Research on World Agricultural Economy
https://journals.nasspublishing.com/index.php/rwae

ARTICLE

Geoclimatic and Socioeconomic Influences on Water Use Efficiency in Cotton Crops Productivity: A Sustainable Business and Management Farming Perspective

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ARTICLE INFO
Received: 30 April 2025 | Revised: 23 June 2025 | Accepted: 1 August 2025 | Published Online: 4 September 2025
DOI: https://doi.org/10.36956/rwae.v6i4.2092

CITATION
Abdalla, A.A., Shabbir, M.S., FOTACHE, G., et al., 2025. Geoclimatic and Socioeconomic Influences on Water Use Efficiency in Cotton Crops Productivity: A Sustainable Business and Management Farming Perspective. Research on World Agricultural Economy. 6(4): 205–217. DOI: https://doi.org/10.36956/rwae.v6i4.2092

ABSTRACT

The objective of this study is to investigate the impact of geo-climate and socio-economic influences on water use efficiency in cotton crops. Consequently, the current water demand for cotton has substantially increased, posing significant threats and challenges to crop productivity. This study uses an annual time series data set for two provinces of Pakistan. For this purpose, an auto regressive distributed lag (ARDL) model is used for data analysis. According to the study's findings, there is a significant relationship between environmental conditions and water consumption efficiency. Additionally, empirical findings show that the country's water-scarce regions are primarily virtual water-importing zones, whereas several provinces in the north and west are water-selling regions. Negative effects will be significantly more prominent in less fortunate, more sweltering, and lower-lying nations. This study is aimed at having a better understanding of the reasons for climate change, which further causes economic costs. Also, to know how, as human beings, we can overcome this problem soon. While some variables exhibit positive correlations, others reveal negative relationships, highlighting the need for sustainable resource management. This transition can lower agricultural emissions and enhance resilience against climate shocks, paving the way for a more sustainable future.

Keywords: Geo–climate and Socio–economic; Sustainable Business Farming; Water Use Efficiency; Cotton; Pakistan

1. Introduction

In recent years various studies and assessments suggest that Pakistan is not on track to achieve Sustainable Development Goals 1, 2, and 6 due to frequent increases in droughts, floods, El Niño, La Niña, unprecedented rainfall patterns, and aggravated population pressure [1–3]. These phenomena pose potential risks to human well-being and economic growth in the country [4,5]. Various studies signified [6,7], that primary crops: maize, pulses give larger yield than cotton, as the crop always requires around 10% more water compared to primary crops. Additionally, it takes 6 months to complete harvest, and a longer period to water the plant because its season lasts 180 to 195 days in a year [8]. Similarly, rice output has decreased; in the most recent year, it decreased by almost 22% [9].

The role of finance in addressing environmental challenges and achieving sustainability has gained unprecedented attention in recent years. This recognition was most prominently highlighted during COP–29, where global leaders and policymakers emphasized the indispensable role of financial systems in combating climate change and achieving sustainability goals. The Signority states of COP–29 made a collective commitment to triple climate finance, with a particular focus on aiding developing economies in their pursuit of sustainability [10]. Financial mechanisms were highlighted not only as critical tools for mobilizing resources but also as strategic instruments for channeling investments into renewable energy, and environmentally friendly technologies [11]. This, in turn, helps the economies to mitigate the adverse impacts of climate change and helps to achieve sustainability.

Green innovation requires robust financial systems to channel resources effectively into renewable energy technologies, sustainable manufacturing, and other environmentally friendly advancements. Without a strong foundation in these financial dimensions, the transition to GREG remains a significant challenge for these economies. Sustainability ensures that development occurs in a manner that protects ecosystems, reduces carbon emissions, and promotes the efficient use of resources. Many researchers realized sustainability with the concept of green economic growth (GREG). Unlike traditional growth models, which often prioritize industrialization and resource exploitation, GREG focuses on achieving economic prosperity while preserving natural ecosystems, reducing emissions, and combating climate change [12,13]. It is defined as a model of development that decouples economic progress from environmental problems. Importantly, GREG represents a shift toward a future where growth is inclusive and sustainable. However, the transition to GREG requires substantial financial resources and robust financial systems capable of supporting sustainable initiatives. The capacity of financial systems to drive this transition is encapsulated in the concept of financial availability, which includes financial development, financial openness, and financial depth.

Among the current agricultural challenges in South Asia, the water use efficiency (WUE) in crop production particularly in Cotton farming has come to the forefront as a sought-after issue because of the drought-prone condition of the region coupled with the occurrence of salinity and fluctuating rain patterns. Cotton is a crop that is very demanding in water which causes it problems when ineffective irrigation is implemented and also when poor agronomy is practiced, especially in Pakistan and India, which are among the global top producers in cotton production [14,15]. The geoclimatic conditions (arid zones of climate, groundwater deficiency, rising temperatures, etc.) have a strong impact on the requirements of irrigation and crop production. Simultaneously, socioeconomic factors such as the size of landholding, education among the farmers, access to technology, and extension services are also the key determinants in the effective use of water resources [16,17]. Enhancement of WUE is not only beneficial in helping farmers to adapt to climate stress but also to sustainable business models in agriculture enterprises, lower costs of inputs and sustainability in the long-term of the farm sector. Additionally, energy-efficient water consumption in cotton growing is directly connected to various SDGs, including sustainable industry (SDG 9), responsible consumption (SDG 12), and climate action (SDG 13), and it stresses the significance of integrated plans in water-scarce farmland regions [18,19].

An eminent example in this frame of reference is that in 2007-08 a food crisis took place around the globe, which led to a sudden increase in staple crop (Wheat, Rice, Maize, and Soya) prices. Since then, food crises have emerged in the world food market, and the agricultural sector growth pattern and food production system have changed in nature [20]. Most previous studies on farm size have concentrated on the connection between farm size and output [21]. Nonetheless, the size of a farm affects how agriculture affects its surroundings, including emissions of greenhouse gases (GHG) and the preservation of carbon linked to agricultural inputs [22,23].

Resource-Based Theory highlights the role of financial resources as a strategic asset in achieving sustainability and promoting sustainable growth. According to the theory, countries with well-developed financial systems are better equipped to allocate resources strategically toward innovations [24]. This, in turn, helps them to gain a competitive edge in the global transition toward sustainability. The theory suggests that financial resources not only enable the development of innovative green technologies but also support their scaling and diffusion. Importantly, the countries with sufficient financial availability can consistently fund R&D to foster technological advancements and create pathways for innovation to drive long-term sustainable development.

Because of this worldwide blending, the effect of emanations of these gases doesn't rely upon where on the planet they are discharged [25,26]. Significant brief substances that influence the atmosphere to incorporate water fume, ozone in the troposphere, contaminations that lead to ozone development, and mist concentrates (environmental particles, for example, black carbon and sulfates [27,28]. Water fume, tropospheric ozone, and dark carbon add to warming, while different mist concentrates produce a cooling impact. Since these substances are brief, their atmospheric effect can be affected by the area of their emanations, with focuses differing extraordinarily here and there [29]. We expect the extra intrigue installments owing to the atmosphere weakness to increase between USD 146–168 billion throughout the following decade [30].

It is argued that climate change is largely attributable to solar variability, which is considered responsible for most, if not all, of the warming observed in the late twentieth century and is expected to remain the dominant influence on the climate throughout the twenty-first century, irrespective of anthropogenic greenhouse gas emissions [31]. The more noteworthy the cloud albedo, the more approaching sun-based radiation gets shut and reflected out to space [32]. However, the human outflows of ozone harming substances, chiefly carbon dioxide (CO2), methane, and nitrous oxide, are causing a disastrous ascent in worldwide temperatures.

Cotton is a major cash crop in Pakistan, and it is a mainstay of the agricultural GDP and job creation in the country. Nevertheless, cotton cultivation is highly demanding, and the water use intensity (WUE) of cotton is under continuous menace with the interrelated problems of climatic variability, extreme weather events, and mounting water scarcity. In that regard, it is not just an agronomically speaking issue to understand the factors that have an influence on the efficient use of water during cotton cultivation but is also a socio-environmental necessity. The topicality of the modern study relates to the necessity to overcome the existing inefficiency in the usage of water resources designated to cotton-growing under the impact of climate-related risks, unstable rain patterns, and socioeconomic conditions of agricultural societies. Although the concept of WUE has been examined in other countries and regions around the world, little is developed on how the geoclimatic and socioeconomic conditions interact to affect the practices of water utilization in specific areas like cotton growing regions in Pakistan.

Even though both geoclimatic factors (e.g., rainfall, soil quality, temperature, evapotranspiration) and socioeconomic aspects (e.g., land tenure, input prices, farmer awareness) of agricultural water use efficiency have been addressed by previous studies, they have not been handled in most instances separately. As an example, previous research analyzed climatic factors making an impact on irrigation water productivity [33], whereas other research also discussed economic motives of water conservation. However, the extant literature has practically no studies that utilize a practice-based integrative system that incorporates environmental variables as well as social-economic variables to conduct a comprehensive evaluation of the efficiency of water use on a crop-specific basis. This research endeavors to complete that gap by adopting combined a geoclimatic and socioeconomic perspective to scrutinize the motifs of WUE in cotton agriculture specifically in Pakistan. The finer picture enables better access and understanding of the problems and potential of sustainable cotton production in the region within the existing and emerging climatic conditions.

There are various stakeholder groups that are affected by the research in terms of practicality. The findings can guide an evidence-based approach to water allocation and water pricing strategies by policymakers and planners within the agriculture and irrigation sectors. The insights can be used to formulate region-specific interventions by the development agencies and the NGOs engaged in climate adaptation and sustainable agriculture. In addition, agricultural extensions and farmer groups can easily know how socio-climatic conditions can impact most on the WUE and how specific training or technology (such as drip irrigation or planting based on weather) can be implemented [8]. In the end, the research can contribute to the achievement of larger aims of sustainable water management and climate resilient farming practices and is in line with Sustainable Development Goals (SDGs) 2 (Zero Hunger), 6 (Clean Water and Sanitation), and 13 (Climate Action).

Freshwater Resources and Sustainability

Maximizing the use of available fresh water is a key to the sustainability of agricultural production systems particularly, in the case of water-intensive crops such as cotton. Water use efficiency (WUE) is a given performance measure utilized in the framework of sustainable business and farm management integrating environmental sustainability and economic stability. These expenses are probably going to be critical in certain districts, and those costs will definitely be transmitted to the worldwide economy somehow [34]. In a Hamilton Project proposition, depicts the circumstances where clean execution gauges can be actualized in a moderately productive way. At the nearby, national, and universal levels, 57 carbon evaluation programs have been executed or planned for use [35]. When introducing carbon pricing mechanisms, policymakers have typically prioritized the power sector while excluding other major sources of emissions, particularly energy-intensive industries.

The carbon estimating frameworks that do exist are not uniformly dispersed over the. Europe has created 33 percent of worldwide CO2 emissions since 1850, the United States 25 percent, and China 13 percent. As indicated by as of now planned and actualized activities, in 2020, the United States will account for just 1.0 percent of worldwide GHG outflows; by comparison, Europe will account for 5.5 percent, and China will account for7.0 percent. Notwithstanding this action, all things considered, a carbon cost will in any case not be applied to 80 percent of worldwide outflows of GHGs in 2020 [36].

In terms of sustainable business and management, therefore, it is imperative to be aware of the interconnection between water stress as a climate change and socioeconomic indicators on the farms. The current study contributes to the discussion of water use efficiency because of cotton within the environmentally bounded sustainability of the farm management nexus. It aims at producing empirical support on interventions that are specific to the region and are data-driven to improve cotton productivity and conserve water as a scarce resource, which is becoming a very competitive one. It is with this view that the next chapter makes efforts to explore the dual relationship between geoclimatic and socioeconomic factors and their impact on WUE.

2. Literature Review

Over the last few decades, agricultural production in the Global South has been pressured owing to population pressure, climate variability, and scarcity of resources. Effective use of water has become a major issue of sustainable agriculture especially in arid and semiarid zones [37]. This literature review provides a synthesis of the current evidence on water use efficiency (WUE), climate variability and their impacts on the productivity of crops but also brings out constructs related to the economics and institutional aspects of the decisions made regarding water and land use in agriculture.

The initial conceptualisation of water utilisation efficiency (WUE) was the ratio of plant productivity to the water quantity utilised. Since that time, there has been a great range of studies investigating its effect in augmenting farming yields. As a case in point, shallow groundwater in major irrigation zones of China, Hetao Irrigation District and Jiefangzha Irrigation Sub-district contributed over 16 per cent of the total region evapotranspiration (ET) and was very crucial in enhancing Real Evapotranspiration Water Consumption (REWC) and Real Water Productivity (RWP). These results show the importance of aquifer management to tap into increased productivity during limited water supply.

There is a corresponding use of water in the region over economic indicators at the macro level. In one study, the inter-regional input-output model was utilized to process the water footprint alignments between various provinces in China, and it was prominently articulated that water footprints and the GDP of various provinces were inseparably associated [38]. One of the studies among cotton growers in Punjab indicated that irrigation needs to be managed carefully so farmers can sustain through such environmental conditions [39]. They were evaluated with the help of DEA-CCR and radial super-efficiency models. Conversely, the nonmarket effects like health effects and ecological impact are usually given values using the method of benefit transfer which relies on epidemiological and mortality risk studies. This indicates the difference in the methodology of the estimation of the impacts of climate and underlines the necessity to combine physical, ecological, and economic evaluations.

The climate change effects are especially pronounced in Pakistan's cotton cultivation areas because of the geography and scarcity of water. Natural resources have already been hearing the squeals of the population pressures and intense cropping [40]. Accordingly, the estimation of the effects of climate change on WUE in cotton farming is essential in the development of region-based adaptation and irrigation related policies [41]. They investigated the synergistic association between FD, GRIN, and GREG by utilizing the sample of countries that have high EFP. Researchers have shown that countries with high FD experienced high GRIN and GREG. This is likely because such economies have more finance that can be easily channeled to invest in green energy technologies. Such technologies, in turn, help to promote sustainable economic growth and discuss the significance of financial openness in promoting GREG [42].

3. Data and Methodology

This research was conducted in two provinces of Pakistan namely Punjab and Sindh from 1980 to 2022. In this study time series data of climatic factors (T1: minimum; T2: maximum average temperature and P;

rainfall) have been considered. Besides these other key variables L: land use (total cropped area of cotton in a year in the province of Sindh and Punjab, Pd: population density, E: primary school enrollment as an indicator of education. CW: canal water withdrawal in MAF in the kharif period in the provinces (Sindh & Punjab). F: fertilizer consumption per acre in both provinces, GE: government expenditure on planning and development, and WP: water prices for each province are considered. The study is based on secondary time-series data collected for two major cotton-producing provinces in Pakistan Punjab and Sindh for the period 1980–2022.

The data was sourced from the Pakistan Bureau of Statistics (PBS), Ministry of Planning and Development, Economic Survey of Pakistan, Pakistan Meteorological Department, FAO AQUASTAT, and WAPDA reports. These sources are widely recognized in scholarly and policy circles for their credibility, accuracy, and regular data audits. Moreover, institutional data such as government development expenditures and canal water withdrawals were cross-verified from official provincial annual reports to ensure consistency and reliability.

The choice of geoclimatic variables (T1: minimum temperature, T2: maximum temperature, P: rainfall) and socioeconomic indicators (land use, population density, education, canal water withdrawals, fertilizer consumption, government expenditure, and water prices) is grounded in well-established literature in agricultural and water resource economics. For instance, rainfall and temperature are widely recognized as key climatic determinants of crop yield and water demand [43]. Similarly, socioeconomic variables such as education (proxied by primary school enrollment) have been used to reflect farmer knowledge and technology adoption capacity [44,45]. Land use and population density influence water stress and irrigation efficiency [46], while fertilizer use, water pricing, and public expenditure shape resource allocation and productivity decisions [47].

The dependent variable of this study is water use efficiency for cotton (WUEc) in Punjab and Sindh. The other variables' data are gathered from the economic survey of Pakistan. This can help to reduce our environmental impact and conserve natural resources for future generations. The selected variables reflect both direct and indirect drivers of water use efficiency in cotton farming. Their inclusion is based on prior literature [48] and empirical studies that emphasize climate, infrastructure, education, and policy influences on agricultural water outcomes.

The production function for the research study is:

$$Y = f\,(A, R, W, K) \tag{1}$$

1. Y= Output (Yield Kg Per Acer)
2. A= Technological Advancement (TFP)
3. R= Natural resources
4. W= Water
5. K= Capital

This formulation builds upon the neoclassical Cobb-Douglas production function frequently used in agricultural productivity studies [49]. It integrates both biophysical and economic components to explain output variability. The function is not an exact replica of an existing cotton-specific model but rather a conceptual synthesis adapted from broader agricultural productivity frameworks, with literature-backed variable selection to suit the cotton sector context in Pakistan. This hybrid approach allows for flexibility in modeling context-specific influences such as canal water access, temperature stress, and infrastructure support on cotton WUE.

In this study, water use efficiency for cotton (WUEc) is treated as a derived outcome from the broader production environment described by Equation (1). Specifically, while Equation (1) captures the macro-level determinants of yield (Y), Equation (2) focuses on WUE as the ratio of output to water input. Thus, WUE acts as the dependent variable influenced by all upstream factors in the production function: technological (A), environmental (R), capital inputs (K), and particularly water-related variables (W). By decomposing this relationship, the study empirically examines how changes in geoclimatic and socioeconomic factors affect WUE under varied regional and temporal conditions.

In this study, a two-stage analytical approach has been employed for empirical investigation. The following formula in equation no 1 is used to calculate water use efficiency (WUE):

$$WUE = (Crop\ yield) / (Water\ applied) \quad (2)$$

In the second stage, the causal and long-run relationships between WUE and explanatory variables are examined using ARDL bounds testing and correlation matrix analysis.

The Autoregressive Distributed Lag (ARDL) bounds test[50], is appropriate for this study because it accommodates variables that are integrated at different orders (I(0) and I(1)), and allows for small sample inference, suitable for province-level annual data over 43 years.

4. Results

The bound test outcomes are shown and examine both short- and long-term dynamics between variables in **Table 1**. The bound test is frequently used in conjunction with ARDL (autoregressive distributed lag) models. The study's research questions are validated by the consistent estimations derived from the bound analysis.

The correlation matrices (**Table 2**) of Punjab and Sindh exhibit some key relationships between water use efficiency (WUEC), water pricing (WP), temperature variables (T1, T2), population density (PD), and government expenditure (GE1). Meanwhile, a positive correlation between WUEC and WP (0.45) in Punjab indicates that the higher the price of water, the better use of water. Furthermore, WUEC is positively associated with the temperature indicators T1 (0.42) and T2 (0.37), which means increasing temperature will enhance water use efficiency because of the increased water demand. Additionally, the positive correlation (0.32) between GE1 and WUEC in Sindh is stronger so that the effect of government spending on water-use efficiency in this region may be more significant[51].

Table 1. Bound Test.

Punjab			Sindh		
Test (Statistic)	**Value**	**k**	**Test (Statistic)**	**Value**	**K**
F-statistic	4.912	10	**F-statistic**	6.341	10
	Critical Values Bound				
Significance	**I0 Bound**	**I1 Bound**	**Significance**	**I0 Bound**	**I1 Bound**
0.15	1.79	2.79	0.21	1.79	3.1
0.07	2.05	3.12	0.04	2.07	3.13
0.03	2.21	3.41	0.03	2.33	3.43
0.02	2.43	3.59	0.04	2.49	3.79

Table 2. Correlation Matrix.

PUNJAB							
Variable	**WUEC**	**T1**	**T2**	**WP**	**P**	**PD**	**GE1**
WUEC	1	0.42	0.37	0.45	0.3	−0.1	0.28
T1	0.42	1	0.5	0.33	0.21	0.05	0.17
T2	0.37	0.5	1	0.48	0.29	0	0.22
WP	0.45	0.33	0.48	1	0.41	−0.12	0.25
P	0.3	0.21	0.29	0.41	1	0.09	0.18
PD	−0.1	0.05	0	−0.12	0.09	1	−0.06
GE1	0.28	0.17	0.22	0.25	0.18	−0.06	1
SINDH							
Variable	**WUEC**	**T1**	**T2**	**WP**	**P**	**PD**	**GE1**
WUEC	1	0.35	0.5	0.39	0.26	−0.15	0.3
T1	0.35	1	0.41	0.3	0.18	0.08	0.14
T2	0.5	0.41	1	0.36	0.25	−0.05	0.2
WP	0.39	0.3	0.36	1	0.32	−0.1	0.23
P	0.26	0.18	0.25	0.32	1	0.11	0.16
PD	−0.15	0.08	−0.05	−0.1	0.11	1	−0.03
GE1	0.3	0.14	0.2	0.23	0.16	−0.03	1

Before estimation of the model Augmented Dickey-Fuller (ADF) and KPSS tests were undertaken to verify the integration order of all variables. ARDL bounds testing was appropriate by finding that the series were I (0) or I (1). Determining Lag length occurred based on the obtained Akaike Information Criterion (AIC).

Table 3 shows that maximum temperature (T2) and water pricing (WP) significantly negatively impact the outcome in Sindh. Canal water withdrawal (CW) similarly shows a significant negative effect in both Punjab and Sindh. The error correction term (CointEq(−1)) is significantly negative in both provinces, indicating a strong tendency to return to long-run equilibrium [52].

A Multivariate Stochastic Model with Error Correction (VECM):

In order to include possible endogeneity and robustness of the ARDL long run relations, a Vector Error Correction Model (VECM) was estimated [53]. The large and negative error correction coefficients of both provinces indicate convergence to the long run equilibrium. A multivariate and stochastic model, the vector error correction model (VECM) incorporates an error correction term.

Table 4 reveals short-term relationships: in Punjab, current water use efficiency is negatively related to its Lag values, influenced by temperature and precipitation lags, and water price lags. Conversely, Sindh shows a positive association between current water use efficiency and minimum/maximum temperatures, precipitation, and government expenditure [54].

Table 3. Outcomes of Long-run Coefficients.

	Punjab			Sindh		
	Long Run Coefficients					
Variables	Coefficient	t-Statistic	Prob.	Coefficient	t-Statistic	Prob.
C	0.187 (0.248)	0.699	0.45	0.351 (0.201)	1.487	0.107
T2	0.026 (0.007)	2.027*	0.05	−0.003 (0.003)	−2.294*	0.069
T1	−0.032 (0.003)	−3.019**	0.01	0.002 (0.003)	0.542	0.502
WP	0.001 (0.002)	0.221	0.69	−0.0011 (0.001)	−2.335*	0.034
P	−0.002 (0.001)	−2.663*	0.019	−0.000 (0.002)	−3.531**	0.001
GE1	0.001(0.001)	−0.39	0.61	0.002 (0.001)	2.312*	0.029
PD	0.003 (0.000)	2.391*	0.08	0.0001 (0.001)	2.491*	0.057
E	0.013 (0.001)	2.497*	0.065	0.011 (0.000)	2.311*	0.029
F	0.007 (0.000)	1.058	0.299	0.009 (0.000)	2.397*	0.024
A	0.009 (0.001)	0.348	0.697	0.0008 (0.000)	-0.694	0.391
CW	−0.012 (0.005)	−4.491**	0	−0.0069 (0.001)	−3.222**	0.004
CointEq(−1)	−0.497 (0.154)	−3.297**	0	−0.875 (0.139)	−5.731***	0.001

Note: *, **, *** denote the level of significance as 1%, 5% and 10% respectively.

Table 4. Error Correction Model (ECM).

	Punjab			Sindh		
Variable	Coefficient	t-Statistic	Prob.	Coefficient	t-Statistic	Prob.
D (WUEC(−1))	−0.221(0.11)	−1.592	0.109	−0.311(0.131)	−1.792*	0.069
D(T1)	−0.003(0.001)	−1.499	0.131	0.002(0.00)	0.651	0.443
D(T2)	−0.001(0.001)	−0.892	0.297	0.005(0.002)	1.793*	0.069
D(T2(−1))	−0.006(0.002)	−3.651**	0.001	0.007(0.002)	2.197*	0.041
D(P)	−0.002(0.001)	−2.098*	0.018	0.000(0.000)	−2.265*	0.029
D(WP)	−0.001(0.000)	−2.391*	0.022	0.000(0.001)	0.234	0.791
D(WP(−1))	−0.002(0.000)	−4.199***	0	0.001(0.001)	1.298	0.178
D(PD)	0.000(0.000)	0.539	0.565	−0.007(0.003)	−1.753*	0.087
D(GE1)	−0.000(0.000)	−3.011**	0.005	0.000(0.000)	3.198**	0.003
D(F)	0.000(0.000)	1.076	0.275	0.000(0.000)	−2.465*	0.023
D(E)	0.000(0.000)	1.453	0.141	0.000(0.000)	1.768*	0.055
D(CW)	0.002(0.001)	1.875*	0.059	−0.002(0.002)	−0.887	0.332
D(CW(−1))	0.004(0.001)	3.498**	0.003	0.000(0.000)	−2.532*	0.014
D(A)	0.000(0.000)	0.298	0.729			

Note: *, **, *** denote the level of significance as 1%, 5% and 10% respectively.

The ARDL and VECM models' results reveal that canal water extractions, precipitation and temperature change have a substantive influence on water use effectiveness in Punjab and also Sindh. Such empirical findings provide evidence-backed suggestions: First, the adverse effect of uncontrolled canal extractions demonstrates the necessity of better irrigation management and canal modernization [55]. Second, the issue of the sensitivity of water use efficiency to temperature extremes implies reporting the regional water policies with the issue of climate adaptation. Third, Sindh has reinforced the positive effect of government spending on the maintenance of continuing investments in water infrastructure as the policy instrument of water efficiency [56].

Endogeneity is a serious issue in time-series research that focuses on climatic and institutional variables, as well as economic variables, where feedback loops or omitted variables bias coefficient estimates as mentioned in **Table 5**. To deal with possible endogeneity, two critical ways are taken in this study [57]. To begin with, the fact that the ARDL bounds testing method is used automatically provides some relief of endogeneity challenges since modeling dynamic lags permits the system to adapt to changing circumstances with time hence minimizing the simultaneity bias [58]. Second, in order to strengthen the inference of causality and confirm long-run relationships, the Vector Error Correction Model (VECM) has been used [59]. The VECM model portrays short-run development and long-range equilibrium modification via the mistake correction term (ECT) that was identified to be statistically essential and important to the two states of Punjab and Sindh [60].

Table 5. Robustness Check.

Test	**Statistic**	***p*-value**	**Statistic**	***p*-value**	**Result**
	Sindh		**Punjab**		
Breusch-Godfrey LM	1.33	0.15	1.38	0.18	No serial correlation
Breusch-Pagan	3.01	0.17	3.08	0.15	Homoskedastic
Jarque-Bera	1.89	0.31	1.76	0.28	Normal residuals
CUSUM	–	–	–	–	Stable
CUSUMSQ	–	–	–	–	Stable

This negative effect of canal water withdrawals (CW) on WUEC is in line with the previous empirical evidence that demonstrated the inefficiencies and losses that are attributed to various traditional irrigation systems, especially in the developing financial agricultural sectors, such as found in Pakistan [61–64]. On a similar note, the positive relationship between government expenditure (GE1) and WUEC again concurs with the larger body of evidence that higher governmental spending on water infrastructure development, including lining canals, metering, and rehabilitative exercises, can promote long-term and sustainable efficiency of water consumption [65,66]. These dynamics at the regional level exhibit sensitivity to the climatic stressors, institutional adaptation and infrastructural quality in molding the water productivity [67].

5. Conclusion

This study examines how geo-climatic and socio-economic factors affect water use efficiency (WUE) in cotton farming in Punjab and Sindh provinces in-Pakistan based on time-series statistics. It is observed from the empirical findings of ARDL and VECM estimations that water pricing, canal water withdrawals, and temperature variability are key factors affecting WUE. It is worth noting that the findings indicate the increased importance of government indicators to enhance water efficiency in Sindh, whereas WUE is responsive in the case of Punjab to precipitation and lagged canal water availability. The evidence indicates that adequate water pricing systems and irrigational infrastructure investment are ways of increasing efficiency in water usage. Also, the correlation established between the indicators of education and WUE suggests that better primary education can have an indirect positive effect on the implementation of efficient irrigation practices, at least among smallholder farmers. Awareness and training as part of developing human capital therefore qualify as a significant channel in the application of smart water management in farming activities.

The main limitation of the study is the availability of the data, especially the ones of higher spatial resolution. Because of data accessibility issues and the constrained amount of time, the research uses aggregated annual data and does not include the firm-level or household survey data. And there is also the limit of two provinces which does not allow for generalization wider.

It has been suggested that future studies use panel data at the district or microdata at the farm level in order to better measure more detailed effects. Analysis of satellite–based climate indicators and household survey data would add to the strength of the results. Finally, there is the recommendation to use custom designs of the policy that account for regional disparities, such as greater sensitivity of the climate experienced in Sindh and the extensive irrigation intensity in Punjab, to enhance water use efficiency in both the short–run and long–run.

It is essential to deepen financial systems to support long–term, capital–intensive green projects. Robust financial systems that provide diverse funding options, such as venture capital and infrastructure bonds, create a stable environment for businesses and industries to undertake transformative green initiatives. These include large–scale renewable energy installations, smart urban infrastructure, and sustainable agriculture practices. Policymakers should prioritize measures that increase the liquidity and resilience of financial markets to ensure the sustained availability of resources for long–term sustainability efforts.

Author Contributions

All authors equally and significant work in this paper.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data is available on request.

Conflicts of Interest

The authors declare no conflict of interest.

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