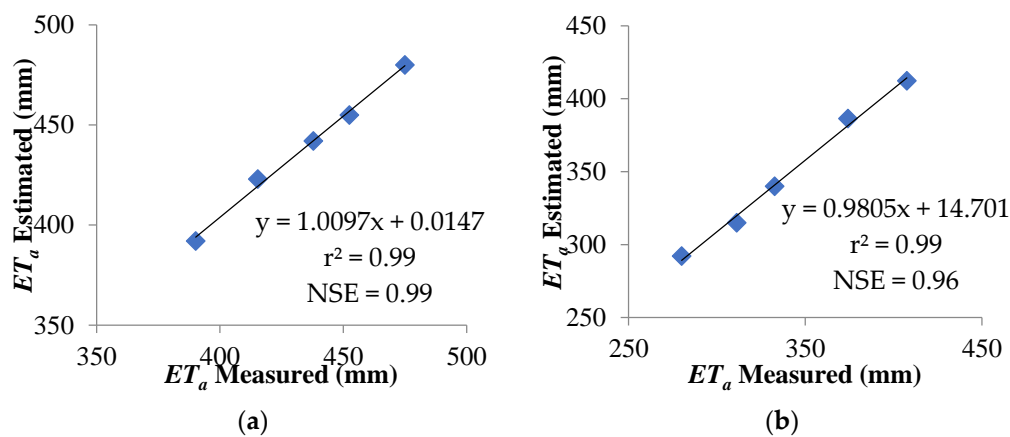


Figure 6. Correlation between measured and simulated evapotranspiration (ET_a) in the (a) spring and (b) summer seasons.

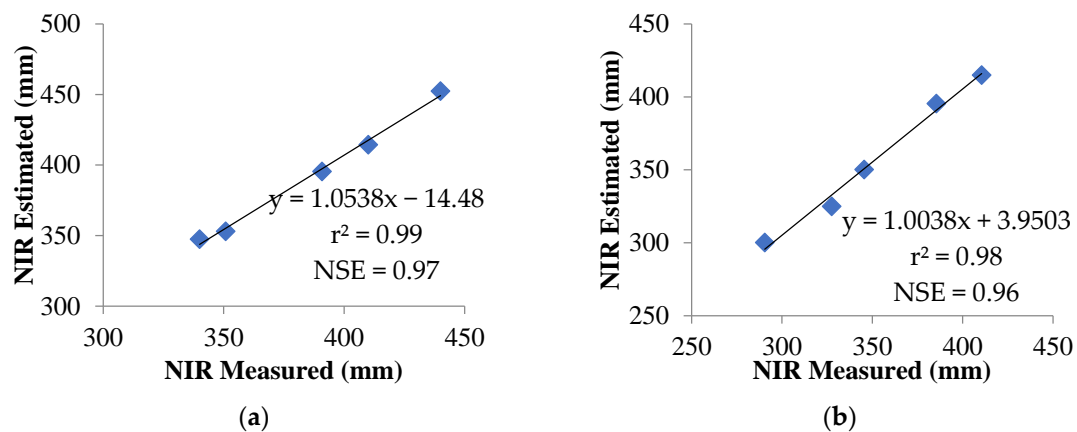


Figure 7. Correlation between measured and simulated net irrigation requirements (NIR) in the (a) spring and (b) summer season.

4. Conclusions

Most of Pakistan is arid to semiarid and faces water scarcity. A limited supply of irrigation water makes agricultural production in this region more expensive. Therefore, the development of water-saving agricultural practices is required to cope with water shortages during different growth stages of the maize crop in Pakistan. It was concluded from the results of this study that in Pakistan, the sowing of summer maize is more profitable compared to spring-sown maize. Experimental results also showed that different irrigation techniques have significantly affected the water use efficiency, the irrigation water use efficiency, the soil water balance, and crop yield. The best results were obtained for the furrow-irrigated raised bed covered with plastic mulch treatment. Results further showed that this treatment also produced an increase in soil water storage. Our findings further clarified that the Irrigation Management System Software could be an effective tool for irrigation scheduling for successful crop production in Pakistan's semiarid regions. We recommend to the farmers of this region to use this software for irrigation scheduling.

Author Contributions: Conceptualization, A.G.K., A.-u.-H.K., A.F., J.Š., A.A.A., M.N.A. and S.A.; Data curation, A.G.K. and M.I.; Formal analysis, A.G.K., M.I. and T.U.-H.; Funding acquisition, A.A.A. and M.N.A.; Investigation, M.I., A.F. and T.U.-H.; Methodology, A.G.K., M.I. and T.U.-H.; Project administration, J.Š.; Resources, A.-u.-H.K., J.Š., T.U.-H., A.A.A. and M.N.A.; Software, A.-u.-H.K., A.F. and S.A.; Supervision, A.-u.-H.K.; Validation, A.G.K. and M.I.; Visualization, M.I. and T.U.-H.; Writing—original draft, A.G.K., M.I., A.A.A. and S.A.; Writing—review & editing, A.-u.-H.K., A.F., J.Š., M.N.A. and S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially supported by the Higher Education Commission, Pakistan, under IRSPI Program. The authors would like to extend their sincere appreciation to the Researchers Supporting Project Number (RSP-2020/236), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research was partially supported by the Higher Education Commission of Pakistan. The authors would like to extend their sincere appreciation to the University of Agriculture, Faisalabad. The authors would like to extend their sincere appreciation to the Researchers Supporting Project Number (RSP-2020/236), King Saud University, Riyadh, Saudi Arabia.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wolf, T.A. (Ed.) *Conflict Prevention and Resolution in Water Systems*; Edward Elgar Publishing Ltd: Cheltenham, UK, 2002.
2. Seckler, D.; Upali, A.; Molden, D.; de Silva, R.; Barker, R. *World Water Demand and Supply, 1990 to 2025: Scenarios and Issues. Research Report 19*; Iwmi: Colombo, Sri Lanka, 1998.
3. Kahlowan, A.; Ashraf, M.; Hussain, M.; Salam, A.; Bhatti, A. *Impact Assessment of Sewerage and Industrial Effluents on Water Resources, Soil, Crops and Human Health in Faisalabad*; Pakistan Council of Research in Water Resources (PCRWR), Khyaban-e-Johar, H-8/1: Islamabad, Pakistan, 2006.
4. Abdelrahman, M.A.E.; Arafat, S.M. An Approach of Agricultural Courses for Soil Conservation Based on Crop Soil Suitability Using Geomatics. *Earth Syst. Environ.* **2020**. [CrossRef]
5. FAO. *Progress on Water Use Efficiency—Global Baseline for SDG 6 Indicator 6.4.1 2018*; FAO: Rome, Italy, 2018.
6. Byrne, J.; Quinn, G.; Mpitsos, J.; Lederhändler, I.; Belardetti, F.; Biondi, C. Plant Productivity and Environment. *Science* **1982**, *218*, 443–448.
7. Khan, S.; Abbas, A. Upscaling water savings from farm to irrigation system level using gis-based agro-hydrological modelling. *Irrig. Drain. J. Int. Comm. Irrig. Drain.* **2007**, *42*, 29–42. [CrossRef]
8. Govaerts, B.; Sayre, K.D.; Deckers, J. Stable high yields with zero tillage and permanent bed planting? *Field Crops Res.* **2005**, *94*, 33–42. [CrossRef]
9. Fang, Q.; Ma, L.; Yu, Q.; Ahuja, L.R.; Malone, R.W.; Hoogenboom, G. Irrigation strategies to improve the water use efficiency of wheat–maize double cropping systems in North China Plain. *Agric. Water Manag.* **2010**, *97*, 1165–1174. [CrossRef]
10. Kang, S.Z.; Zhang, L.; Liang, Y.L.; Hu, X.T.; Cai, H.J.; Gu, B.J. Effects of limited irrigation on yield and water use efficiency of winter wheat in the Loess Plateau of China. *Agric. Water Manag.* **2002**, *55*, 203–216. [CrossRef]
11. Sayre, K.D. Effect of tillage, crop residue retention and nitrogen management on the performance of bed planting, furrow irrigated spring wheat in Northwest Mexico. In Proceedings of the 15th Conference International Soil and Tillage Research Organization, Fort Worth, TX, USA, 2–7 July 2000.
12. Hassan, I.; Hussain, Z.; Akbar, G. Effect of permanent raised beds on water productivity for irrigated maize–wheat cropping system. *Eval. Perform. Perm. Rais. Bed Crop. Syst. Asia Aust. Mex.* **2005**, *121*, 59–65.
13. Jay, L.; Jack, K.; Janet, K.L.; Thomas, B.K. *Surface and Agricultural Water*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2005.
14. Sharma, S.K. *Principles and Practices of Irrigation Engineering*; Oxford and IBH Publication Co.: New York, NY, USA, 1984.
15. Haq, N. Evaluation of Modern Irrigation Techniques for Sandy Loam Soil Having Low Slopes. Master’s Thesis, Department of Irrigation and Drainage, University of Agriculture, Faisalabad, Pakistan, 1990.
16. El Shirbeny, M.A.; Ali, A.M.; Savin, I.; Poddubskiy, A.; Dokukin, P. Agricultural Water Monitoring for Water Management Under Pivot Irrigation System Using Spatial Techniques. *Earth Syst. Environ.* **2020**. [CrossRef]
17. Li, X.Y.; Gong, J.D.; Gao, Q.Z.; Li, F.R. Incorporation of ridge and furrow method of rainfall harvesting with mulching for crop production under semiarid conditions. *Agric. Water Manag.* **2001**, *50*, 173–183. [CrossRef]
18. Li, X.Y.; Gong, J.D. Effects of different ridge: furrow ratios and supplemental irrigation on crop production in ridge and furrow rainfall harvesting system with mulches. *Agric. Water Manag.* **2002**, *54*, 243–254. [CrossRef]
19. Alewoye Getie, M.; Legesse, S.A.; Mekonnen, M.; Aschalew, A. Soil Properties and Crop Productivity Strategies as a Potential Climate Variability Adaptation Options in Adefwuha Watershed, Ethiopia. *Earth Syst. Environ.* **2020**, *4*, 359–368. [CrossRef]
20. Sarmah, A.K.; Kookana, R.S.; Alston, A.M. Application of varleach and leachm models to experimental data on leaching of a non-reactive tracer and three sulfonyleurea herbicides. *Aust. J. Soil Res.* **2001**, *39*, 1041–1058. [CrossRef]
21. Fares, A. *Water Management Software to Estimate Crop Irrigation Requirements or Consumptive Use Permitting In Hawaii*; Department of Land and Natural Resources: Honolulu, HI, USA, 2008. Available online: <http://treephys.oxfordjournals.org/cgi/reprint/15/9/611> (accessed on 26 December 2020).
22. Khan, A.G.; Iqbal, M.; Ullah, E. Assessing the performance of different irrigation techniques to enhance the water use efficiency and yield of maize under deficit water supply The treatments consisted of four irrigation practices. *Soil Environ.* **2015**, *34*, 166–179.

23. Finance Division, Government of Pakistan. Anonymous Economic Survey of Pakistan. 2018. Available online: http://www.finance.gov.pk/survey/chapters_19/Economic_Survey_2018_19.pdf (accessed on 26 December 2020).
24. Bouyoucos, G.J. Hydrometer method improved for making particle size analyses of soils. *Agron. J.* **1962**, *54*, 464. [[CrossRef](#)]
25. Ryan, J.; Estefan, G.; Rashid, A. *Soil and Plant Analysis Laboratory Manual*; ICARDA: Aleppo, Syria, 2001.
26. Dane, J.H.; Hopmans, J.W. *Laboratory Determination of Water Retention*; Dane, J.H., Topp, G.C., Eds.; Method.; Soil Science Society of America, Inc.: Madison, WI, USA, 2002.
27. Blake, G.R.; Hartge, K.H. Bulk density. In *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods, Agronomy Monograph No. 9*, 2nd ed.; Klute, A., Ed.; Wiley Online Library: Madison, WI, USA, 1986; pp. 363–375.
28. Dwyer, L.M.; Stewart, D.W. Leaf Area Development in Field-Grown Maize. *Agron. J.* **1986**, *78*, 334–343. [[CrossRef](#)]
29. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements*; FAO Irrigation and Drainage Paper 56; Food and Agriculture Organization of the United Nations: Rome, Italy, 1998.
30. Cassel, D.K.; Nielsen, D.R. *Field Capacity and Available Water Capacity*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2018; pp. 901–926.
31. Hussain, G.; Al-Jaloud, A.A.; Al-Shammary, S.F.; Karimulla, S. Effect of saline irrigation on the biomass yield and the protein, nitrogen, phosphorus and potassium composition of alfalfa in a pot experiment. *J. Plant Nutr.* **1995**, *18*, 2389–2408. [[CrossRef](#)]
32. Fares, A.; Fares, S. Irrigation Management System, IMANSYS, a User-Friendly Computer-Based Water Management Software Package. In Proceedings of the Irrigation Show and Education Conference, Orlando, FL, USA, 2–6 November 2012.
33. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models part I—A discussion of principles. *J. Hydrol.* **1970**, *10*, 282–290. [[CrossRef](#)]
34. Steel, R.G.D.; Torrie, J.H.; Dicky, D.A. *Principles and Procedures of Statistics- A Biometrical Approach*, 3rd ed.; McGraw Hill Book International Co.: New York, NY, USA, 1997; pp. 352–358.
35. StatSoft, Inc. STATISTICA. Data Analysis Software System, Version 8. 2001. Available online: <http://www.statsoft.com> (accessed on 14 February 2018).
36. Wang, F.H.; Wang, X.Q.; Sayre, K. Conventional, flood irrigated, flat planting with furrow irrigated, raised bed planting for winter wheat in China. *Field Crop Res.* **2004**, *87*, 35–42.
37. Li, S.X.; Wang, Z.H.; Li, S.Q.; Gao, Y.J.; Tian, X.H. Effect of plastic sheet mulch, wheat straw mulch, and maize growth on water loss by evaporation in dryland areas of China. *Agric. Water Manag.* **2013**, *116*, 39–49. [[CrossRef](#)]
38. Zhou, J.; Wang, C.; Zhang, H.; Dong, F.; Zheng, X.; Gale, W.; Li, S. Effect of water saving management practices and nitrogen fertilizer rate on crop yield and water use efficiency in a winter wheat-summer maize cropping system. *Field Crops Res.* **2011**, *122*, 157–163. [[CrossRef](#)]
39. Sun, H.Y.; Liu, C.M.; Zhang, X.Y.; Shen, Y.J.; Zhang, Y.Q. Effects of irrigation on water balance, yield and WUE of winter wheat in the North China Plain. *Agric. Water Manag.* **2006**, *85*, 211–218. [[CrossRef](#)]
40. Jat, M.L.; Srivastava, A.; Sharma, S.K.; Gupta, R.K.; Zaidi, P.H.; Rai, H.K.; Srinivasan, G. Evaluation of maize-wheat cropping system under double-no-till practice in indo-gangetic plains of India. In Proceedings of the Asian Regional Maize Workshop, Beijing, China, 5–9 September 2005.
41. Deng, X.P.; Shan, L.; Zhang, H.; Turner, N.C. Improving agricultural water use efficiency in arid and semiarid areas of China. In *Agricultural Water Management*; Elsevier: Amsterdam, The Netherlands, 2006; Volume 80, pp. 23–40.
42. Saif, U.; Masood, M.; Farooq, M.; Hussain, S.; Habib, A. Effect of planting patterns and different irrigation levels on yield and yield component of Maize (*Zea mays* L.). *Int. J. Agric. Biol.* **2003**, *5*, 64–66.
43. Hamilton, G. *Refinement and Adoption of Permanent Raised Bed Technology for the Irrigated Maize-Wheat Cropping System in Pakistan*; Australian Centre for International Agricultural Research: Canberra, Australia, 2006. Available online: <http://www.aciar.gov.au/project/LWR/2002/034> (accessed on 26 December 2020).
44. Hobbs, P.R.; Singh, Y.; Giri, G.S.; Lauren, J.G.; Duxbury, J.M. *Direct Seeding and Reduced Tillage Options in the Rice-Wheat Systems of the Indo-Gangetic Plains of South Asia*; IRRI workshop: Bangkok, Thailand, 2000; pp. 25–26.
45. Abbas, G.; Hussain, A.; Ahmad, A.; Wajid, S.A. Water use efficiency of maize as affected by irrigation schedules and nitrogen rates. *J. Agric. Soc. Sci.* **2005**, *1*, 339–342.
46. Huang, Y.L.; Chen, L.D.; Fu, B.J.; Huang, Z.L.; Gong, J. The wheat yields and water-use efficiency in the Loess Plateau: Straw mulch and irrigation effects. *Agric. Water Manag.* **2005**, *72*, 209–222. [[CrossRef](#)]
47. Zhang, S.L.; Lövdahl, L.; Grip, H.; Tong, Y.A.; Yang, X.Y.; Wang, Q.J. Effects of mulching and catch cropping on soil temperature, soil moisture and wheat yield on the Loess Plateau of China. *Soil Tillage Res.* **2009**, *102*, 78–86. [[CrossRef](#)]