Type of the Paper (Article, Review, Communication, etc.)

Agricultural Water balance Study in Sindh (Pakistan) using Satellite-derived Actual Evapotranspiration

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Abstract: The rising water demand, coupled with mismanagement and misallocation of water, has caused water scarcity in the Sindh Province of Pakistan. The Sindh province almost entirely relies on the Indus River supply to meet its agricultural demand. The rising population will demand more food, but at the same time, agricultural water share will be under pressure due to the increasing demand of other competing users. Many studies have predicted a shortfall of water in the coming years that will cause food security issues. Since agriculture is the largest water user among all sectors, water management in this sector will significantly be affected. A water balance study is presented in this paper to evaluate the current and future water supply and demands and develop sustainable agriculture water budgeting. In this study, actual evapotranspiration (consumptive water) in Sindh's irrigated region was estimated during 2017-2019. The study utilized Landsat satellite data product from the Earth Engine Evapotranspiration Flux (EEflux). Study results identified shortages during the *Rabi* seasons when flows are usually low, and consumptive water use is more than the available quantum of canal flows and rainwater. However, the *Kharif* season presented the opposite trend. Within canal command areas (CCAs), the supplies and demands showed variable trends that can be balanced by adjusting surplus and deficit supplies by recalculating canal allocations. Suggestions for balancing water in these CCAs were also presented in this study.

Keywords: Agriculture; ET; Earth Engine Evapotranspiration; EE Flux; GIS; Indus River; Satellite Remote Sensing.

1. Introduction

In arid and semi-arid regions of the world, water availability is a major challenge for crop production due to inadequate rainfall patterns [1,2]. Irrigated agriculture consumes more than 70% freshwater globally and more than 80% in arid and semi-arid regions [3,4]. According to the United Nations Educational Scientific Cultural Organisation (2012), over the last 50 years, the demand for water in almost every country across the globe has tripled [5]. On the other hand, the exponential increase in population growth and increase in demand for irrigated food production is likely to rise, which has raised concerns about resources' availability and sustainability [6]. This situation demands essential improvements in agricultural water management efficiency. Researchers worldwide have also recognized this as one of the key topics associated with water scarcity and droughts [7]. Despite the critical pressure of agriculture on water resources, information on irrigated water is often unavailable. Thus, monitoring and assessing the agricultural water balance between supply and demand is critical for efficient water resources management.

Pakistan, located in the Indus River Basin and has more glaciers than anywhere else globally [6], faces acute water shortage, especially by its low riparians. The food production in Pakistan largely depends on irrigation, which provides more than 90% of the country's wheat, pulses, and nearly all other types of crops [8]. Irrigation of pasture also provides the main feed for milk production and the feed for meat livestock [8]. However, with the growing population, the per capita availability of water is declining. Around a 50% increase in the irrigation water requirement was predicted by 2025 in 2003 by Azad et al. (2003) [9,10]. These demands may further escalate dramatically with the induced effects of climate change and high water stress conditions. The current study assesses agricultural consumptive water use in Sindh, the most water-scarce province of Pakistan situated in the Indus River's tail-end. This study is based on secondary data from governmental and non-governmental agencies and remote sensing-derived information.

The consumptive water use can be estimated using various models and methods [11,12]. These models need input data regarding atmospheric and terrestrial information. Pakistan also lacks an efficient and comprehensive monitoring system to record relevant data in time and space. However, remote sensing (RS) application to estimate consumptive water use or water demand in larger areas prone to high demand variations has gained much popularity in the recent era of freely available satellite data due to its extended temporal and spatial scope [13,14,15,16,17].

Remote sensing uses various energy balance models for calculating actual evapotranspiration (ETa) [18,19,20,21,22,23]. In this study, satellite data were used to estimate ETa (consumptive water use) to evaluate the current and future water supply and demands and develop sustainable agriculture water budgeting. In this paper, two *Rabi* (winter) of 2017-2018 and 2018-2019 and one *Kharif* (summer) seasons of 2018 were studied. Average ETa was estimated in the entire irrigated land of the Sindh province comprising 14 culturable command areas (CCA) using Earth Engine Evapotranspiration Flux (EEFlux) data. The purpose of that study was to propose sustainable water budgeting for the Sindh province to manage its water resources in the agricultural sector.

2. Materials and Methods

2.1 Study Area

Sindh is the third-largest (area wise) and second-most populous province of Pakistan. It is located in the lower part of the Indus Basin. The province area is about 140,900 km^2, which is 17.7% of the total area of Pakistan. The agricultural activities of Sindh province largely depend on canal irrigation. In the Sindh province, there are three barrages—Guddu, Sukkur, and Kotri— and 14 canals and their command areas (Figure 1). The Indus River flows vary throughout the year. There are 29 districts in the province [24]. Sindh's reported population in the 2017 census was about 48 million (25 million in urban and 23 million in rural areas)—around 23% of its total population [24].

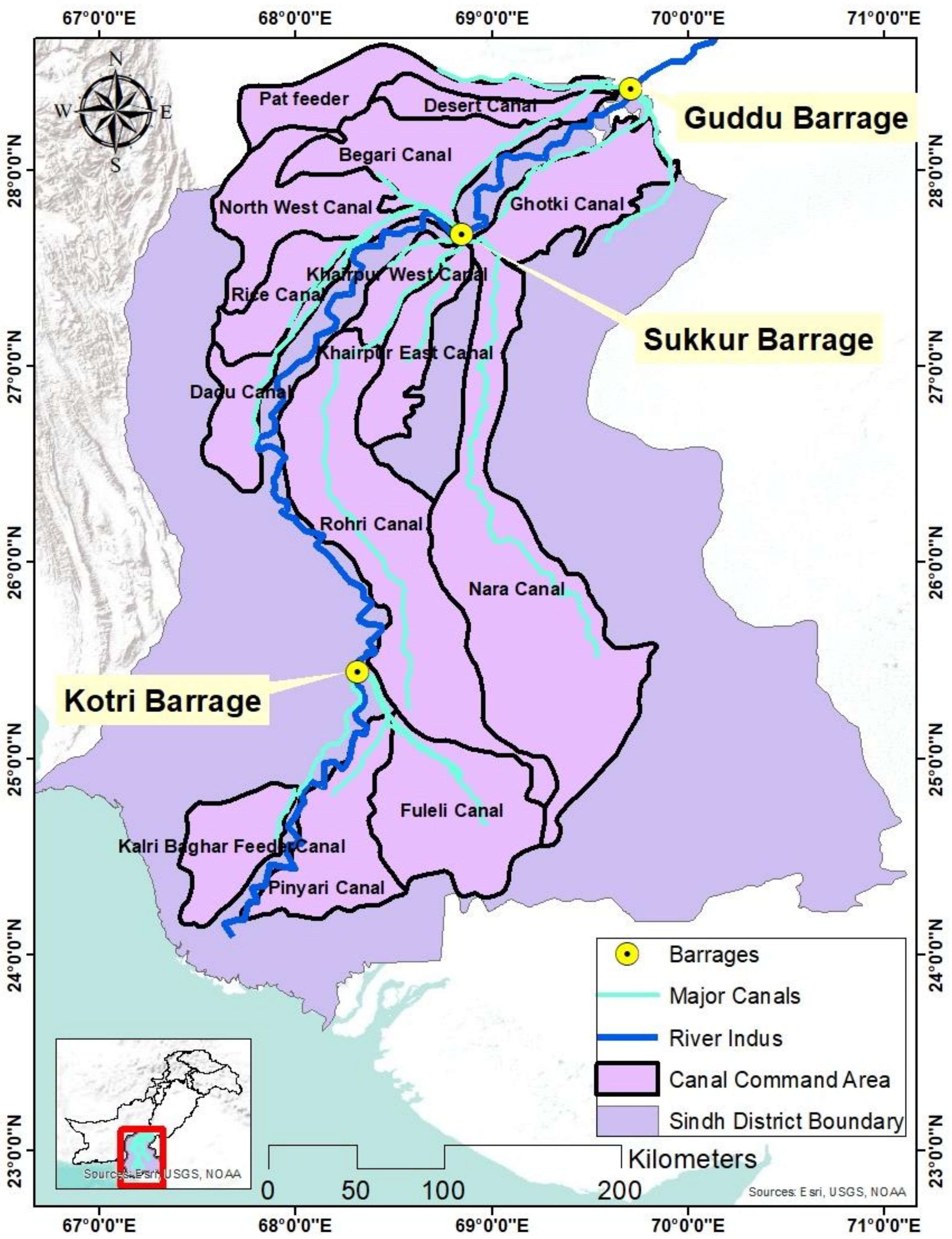

Figure 1: Sindh Canal Command Area

2.2 Study Data

For this study, open-source Landsat satellite data products for study seasons were downloaded from the Google Earth Engine Evapotranspiration Flux (EEFlux) website. EEFlux ET estimations are based on the METRIC (Mapping Evapo-Transpiration at high Resolution with Internalized Calibration) algorithm. Moreover, weather and climatic data were also acquired from the Pakistan Meteorological Department (PMD) for the entire Sindh province during 2014-2018. The analysis was based on inflow and outflow data from secondary sources such as statistical reports, Sindh Irrigation and Drainage Authority (SIDA), Sindh Irrigation Department (SID), and Water Sector Improvement Project (WSIP).

2.2 Methodology

2.2.1 Agricultural Water Assessment

Agriculture water use in terms of actual ET or consumptive water was estimated using ETrF from METRIC-EEFlux. The following sections describe the processing steps.

2.2.1.1 Reference ET Fraction (ETrF)

ETrF is the ratio of the actual ET (ETa) of each pixel to the reference ET (ETr) (Eq (1)). ETr values for the study area were obtained from previous studies [25, 26]. ETrF is similar to crop-coefficient (Kc) and used to extrapolate ETa for extended periods [27-28].

$$\mathrm{ETrF} = \frac{\mathrm{ET_a}}{\mathrm{ET_r}} \tag{1}$$

Where ETa is actual ET in mm, and ETr is the reference ET in mm.

2.2.1.2 Consumptive Water Use (WU)

Consumptive water use (WU) is the total amount of water consumed by agricultural lands. WU was estimated by aggregating the total amount of water transpired through the agricultural lands in the form of ETa during the entire growing season. Eq (2) was used to calculate the consumptive water use in million acre-ft (MAF) for each of the 14 CCAs separately.

$$\mathrm{WU} = \sum_{i}^{n} ET_{\mathrm{i}} \times a_{\mathrm{i}} \tag{2}$$

ETa is the actual ET in ft, *n* is the total pixel count, and *a* is the area of a pixel of Landsat image in acres.

3. Results and Discussions

a. Actual Evapotranspiration (ETa) for Sindh

During three growing seasons, the actual ET values, *Rabi* 2017-18, *Kharif* 2018, and *Rabi* 2018-19, are shown in Figure 2. The highest values of ET were observed during *Kharif* 2018, more specifically in the *Rohri* CCA.

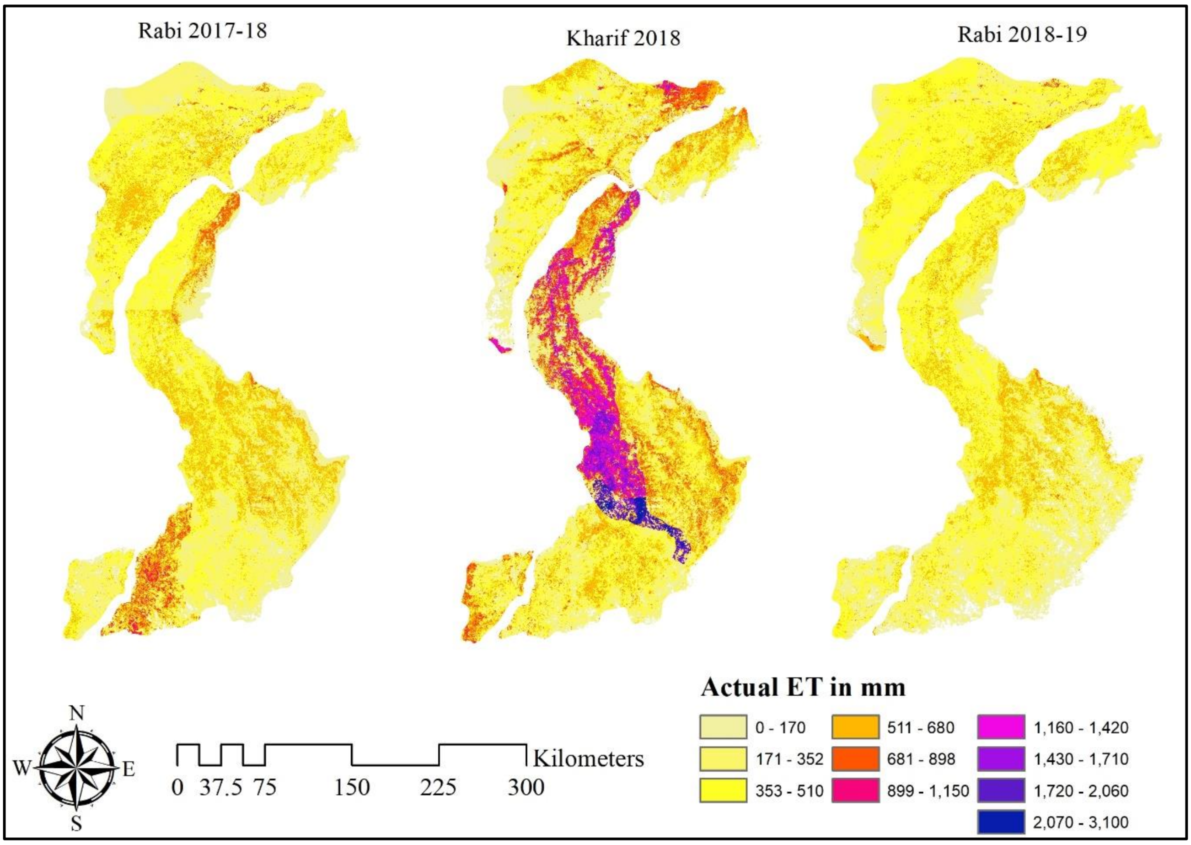

Figure 2: Seasonal Actual ET

b. Canal Water Supply and Consumptive Water Use (WU)

Tables 1, 2, and 3 give WU details calculated from actual ET in each CCA, authorized canal supply, and precipitation volumes, respectively, for *Rabi* 2017-18, *Kharif* 2018, and *Rabi* 2018-19. The information provided in these tables helps calculate surplus or deficit waters at the CCA level. The surplus and deficit water-flows for each CCA were calculated (canal diversions + rainfall - consumptive water). It was observed that surplus flows are mostly available in the *Kharif* season, while deficit or negative flows were observed during both *Rabi* seasons. The highest surplus flow of 2.0 MAF was observed in the *Fuleli* canal off-shooting from the Kotri Barrage during the *Kharif* 2018 season. In this analysis, it was observed that the *Rohri* canal CCA remained in deficit due to high consumptive demands in all seasons. It is also interesting to note that the *Rohri* canal is a highly productive CCA in Sindh [28]. The highest deficit value of all seasons was -1.28 MAF in the *Rohri* CCA during *Rabi* 2018-19.

The estimated water balance information helps manage the flows by adjusting the canals' flows by reducing the surplus amounts and reallocating them into the water deficit areas. Regulating the water flows according to the consumptive water need of a CCA can ensure an optimal water balance in the province.

Table 1: Authorized Canal Flows and Water Consumption during *Rabi* 2017-2018

Source	Canal	CCA (MHa)	Authorized Canal Volume (MAF)	Precipitation (MAF)	Consumptive Use (MAF)
Guddu Barrage	Beghari Sindh Canal	0.424	0.14	0.03	1.17
	Desert & Pat Feeder	0.501	1.09	0.03	0.50
	Ghotki Feeder Canal	0.392	1.00	0.02	1.06
	Total	**1.317**	**2.23**	**0.08**	**2.73**
Sukkur Barrage	North West Canal	0.452	0.73	0.04	1.51
	Rice Canal	0.222	0.19	0.02	0.83
	Dadu Canal	0.235	0.65	0.02	0.60
	Nara Canal	1.002	2.30	0.02	2.97
	Khairpur East Feeder	0.240	0.37	0.01	0.52
	Rohri Canal	1.092	2.38	0.03	3.47
	Khairpur West Feeder	0.136	0.29	0.01	0.56
	Total	**3.379**	**6.91**	**0.15**	**10.46**
Kotri Barrage	KB Feeder	0.284	0.85	0.00	0.65
	Pinyari Canal	0.437	0.21	0.01	0.92
	Fuleli Canal	0.620	0.61	0.04	1.15
	Total	**1.341**	**1.67**	**0.05**	**2.72**
Overall	**Grand Total**	**6.037**	**10.81**	**0.28**	**15.91**

Table 2: Authorized Canal Flows and Water Consumption during *Kharif* 2018

Source	Canal	CCA (MHa)	Authorized Canal Volume (MAF)	Precipitation (MAF)	Consumptive Use (MAF)
Guddu Barrage	Beghari Sindh Canal	0.424	2.57	0.03	1.20
	Desert & Pat Feeder	0.501	2.69	0.04	1.64
	Ghotki Feeder Canal	0.392	2.27	0.04	1.21
	Total	**1.317**	**7.53**	**0.11**	**4.05**
Sukkur Barrage	North West Canal	0.452	1.51	0.06	1.21
	Rice Canal	0.222	2.62	0.03	1.50
	Dadu Canal	0.235	0.93	0.01	0.36
	Nara Canal	1.002	3.88	0.46	3.26
	Khairpur East Feeder	0.240	0.54	0.03	0.54
	Rohri Canal	1.092	3.67	0.21	3.56
	Khairpur West Feeder	0.136	0.41	0.02	0.64
	Total	**3.379**	**13.6**	**0.82**	**11.1**
Kotri Barrage	KB Feeder	0.284	1.81	0.06	1.02
	Pinyari Canal	0.437	2.36	0.12	1.12
	Fuleli Canal	0.620	4.16	0.29	1.87
	Total	**1.341**	**8.30**	**0.47**	**4.00**
Overall	**Grand Total**	**6.037**	**29.43**	**1.4**	**19.15**

Table 3: Authorized Canal Flows and Water Consumption during *Rabi* 2018-2019*

Source	Canal	CCA (MHa)	Authorized Canal Volume (MAF)	Consumptive Use (MAF)
Guddu Barrage	Beghari Sindh Canal	0.424	0.09	0.30
	Desert & Pat Feeder	0.501	0.96	1.44
	Ghotki Feeder Canal	0.392	0.95	1.15
	Total	**1.317**	**2.00**	**2.89**
Sukkur Barrage	North West Canal	0.452	1.02	1.44
	Rice Canal	0.222	0.28	0.85
	Dadu Canal	0.235	0.64	0.48
	Nara Canal	1.002	2.34	2.37
	Khairpur East Feeder	0.240	0.31	0.64
	Rohri Canal	1.092	2.17	3.45
	Khairpur West Feeder	0.136	0.24	0.44
	Total	**3.379**	**7.00**	**9.67**
Kotri Barrage	KB Feeder	0.284	1.58	0.62
	Pinyari Canal	0.437	0.36	0.21
	Fuleli Canal	0.620	0.87	1.30
	Total	**1.341**	**2.80**	**2.13**
Overall	**Grand Total**	**6.037**	**11.8**	**14.69**

* No precipitation was recorded during *Rabi* 2018-2019

c. Agricultural Water Balance

A water balance chart is shown in Figure 3, where the balance bars (in red color) present the reductions (negative values) or additions (positive values) in the canal flows during the entire study period. The *Rohri* canal remained in deficit during all study seasons and called for the highest water need (i.e., 2.49 MAF in addition to the authorized flows). KB Feeder canal had maximum surplus water during all three growing seasons (i.e., 1.87 MAF minus municipal demand of Karachi). Effective water management and planning at the canal level can be achieved by appropriating the balanced flows to meet the consumptive water demands of all 14 CCA. The inflows and outflows of the *Beghari* CCA were balanced well with 0.07 MAF surplus water than the authorized flows.

This analysis can also help identify crop selection in a particular CCA against the available water quantity. Elevated water-intensive intensities may need to be controlled in a CCA if its demand is extensively higher than the available supply. A better and water-efficient cropping pattern for farmers may help meet the sustainable development goal of conserving water.

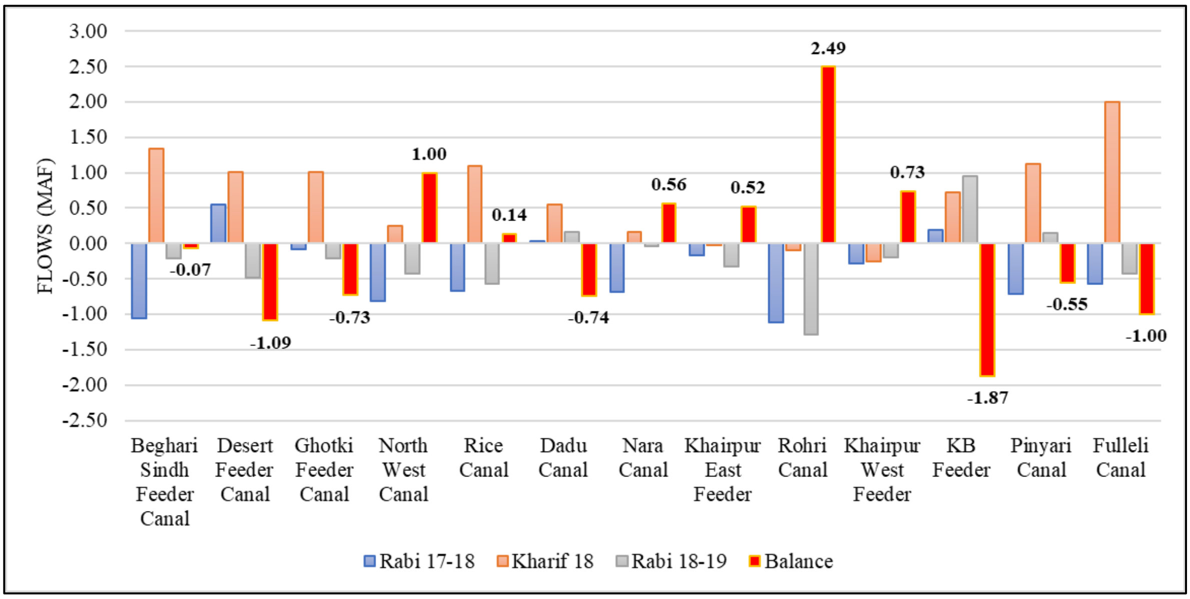

Figure 3: Agricultural Water Balance for Sindh Canals during *Rabi* 2017-18 to *Rabi* 2018-19

4. Conclusions

This paper utilizes remote sensing estimates of evapotranspiration to study Sindh's agricultural water requirement. The approach presented in this study was to evaluate the agricultural water resources of Sindh using remote sensing and secondary data that will help in efficiently managing the irrigation activities. Literature-based water demand estimates indicate 93-95% utilization in the agriculture sector [29]; however, our analysis for the recent year (2018-2019) estimates lower utilization (around 80% of the total water available at the CCA level, including canal diversions and precipitation).

This study can help decide the Sindh water sector's policy reforms for sustainable and equitable water distribution among all 14 canal command areas. However, detailed analysis and data of groundwater sources and their consumption are needed to improve the surplus and deficit flows' accuracy to refine the study results further. This study's key findings, including satellite-based consumptive water use of Sindh canals' command areas, provide mathematically sound data essential for developing knowledge-based policies and recommendations for efficiently managing the available water resources.

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Author Contributions: Arjumand Zaidi was the principal investigator of this study and overall supervised the research and wrote the paper; Nabeel Ali Khan did all remote sensing related processing; Bakhshal Khan Lashari conceived the study and reviewed the study report; Farooq Ahmed Laghari delineated the CCAs and provided auxiliary data, Vengus Panhwar helped in data processing and paper writing.

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

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