



Irrigation dynamics, water constraints and agricultural sustainability in Algeria: Assessing the role of solar energy

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Abstract:

This paper analyses irrigated area dynamics in Algeria under water, energy, and climate constraints. Using an ARDL model on annual data for 1990-2023, it distinguishes short-run adjustment from long-run relationships. The results show strong persistence in irrigated area, consistent with irrigation as a slowly adjusting productive stock. Although the bounds test supports a long-run relationship, the individual long-run coefficients remain weakly robust and require cautious interpretation. In particular, solar radiation does not emerge as a robust direct determinant of historical irrigation expansion. These findings stress the importance of inertia, water governance, and long-term policy coordination.

Keywords: irrigation dynamics; water constraint; Agricultural sustainability; Solar Energy; ARDL model; Algeria.

Jel Classification Codes: Q15 ; Q25 ; Q42 ; C22.

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1. Introduction

Algerian agriculture operates under strong structural constraints, including increasing water scarcity, rising climate variability, and persistent dependence on conventional energy systems. In a country that is largely semi-arid, irrigation plays a central role in stabilizing agricultural production, yet it also places significant pressure on natural resources. Institutional assessments by the World Bank (1992) and the FAO (2015) have long stressed the strategic importance of irrigation and water management in Algeria, where agricultural and urban uses jointly exert substantial pressure on available water resources.

Since the early 1990's, Algeria has made significant efforts to expand irrigated land in order to improve agricultural yields and strengthen food security. In general, Darko and al. (2016) argue that irrigation remains a key productive instrument for agriculture and food security, especially under strong climatic constraints. In the Algerian case, however, irrigation expansion has also been associated with greater water mobilization and higher energy requirement linked to pumping, raising concerns about the long-term sustainability of this trajectory.

In this context, renewable energy, and solar energy in particular, is often presented as a promising solution for easing energy constraints and supporting more sustainable irrigation systems. This view, however, requires qualification. Closas and Rap (2017) show that solar-based pumping may reduce energy costs and improve access to irrigation, but they also warn that it can intensify pressure on groundwater where regulation is weak. This issue is therefore not whether solar energy is automatically compatible with sustainability, but under what conditions it reshapes the trade-offs between water, energy and irrigation.

Empirically, relatively few studies analyse the dynamic drivers of irrigation expansion while jointly accounting for water, energy and climate constraints, and fewer still examine the place that solar potential may occupy within these dynamics in the Algerian case. In

particular, the literature still pays limited attention to the inertia that characterizes irrigation investment decisions, as well as to the distinction between short-run adjustments and long-run structural determinants.

This study addresses the gap. Its objective is not to establish a direct causal effect of solar energy on irrigation expansion, but to analyse how irrigation dynamics in Algeria are shaped by the interaction between water constraints, energy conditions, climatic factors, and structural characteristics in a context marked by high solar potential. More specifically, the paper examines whether, and under what conditions, this potential may modify the economic and physical environment within irrigation adjusts, without assuming that it constitutes an immediate engine of expansion.

To this end, the study uses an Autoregressive Distributed Lag (ARDL) model estimated on an annual time-series data covering the period between 1990 and 2023. This framework makes it possible to distinguish short-run effects, including those related to climatic shocks, from longer-run relationships that may reflect more structural dynamics in irrigated agriculture. The dependent variable is total irrigated area, treated as a slowly adjusting productive stock, while the explanatory variables include water mobilization, a proxy for agricultural energy use, climatic conditions, and an indicator of solar potential.

The result first suggest a strong degree of persistence in irrigation dynamics in Algeria, consistent with the view that irrigated area adjusts only gradually over time. They also indicate that the short-run adjustments are sensitive to some climatic and energy-related factors. By contrast, the interpretation of individual long-run effects must remain cautions. In particular, solar potential does not emerge as a robust direct determinant of the historical expansion of irrigated land, but rather as a contextual element that may shape the future sustainability conditions of irrigation systems. These findings therefore call for a more cautions reading of technicist narratives of

sustainability and support a broader reflection on water governance and the long-term trajectory of agricultural development in Algeria.

2. Literature review

2.1 Irrigation as a productive stock: inertia, investment and slow adjustment

Irrigation should not be viewed as a variable input that can be adjusted instantaneously. As Darko et al. (2016) emphasize, irrigation is a major productive instrument for agricultural output and food security, but its effectiveness depends on technical, environmental, and institutional conditions. In practice, irrigation relies on durable infrastructure and capital equipment, including boreholes, pumps, conveyance systems and irrigation networks, whose installation and maintenance involve fixed costs, partial irreversibility and organizational constraints.

This perspective supports treating irrigated area as a slowly adjusting productive stock rather than as a simple annual response to changes in prices, yields, or climatic conditions. More broadly, irrigation trajectories are often shaped by past investment choices, adjustment costs, and the persistence of existing technical arrangements. In semi-arid environment, this inertia is reinforced by the stabilizing role of irrigation under rainfall uncertainty. Once irrigation infrastructure has been installed, adjustment tends to be gradual because the system is embedded in both physical capital and institutional routines.

This analytical framework is particularly relevant to Algeria. Since the early 1990s, irrigation expansion has been closely linked to public investment, hydraulic development and agricultural support policies. For the purposes of this study, the key implication is that irrigated area should be interpreted as a dynamic variable marked by persistence rather than as a purely contemporaneous outcome.

2.2 Water, energy and endogeneity: A constrained interaction rather than a one-way relationship

Water occupies a central place in any analysis of irrigation, but it also raises an important econometric difficulty. Irrigation expansion increases water use, while water availability and water mobilization capacity also condition irrigation itself. As a result, the relationship between irrigated area and water mobilized for irrigation cannot be treated as a simple one-way causal mechanism. It is better understood as an interaction shaped by supply constraints, institutional allocation rules, and demand generated by irrigation expansion.

This point is consistent with the econometrics of water allocation. Tsur (2009) argues that water should be analyzed as a scarce resource whose use depends on both physical and institutional constraints rather than as a freely adjustable production factor. In the same spirit, Scheierling and al. (2006) show in their meta-analysis that irrigation water demand is often relatively price-inelastic, especially in the short run, which suggests that adjustment is constrained by deeper technical and structural conditions rather than driven solely by market signals.

Energy introduces a second layer of constraint. In any agricultural system, pumped irrigation directly links the feasibility of irrigation to energy availability and cost. At the same time, agricultural energy use is often measured through aggregated indicators that include mechanization and processing in addition to pumping. For this reason, energy should be interpreted cautiously in empirical models: it can capture an important operating condition of irrigation without necessarily constituting a clean measure of pumping alone.

In the Algerian case, institutional and sectoral assessments by the World Bank and FAO have long stressed the pressure exerted on water resources by irrigation and competing urban uses. These sources also underline the importance of irrigation efficiency and water governance for long-term agricultural sustainability. This context

justifies treating water constraints as a core structural dimension of irrigation dynamics in Algeria.

2.3 Solar energy and irrigation: Between normative promise and limited empirical evidence

Recent work on solar energy in irrigation points to double-edged dynamic. Closas and Rap (2017) show that solar based pumping can reduce energy costs and improve access to irrigation water, but they also warn that lower pumping costs may intensify groundwater extraction where regulatory institutions are weak. Their argument is central to this paper because it shows that solar energy cannot be treated as an automatically sustainable solution independently of water governance.

This caution is reinforced by more recent empirical evidence. Gupta (2019) finds that solar water pumps may affect not only energy use, but also water extraction and cropping decisions. The relevant question is therefore not whether solar energy is inherently beneficial or harmful, but under what institutional and economic conditions it reshapes the trade-offs between water, energy and irrigation.

A major methodological challenge lies in measurement. At the national level, solar potential tends to vary only slightly over time, while the actual adoption of solar technologies depends on different factors, including public policy, equipment costs, access to finance and local governance arrangement. If solar potential is conflated with actual technology adoption, the empirical scope of the results may easily be overstated.

This distinction is especially important in Algeria. Bouzidi (2011) shows that solar- or wind-powered pumping can be technically and economically viable in Saharan regions such as Adrar. However, that type of study addresses local technological feasibility rather than the macro-temporal role of solar conditions in national irrigation dynamics. The gap between local feasibility studies and long-run aggregate irrigation dynamics is precisely what calls for a cautious treatment of solar potential in the present article.

2.4 Positioning the study

Taken together, the existing literature suggests three main conclusions. First, irrigation is better understood as a persistent and cumulative process than as a purely short-run adjustment. Second, the relationships linking irrigated area, water mobilization and energy conditions are complex, potentially endogenous, and strongly shaped by physical and institutional constraints. Third, solar energy opens important opportunities, but its implications for agricultural sustainability depend heavily on governance conditions and cannot be inferred mechanically from solar potential alone.

For Algeria, the available literature documents water scarcity, irrigation pressures and the strategic importance of hydraulic development. However, relatively few studies combine irrigated area, water mobilization, energy conditions, climatic factors and solar potential withing a single dynamic framework over a long annual period. It is withing this gap that the present study is positioned.

3. Data and variables

3.1 Data sources and study period

The empirical analysis relies on annual time-series data for Algeria covering the period 1990-2023. This period was selected in order to capture both the phases of irrigation expansion that began in the early 1990s and the more recent developments associated with increasing water and climate constraints.

The data are drawn from international sources widely used in empirical research for their relative reliability and comparability. Agricultural statistics were obtained from FAOSTAT, water-related data from AQUASTAT, and macroeconomics indicators from the World Development Indicators of the World Bank. Climatic and solar variables were derived from ERA5/ECMWF and NASA POWER. All quantitative variables were transformed into natural logarithms in

order to facilitate elasticity-based interpretation and to moderate scale effects and some extreme fluctuations.

3.2 Dependent variable

The dependent variable is total area irrigated area, measured in hectares. It captures the extent of agricultural land benefiting from access to irrigation and serves as synthetic indicator of installed irrigation capacity at the national level.

Rather than being interpreted as a simple annual intensity measure, irrigated area is treated here as a productive stock resulting from cumulative investment in hydraulic infrastructure and pumping equipment. This interpretation is consistent with the persistence hypothesis discussed in the literature.

3.2 Explanatory variable

The explanatory variables are grouped into four broad dimensions: water, energy, climate and the economic structure of agriculture.

Water mobilized for irrigation measures the total volume of water mobilized for irrigation purposes, expressed in cubic meters. It captures an important dimension of pressure on water resources. At the same time, this variable is characterized by intrinsic simultaneity with irrigated area: an expansion in irrigated land mechanically increases water use. It is therefore interpreted not as a strict causal determinant, but as an indicator related to water mobilization for irrigation and pressure on the resource.

Agricultural energy use measured through a proxy expressed in kilowatt-hours. This variable is intended to approximate energy consumption in agricultural activities, including, but not limited to, water pumping for irrigation. Because pumping-specific long-run data are unavailable for Algeria, this proxy necessarily aggregates several agricultural energy uses, which weakens its interpretation as a direct measure of pumping alone.

Climatic conditions are captured through annual precipitation, average annual temperature and average annual solar radiation. Precipitation reflects direct water input and is expected to influence irrigation needs in the short run. Temperature captures broader climatic stress through its potential effects on evapotranspiration and agricultural water demand. Solar radiation reflects the territory's physical solar endowment. It is important to not that solar radiation does not measure the actual adoption of solar technologies; rather, it captures a structural physical characteristic whose temporal variation remains limited at the national level.

Finally, the broader economic structure of the agricultural sector is captured through agriculture's share in GDP. This indicator reflects the relative weight of agriculture in the national economy and provides indirect information about the sector's position within broader macroeconomic constraints.

Table 1: Summary of variables and main limitations

Variable	Definition	Economic interpretation	Main limitation
LIRRIG_HA	Irrigated area (ha)	Slowly adjusting productive stock	Aggregate national measure
LWATER_M3	Water mobilized for irrigation	Indicator of water mobilization and water pressure	Simultaneity with irrigated area
LENERGY_PROXY_KWH	Agricultural energy use	Imperfect proxy for irrigation-related energy conditions	Aggregates multiple energy uses
LRAIN_MM	Precipitation	Short-run climatic condition	High interannual variability
LTEMP_C	Average temperature	Indicator of climatic constraint	Indirect channel of influence
LSOLAR_IRRD	Solar radiation	Structural indicator of the solar context	Limited time variation; does not measure technology adoption
LAGRIVA_PCT GDP	Agriculture share in GDP	Structural indicator of agriculture's weight in the economy	Ambiguous economic interpretation

Source: *Author's elaboration.*

4. Empirical methodology

To analyse irrigation area dynamics in Algeria, this study uses ARDL model estimated on annual data for 1990-2023. This approach is appropriate because it allows short-run adjustment and longer-run relationships to be examined withing a single framework, while remaining suitable for relatively small sample and for variables that may be integrated of order zero or one, provided that none is integrated of order higher than one (Pesaran and al., 2001). In the present context, the ARDL model is used as a dynamic empirical framework for characterizing conditional relationships between irrigated area and its potential determinants, rather than as a device for strong causal identification.

The general specification can be written as follows:

$$\begin{aligned}
 LIRRIG_{HA_t} = & \alpha_0 + \sum_{i=1}^p \alpha_i LIRRIG_HA_{t-i} + \sum_{j=0}^{q1} \beta_j LWATER_M3_{t-j} \\
 & + \sum_{k=0}^{q2} \gamma_k LENERGY_PROXY_KWH_{t-k} \\
 & + \sum_{l=0}^{q3} \delta_l LRAIN_MM_{t-l} + \sum_{m=0}^{q4} \phi_m LTEMP_C_{t-m} \\
 & + \sum_{n=0}^{q5} \psi_n LSOLAR_IRR_{t-n} \\
 & + \sum_{r=0}^{q6} \theta_r LAGRIVA_PCTGDP_{t-r} + \varepsilon_t
 \end{aligned}$$

The estimated specification includes lagged irrigated area, water mobilized for irrigation, agricultural energy use, precipitation, average temperature, solar radiation and agriculture's share in GDP. Lag order are selected using the Akaike Information Criterion. The existence of a long-run relationship is assessed through the bounds cointegration

test, and the short-run dynamics are examined through the associated error-correction representation. Standard residual diagnostics are also used to evaluate autocorrelation and heteroskedasticity. Given the aggregated nature of the data and the use of proxy variables for some dimensions, the estimated coefficients are interpreted with caution, especially in the long run.

5. Empirical methodology

5.1 ARDL estimation and the general dynamic of irrigation

The ARDL estimation reveals a strongly persistent pattern in irrigation dynamics in Algeria. The two lagged values of irrigated area are statistically significant, with a coefficient of 1,3037 for the first lag ($p < 0,001$) and -0,4240 for the second lag ($p = 0,004$). This configuration is consistent with a gradual adjustment process in irrigated area rather than an immediate response to changes in the explanatory variables.

This result supports the interpretation of irrigated area as a slowly adjusting productive stock shaped by past investment, existing infrastructure, and non-negligible adjustment costs. It also suggests that persistence is most robust feature of irrigation dynamics in the estimated model.

5.2 Long-run relationship and cointegration test

The bound cointegration test supports the existence of a levels relationship between irrigated area and the explanatory variables considered jointly. The F-stat is 5,972 which is above the upper critical bound at conventional significance levels, including at the global level of the model.

This conclusion, however, must be interpreted cautiously when examining the individual long-run coefficients. In the levels equation, most coefficients are not statistically robust. Water mobilized for irrigation has a negative coefficient of -2,3269 ($p = 0,4056$), agricultural energy use a positive coefficient of 2,0256 ($p = 0,2101$),

average temperature a coefficient of 0,0561 ($p=0,7595$), solar radiation a coefficient of -1,8106 ($p=0,1947$), and agriculture's share in GDP a coefficient of -0,2071 ($p=0,3545$). Only precipitation displays a positive coefficient of 0.8850, with marginal significance ($p= 0.0526$).

In other words, the bounds test supports the existence of an overall long-run relationship, but the estimates do not allow equally robust identification of an autonomous long-run effect for each variable taken separately. In particular, solar radiation does not appear as a robust direct long-run determinant of the expansion of irrigated area.

5.3 Short-run dynamics and transitory adjustment

The short-run results are clearer for some variables. Changes in agricultural energy use are statistically significant in the error-correction model, with a contemporaneous coefficient of 0,2260 ($p=0,0055$) and a lagged coefficient of -0,2464 ($p=0.0046$). These results suggest that energy conditions influence annual adjustments in irrigated area, most likely through the operating conditions of pumping.

Precipitation is also significant in the conditional form of the model, with a coefficient of 0,1064 ($p = 0,0006$), which is consistent with the role of rainfall variability in short-run irrigation adjustment. By contrast, average temperature does not display a statistically robust effect in the reported estimates, with a coefficient of 0,0067 ($p=0,7591$). It is therefore preferable not to attribute a direct empirical role to temperature on the basis of the estimated model.

5.4 Error-correction model and speed of adjustment

The error-correction model yields a negative and highly significant error-correction term. The estimated coefficient is -0,1203 ($p < 0,001$), indicating that approximately 12% of the deviation from long-run equilibrium is corrected each year.

This speed of adjustment is relatively slow, reinforcing the interpretation of irrigated area as a highly persistent variable. Economically, this result is consistent with the rigidity of irrigation infrastructure, fixed investment costs, and the difficulty of adjusting irrigated area rapidly in response to temporary disequilibria.

5.5 Diagnostic tests and model adequacy

The diagnostic tests do not indicate any major problem of residual autocorrelation. The Breusch–Godfrey test yields a p-value of 0,5544 for the F-statistic and 0,3817 for the Obs*R² statistic, which does not lead to rejection of the null hypothesis of no serial correlation.

The heteroskedasticity results call for a more cautious reading. The Breusch–Pagan–Godfrey test yields a p-value of 0,0682 for the F-statistic and 0,0954 for the Obs*R² statistic. There is therefore no clear rejection of homoskedasticity at the 5% level, but these results remain close enough to conventional thresholds to justify some caution in statistical inference.

5.6 Summary of results

Taken together, the empirical results point to three main findings. First, irrigation dynamics in Algeria are characterized by strong persistence, as indicated by the significance of lagged irrigated area and the slow adjustment toward equilibrium. Second, short-run adjustments appear to be linked primarily to energy conditions and precipitation. Third, although the bounds test supports the existence of a long-run relationship among the variables considered jointly, the individual long-run coefficients remain weakly robust, which calls for cautious interpretation, especially with respect to water mobilization and solar radiation.

6. Discussion

6.1 Irrigation as a persistent trajectory

The most robust result of the analysis concerns the strong persistence of irrigated area. The estimated coefficients on lagged irrigated area, together with the coefficient of the error-correction term, are consistent with the view that irrigation evolves through a process of slow adjustment rather than immediate response. The error correction coefficient of -0,1203 suggests a gradual return to equilibrium at a rate of about 12% per year.

In the Algerian case, this persistence may be interpreted as the combined outcome of public investment policies, the capital-intensive nature of hydraulic systems, and institutional constraints that make rapid reallocation difficult. The main contribution of the model therefore lies less in identifying a single determinant than in highlighting a strongly inertial irrigation dynamic.

6.2 Water and irrigation: Caution in empirical interpretation

Water mobilized for irrigation occupies a central place in the economic and institutional reasoning of the paper, but the econometric results do not identify a robust individual long-run effect. The estimated coefficient in the long-run equation is negative (-2,3269), but statistically insignificant ($p = 0,4056$).

This lack of robustness may reflect simultaneity between water mobilization and irrigated area, the national aggregation of the data, and the difficulty of distinguishing empirically between mobilization capacity and demand induced by the expansion of irrigated land. It is therefore more accurate to treat water as a central element of the broader water-constraint context than as an autonomously identified determinant in the model.

6.3 Energy and irrigation: Primarily a short-run result

The clearest effects, apart from persistence itself, concern agricultural energy use in the short run. The coefficients associated with changes in agricultural energy use are statistically significant, suggesting that energy conditions influence annual irrigation adjustment. This reading is consistent with the role of pumping in energy-dependent irrigation systems.

By contrast, the long-run coefficient of energy, although positive (2,0256), is not significant ($p = 0,2101$). It is therefore more rigorous to conclude that energy acts mainly as a short-run operational constraint rather than as a clearly established long-run structural driver.

6.4 Solar Energy: Maximum caution in interpretation

Solar energy is the most sensitive point of the paper. In the long run equation, the coefficient associated with solar radiation is negative (-1,8106), but not significant ($p = 0,1947$). This result does not support the idea of a robust direct effect of solar potential on the long run expansion of irrigated area.

This does not mean that solar technologies are irrelevant to the future of irrigated systems. It simply means that, in this macro temporal model based on a national indicator of solar radiation, no robust individual structural effect is identified. This limitation is consistent with the fact that the variable captures physical potential rather than the actual adoption of solar pumping technologies.

6.5 Climate and dependence on the natural environment

Precipitation appears to be the climatic variable most clearly linked to the estimated dynamics. In the long-run equation, its coefficient is 0.8850 with marginal significance ($p = 0,0526$), while in the conditional form, the short-run coefficient is 0,1064 ($p = 0,0006$). This configuration suggests that rainfall variability plays a role in irrigation adjustment.

By contrast, average temperature does not display a statistically robust effect in the estimates. It is therefore preferable to distinguish between climatic variables actually supported by the results and those whose importance remains primarily theoretical within the estimated model.

6.6 Scope and limits of the analysis

Overall, the results call for a cautious reading of irrigation development strategies based on isolated technological solutions. The model strongly supports the idea of persistent irrigation dynamics and slow adjustment, but it identifies individual long-run effects of the explanatory variables less clearly.

This limitation does not invalidate the analysis, but it does define its scope. The paper's main contribution is to clarify the dynamic structure of irrigation in Algeria and to show that simplified narratives about water, energy, or solar potential must be qualified when examined through an aggregate long-run framework.

7. Conclusion and policy implications

This study set out to analyse the dynamics of irrigated area in Algeria in a context shaped by water, energy, and climate constraints, while also taking into account an environment characterized by high solar potential. Using an ARDL model estimated on annual data covering the period 1990–2023, the analysis sought to distinguish short-run adjustments from longer-run relationships.

The most robust result concerns the strong persistence of irrigation dynamics. The coefficients on lagged irrigated area and the error-correction term indicate that irrigated area behaves as a slowly adjusting productive stock. The error-correction coefficient of -0,1203 suggests that around 12% of the deviation from equilibrium is corrected each year, confirming the slow pace of adjustment.

The analysis also highlights the role of energy conditions in short-run adjustment. By contrast, although the bounds test supports

the existence of a long-run relationship among the variables considered jointly, the individual long-run coefficients remain globally weak. This configuration calls for a cautious reading: the model identifies a general dynamic structure more clearly than it allows one to assign a structurally autonomous role to each explanatory variable with confidence.

Within this framework, water mobilized for irrigation should be understood primarily as a central element of the broader economic, physical, and institutional context of irrigation in Algeria rather than as a clearly identified individual long-run determinant. Similarly, solar potential does not emerge as a robust direct driver of the historical expansion of irrigated area. This result does not undermine the relevance of solar technologies, but it does suggest that their impact depends strongly on adoption conditions, regulation, and water governance.

From a policy perspective, these findings suggest three main lessons. First, irrigation strategies must be designed with a long-term perspective that takes into account the strong inertia of existing systems. Second, energy policies, including those related to solar development, cannot be conceived independently from the regulation of water use. Third, improving water governance remains a key condition for any sustainable trajectory of irrigation development.

This study nevertheless has clear limitations. It relies on aggregated national data and on proxy variables, particularly for energy and solar conditions, which reduces the precision of empirical identification. Future research could use more disaggregated data, incorporate direct measures of solar technology adoption, and distinguish more clearly among local water management regimes.

Ultimately, the main contribution of this paper is not to demonstrate a direct causal effect of solar energy on irrigation, but to show that the dynamics of irrigated area in Algeria are above all characterized by strong persistence, and that the interpretation of the relationships among water, energy, climate, and sustainability must remain closely tied to the empirical limits of the available data.

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9. Appendices

Appendix A. Summary of Main Econometric Results

Block	Main result	Value	Statistical significance	Interpretation
Selected specification	ARDL model	ARDL(2,0,2,0,0,0,0)	—	Specification selected by AIC
Persistence	Irrigated area, lag 1	1.3037	$p < 0.001$	Strong persistence in irrigated area
Persistence	Irrigated area, lag 2	-0.4240	$p = 0.004$	Gradual adjustment rather than instantaneous response
Cointegration	Bounds F-statistic	5.9720	Above upper bound	Supports a long-run relationship at the global level
Long-run coefficients	Precipitation	0.8850	$p = 0.0526$	Marginal evidence only
Long-run coefficients	Water mobilized for irrigation	-2.3269	$p = 0.4056$	No robust individual long-run effect
Long-run coefficients	Agricultural energy use	2.0256	$p = 0.2101$	No robust individual long-run effect
Long-run coefficients	Solar radiation	-1.8106	$p = 0.1947$	No robust direct long-run effect
Short-run dynamics	Agricultural energy use	0.2260	$p = 0.0055$	Significant short-run effect
Short-run dynamics	Agricultural energy use, lag 1	-0.2464	$p = 0.0046$	Significant short-run adjustment
Short-run dynamics	Precipitation	0.1064	$p = 0.0006$	Significant short-run climatic effect
Error-correction	Error-correction term	-0.1203	$p < 0.001$	Around 12% of disequilibrium corrected per year
Diagnostics	Breusch–Godfrey test	$p = 0.5544 / 0.3817$	Not significant	No major residual autocorrelation
Diagnostics	Breusch–Pagan–Godfrey test	$p = 0.0682 / 0.0954$	Borderline	Cautious inference recommended

Source: *Author's calculations.*