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Estimation of Crop Water Productivity Using GIS and Remote Sensing Techniques

Zenobia Talpur [1,2,3,*], Arjumand Z. Zaidi [1], Suhail Ahmed [1], Tarekegn Dejen Mengistu [2,3], Si-Jung Choi [2] and Il-Moon Chung [2,3,*]

[1] US Pakistan Center for Advanced Studies in Water (USPCASW), Mehran University of Engineering and Technology, Jamshoro 76062, Pakistan; arjumand.uspcasw@faculty.muet.edu.pk (A.Z.Z.); engrsam1306@gmail.com (S.A.)

[2] Water Resources and River Research Department, Korea Institute of Civil Engineering and Building Technology, Goyang 10223, Republic of Korea; tarekegnmengistu@kict.re.kr (T.D.M.); sjchoi@kict.re.kr (S.-J.C.)

[3] Civil and Environmental Engineering Department, University of Science and Technology (UST), Daejeon 34113, Republic of Korea

* Correspondence: zenobiatalpur@kict.re.kr (Z.T.); imchung@kict.re.kr (I.-M.C.)

Abstract: The global demand for food is growing with the population and urbanization, which puts pressure on water resources, which need assessing and quantifying water requirements. Adopting efficient irrigation methods to optimize water use is essential in this situation. In this study, crop water productivity (CWP) of major crops in the Rohri canal command area was estimated by the ratio of yield and actual evapotranspiration (ET_a). Analyzing the CWP of major crops, water scarcity challenges can be tackled by selecting the most feasible irrigation methods. However, ET_a was calculated and aggregated for all four stages of the crop growth period: initial, crop development, flowering stage, and maturity seasons. The crop yield data were obtained from the districts' agricultural statistics. For this purpose, evapotranspiration products of Landsat 5 and 8 were downloaded from Earth Engine Evapotranspiration Flux (EEFlux). Landsat images were processed in a GIS environment to calculate ET_a. The approach suggests developing a CWP database for major crops like wheat, cotton, and rice to improve irrigation water management. The objectives of this study are to estimate and analyze the difference in the CWP and evapotranspiration of major crops for the Rabi and Kharif seasons with high and moderate flows during 1998–2019. It comprises nine districts of Sindh that come under the Rohri Canal command area. To analyze the difference in CWP between the Rabi and Kharif seasons for all study crops of the seasons of Rabi (2014–2015 and 2016–2017) and Kharif (1998 and 2017). The growing periods for wheat, cotton, and rice in the Rohri Canal command area are 160, 195, and 180 days, respectively. The estimated ET_a of the Rohri canal command area and CWP were in good agreement with the literature-reported values. Hence, enhanced agricultural productivity can be achieved by making considerable investments to improve agricultural research and extension systems.

Keywords: crop water productivity; evapotranspiration; GIS and remote sensing; Rabi and Kharif seasons

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1. Introduction

It has been reported that the agricultural sector consumes 90% of the world's water, from which 40% of the crops are produced through the irrigation system [1]. Food security is a major challenge; unsustainable agriculture cannot achieve nutrition requirements for the growing population. The agriculture sector faces challenges of low crop water productivity (CWP), and water use must be optimized to produce more food or crop per drop of water. CWP is a crucial factor for the long-term and strategic planning of water supplies; the water supply's real and practical values are difficult to understand [2]. The water productivity idea in agriculture has gained recognition over the last few years through a paradigm shift from land to water productivity due to low water availability and crop water productivity.

Pakistan's agriculture sector contributes 24% of the Gross Domestic Production (GDP) and employs 45% of its total labor force [2–5]. Pakistan has two main cropping seasons—Rabi and Kharif. The Kharif crop is heavily reliant on the amount and distribution of rainfall, especially during the monsoon season [6]. The canal system of the Indus River mainly supports agriculture. The Sukkur Barrage is the oldest among them. Before the Sukkur Barrage, the 350 km long Rohri Canal, one of the oldest canals, was built [7]. The Canal irrigates farms on the left bank of the river Indus down the Sukkur Barrage. Approximately 2.9 million acres of agricultural land get water from the Rohri Canal in nine districts. Rohri Canal irrigates lands as far as the Sindh Coastal district of Badin for orchards and areas where cash crops such as sugarcane, cotton, and wheat are grown [8].

The declining water availability in Pakistan is alarming, reducing from 5600 m^3/capita to 1200 m^3/capita due to rapid urbanization and industrialization over the past fifty years. The surface water sources and reservoirs are inadequate to satisfy agricultural requirements. In addition to the Indus River, other water resources in Pakistan are groundwater and precipitation [5,7–12]. However, the groundwater is depleting at a massive rate due to extensive over-exploitation [12]. The Sindh province experiences inconsistent and limited rainfall.

The need for irrigation has grown significantly during the recent 20 years owing to the restoration and extension of the crop area and changes in the planting structure and cropping pattern [13]. On the other hand, water is lost due to inefficient irrigation techniques, which need to be mitigated. Limiting irrigation water in many regions is necessary to fulfill the industrial, municipal, and environmental water demands. The nation faces significant challenges due to escalating water demand for irrigation and the increasing conflicts over water usage [11].

Many studies showed shortfalls in the Canal's flows in summer. Water supply was less than 26% of crop water demands in the summer of 2012; in winter, it was about 20% surplus [14]. The primary use of water in the canal command is for drainage supplies where the groundwater source is inadequate, as demonstrated by the researchers through adjustments in the amount of groundwater. Refs. [13,15] indicated that farming at the Indus River possesses a demand of 220 BCM and 210 BCM, respectively. The IBIS losses are 62 BCM, excluding the sea outflows (outflows to the Arabian Sea are environmental flows needed to sustain the coastal ecosystem). The Indus River has a productivity of 54%, while the Sindh irrigation system's productivity is just 35% [11]. The major water management problem is an early season water shortage followed by excessive water with the monsoon onset.

Water accounting and water efficiency principles help evaluate current output and explore strategies for saving actual water from fields to the basins. Such principles include a thorough understanding of the existing water usage pattern and the water balance's interaction of different complex components on various spatial and temporal levels [14,15]. Management and technological improvements have dramatically reduced irrigation water withdrawals, especially quitting surface irrigation practices (gravity, furrow, flood, etc.) to efficient irrigation (micro and sprinkler). Water timing may also significantly impact yield affecting seed growth [16].

CWP is the idea of getting the most out of crops, livestock, and other things while using the least amount of water possible [17]. The data regarding the amount of water utilized by the crops must be obtained as a prerequisite before using this strategy or procedure. The lysimeter method, the field plot method, and many others are examples of direct approaches for collecting data [18]. To gather such data for analysis, though, these procedures demand a lot of time and work. Using evapotranspiration (ET) values to solve simple equations to determine the amount of water consumed can, therefore, be a solution to this time-constrained problem. In this paper, the actual evapotranspiration (ET_a)

measurements are obtained from the satellite photos of ETrf (fraction of alfalfa reference ET) for further processing.

This study analyzes the actual evapotranspiration (ET_a) and CWP of wheat, rice, and cotton in nine Sindh districts within the Rohri Canal command area. This study will help identify high agricultural performance areas and provide insight into the irrigation system's management, leading to sustainable water productivity [11,16,17]. Remote sensing provides large-scale evapotranspiration data to predict water balance and canal command area performance [19]. This study used a powerful data portal based on remote sensing—Google Earth Engine Evapotranspiration flux (EEFlux) based on 'Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC)'. This data site has a high potential in estimating ET_a [20]. METRIC is a modified version of the 'Surface Energy Balance Algorithm for Land (SEBAL), used nowadays to map evapotranspiration [21]. METRIC requires manual pixel selections, so automatic calibration models have been developed due to uncertainty that may occur during its calibration with different users. Automatic models also require huge pre-processing like assembling various layers, local climate, satellite data, land use/cover and soil maps, and data entry [22]. EEFlux not only provides an automatic data input mechanism but it is also connected to the Google Earth Engine (GEE) with the METRIC algorithm [21]. EEFlux provides ET maps for Landsat 5, 7, or 8. In this study, Landsat 5 and 8 images were used. EEFlux also provides Vegetation Index (NDVI), Surface Temperature (Ts), Normalized Difference, and Albedo maps, which can be used for applications other than ET [23].

2. Materials and Methods

2.1. Description of the Study Area

Rohri Canal is a principal constituent of the agricultural sector in Sindh [8]. This Canal (Figure 1) is an artificial channel built on the Sukkur barrage with 2.6 million acres for irrigation. Rohri canal command area (25°15′39″ N and 68°34′44″ E) covers and provides water to major parts of the nine districts of Sindh—Naushero Feroze, Nawabshah, Matiyari, Hyderabad, Tando Allahyar, Tando Muhammad Khan, Mirpurkhas, Sanghar, and Badin). The Rohri Canal command area is in a hot climate with an annual rainfall of no more than 200 mm and a minimum temperature of 18 °C. The main crops produced in these districts are cotton and wheat. Rice is also grown in this region but is not among the major crops.

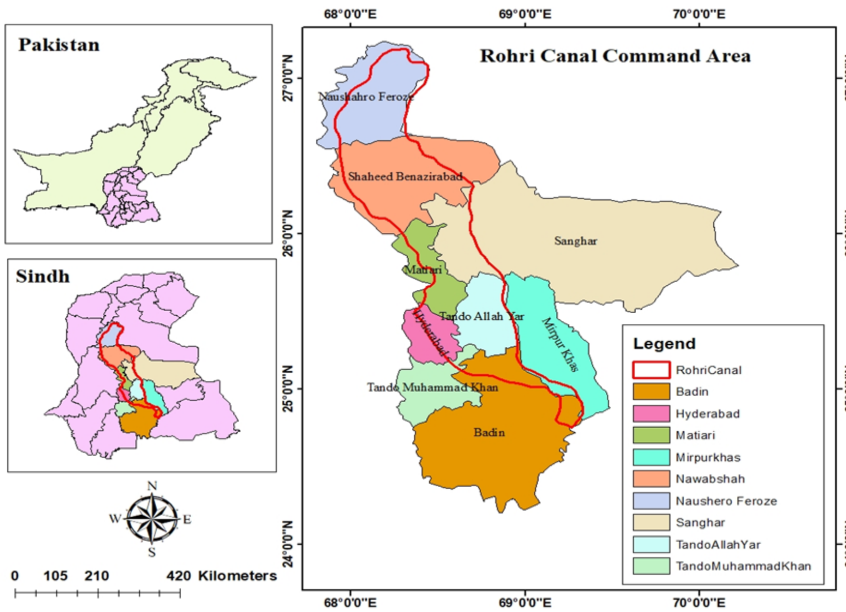


Figure 1. Location of the study area.

2.2. Methodology

The Crop Water Productivity (CWP) defined as the ratio of crop yield divided by the quantity to water used to produce it. The CWP was calculated for wheat, cotton, and rice for Kharif (1998 and 2017) and Rabi (2014–2015 and 2016–2017. The CWP was measured in kg/m^3 for consistency since literature in this regard predominately represented physical CWP. The crop water uses, or ET_a, is extensively calculated from remote sensing data [24]. Using satellite data, crop water use can be measured over larger temporal and spatial scales [21]. This study's critical secondary data include water availability at Rohri Canal (inflow), cropping pattern, and satellite images from the sources such as Sindh irrigation department, Pakistan, and images from USGS.

The crop productivity can be the yield, biomass, or grain, and the amount of water means the supplied water or actual Evapotranspiration (ET_a) to the crops [23–25]. The CWP depends on various factors such as the water vapor pressure deficit of the atmosphere, irrigation, soil fertility, pest, and disease control. CWP is often increased by any management factors that improve crop production since evapotranspiration is usually less reactive to these factors' changes than yield [22]. CWP is essential to understand the relationship between water and food [26,27]. The CWP values for wheat, cotton, and rice were estimated using Equation (1):

$$CWP = \frac{\text{y}\ (Yield)}{ET_a}, \tag{1}$$

where:

CWP stands for Crop Water Productivity (kg/m^3), used for wheat, cotton, and rice crops, y represents the yield (kg/m^2),

ET_a is the actual seasonal evapotranspiration (m^3/ha^1).

For this study, the irrigated area and wheat, cotton, and rice yields were taken from the crop reporting service department in Hyderabad, Sindh [28].

2.3. Datasets

2.3.1. Crop Data

The crop data were obtained from the Sindh statistical report [29,30]. The agricultural department was also contacted to get the details for crops.

2.3.2. Crop Masks

The crop mask can be defined as the spatial information of various crops' distribution. The crop masks for wheat (2013–2014) and cotton and rice (2014–2015) were developed by the Food and Agriculture Organization (FAO), Pakistan's Space and Upper Atmosphere Research Commission (SUPARCO), and the United States Department of Agriculture (USDA) as part of the project "Agriculture Information System-Building Provincial Capacity in Pakistan for Crop Estimation, Forecasting, and Reporting based on the integral use of Remotely Sensed Data". SPOT-5 Satellite imageries have been used to make these crop masks [13,23]. SUPARCO started Phase-1 to develop crop masks for Sindh and Punjab for Rabi 2013–2014 and Kharif 2014–2015 seasons [31].

2.3.3. Reference Evapotranspiration

To estimate reference evapotranspiration (ET_r), we assumed that the land was covered with grass or alfalfa grass and calculated evapotranspiration from that grass. For the Indus Basin, in this study, reference evapotranspiration values using the Penman–Monteith method are used. The downloaded ETrf satellite data from the internet were processed on ArcMap10.4.1 software to calculate average evapotranspiration.

2.3.4. Remotely Sensed Data

Table 1 shows the Landsat images obtained from the Earth Engine Evapotranspiration Flux (EEFlux) portal, which provides processed Landsat 5 and 8 images. It is based on METRIC (Mapping Evapotranspiration at High Resolution with Internalized Calibration). The Landsat-image-based process operates on the Google Earth Engine system [10–12,15,16,20,21,32,33]. The temporal resolution is 16 days with a spatial resolution of 30 m. Using the Penman–Monteith equation for alfalfa crop reference, EEFlux includes North American Land Data Assimilation System (NLDAS) for reference ET (ETr) estimation [32–34]. The years 1998, 2017, 2014–2015, and 2016–2017 were selected based on the low and high flows which were obtained from the flow data by using the frequency analysis.

Table 1. Data types and sources.

Platform/Sensor	Year	Season	Spatial Resolution (m)	Bands	Crop	Source
Landsat 5	1998	Kharif	30	1	Cotton, Rice	EEflux
Landsat 8	2017	Kharif	30	1	Cotton, Rice	EEflux
Landsat 8	2014–2015	Rabi	30	1	Wheat	EEflux
Landsat 8	2016–2017	Rabi	30	1	Wheat	EEflux

2.3.5. Actual Evapotranspiration

EEFlux provides calibrated images that assign a value of ET_r to each pixel, and the value of actual evapotranspiration ET_a per day was calculated by multiplying ET_r and potential evapotranspiration ET_o [17]. EEFlux images were processed for Rabi (2014–2015 and 2016–2017) and Kharif (1998 and 2017). Landsat images and crop masks extracted ETr of the wheat, cotton, and rice crops. Reference evapotranspiration factor (ETrf) dates were selected from the Sindh Irrigation Department standards and from the time period of crop growing stages from initial to maturity (https://agri.sindh.gov.pk/showing-period (accessed on 23 February 2019). However, every crop has different times of growing time periods. ET_a is considered as residual of surface energy balance. It is given in Equation (2).

$$LE = R_n - H - G, \tag{2}$$

where LE is the latent heat flux R_n $\left(\mathrm{Wm}^{-2}\right)$ is net radiation G (Wm^{-2}) is heat flux of soil and H (Wm^{-2}) is sensible heat flux.

ET_rF (Reference evapotranspiration factor) was calculated by Equation (3) and cumulative ET_a for each season was calculated by using Equation (4) for different crop development phases, including Initial, Crop development, flowering, and maturity stages. The average actual evapotranspiration (ET_a) of all stages by multiplying ET_rF and ET_r with specific days and take the mean values of all pixels.

$$ET_r\mathrm{F} = \frac{ET_a}{ET_r(Reference\ ET)}, \tag{3}$$

$$ET_{season} = ET_r F_{season} \Sigma_q^n ET_{r-24}, \tag{4}$$

where:

$ET_r f$ represents the reference ET for a particular growth stage period.
ET_{r-24} is a daily reference ET for a certain number of days.
n indicates no of days.
ET_r values of the required canal command area were taken from [35].

2.4. Crop Calendars

The crop calendar differs for different regions and varies from crop to crop, such as wheat being grown in Rabi and cotton grown in Kharif. Crop calendars for the middle and lower Sindh regions were used to calculate actual evapotranspiration (ET_a). The dates for the middle and lower parts are different for sowing and harvesting. The initial sowing stage in lower Sindh begins one month earlier than the middle Sindh. The Rabi season's wheat crop starts in October and November, respectively, in the province's lower and upper parts. In contrast, cotton and rice crops are grown in the Kharif season starting from April. The crop calendars used in the study were adopted after an extensive literature review and by consulting agriculture scientists and researchers.

3. Results and Discussions

3.1. River Flows

The annual seasonal flows were assessed. Percentile is being calculated by this flow chart, which flows from the Sukkur Barrage. The N Maximum Annual Discharge data is listed in the table below (for the largest flow rank M = 1 and the smallest flow rank M = n or 21 in this study). However, Equation (4a) shows the average interval of two discharges of equal (or greater) magnitude in years between occurrences is known as the Recurrence Interval (RI). This relationship, known as the equation of Weibull, can be written as:

$$RI = \frac{N+1}{M} \tag{4a}$$

where:

RI = Recurrence Interval
N = Maximum Annual Discharge
M = Rank

Equation (4b) can define a probability of a given magnitude of a flood each year.

$$P = \left(\frac{1}{RI}\right) \times 100 \tag{4b}$$

Figure 2a shows the years and the Rabi season's flows from 1998–1999 to 2018–2019 of the Sukkur Barrage, while the ranks were assigned and arranged according to the flows such as high, medium, and low. The exceedance probability (P) has been calculated for the Rabi season in which the wheat crops are cultivated. There was a high flow in 2014–2015 with 15.54 Million Acre-Foot (MAF). The medium flow was recorded in 2003–2004; however, it has not been used in the study due to the error in corresponding images (Landsat 7 error). The year 2016–2017 was considered medium flow with 10.86 MAF and 2001–2002 with 7.03 MAF on the last rank, which was considered the low flow year.

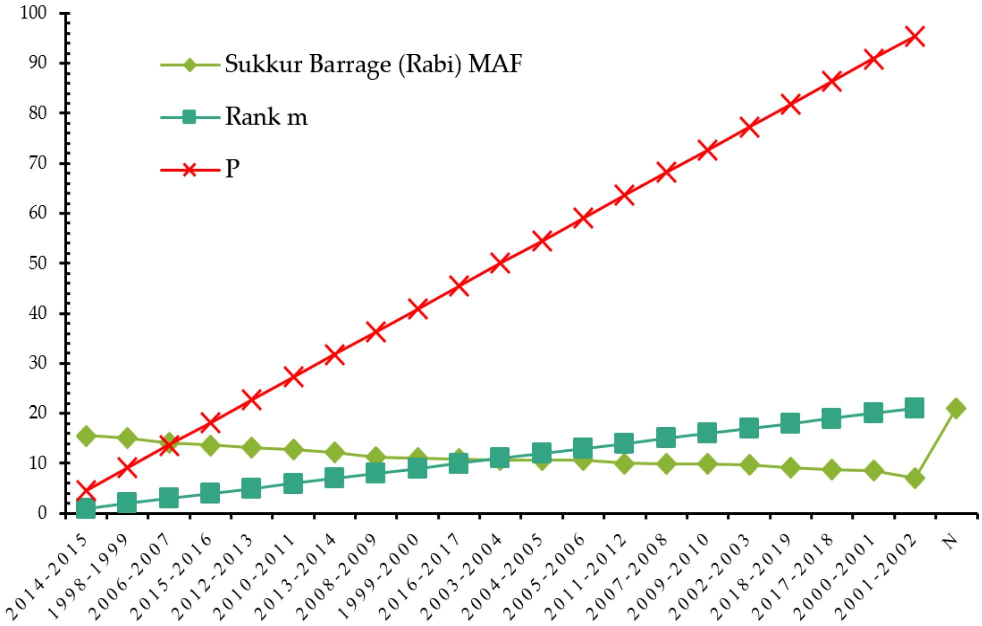
Figure 2b presents the frequency analysis of Kharif season flows from 1998 to 2017 of the Sukkur Barrage. The flows were categorized as high 76.13 (MAF), medium 38.41 (MAF), and low (23.97 MAF). The 2010 Kharif the wet year due to the riverine flood, which causes damages in Sindh. Therefore, 1998 with 70.03 MAF was chosen as the high flow year for this study (next highest after 2010). The medium flow year was 2017, and the low flow year was 2004. Rice and cotton crops grown in the Kharif season during high and medium flow periods were analyzed in this study.

3.2. Actual Evapotranspiration

The actual monthly evapotranspiration was calculated for the study area, which calculates crop water productivity (CWP). It can be observed that the initial stage has the lowest ET_a. In contrast, the flowering stage has the highest evapotranspiration since more water is required for plant growth at this stage.

3.2.1. Wheat Crop

Actual evapotranspiration has been calculated using crop masks for the four stages: initial, crop development, flowering, and maturity. Figure 3a illustrates the Rabi season's wheat crop's actual evapotranspiration, calculated by multiplying the ET_rf and ET_r. ET_a is low in the initial stage, as it is the sowing stage, whereas ET_a was higher in the flowering stage (340.08 mm in 2014–2015). Figure 3b shows the ET_a value of 202.19 mm for 2016–2017, lower than the value for 2014–2015.



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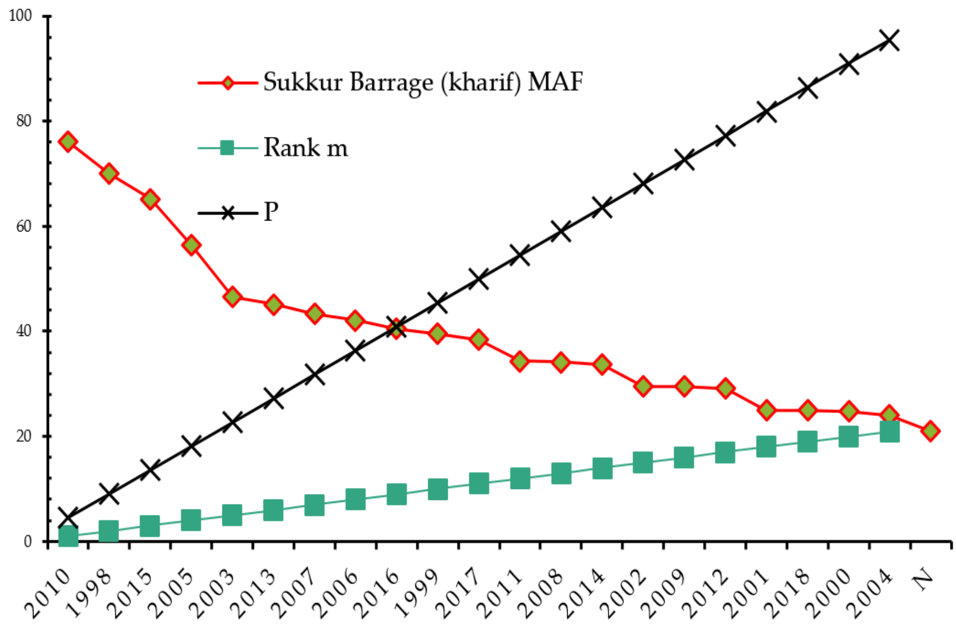
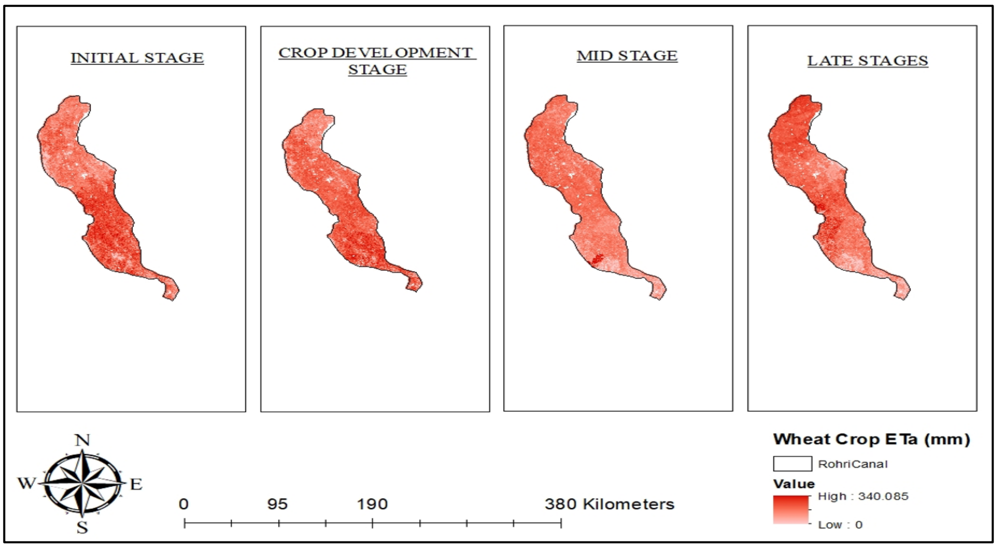


(**b**)

Figure 2. (**a**) Sukkur barrage flow in Rabi season. (**b**) Sukkur barrage flow in Kharif season.



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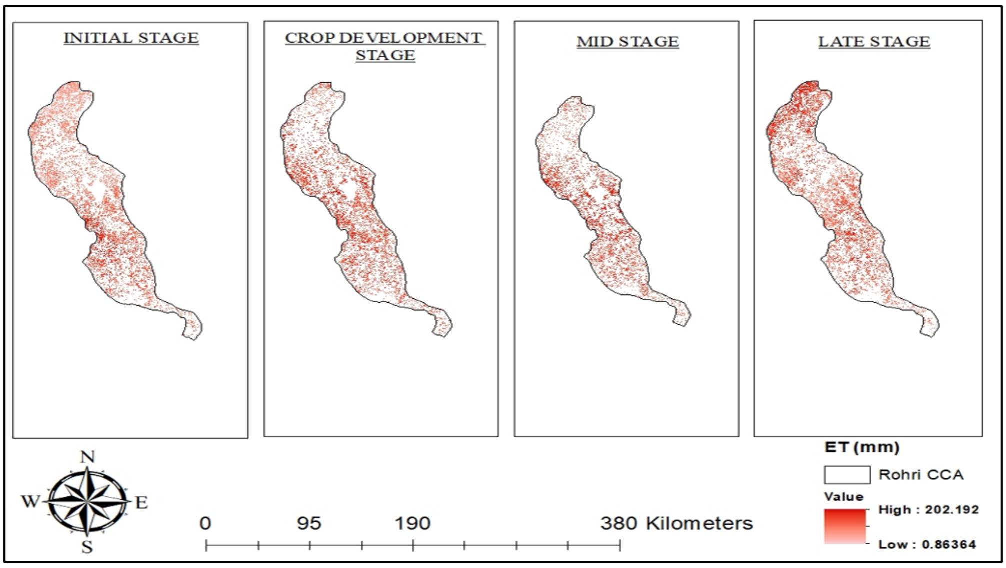


(**b**)

Figure 3. (**a**) Wheat crop actual evapotranspiration (2014–2015). (**b**) Wheat crop actual evapotranspiration (2016–2017).

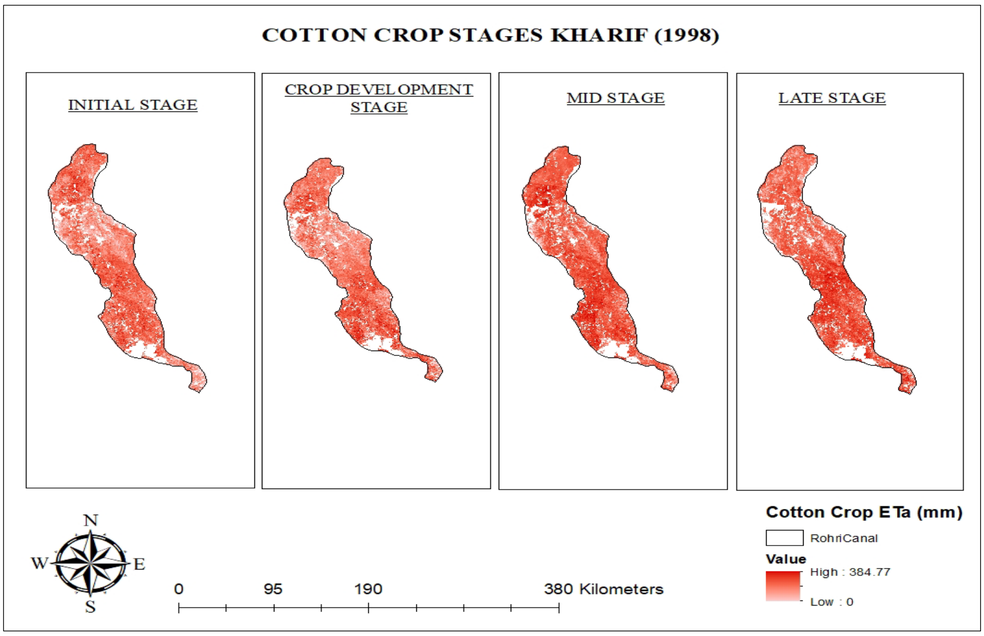
3.2.2. Cotton Crop

Actual evapotranspiration (ET_a) was more for the cotton crop than for wheat. Figure 4a presents ET_a for the cotton crop of the Kharif season of 1998 as 384.77 mm when the flow was high. Figure 4b shows the highest ET_a value, 481.22 mm for 2017, higher than in 1998, and 384.77 mm. In 2017, the flows were normal/moderate. That indicates that higher flows are not necessarily associated with higher ET_a values.

3.2.3. Rice Crop

Figure 5a illustrates the rice crop's actual evapotranspiration (418.72 mm) in 1998, the highest among other crops such as wheat and cotton. Rice consumes more water, and the flood irrigation technique is generally used in the study area. However, rice is not the major crop of Sindh. Still, it was reportedly cultivated in the Rohri Canal command area in 1998 [35]. Due to the unavailability of production data for Tando Allahyar, Tando Muhammad Khan, and Matiyari, the CWP values in 1998 were not calculated for these districts. Figure 5b presents the ET_a of Hyderabad, Badin, and Matiyari for 2017 as

524.87 mm. Rice crop is cultivated in Sindh districts. However, it is banned in lower Sindh due to water scarcity since rice consumes more water than other crops.



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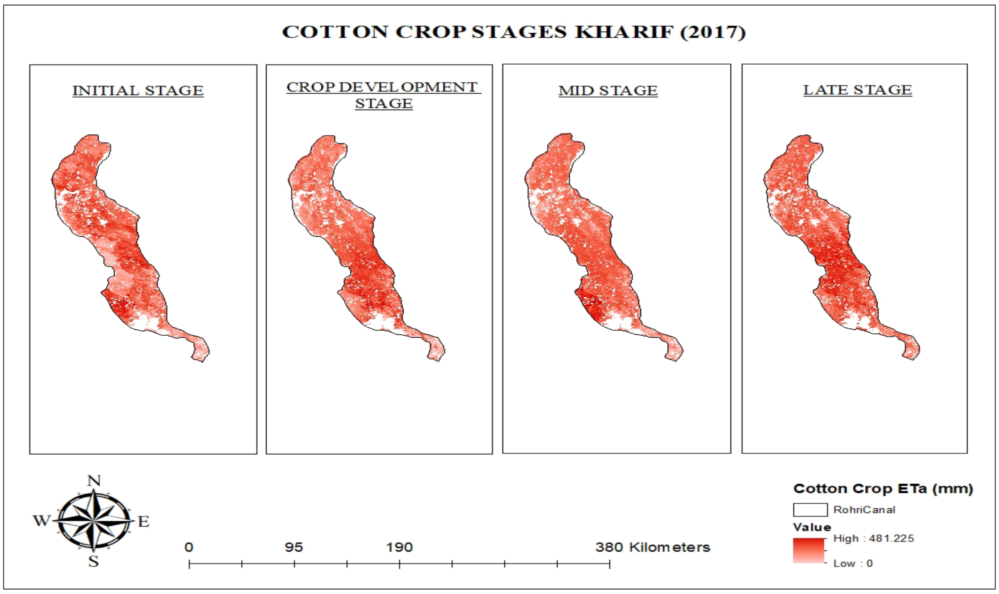


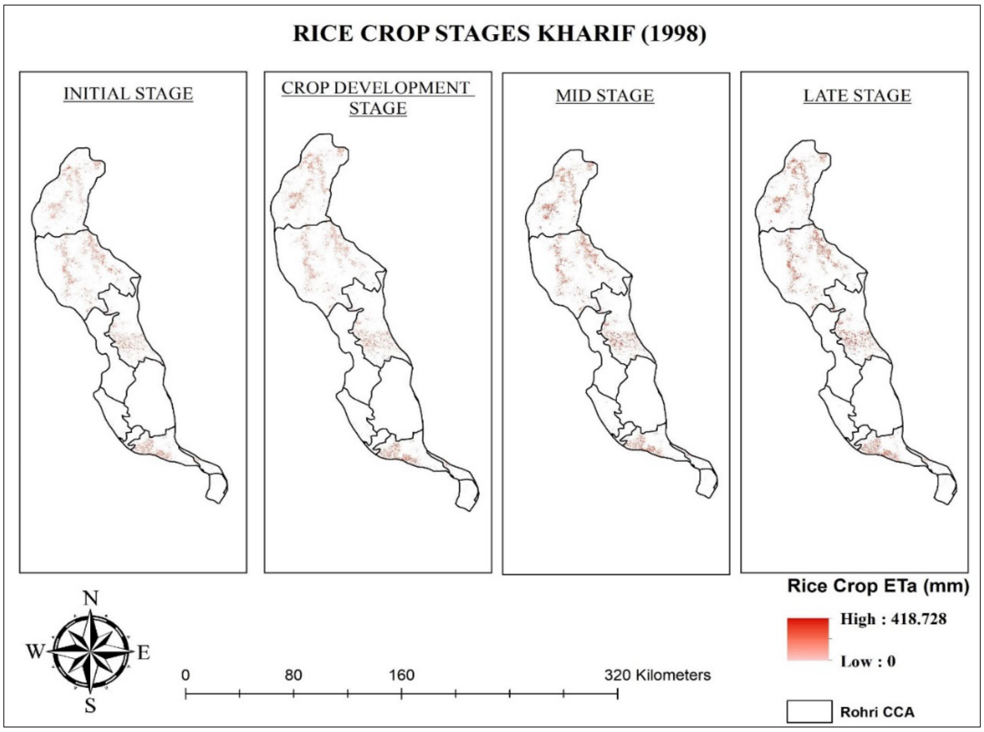
(**b**)

Figure 4. (**a**) Cotton crop actual evapotranspiration (1998). (**b**) Cotton crop actual evapotranspiration (2017).

3.3. Crop Water Productivity of Major Crops

3.3.1. Wheat Crop (2014–2015 and 2016–2017)

The average global CWP of wheat is 0.86 kg/m^3 to 1.80 kg/m^3. There are three global categories for CWP of wheat: low ($\leq$0.75 kg/m^3), medium (>0.75 kg/m^3 to <1.10 kg/m^3), and high ($\geq$1.10 kg/m^3) [21,36]. For Pakistan, the average CWP is 0.80 kg/m^3 to 0.91 kg/m^3, which falls under the medium category [37]. There was a higher flow in 2014–2015, whereas 2016–2017 was moderate (Figure 6). In 2014–2015, the crop water productivities of Hyderabad, Mirpurkhas, Sanghar, Tando Allahyar, and Nawabshah were, respectively, 1.11, 0.96, 1.05, 1.04, and 1.13 kg/m^3. In contrast, Matiyari, Tando Muhammad Khan, and Naushero Feroz CWP values were, respectively, 0.91, 0.89, and 1.1 kg/m^3. The CWP of Badin was not changed, i.e., 1.09 kg/m^3. The average CWP for the wheat crop was 1.03 kg/m^3 in 2014–2015 and 1.02 kg/m^3 in 2016–2017. Overall, the CWP of the wheat crop is under the reported range, i.e., between 0.32 kg/m^3 to 1.08 kg/m^3 [35,36].



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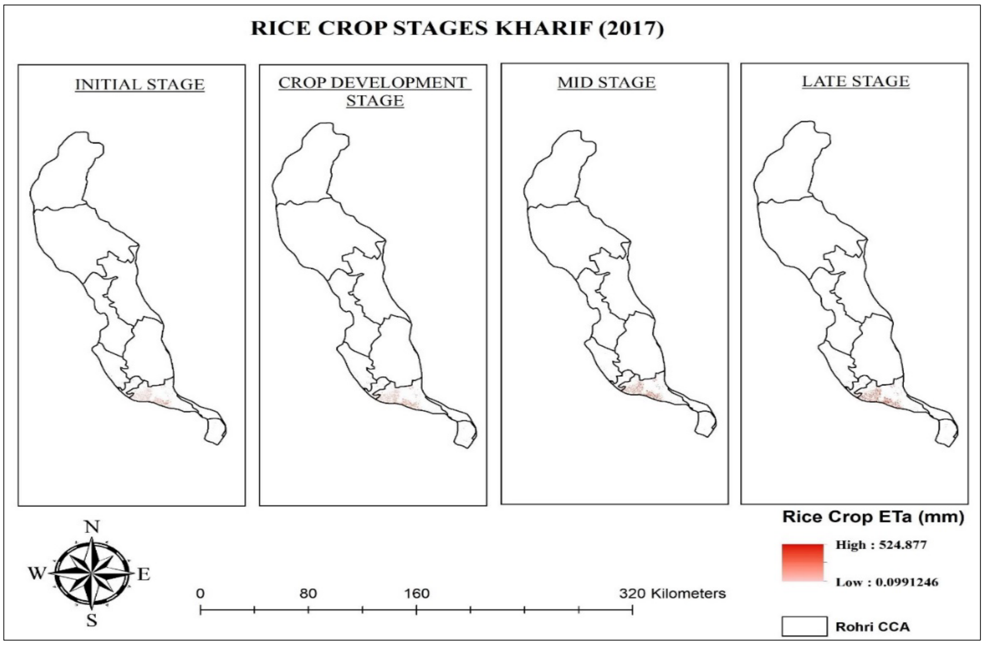

(**b**)

Figure 5. (**a**) Rice crop actual evapotranspiration (1998). (**b**) Rice crop actual evapotranspiration (2017).

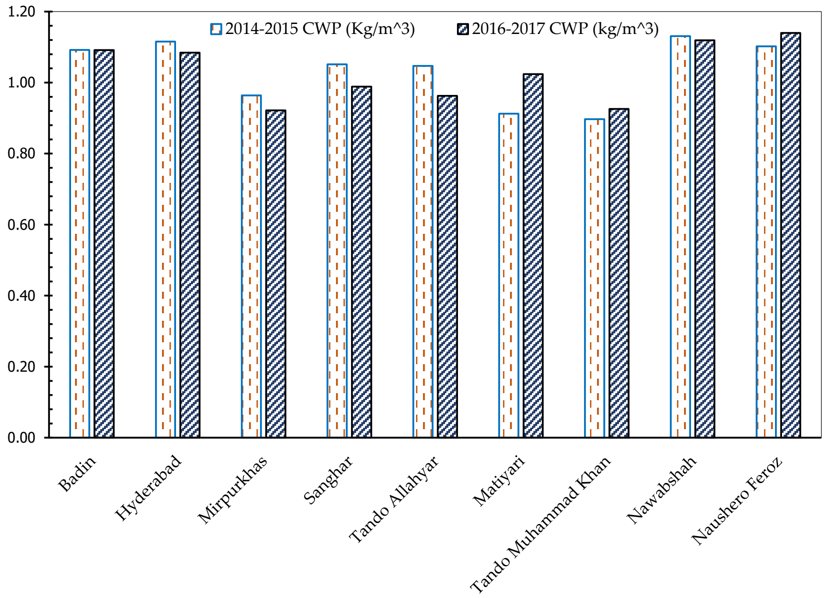

Figure 6. Crop water productivity of wheat crop.

The average CWP of the study area for wheat in 2014–2015 and 2016–2017 were 1.03 kg/m^3 and 1.02 kg/m^3, respectively, in the range given in the literature. Due to waterlogging, salinity, soil conditions, and lack of groundwater availability, the CWP of Sindh is less than Punjab. The wheat yield of Sindh is 33% less than the wheat yield of Punjab due to the water logging and availability of groundwater [11,37–41].

3.3.2. Cotton Crop

Figure 7 represents the CWP of cotton for the Kharif season (1998 and 2017). For the years 1998 and 2017, CWP values of the cotton crop were consistent in Badin, Naushero Feroz, Nawabshah, Sanghar, Hyderabad, Tando Allahyar, Tando Muhammad Khan, Mirpurkhas, and Matiyari districts. The average CWPs of the study area of cotton crops of 1998 and 2017 were 0.12 kg/m^3 and 0.16 kg/m^3, whereas the calculated CWPs were in the range. The average values of CWP for cotton were 0.22 kg/m^3 and 0.26 kg/m^3 as revealed in [41]. The lowest CWP of Badin is due to the bad image quality and cloud cover. For these shortcomings, it became difficult to calculate the actual evapotranspiration. Cloud corrections were applied where cloud cover was approximately 50%, and missing data were interpolated.

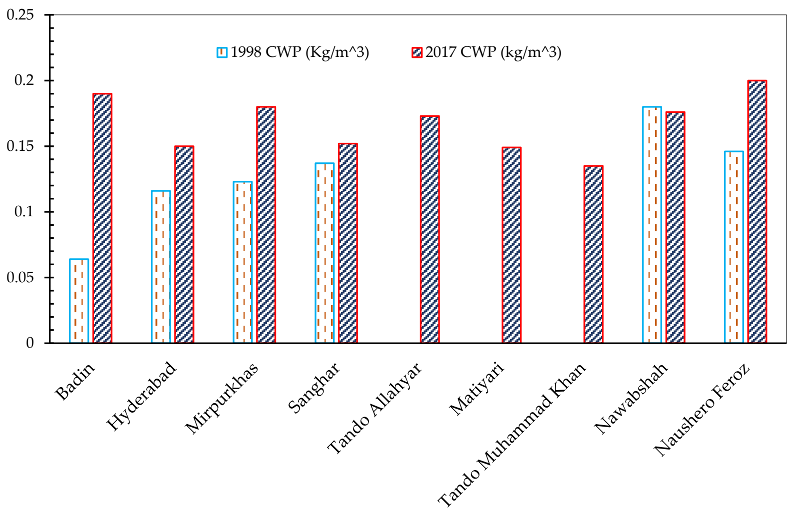

Figure 7. Crop Water Productivity of Cotton Crop.

3.3.3. Rice Crop

Figure 8 shows the crop water productivity of rice cultivated in the study area. Most of the crops selected in this study are major crops, except rice. Rice is one of the other crops the Sindh government banned due to the water shortage. However, Rice was cultivated in 1998 all over Sindh, whereas no precise information was available on rice production in districts other than Hyderabad, Badin, and Tando Muhammad Khan. In 2017, the CWPs of Badin, Hyderabad, and Tando Muhammad Khan were 0.67, 0.43, and 0.52 kg/m^3, respectively. Overall, the rice average CWP values in 1998 and 2017 were 0.32 kg/m^3 and 0.54 kg/m^3, respectively. The results of this study on rice crops were compared with findings from various global studies from the literature [42]. According to the previous research for crop water productivity, the wheat and cotton crops are cash crops, and their CWP values match the present study results. Since rice was not banned in 1998 in the study area, water for other crops was used for rice. The other crops got enough water after stopping rice cultivation.

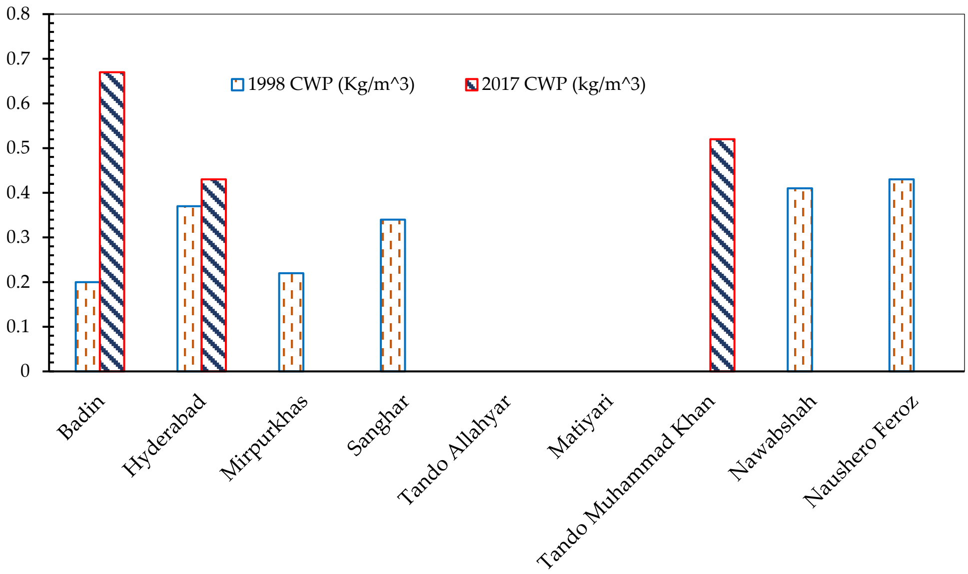

Figure 8. Crop Water Productivity of Rice Crop.

4. Conclusions

This study estimated the crop water productivity (CWP) of wheat, cotton, and rice in the Rohri Canal command area during different flow regimes using remotely sensed data in the GIS environment. The actual evapotranspiration was calculated for the nine districts (Naushero Feroz, Nawabshah, Mirpurkhas, Sanghar, Matiyari, Hyderabad, Tando Allahyar, Tando Muhammad Khan, and Badin) for two Rabi seasons (2014–2015 and 2016–2017) and two Kharif seasons (1998 and 2017). The years were selected based on the high and moderate flows passing through Sukkur Barrage.

The ET_a was higher in the rice crop due to the crop's excess water requirement, whereas the ET_a was less than the cotton crop for the wheat crop. ET_a depends on the crop type since some crops need more water than others. The study results summarized that estimating actual ET is vital for managing irrigation water and crop stress conditions. This advanced technique of using the EEFlux model to obtain ET_rf images is feasible for processing them with minimum effort.

The average CWP of the wheat crop for 2014–2015 and 2016–2017 were, respectively, 1.03 kg/m^3 and 1.02 kg/m^3. The CWP increased in the year 2014–2015 as compared to 2016–2017. There is a limitation of data in three districts (Matiyari, Tando Allahyar, and Tando Muhammad Khan) regarding crop area and production for cotton and rice in 1998. Therefore, cotton and rice average CWPs were calculated (1998 = 0.12 kg/m^3 and 0.16 kg/m^3—2017 = 0.32 kg/m^3 and 0.54 kg/m^3) for six districts only. In 1998, overall, CWP increased for both crops. Rice has been banned by the Sindh government in Sindh Province due to the water shortage since rice consumes more water than other crops. Rice takes more water than other crops, and the saved water can be used for domestic and industrial purposes.

The CWP is affected by agricultural practices comprising land preparation, sowing methods, seed and soil quality, water and fertilizer application, and weed and pest control. The proposed approach is quite feasible and can be used for different areas with various crops. Results are in good agreement and promoted remote sensing techniques to manage crop production effectively. In addition, the Accuracy assessment of crop mask could have been conducted. The research outputs will provide a starting point for more elaborate studies.

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References

1. Döll, P.; Siebert, S. Global modeling of irrigation water requirements. *Water Resour. Res.* **2002**, *38*, 8-1–8-10. [CrossRef]
2. Zwart, S.J.; Bastiaanssen, W.G.M.; de Fraiture, C.; Molden, D.J. WATPRO: A remote sensing based model for mapping water productivity of wheat. *Agric. Water Manag.* **2010**, *97*, 1628–1636. [CrossRef]
3. Ahmad, D.; Chani, M.I.; Humayon, A.A. Major Crops Forecasting Area, Production and Yield Evidence from Agriculture Sector of Pakistan. *Sarhad J. Agric.* **2017**, *33*, 385–396. [CrossRef]
4. Baig, M.B.; Shahid, S.A.; Straquadine, G.S. Making rainfed agriculture sustainable through environmental friendly technologies in Pakistan: A review. *Int. Soil Water Conserv. Res.* **2013**, *1*, 36–52. [CrossRef]
5. Kazmi, D.H.; Rasul, G. Early Yield Assessment of Wheat on Meteorological Basis for Potohar Region. *Pak. J. Meteorol.* **2006**, *6*, 73–87.
6. Adnan, S.; Khan, A.H. Effective Rainfall for Irrigated Agriculture Plains of Pakistan. *J. Meteorol.* **2011**, *6*, 61–72.
7. Thakker, R.P.; Solanki, H.; Thakker, P.S. Indus Water from Sindh Pakistan Entered the Nal Sarovar, Located in Ahmedabad District, Gujarat, India. *Life Sci. Leafl.* **2010**, *4297*, 76–82.
8. van Steenbergen, F.; Kaisarani, A.B.; Khan, N.U.; Gohar, M.S. A case of groundwater depletion in Balochistan, Pakistan: Enter into the void. *J. Hydrol. Reg. Stud.* **2015**, *4*, 36–47. [CrossRef]
9. Investment, F.A.O.; Occasional, C.; Series, P.; December, N. *Pakistan Sindh Water Resources Management—By Fao/World Bank Cooperative Programme Pakistan Sindh Water Resources Management Issues and Options*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2003.
10. Shen, Y.; Li, S.; Chen, Y.; Qi, Y.; Zhang, S. Estimation of regional irrigation water requirement and water supply risk in the arid region of Northwestern China 1989–2010. *Agric. Water Manag.* **2013**, *128*, 55–64. [CrossRef]
11. Ahmad, M.-D.; Steward, J.; Peña-Arancibia, J.; Kirby, M. *Sindh Water Outlook: Impacts of Climate Change, Dam Sedimentation and Urban Water Supply on Irrigated Agriculture*; The Commonwealth Scientific and Industrial Research Organisation: Canberra, Australia, 2020; p. 35.
12. Hussain, I.; Hussain, Z.; Sial, M.H.; Akram, W.; Farhan, M.F. Water Balance, Supply and Demand and Irrigation Efficiency of Indus Basin. *Water* **2011**, *49*, 13–38.
13. Qureshi, A. Optimization of Irrigation Water Management: A Case Study OF Secondary Canal, Sindh, Pakistan. In Proceedings of the Sixteenth International Water Technology Conference, Istanbul, Turkey, 7–10 May 2012; pp. 1–15.
14. Ahmad, M.D.; Turral, H.; Nazeer, A. Diagnosing irrigation performance and water productivity through satellite remote sensing and secondary data in a large irrigation system of Pakistan. *Agric. Water Manag.* **2009**, *96*, 551–564. [CrossRef]
15. Aslam, M. Agricultural Productivity Current Scenario, Constraints and Future Prospects in Pakistan. *Sarhad J. Agric.* **2016**, *32*, 289–303. [CrossRef]
16. Allen, R.G.; Tasumi, M.; Morse, A.; Trezza, R.; Wright, J.L.; Bastiaanssen, W.; Kramber, W.; Lorite, I.; Robison, C.W. Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC)—Applications. *J. Irrig. Drain. Eng.* **2007**, *133*, 395–406. [CrossRef]

17. Molden, D.; Oweis, T.; Steduto, P.; Bindraban, P.; Hanjra, M.A.; Kijne, J. Improving agricultural water productivity: Between optimism and caution. *Agric. Water Manag.* **2010**, *97*, 528–535. [CrossRef]
18. Mata, M.D.; Salunke, K.A.; PBhangale, P. Evaluation of Evapotranspiration. *Int. J. Res. Eng. Technol.* **2014**, *3*, 43–47. [CrossRef]
19. Maupin, M.A.; Kenny, J.F.; Hutson, S.S.; Lovelace, J.K.; Barber, N.L.; Linsey, K.S. *Estimated Use of Water in the United States in 2010*; Circular 1405; U.S. Geological Survey Circular: Reston, Virginia, 2010; ISBN 9781411338623.
20. Allen, R.; Morton, C.; Kamble, B.; Kilic, A.; Huntington, J.; Thau, D.; Gorelick, N.; Erickson, T.; Moore, R.; Trezza, R.; et al. *E EEFlux: A Landsat-Based Evapotranspiration Mapping Tool on the Google Earth Engine*; DigitalCommons@University of Nebraska-Lincoln: Lincoln, NE, USA, 2015.
21. Foley, D.J.; Thenkabail, P.S.; Aneece, I.P.; Teluguntla, P.G.; Oliphant, A.J. A meta-analysis of global crop water productivity of three leading world crops (wheat, corn, and rice) in the irrigated areas over three decades. *Int. J. Digit. Earth* **2020**, *13*, 939–975. [CrossRef]
22. Foolad, F.; Blankenau, P.; Kilic, A.; Ekonomiczno-humanistyczna, A.; Allen, R.G. Comparison of the Automatically Calibrated Google Evapotranspiration Application—EEFlux and the Manually Calibrated METRIC Application. *Preprints.org* **2022**, 2018070040. [CrossRef]
23. He, T.; Gao, F.; Liang, S.; Peng, Y. Mapping Climatological Bare Soil Albedos over the Contiguous United States Using MODIS Data. *Remote Sens.* **2019**, *11*, 666. [CrossRef]
24. Faso, B. *Policy Guide to Improve Water Productivity in Small-Scale Agriculture*; FAO: Rome, Italy, 2020; ISBN 9789251321430.
25. Varzi, M.M. Crop Water Production Functions—A Review of Available Mathematical Method. *J. Agric. Sci.* **2016**, *8*, 76. [CrossRef]
26. Liu, J.; Williams, J.R.; Zehnder, A.J.B.; Yang, H. GEPIC—Modelling wheat yield and crop water productivity with high resolution on a global scale. *Agric. Syst.* **2007**, *94*, 478–493. [CrossRef]
27. Wang, X.; Xin, L.; Tan, M.; Li, X.; Wang, J. Impact of spatiotemporal change of cultivated land on food-water relations in China during 1990–2015. *Sci. Total Environ.* **2020**, *716*, 137119. [CrossRef] [PubMed]
28. Solangi, G.S.; Shah, S.A.; Alharbi, R.S.; Panhwar, S.; Keerio, H.A.; Kim, T.W.; Memon, J.A.; Bughio, A.D. Investigation of Irrigation Water Requirements for Major Crops Using CROPWAT Model Based on Climate Data. *Water* **2022**, *14*, 2578. [CrossRef]
29. Japan International Cooperation Agency. *Data Collection Survey on Agricultural Sector in Sindh Province in the Islamic Republic of Pakistan*; Final Report; Japan International Cooperation Agency: Tokyo, Japan, 2022.
30. JECFA. *Evaluation of certain contaminants in food, Prepared by the Eighty-third report of the Joint FAO/WHO Expert Committee on Food Additives*; JECFA: Rome, Italy, 2017; ISBN 9789241210027.
31. Liaqat, M.U.; Cheema, M.J.M.; Huang, W.; Mahmood, T.; Zaman, M.; Khan, M.M. Evaluation of MODIS and Landsat multiband vegetation indices used for wheat yield estimation in irrigated Indus Basin. *Comput. Electron. Agric.* **2017**, *138*, 39–47. [CrossRef]
32. Allen, R. *Google Earth Engine Evapotranspiration Flux—EEFlux*; EEFlux-Development Team: Fortaleza, Brasil, 2015.
33. Shahid, M.A.; Chauhdary, J.N.; Usman, M.; Qamar, M.U.; Shabbir, A. Assessment of Water Productivity Enhancement and Sustainability Potential of Different Resource Conservation Technologies: A Review in the Context of Pakistan. *Agriculture* **2022**, *12*, 1058. [CrossRef]
34. Zaidi, A.; Khan, N.; Lashari, B.; Laghari, F.; Panhwar, V. Agricultural Water Balance Study in Sindh (Pakistan) Using Satellite-Derived Actual Evapotranspiration. In Proceedings of the 5th International Electronic Conference on Water Sciences, Online, 16–30 November 2020; p. 8021. [CrossRef]
35. Khan, M.I.; Saddique, Q.; Zhu, X.; Ali, S.; Ajaz, A.; Zaman, M.; Saddique, N.; Buttar, N.A.; Arshad, R.H.; Sarwar, A. Establishment of Crop Water Stress Index for Sustainable Wheat Production under Climate Change in a Semi-Arid Region of Pakistan. *Atmosphere* **2022**, *13*, 2008. [CrossRef]
36. Hong, Y. Actual evapotranspiration estimation for different land use and land cover in urban regions using Landsat 5 data. *J. Appl. Remote Sens.* **2010**, *4*, 041873. [CrossRef]
37. Gao, H.; Zhang, X.; Wang, X.; Zeng, Y. Phenology-Based Remote Sensing Assessment of Crop Water Productivity. *Water* **2023**, *15*, 329. [CrossRef]
38. Zwart, S.J.; Bastiaanssen, W.G.M. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agric. Water Manag.* **2004**, *69*, 115–133. [CrossRef]
39. Summer, W.; Summer, A. Report on Wheat. In *Taking Root: The Nature Writing of William and Adam Summer of Pomaria*; Kibler, J.E., Ed.; University of South Carolina Press: Columbia, SC, USA, 2018; pp. 47–52. [CrossRef]
40. Usman, M.; Liedl, R.; Shahid, M.A. Managing Irrigation Water by Yield and Water Productivity Assessment of a Rice-Wheat System Using Remote Sensing. *J. Irrig. Drain. Eng.* **2014**, *140*, 04014022. [CrossRef]
41. Shabbir, A.; Arshad, M.; Bakhsh, A.; Usman, M.; Shakoor, A.; Ahmad, I.; Ahmad, A. Apparent and real water productivity for cotton-wheat zone of Punjab, Pakistan. *Pak. J. Agric. Sci.* **2012**, *49*, 323–329.
42. Alzahrani, K.; Ali, M.; Azeem, M.I.; Alotaibi, B.A. Efficacy of Public Extension and Advisory Services for Sustainable Rice Production. *Agriculture* **2023**, *13*, 1062. [CrossRef]

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