Assessment of Wheat Crop Water Productivity of Larkana District: A Remote Sensing Approach

Tarique Aziz[1], Ruksana Begum[2], Najam us Saqib Fraz[3] and Ghunwa Shah[4]

https://doi.org/10.62345/jads.2024.13.2.40

Abstract

The growing global population is driving up food demand, which in turn is exerting pressure to boost crop production. Therefore, there is a need to improve crop production using limited resources. This study uses satellite imagery to estimate crop water productivity (CWP) in the Larkana district of Sindh province, Pakistan. Wheat was selected as the subject crop in this study due to its significant importance in the Pakistan Rabi crop season. The processed satellite data were obtained from the Google Earth Engine Evapotranspiration Flux (EEFlux), a version of Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC), a land-image-based process. The wheat growing period spans 160 days, from November 1, 2017, to April 10, 2018. The results showed that the mean actual evapotranspiration (ETa) values for the initial, development, mid, and late stages were 28.14, 67.95, 162.8, and 92.83 mm, respectively, with total consumptive use for the season being 358 mm. The CWP of wheat was found to be 0.89 kg/m³, higher than Pakistan's average of 0.76 kg/m³. However, the CWP in the Larkana district is lower than that in developed countries such as Germany and France, where it equals 1.42 and 1.35 kg/m³, respectively. The findings emphasize the importance of utilizing advanced remote sensing technologies to enhance agricultural water management, which is crucial for improving food security and promoting sustainable farming practices in water-scarce regions.

Keywords: Crop Water Productivity (CWP), Evapotranspiration (ET), METRIC-EEFlux, Wheat, Larkana.

Introduction

Pakistan, located in Asia's arid and semi-arid regions (Us Saqib et al., 2022), faces a decline in freshwater resources due to a burgeoning population (Qureshi et al., 2012; Shah et al., 2024). The country experiences rainfall ranging from 254 mm to 365 mm (Cai & Sharma, 2010). In such semi-arid regions, evapotranspiration plays a crucial role in the water cycle. Remote sensing has

[1]*Civil and Environmental Engineering, University of Utah, Salt Lake City, Utah, United States.*
Corresponding Author Email: tariquea86@gmail.com
[2]*University of Illinois Springfield- Management Information System, Springfield, Illinois, United States.*
Email: ruksana128@gmail.com
[3]*Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Department of Civil Engineering, Topi.*
Email: najam.fraz@gmail.com
[4]*US Pakistan Center for Advance Studies in Water (USPCAS-W), Mehran University of Engineering and Technology, Jamshoro, Sindh, Pakistan. Email: ghanwasyeda@gmail.com*
Acknowledgments: *Authors are thankful for the support of the Pakistan Center for Advanced Studies in Water (PCAS-W), Mehran University of Engineering and Technology Jamshoro, Pakistan. The authors thank Dr. Arjamand Zehra Zaidi, Senior Research Fellow at USPCAS-W, and Mr. Nabeel Khan for their guidance.*

Compliance with ethical standards: There are no conflicts of interest (financial or non-financial). This study did not receive any funding.

emerged as a vital tool for estimating large-scale evapotranspiration, aiding in water balance prediction and canal command area performance assessment (Ahmad et al., 2009; Acharya & Joshi, 2020; Allen et al., 2007). The Google Earth Engine Evapotranspiration Flux (EEFlux) application demonstrates significant potential for estimating ETa (de Oliveira Costa et al., 2020; Fraz & Aziz, 2023).

Wheat, Pakistan's primary staple food crop, constitutes 60% of the daily diet and contributes 9.1% and 1.7% to the agricultural sector and the gross domestic product (GDP), respectively. Ensuring food security requires maximizing wheat production. Punjab leads in production, followed by Sindh, which accounts for 21% of the total output. Since 1975, the total area under cultivation of wheat and the yield per hectare have increased by 27% and 52%, respectively. However, the per capita yield has risen only 33%. The 2017-2018 season saw a total production of 25.492 million tons, slightly decreasing to 24.349 million tons in the 2019-2020 season, accounting for 8.7% of total agricultural output and contributing 1.7% to GDP (GOP, 2020).

In response to population growth, the Pakistani government has initiated reforms in the agriculture sector to increase wheat production, which has increased from 3.35 to 25 million tonnes since 1948, while the cultivation area expanded from 3.9 to 8.9 million hectares. Despite these gains, the increase in production has not kept up with the demand from a population that has grown from 75 million to 220 million. Thus, addressing the challenge of population growth requires enhancing food production through two main strategies: 1) increasing land and water availability and 2) improving crop production with limited water resources (Khan, 1984). The former approach is deemed impractical and costly, while the latter, focused on research-driven improvements in crop production, holds promise (Basharat & Rizvi, 2016). Enhancing crop productivity with limited water is vital where water is scarce. CWP is the crop yield ratio to water consumption (Kuscu, 2019). Wheat CWP in Konni, Niger, ranged from 0.42-0.93 kg/m³ (Pandey et al., 2001) and in Benerpota, Bangladesh, from 0.54-1.94 kg/m³ (Rehman et al., 2015), while Tel Hadiya, Syria, reported 0.48-1.10 kg/m³ (Khan et al., 2020). In Pakistan, the World Bank (2003) and studies in Punjab (Ahmad et al., 2004) have explored wheat CWP, with averages of around 0.76 kg/m³, varying from 0.65 to 2.0 kg/m³. Comparative research in India's Siri District and Bhima catchment indicated higher CWP values than in Pakistan, with 1.39 kg/m³ and 1.3 kg/m³, respectively (Singh et al., 2006; Immerzeel et al., 2008), against Pakistan's 1.11 kg/m³ (Hussain et al., 2003). Usman et al. (2012) evaluated wheat CWP in the upper Gogera branch of the lower Chenab canal, combining surface and groundwater data to estimate a value of 0.94 kg/m³. Us Saqib and Aziz (2023) have used the METRIC-EEFLUX approach to estimate Eta and CWP for the Nawab Shah district, which is about 367.57 mm and 1.03 kg/m3, respectively. This study aims to evaluate wheat crop water productivity (CWP) in the Larkana district during the Rabi season of 2017-2018 by estimating the actual evapotranspiration (ETa) at each growth stage and comparing the CWP with those in other global regions.

Materials and Methods

Study Area

The study was conducted in the Larkana district, located in the north-west of Sindh, for the year 2017-2018. It has coordinates of 27°33′36″ north and 68°13′35″ east (Figure 1). It has a hot desert climate with sweltering summers of 53 ° C and mild winters of -4 ° C, with an annual average rainfall of 127.4 mm in the monsoon (July-September). It is essential in Sindh's agricultural sector due to its climate. Along with wheat, it produces gram, oilseed, and cotton in the Rabi season.

Agriculture is fed from the North West, Rice, and Dadu canals (figure 2). The district has a total area of 51,923 ha, of which 48,645 ha are used for irrigation (SindhBos, 2018).

Figure 1: Location map of the study area

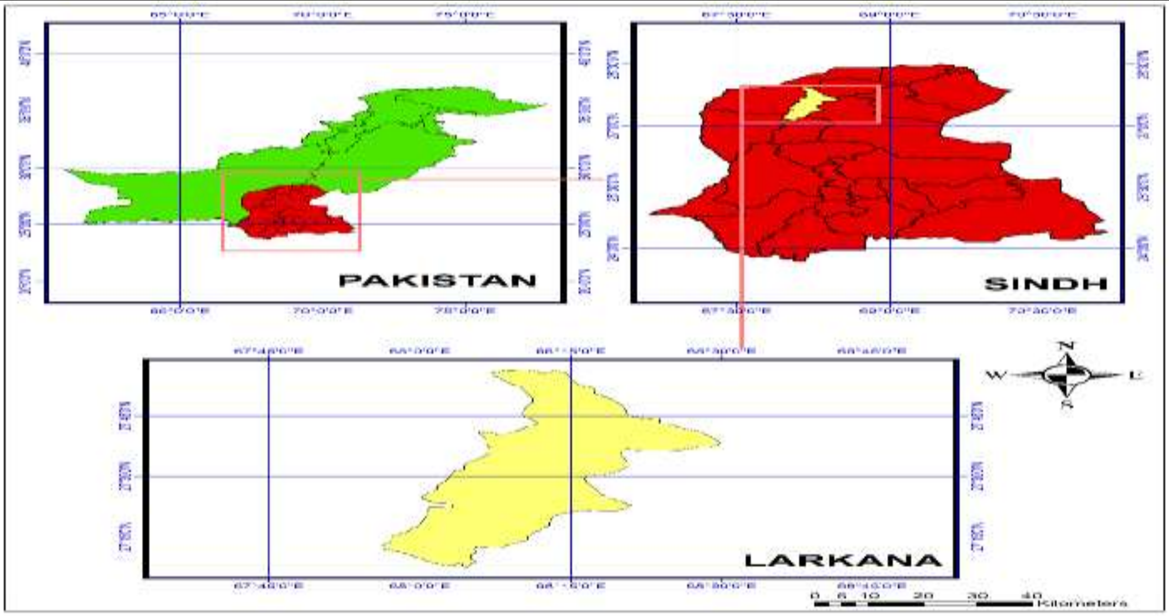
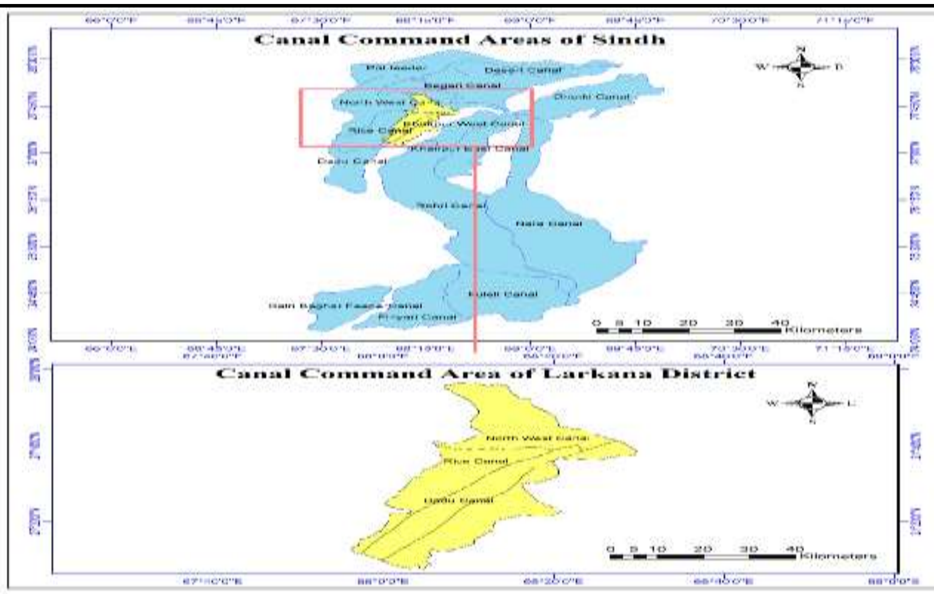


Figure 2: Canal command area of the district



Datasets

Crop Statistics

The Larkana district comprises 51,923 ha. The irrigated area is 94%, which has produced 165,887 metric tons of wheat for 2017-2018 (SindhBos, 2018).

Remotely Detected Data and Estimate of ETrF

Satellite images were downloaded from the EEFlux portal (Earth Engine Evapotranspiration Flux), which provides processed Landsat 8 images with 30m resolution. It is based on METRIC, which runs on the Google Earth Engine system.

EEFlux provides ETrF images that use daily tall (0.5m height) alfalfa reference defined by the American Society of Civil Engineers (ASCE) Standardized Penman-Monteith equation (Walter et al., 2000). It was developed through the energy balance process. ETrF is a fraction of alfalfa reference ET; it ranges from 0 to 1.1 (Irmak et al., 2011). The mathematical formula for estimating ETrF is given (equation 1).

$$ETrF = \frac{ETa}{ETr} \quad (1)$$

Reference Evapotranspiration (ETr)

ETr combines evaporation, water lost from the soil surface, and transpiration, water lost from the plant surface. ETr was calculated using the Penman-Monteith method for the Indus Basin (Ullah et al., 2001). Monthly ETr in millimeters for the Northwest, Rice, and Dadu canals, taken from the Sukkur barrage on its right-hand side, data were taken from Ullah et al. (2001) given (table 1).

Table 1: Monthly ETr for various canals (Ullah et al., 2001)

Name of Canal	Reference Evapotranspiration (ETr) in mm											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
North-West Canal	77	96	167	218	282	300	238	207	182	140	92	69
Rice Canal	74	94	163	210	278	295	230	200	182	137	93	70
Dadu Canal	80	99	160	206	273	289	227	195	183	144	96	77

Actual ET (ETa)

Landsat eight images from EEFlux were processed in ArcMap. EEFlux provides calibrated images that assign an ETr value to each pixel, and the ETa value per day was calculated by multiplying ETr and ETrF (de Oliveira Costa et al., 2020). Equation 2 calculates Eta per day for the *Rabi* wheat season. The days for each stage are given (table 2).

$$\mathrm{ET_a} = \mathrm{ETrF} \times \frac{\mathrm{ET_r}}{\mathrm{day}} \times \text{ No. of days} \quad (2)$$

Crop Masks

The wheat crop mask (2013-2014) was developed with the collaboration of the Space and Upper Atmosphere Research Commission (SUPARCO), the Food Agricultural Organization (FAO) of the United Nations, and the United States Department of Agriculture (USDA) (Pena-Arancibia et al., 2020). SUPARCO conducted field surveys for crop data to develop wheat crop masks using SPOT-5 at a resolution of 5m.

Crop Calendar

Sindh is divided into upper, middle, and lower zones—the dates for each agricultural stage of wheat in the Larkana district (table 2).

Table 2: Date-wise distribution of stages

Wheat Upper Sindh (Crop Calendar)			
No. of Days	**Days of Year (DOY)**	**Date**	**Stages**
0	305	1-Nov-17	Initial
20	325	21-Nov-17	
60	365	31-Dec-17	Crop Development
70	375	10-Jan-18	
71	376	11-Jan-18	Mid
119	424	28-Feb-18	
130	435	11-Mar-18	
160	465	10-Apr-18	Late

Crop Water Productivity

Crop water productivity is the ratio of crop yield (kg) to actual evapotranspiration (m^3) for the growing season. It accurately indicates the agricultural productivity of the consumptive use of water of the crop (World Bank, 2003).

Crop water productivity was calculated (equation 3).

$$CWP = \frac{Yield\ (kg)}{Area\ (m^2) \times ET_a (mm)} \quad (3)$$

Results and Discussion

Actual Evapotranspiration (ETa)

ETa is for the development of the initial crop, mid and late-stage (Figure 3). During the initial stage, ET is minimal and starts to increase while moving to the development stage (Figure 3b). This increase is due to the increased water usage of plants, making them more susceptible to evapotranspiration. In addition, it is also seen that as water usage increases, evapotranspiration increases in the middle areas of the lower regions of Larkana and the peripheral regions of the upper part of Larkana.

Similarly, for the mid-stage, ET is at its maximum (figure 3c) because the crop is at its growth peak. Currently, the crop is in development, and the fruit is ripening. A good quantity of water is needed to perform these actions. As consumption increases, there is an increase in transpiration.

Figure 3: Spatial analysis of ETa for wheat crops in Larkana District: (a) Initial, (b) Crop Development, (c) Mid and (d) Late stage.

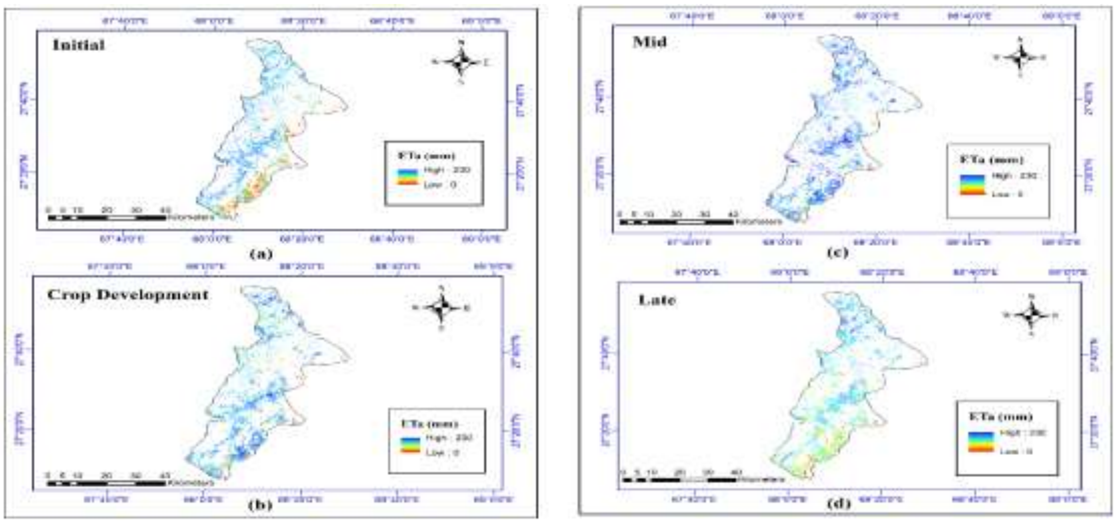


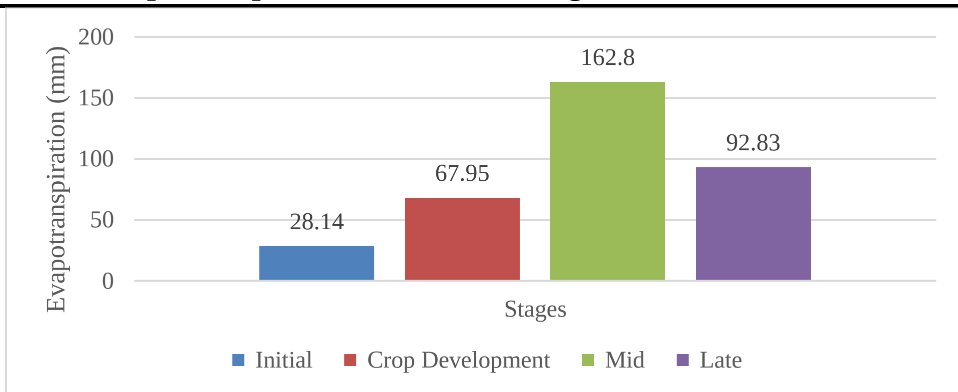
Table 3: Wheat Cropping Stages

Wheat Growing Stages	No of Days	Growing Stage Mean Eta(mm)	Cumulative Seasonal Mean Eta(mm)	Crop Water Productivity (kg/m^3)
Initial	20	28.14	357.8	0.89
Crop development	50	67.95		
Mid-stage	60	162.8		
Late	30	92.83		

Table 3 illustrates that the initial stage has the lowest ET, and the middle stage has the highest. ETa is shown for each stage (Figure 4). The wheat productivity in Pakistan is 0.76 kg/m^3, and the global average is 1.0 kg/m^3, which is 24% less (World Bank, 2003).

The CWP varies throughout Pakistan since Sindh ranges from 0.32 to 1.15, and Punjab has a median of 1.08 kg/m^3 (Van et al., 2015). It is due to waterlogging and salinity problems in Sindh. Furthermore, further studies are required for all canals where the water used for irrigation could be estimated before allowing fields, and the temperature and rainfall should be considered for proper water measurement.

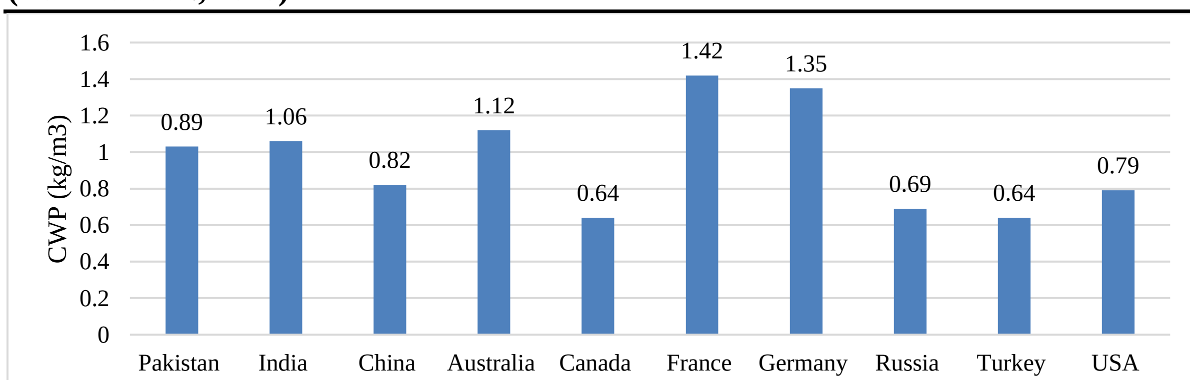
Figure 4: Actual Evapotranspiration for various stages



Crop Water Productivity (CWP)

The CWP of the Larkana district was calculated as 0.89 kg/m^3. The wheat CWP of Sindh ranges from 0.32-1.15 kg/m3, which is lower than that of Punjab due to the waterlogging and salinity problems in the region (Van Steenbergen et al., 2015). Canal seepage and inadequate agricultural land drainage adversely affect waterlogging and salinity (Kori et al., 2013; Mahessar et al., 2018). Also, figure 5 presents a recent comparison of the CWP of Larkana with that of the developed world. Edreira et al. (2018) presented the values of CWP for different countries (figure 5). Compared to the Larkana district, it is higher than some developed countries like China, the USA, Turkey, and Russia. In contrast, it is less than India, Germany, France, and Australia. These countries have used better management of irrigation practices.

Figure 5: Comparison of Water Productivity for Wheat Crops Across Different Countries (Edreira et al., 2018)



Conclusion

The Crop Water Productivity (CWP) in the Larkana district was determined to be 0.89 kg/m^3, surpassing Pakistan's average of 0.76 kg/m^3. Various agricultural practices, including land preparation, selection of seed varieties, sowing methods, timely application of fertilizers, weed and pest control, and appropriate irrigation scheduling, can significantly influence variation in CWP. Inadequate irrigation techniques and improper water supply scheduling are the primary contributors to reduced CWP in the Larkana district. This study used secondary data from various sources, including statistical data and SUPARCO crop masks. Integration of the METRIC EEFlux application with GIS facilitated evapotranspiration calculation at each growth stage, with the highest values observed during the mid-crop stage. Utilizing remotely sensed data for estimating ETa enhances the efficiency of components of the hydrological model, such as water balance, the hydrological cycle, and the crop maturity cycle. However, it was found that the CWP in Larkana was below the global average of 1.0 kg/m³.

References

- Acharya, B., & Joshi, B. (2020). Flood frequency analysis for an ungauged Himalayan river basin using different methods: a Modi Khola, Parbat, Nepal case study. Meteorology Hydrology and Water Management. *Research and Operational Applications, 8*(2), 46-51.
- Ahmad, M. U. D., Turral, H., & Nazeer, A. J. A. W. M. (2009). Diagnosing irrigation performance and water productivity through satellite remote sensing and secondary data in a large irrigation system of Pakistan. *Agricultural water management, 96*(4), 551-564.
- Ahmad, M. U. D., Masih, I., & Turral, H. (2004). Diagnostic analysis of spatial and temporal variations in crop water productivity: A field scale analysis of the rice-wheat cropping system of Punjab. *Journal of Applied Irrigation Science, 39*(1), 43-63.
- Allen, R. G., Tasumi, M., & Trezza, R. (2007). Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC)—Model. *Journal of irrigation and drainage engineering, 133*(4), 380-394.
- Basharat, M., & Rizvi, S. A. (2016). *Irrigation and drainage efforts in Indus Basin-a review of past, present and future requirements.*
- Cai, X. L., & Sharma, B. R. (2010). Integrating remote sensing, census and weather data for an assessment of rice yield, water consumption and water productivity in the Indo-Gangetic river basin. *Agricultural Water Management, 97*(2), 309-316.
- de Oliveira Costa, J., José, J. V., Wolff, W., de Oliveira, N. P. R., Oliveira, R. C., Ribeiro, N. L., & Schlichting, A. F. (2020). Spatial variability quantification of maize water consumption based on Google EEflux tool. *Agricultural water management, 232,* 106037.
- Edreira, J. I. R., Guilpart, N., Sadras, V., Cassman, K. G., van Ittersum, M. K., Schils, R. L., & Grassini, P. (2018). Water productivity of rainfed maize and wheat: A local to global perspective. *Agricultural and forest meteorology, 259,* 364-373.
- Government of Pakistan. (2019-2020). *Economic Survey of Pakistan*. Ministry of Finance Division, Economic Advisor's Wing, Islamabad, Pakistan. Retrieved from http://www.finance.gov.pk/survey_1920.html
- Hussain, I., Sakthivadivel, R., Amarasinghe, U., Mudasser, M., & Molden, D. (2003). *Land and water productivity of wheat in the western Indo-Gangetic plains of India and Pakistan: A comparative analysis* (Vol. 65). IWMI.
- Immerzeel, W. W., Gaur, A., & Zwart, S. J. (2008). Integrating remote sensing and a process-based hydrological model to evaluate water use and productivity in a south Indian catchment. *Agricultural water management, 95*(1), 11-24.
- Irmak, A., Ratcliffe, I., Ranade, P., Hubbard, K. G., Singh, R. K., Kamble, B., & Kjaersgaard, J. (2011). Estimation of land surface evapotranspiration with a satellite remote sensing procedure. *Great plains research,* 73-88.
- Khan, M.H. (1984). Agricultural policy issues in Pakistan. *Pakistan Development Review, 23*(2–3), 241–255.
- Khan, M. A., Tahir, A., Khurshid, N., Husnain, M. I. U., Ahmed, M., & Boughanmi, H. (2020). Economic effects of climate change-induced loss of agricultural production by 2050: A case study of Pakistan. *Sustainability, 12*(3), 1216.
- Kori, S. M., Qureshi, A. L., Lashari, B. K., & Memon, N. A. (2013). Optimum strategies of groundwater pumping regime under scavenger tubewells in lower Indus Basin, Sindh, Pakistan. *International Water*

Technology Journal, 3(3), 138-145.

- Kusco, H. (2019). Mathematical modelling of crop water productivity for processing tomato. *Journal of Agricultural Sciences, 25*(2), 137-146.
- Mahessar, A. A., Qureshi, A. L., Laghari, A. N., Qureshi, S., Shah, S. F., & Shaikh, F. A. (2018). Impact of Hairdin, Miro Khan and Shahdad Kot Drainage on Hamal Dhand, Sindh. Engineering, *Technology & Applied Science Research, 8*(6).
- Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., & Kijne, J. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural water management, 97*(4), 528-535.
- Pandey, R. K., Maranville, J. W., & Admou, A. (2001). Tropical wheat response to irrigation and nitrogen in a Sahelian environment. I. Grain yield, yield components and water use efficiency. *European Journal of Agronomy, 15*(2), 93-105.
- Pena-Arancibia J L, Ahmad M D, Yu Y, Kirby J M (2020). *High resolution remotely sensed multi-annual seasonal crop system dynamics in districts of the Nara canal in Sindh, Pakistan: Implementation, evaluation and analysis.* Sustainable Development Investment Portfolio (SDIP) project. CSIRO, Australia. 42 pages.
- Qureshi, A. L., Khero, Z. I., & Lashari, B. K. (2012, May). *Optimization of irrigation water management: A case study of secondary canal, Sindh, Pakistan. In 16th Int*. Water Technology Conf., IWTC (Vol. 16).
- Rehman, A., Jingdong, L., Shahzad, B., Chandio, A. A., Hussain, I., Nabi, G., & Iqbal, M. S. (2015). Economic perspectives of major field crops of Pakistan: An empirical study. *Pacific science review b: humanities and social sciences, 1*(3), 145-158.
- Shah, G., Zaidi, A., Qureshi, A. L., Hussain, S., Rizwan, & Aziz, T. (2024). Rainfall-runoff modeling using machine learning in the ungauged urban watershed of Quetta Valley, Balochistan (Pakistan). *Earth Science Informatics*, 1-17.
- Singh, R., van Dam, J. C., & Feddes, R. A. (2006). Water productivity analysis of irrigated crops in Sirsa district, India. *Agricultural Water Management, 82*(3), 253-278.
- SindhBOS (2018). *Development Statistics of Sindh.* Retrieved from http://sindhbos.gov.pk/wp-content/uploads/2019/09/Development-Statistics-of-Sindh-2018.pdf
- Us Saqib, N., Saeed, F., & Aziz, T. (2022). Effect Of Man-Made Structures On Natural Wetlands In Pakistan: A Case Study Of Chotiari Reservoir. *Journal Clean WAS (JCleanWAS), 6*(1), 01-04.
- Us Saqib, N., & Aziz, T. (2023). Estimation Of Wheat Crop Productivity Of District Nawab Shah Using Metric EEFLUX imagery. *J. Agric. Res, 61*(1), 77-82.
- Usman, M., Kazmi, I., Khaliq, T., Ahmad, A., Saleem, M. F., & Shabbir, A. (2012). *Variability in water use, crop water productivity and profitability of rice and wheat in Rechna Doab, Punjab, Pakistan.*
- Ullah, M. K., Habib, Z., & Muhammad, S. (2001). *Spatial distribution of reference and potential evapotranspiration across the Indus Basin Irrigation Systems* (Vol. 24). IWMI.
- Van Steenbergen, F., Basharat, M., & Lashari, B. K. (2015). Key challenges and opportunities for conjunctive management of surface and groundwater in mega-irrigation systems: Lower Indus, Pakistan. *Resources, 4*(4), 831-856.
- Walter, I. A., Allen, R. G., Elliott, R., Jensen, M. E., Itenfisu, D., Mecham, B., & Martin, D. (2000). *ASCE's standardized reference evapotranspiration equation.* Watershed management and operations management, 2000, 1-11.
- World bank, Washington (2003). *Crop and Water Productivity of the Pakistan Wheat and Rice Systems.*