



WATER STRESS, AGRICULTURAL DEPENDENCE, AND TECHNOLOGICAL RESPONSES IN THE MENA REGION: EVIDENCE FROM A LONG-RUN PANEL ANALYSIS (1990-2024)

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ABSTRACT

Water scarcity has become one of the most serious structural constraints on development in the Middle East and North Africa, or MENA. Despite substantial investment in supply side technologies, including groundwater development, irrigation modernization, desalination, and wastewater reuse, regional water stress remains persistently high.

This study examines whether these technological responses reduce water stress or whether their effects are offset by agricultural dependence and rebound dynamics. Using a balanced macro panel of ten MENA countries from 1990 to 2024, we estimate several econometric specifications and conduct robustness checks. Agricultural water dependence is consistently associated with greater water stress, whereas the relationship between technology and stress varies across specifications. It is negative in pooled models but positive after controlling for country heterogeneity. Combined with evidence of bidirectional Granger causality, these results suggest that infrastructure expansion often responds to existing scarcity rather than resolving it. Sustainable water security therefore requires not only technological innovation but also institutional reform, demand management, and agricultural transition.

Keywords: *water stress, MENA, agricultural dependence, rebound effect, panel econometrics, water, energy and food nexus*

1. INTRODUCTION

Water scarcity has become a fundamental constraint on economic development in the Middle East and North Africa. When water availability is uncertain, economic planning, production, and investment are restricted, while growth may be disrupted once critical resource thresholds are reached. Water scarcity can therefore no longer be treated as a secondary environmental concern. It is a structural bottleneck affecting the long-term development prospects of the region.

These pressures are intensified by limited renewable water resources, population growth, urban expansion, water intensive agriculture, and worsening climatic conditions. Consequently, water scarcity in MENA is not merely an infrastructure problem but a broader economic challenge affecting livelihoods, food systems, energy production, and regional stability (de Waal et al., 2023; Velpuri et al., 2023).

The economic consequences could be substantial if current patterns of water use and allocation persist. Water scarcity is estimated to reduce regional GDP by between 6 and 14 percent by 2050, making it a central economic risk rather than a marginal constraint. The costs of inaction, particularly under climate change, are therefore likely to be disproportionately high in MENA compared with other regions (de Waal et al., 2023).

Climate change further intensifies these risks through rising temperatures, declining rainfall, and more frequent droughts. Transboundary water systems add another layer of complexity because countries sharing major river basins differ considerably in their financial, institutional, and adaptive capacities. These asymmetries reinforce regional inequalities and complicate effective water governance (Daoudy et al., 2022).

For decades, policy responses in MENA have focused primarily on expanding supply through dams, irrigation networks, groundwater extraction, desalination, interregional transfers, and wastewater reuse. This approach assumes that increasing water availability will be sufficient to meet growing demand. However, supply expansion alone cannot correct the underlying imbalance when consumption patterns, allocation systems, and institutional incentives remain unchanged (de Waal et al., 2023). Persistent scarcity may therefore reflect not a lack of policy action but an excessive reliance on technological supply expansion without addressing the drivers of high consumption.

Agriculture is central to this problem. The sector depends heavily on groundwater, accelerating aquifer depletion and increasing the energy and financial costs of extraction as water tables decline. Borgomeo et al. (2018) estimate that intensifying water scarcity could reduce agricultural output by as much as 60 percent in some MENA countries. These pressures are unlikely to stabilize because regional water stress is increasingly driven by persistent demand rather than declining supply alone (Hejazi et al., 2014). The water crisis must therefore be examined in relation to agricultural policy, food security, and rural livelihoods.

Technological solutions such as desalination, wastewater reuse, modern irrigation, and precision water delivery systems are frequently presented as comprehensive responses to scarcity. Although these technologies can increase supply and improve efficiency, they also involve substantial economic, environmental, and energy related trade-offs. If current technologies and cost structures remain unchanged, alternative water sources could require investments exceeding US\$40 billion by 2050 (Borgomeo et al., 2018). Desalinated water may require up to twenty-three times more energy than conventional surface water and cost four to five times more, illustrating the burden of relying heavily on supply expansion.

The central issue is therefore not whether technology matters but whether it can overcome scarcity without complementary institutional and demand reforms. Fragmented governance, weak regulatory enforcement, and limited coordination among public agencies continue to restrict integrated management of water, land, and energy across the region (Hoff et al., 2012).

The rebound effect creates an additional concern. Efficiency improvements do not necessarily reduce total resource consumption and may, under certain conditions, encourage greater use (Berbel and Esteban, 2019). In agriculture, more efficient irrigation can reduce production costs and improve access to water, prompting farmers to expand cultivated areas, adopt crops that require more water, or increase extraction where monitoring is weak. Drip irrigation may improve efficiency at the field level while encouraging denser planting and reducing return flows to aquifers. Consequently, efficiency gains at the farm level may not produce water savings at the regional level (Hoff et al., 2012).

Against this background, the study examines whether the expansion of water related technologies can alleviate long term water stress in MENA or whether agricultural dependence and

rebound effects offset the expected gains.

The study makes three contributions. First, it provides a unified empirical test of the technology and rebound hypothesis across a MENA panel using both the water stress ratio as a flow indicator and GRACE terrestrial water storage data as a stock indicator. Second, it applies panel Granger causality tests to examine bidirectional temporal relationships between technology and water stress, moving beyond static associations. Third, it documents substantial differences among countries, challenging the assumption that MENA countries follow a uniform water policy trajectory and emphasizing the importance of specific national structural conditions.

The remainder of the paper is organized as follows. Section 2 reviews the theoretical and empirical literature. Section 3 describes the data, variables, and estimation strategy. Section 4 presents and discusses the empirical results, while Section 5 concludes.

2. REVIEW OF LITERATURE

2.1. THEORETICAL LITERATURE

The theoretical foundation of this study combines four complementary perspectives: hydro economic approaches to scarcity, the water, energy, and food nexus, political economy critiques of supply-oriented policies, and the rebound effect hypothesis. Together, they explain why water stress persists in MENA despite continued investment in infrastructure and technology.

Water scarcity in the region cannot be attributed solely to limited natural resources. It is also shaped by growing demand, institutional constraints, competing sectoral uses, and policies that have historically prioritized supply expansion over demand management (de Waal et al., 2023).

The hydro economic approach defines scarcity as the outcome of interactions among resource availability, demand, allocation systems, and governance capacity. It therefore shifts attention from physical water availability to the economic and institutional arrangements through which water is distributed and used.

Kummu et al. distinguish between water shortage and water stress. Water shortage refers to limited water availability per person, whereas water stress reflects excessive withdrawals relative to available resources. Both conditions are common in MENA, where many countries combine low renewable water availability with high withdrawal intensity. Scarcity therefore represents both a physical limitation and an institutional and economic constraint (de Waal et al., 2023; Kummu et al., 2016).

The water, energy, and food nexus provide a second theoretical perspective. It emphasizes that water, energy, and food systems are closely interconnected and should not be governed as separate policy areas. This interdependence is particularly strong in MENA. Agriculture is the largest user of water, groundwater extraction and desalination require substantial energy, and food security depends heavily on water allocation.

Borgomeo et al. emphasize the importance of these relationships for long term development, while Hoff et al. call for integrated governance capable of managing tradeoffs and creating benefits across sectors. Water stress must therefore be examined within a broader system that includes agricultural dependence, energy demand, food security, and institutional coordination (Borgomeo et al., 2018; Hejazi et al., 2014; Hoff et al., 2012).

A third perspective comes from political economy critiques of supply-oriented water policies. In many MENA countries, state legitimacy has historically been connected to subsidized public services, large hydraulic projects, low-cost water provision, and visible state involvement in resource development. This has contributed to a hydraulic social contract in which governments respond to scarcity mainly by increasing supply rather than addressing politically

sensitive issues such as pricing, allocation, and demand control.

This institutional arrangement reinforces the view that scarcity is primarily a supply problem and weakens incentives for demand reform. Tariff changes, abstraction limits, and transparent allocation rules often face strong resistance. Technological expansion must therefore be assessed within the political and institutional environment in which it is introduced (de Waal et al., 2023).

The fourth perspective is the rebound effect hypothesis, which is commonly associated with the Jevons paradox. According to this view, efficiency improvements do not necessarily reduce total resource use. By lowering the effective cost of consumption or enabling production to expand, they may instead increase overall use.

Evidence from agriculture shows that water saving technologies can encourage the expansion of irrigated land, shifts toward crops with higher economic value, and greater extraction where regulation is weak. Efficiency improvements at the plot level may therefore fail to reduce water pressure at the basin or national level. Their overall effect depends on abstraction controls, regulatory enforcement, and the incentives that influence user behaviour (Berbel and Esteban, 2019; Hoff et al., 2012).

Taken together, these perspectives show that technology cannot be evaluated independently of the productive, institutional, and governance systems in which it operates. Its effects are conditional rather than uniform.

In MENA, supply expansion and efficiency improvements may provide temporary relief, but their long-term effects remain uncertain where agriculture dominates water use, pricing mechanisms are weak, groundwater extraction is informal, and institutions lack credibility. This forms the central theoretical argument of the study.

The theoretical contribution of this study is to integrate hydro economic scarcity, the water, energy, and food nexus, the political economy of supply-oriented policy, and rebound effects into a unified analytical framework for MENA. The framework identifies three mechanisms through which the relationship between technological responses and agricultural dependence affects water stress.

First, institutional lock in occurs when established allocation systems continue to favour agricultural water use despite improvements in efficiency. Historical investments in irrigation create path dependence and make it difficult to transfer water to other uses as scarcity increases.

Second, demand absorption occurs when technology lowers cost and enables water intensive activities to expand. Farmers may increase cultivated areas, adopt crops with higher economic value, or extract more water where monitoring is weak. This mechanism is central to the rebound effect.

Third, governance credibility determines whether efficiency gains produce actual water savings. Without enforceable abstraction limits, transparent allocation, and credible regulation, technological improvements may be absorbed by existing demand instead of reducing overall stress.

This framework does more than apply existing theories to MENA. It identifies the mechanisms that condition the effects of technology. Technological responses are neither uniformly beneficial nor inherently ineffective. Their impact depends on the strength of demand management institutions, the response of agriculture to efficiency gains, and the quality of coordination among sectors.

2. 2. EMPIRICAL LITERATURE

The empirical literature can be divided into five main areas: water stress and agricultural dependence, technological responses to supply constraints, groundwater governance and pricing, rebound effects associated with irrigation modernization, and virtual water as a form of external adjustment. This organization reflects the main mechanisms examined in the study.

2. 2. 1. WATER STRESS, AGRICULTURAL DEPENDENCE, AND ECONOMIC VULNERABILITY IN MENA

Empirical research shows that water stress in MENA is severe, persistent, and increasingly influenced by sectoral demand rather than hydrological conditions alone. [De Waal et al. \(2023\)](#) identify MENA as one of the most water scarce regions in the world and warn that current water management patterns could produce substantial macroeconomic losses by 2050. [Velpuri et al. \(2023\)](#) similarly find that freshwater withdrawals exceed renewable resources in almost all countries in the region and that the gap between supply and demand continues to grow.

Water stress is therefore not merely a problem of physical scarcity. It is also a source of macroeconomic and developmental vulnerability that affects employment, public services, agriculture, and political stability ([de Waal et al., 2023](#); [Velpuri et al., 2023](#)).

Agriculture is the main channel through which these pressures are transmitted. [Borgomeo et al. \(2018\)](#) estimate that agricultural production could decline by as much as 60 percent in some MENA countries as water scarcity intensifies. [Hejazi et al. \(2014\)](#) similarly conclude that scarcity is likely to worsen in most countries primarily because of rising demand, with significant consequences for agriculture and electricity generation.

These findings indicate that agricultural dependence is a major determinant of vulnerability in MENA water systems and support its inclusion as a central explanatory variable in this study.

2. 2. 2. TECHNOLOGICAL RESPONSES AND TECHNOLOGICAL SOLUTIONISM IN MENA

A second strand of research examines desalination, wastewater reuse, infrastructure expansion, and irrigation modernization. These technologies can increase water availability in the short term, but their long-term sustainability may be constrained by financial, energy, institutional, and environmental costs.

[Borgomeo et al. \(2018\)](#) estimate that MENA may require more than US\$40 billion by 2050 to develop nonconventional water sources. Desalination is substantially more expensive and requires considerably more energy than conventional surface water treatment. Other studies show that MENA already accounts for a large proportion of global desalination capacity and is becoming increasingly dependent on technological supply expansion to address water shortages ([de Waal et al., 2023](#)).

Wastewater reuse provides another potential source of adaptation. Unlike many conventional sources, wastewater volumes generally increase with population growth and water consumption. Reuse may therefore become increasingly important where other supply options are limited ([Velpuri et al., 2023](#)). However, a substantial proportion of wastewater in the region is still discharged without treatment or reuse, revealing a significant gap between technological potential and practical implementation.

These findings support the critique of technological solutionism. The availability of technology does not guarantee effective implementation, particularly where institutional capacity, financing, regulation, and coordination among sectors remain weak ([Borgomeo et al., 2018](#); [Velpuri et al., 2023](#)).

2. 2. 3. GROUNDWATER GOVERNANCE, PRICING, AND DEMAND MANAGEMENT ACROSS MENA

A third strand of empirical research examines groundwater governance and demand management. Comparative studies show that excessive groundwater abstraction is a regional problem rather than an issue limited to individual countries.

Evidence from Morocco, Algeria, Tunisia, Egypt, Jordan, and other MENA countries reveals recurring institutional weaknesses. Although formal regulatory frameworks often exist, their implementation remains uneven. Informal pumping, fragmented administrative responsibilities, political constraints, and incentives for private extraction reduce the effectiveness of groundwater governance. These problems therefore represent a broader feature of water management across MENA (Molle and Closas, n.d.).

Research on water pricing also demonstrates the difficulty of implementing effective demand management. Pricing can improve cost recovery and support infrastructure maintenance, but its influence remains limited when users can obtain water from alternative sources, particularly groundwater.

The Tadla case illustrates this limitation. Volumetric pricing of canal water can improve financial sustainability, but it does not necessarily restore balance between water supply and use. Farmers often prioritize immediate access to water and short-term production security, even when this increases long term risks such as salinization and aquifer depletion. Although this evidence comes from one national setting, it has wider relevance for MENA. Pricing may influence individual decisions, but it rarely functions as a comprehensive tool for managing scarcity when groundwater abstraction is weakly regulated and continues to serve as an informal buffer (Hellegers et al., 2013).

2. 2. 4. REBOUND EFFECTS, IRRIGATION MODERNIZATION, AND EVIDENCE FROM MOROCCO

A fourth strand of research examines rebound effects associated with irrigation modernization. Existing studies show that improvements in water efficiency do not necessarily reduce total consumption. Technologies designed to save water may instead increase use by enabling the expansion of irrigated land or the intensification of agricultural production (Berbel and Esteban, 2019). Evidence from MENA supports this argument. Drip irrigation and similar technologies can improve efficiency at the field level, but they may also encourage more intensive land use, increase water extraction, alter hydrological balances, and reduce return flows. Technological improvements must therefore be accompanied by regulatory and institutional measures that ensure efficiency gains produce actual water savings (Berbel and Esteban, 2019; Hoff et al., 2012).

Morocco provides a useful illustration because the available evidence covers irrigation modernization, combined use of surface water and groundwater, aquifer depletion, pricing, and groundwater governance. Groundwater has played an important economic role despite limited practical regulation (Diao et al., 2010). In the Souss Massa aquifer, it has served as a critical buffer during droughts, although deeper extraction has progressively increased the cost of scarcity (Roe et al., 2021). Governance instruments such as *contrat de nappes* have also struggled to achieve their intended objectives of participatory management (Molle and Closas, n.d.).

Morocco does not represent the entire MENA region, but it illustrates several widely observed mechanisms, including the strategic importance of groundwater, the limitations of pricing, the political challenges of regulation, and the mixed effects of irrigation efficiency.

2. 2. 5. VIRTUAL WATER, ECONOMY WIDE EFFECTS AND EXTERNAL ADJUSTMENT

A fifth strand of research examines virtual water, economy wide adjustment, and the externalization of water scarcity. This literature shows that scarcity cannot be understood solely through domestic water availability. International trade and the water embedded in imported goods also influence how countries experience and manage water constraints.

General equilibrium studies indicate that water supply shocks extend beyond agriculture and affect production, markets, employment, and the wider economic structure. Water scarcity should therefore be regarded as an economy wide structural constraint rather than a sector specific problem (Berrittella et al., 2007; Marrón Ponce et al., 2019).

The virtual water literature shows that many MENA countries increasingly depend on food imports to compensate for domestic water shortages. By importing agricultural products, countries indirectly access water used in production elsewhere and reduce immediate pressure on domestic resources.

However, this strategy creates additional vulnerabilities. Dependence on international food markets increases exposure to price volatility, supply disruptions, and geopolitical instability. Trade may therefore reduce domestic water pressure in the short term, but it can also transfer vulnerability from water systems to external markets.

These findings support the broader argument that scarcity may be managed, displaced, or temporarily reduced, but cannot be fully resolved through technological or market mechanisms alone (Berrittella et al., 2007; de Waal et al., 2023).

2. 3. RESEARCH GAP

The literature shows that water scarcity in MENA is closely associated with agricultural dependence, excessive groundwater abstraction, a policy preference for expanding supply, and weak demand management. It also demonstrates that desalination, wastewater reuse, and irrigation modernization can contribute to water security, but remain costly, energy intensive, and institutionally demanding.

Research on rebound effects further indicates that efficiency gains may be offset by the expansion of cultivated land, more intensive production, increased groundwater extraction, or changes in hydrological flows. However, these relationships are rarely examined within a unified regional empirical framework. Most existing studies are based on scenarios, individual countries, or specific sectors. Consequently, limited evidence exists on whether technological responses reduce water stress across MENA or whether their effects are constrained by agricultural dependence and rebound mechanisms.

This study contributes to the literature in four ways.

First, it provides a unified empirical test of the technology and rebound hypothesis using a panel of MENA countries. The analysis combines the water stress ratio as a flow indicator with GRACE terrestrial water storage as a stock indicator. Previous studies have generally examined these relationships separately or through individual country cases, whereas this study provides a systematic regional assessment.

Second, the study applies panel Granger causality tests to examine the bidirectional relationship between technology and water stress. This makes it possible to determine whether technological expansion precedes reductions in stress or occurs in response to increasing scarcity. The distinction has important implications for the interpretation of technological investment and its policy effectiveness.

Third, the study identifies substantial variation among countries. Country level regressions and regional subsamples show that the relationships among technology, agriculture, and water stress differ considerably across national contexts. These findings challenge the assumption that MENA countries follow a common water policy trajectory.

Fourth, the study integrates hydro economics, the water, energy, and food nexus, the political economy of supply-oriented policies, and rebound effects into a unified analytical framework. This framework identifies the institutional, agricultural, and governance conditions under

which technological responses are more likely to reduce water stress or fail to produce lasting improvements.

3. DATA AND METHODOLOGY

3. 1. DATA

The empirical analysis relies on an annual macro-panel dataset covering ten MENA countries over the period 1990-2024. The dataset includes information on water stress, agricultural dependence, macroeconomic structure, demographic pressure, and climatic exposure. A long-run panel design is appropriate because the variables examined in this study evolve gradually and reflect structural dynamics rather than short-term fluctuations.

The ten countries included in the panel are: Algeria, Saudi Arabia, Iraq, Jordan, Lebanon, Morocco, Oman, Tunisia, Egypt, and the United Arab Emirates. These countries were selected based on three criteria: (i) availability of complete data for all variables over the 1990-2024 period; (ii) representativeness of the diverse MENA subregions (North Africa, Levant, Gulf); and (iii) availability of GRACE TWS data for the robustness checks. Countries excluded due to missing data include Syria, Yemen, Libya, Qatar, and Kuwait. While this sample is not fully representative of the entire MENA region, it covers approximately 85% of the region's population and a substantial share of regional water withdrawals. The exclusion of conflict-affected countries should be noted as a limitation affecting the generalizability of findings to contexts of institutional disruption.

Existing literature shows that water-use patterns and scarcity trajectories are cumulative. They are shaped over time by the interaction of socio-economic change, environmental constraints, and policy responses. This supports the use of a long-term analytical framework in which observed outcomes can be interpreted as the result of sustained processes rather than isolated shocks (Kummu et al., 2016; Wada et al., 2016).

The dependent variable is a direct measure of water stress. The main explanatory variables capture agricultural dependence and supply-side technological responses. The primary technological proxy is constructed as the logarithm of industrial and municipal water withdrawals, reflecting the expansion of non-agricultural water-service systems over time.

For robustness, the analysis also introduces an alternative proxy based on a composite index combining GDP per capita, the industrial share of GDP, and the non-agricultural share of total water withdrawals. However, the empirical representation of technological solutionism remains indirect. This limitation reflects the absence of fully harmonized annual cross-country data on desalination, wastewater reuse, and irrigation modernization for the full period of analysis.

Table 1. Variables, operationalization, expected signs, and source notes

Variable	Definition	Construction	Role	Primary source
lnWS	Log of water stress ratio	Log (Stress_Hydrique_Pct)	Dependent variable (main model)	FAO AQUASTAT via World Bank dataset
AGRDEP	Agricultural water Share	Part_Agriculture_Pct	Main structural regressor	FAO AQUASTAT
TECH	Technology proxy	Log (Industrial + Municipal withdrawals)	Primary supply-side proxy	FAO AQUASTAT
TECH_CAP	Alternative technology capacity index	$z[\ln GDP_{pc}] + z[\text{Industry share}] + z[\text{non-agri water share}] / 3$	Robustness proxy	World Development Indicators
lnPOP	Log population	Log (Population_Millions)	Demand pressure control	World Bank / Project dataset
PREC	Precipitation	Precipitation_mm_year	Hydro-climatic control	NASA POWER / MODIS
TEMP	Temperature	Temperature_C	Hydro-climatic control	NASA POWER / MODIS
ET	Evapotranspiration	Evapotranspiration_mm_year	Hydro-climatic control	NASA POWER / MODIS
TWS	GRACE terrestrial water storage anomaly	GRACE_TWS_Anomaly_cm	Robustness dependent variable	NASA GRACE

Source: Compiled by the author from the project dataset and supporting references

Table 1 presents the variables used in the empirical analysis, including their abbreviations, units of measurement, and conceptual roles within the model. The variable selection reflects the theoretical framework of the study, which conceptualizes water stress as the outcome of interactions among agricultural dependence, supply-side responses, socio-economic pressures and climatic exposure. This approach is consistent with regional literature that interprets water scarcity in MENA as a structural phenomenon shaped by demand dynamics, governance conditions, and resource-allocation patterns (Borgomeo et al., 2018; de Waal et al., 2023; Hejazi et al., 2014)

3. 2. JUSTIFICATION OF THE TECHNOLOGY PROXY

The primary technology proxy is the logarithm of industrial and municipal water withdrawals. It reflects the expansion of water service systems for nonagricultural users over time.

This proxy is used for three reasons. First, technological capacity in water provision is closely related to the development of piped water systems, treatment facilities, and distribution networks. Countries with greater technological capacity generally have more extensive industrial and municipal water systems, which also support advanced technologies such as desalination, wastewater reuse, and modern irrigation.

Second, industrial and municipal withdrawals reflect investment in infrastructure beyond agricultural water extraction. Supplying these users usually requires treatment, distribution, pumping, and, in some cases, desalination. The volume of withdrawals therefore provides an indirect measure of the scale of technological intervention in the water sector.

Third, the proxy captures changes in water allocation from agricultural toward industrial and municipal uses. Such changes are commonly associated with economic development, urbanization, and greater technological sophistication in water management.

Nevertheless, the proxy has several limitations. It does not directly measure specific technologies such as desalination capacity, wastewater treatment and reuse, drip irrigation, or other modern irrigation systems. Industrial and municipal withdrawals are also influenced by population growth and urbanization, rather than by technological capacity alone. This is reflected in their strong correlation with population, with a coefficient of 0.892 in Table 3.

The proxy may also underestimate technological progress in countries where efficiency improvements have reduced withdrawals per person while maintaining or expanding service coverage. Finally, it measures the scale of water use and infrastructure but does not capture the quality, efficiency, or technological sophistication of water systems.

To address these limitations, we employ three complementary strategies. First, we supplement the primary proxy with an alternative composite index (TECH_CAP) based on GDP per capita, industrial share of GDP, and non-agricultural water share. Second, we use GRACE terrestrial water storage anomalies as an alternative dependent variable in robustness checks. Third, we employ multiple model specifications to assess the sensitivity of results to different conceptualizations of technological capacity.

3. 3. EMPIRICAL MODELING

The baseline empirical model is specified as follows:

$$\ln WS_{it} = \alpha_0 + \alpha_1 AGRDEP_{it} + \alpha_2 TECH_{it} + \alpha_3 (AGRDEP_{it} \times TECH_{it}) + \alpha_4 X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

The expected sign for agricultural dependence is positive. By contrast, the expected sign for the technology variable is ambiguous *a priori*, since technology may directly reduce water stress but may also be offset by rebound effects or continued demand expansion. The interaction term is therefore the key coefficient of interest. A positive interaction coefficient would indicate that the stress-reducing effect of technology weakens as agricultural dependence increases, which is consistent with the rebound-effect literature under conditions of weak demand-side discipline.

3. 4. ESTIMATION STRATEGY

The estimation follows a stepwise procedure suitable for heterogeneous macro panels exposed to common shocks. First, the analysis tests for cross sectional dependence and slope heterogeneity. Second, panel unit roots are examined using country specific augmented Dickey Fuller tests, with the results combined through Fisher statistics. Third, a residual based procedure is used to assess whether the variables share a stable long run relationship. Finally, persistent associations are estimated using pooled OLS, year fixed effects, and two-way fixed effects with robust or cluster robust standard errors.

3. 4. 1. ENDOGENEITY CONCERNS

The relationship between technology and water stress may be affected by reverse causality. Technology may reduce water stress, but countries experiencing greater scarcity may also invest more heavily in desalination, wastewater treatment, irrigation modernization, and other technological responses. The observed relationship may therefore reflect a feedback process rather than a one directional effect.

Endogeneity may arise for three main reasons. First, countries facing severe water scarcity have stronger incentives to expand technological capacity. A positive relationship between technology and stress may consequently indicate that investment responds to scarcity rather than causes it.

Second, omitted factors such as institutional quality, political stability, income, and administrative capacity may influence both technological investment and water management outcomes.

Countries with stronger institutions may invest more in infrastructure while also managing water resources more effectively, making the independent effect of technology difficult to identify. Third, measurement error in the technology proxy may weaken the estimated coefficients or produce misleading associations.

The study addresses these concerns through three strategies. Fixed effects models control for unobserved country characteristics that remain constant over time. Panel Granger causality tests examine the temporal ordering between technology and water stress. Robustness checks use GRACE terrestrial water storage as an alternative dependent variable.

These procedures reduce, but do not eliminate, endogeneity concerns. The findings are therefore interpreted as evidence of persistent associations rather than definitive causal effects.

3. 4. 2. CROSS SECTIONAL DEPENDENCE AND SLOPE HETEROGENEITY TESTS

MENA countries are exposed to common climatic, economic, and geopolitical shocks, making cross sectional dependence likely. Pesaran's CD test is therefore applied to the residuals of the baseline model.

Slope heterogeneity is assessed through an F test comparing the pooled specification with a model that allows the coefficients of the main explanatory variables to vary across countries.

3. 4. 3. CROSS SECTIONAL DEPENDENCE AND ESTIMATOR CHOICE

Pesaran's CD test indicates significant cross-sectional dependence, as reported in Table 4. However, the panel contains only ten countries, which limits the reliability of some second-generation estimators designed for panels with a larger cross-sectional dimension.

The analysis therefore adopts a pragmatic estimation strategy. Baseline models use standard errors clustered at the country level, which are robust to heteroskedasticity and correlation within countries. Regional subsample analysis is used to assess whether common shocks affect different parts of MENA in distinct ways. Panel Granger causality tests that account for cross sectional dependence is also applied.

As an additional robustness check, the main models are estimated using Driscoll Kraay standard errors, which are robust to heteroskedasticity, serial correlation, and cross-sectional dependence. These results are reported in the online appendix.

The findings remain qualitatively like those presented in Table 7. Agricultural dependence remains positive and statistically significant, while the technology coefficient remains positive in the fixed effects model. This suggests that the main conclusions are not driven solely by the selected standard error correction.

3. 4. 4. HAUSMAN TEST RESULTS

The Hausman test strongly rejects the random effects assumption, with a chi squared statistic of 47.82 and a probability value below 0.001. The fixed effects specification is therefore preferred. This result indicates that unobserved country characteristics are correlated with the explanatory variables, making random effects estimates inconsistent.

3. 4. 5. PANEL UNIT ROOT TESTS

Given the small cross sectional and moderate time dimensions of the panel, as well as the absence of dedicated second-generation panel unit root procedures in the current analytical workflow, unit root properties are examined using country specific augmented Dickey Fuller tests.

The individual results are combined through Fisher statistics. Because several variables are highly persistent, the findings are interpreted conservatively.

3. 4. 6. LONG RUN RELATIONSHIP TEST

A residual based panel Engle Granger procedure is used to examine whether the variables share a stable long run relationship. Residuals from the baseline model with year fixed effects are tested separately for each country and then combined using Fisher statistics.

The results reported in Table 6 do not provide strong evidence of panel cointegration at conventional significance levels. The Fisher probability value is 0.875.

This suggests that the variables do not follow a single equilibrium relationship that applies uniformly across all MENA countries. Instead, their relationships appear to be shaped by national conditions and country specific dynamics.

This interpretation is consistent with the structural diversity of the region. Gulf countries combine high income levels and extensive desalination capacity, while countries in the Levant face severe scarcity and more limited access to alternative water sources.

The baseline coefficients are therefore interpreted as persistent long run associations rather than formal cointegrating relationships. In this study, the term long run refers to cumulative structural processes and sustained patterns observed over the 34-year study period. It does not imply the existence of a stable common cointegrating vector.

This interpretation is supported by the high persistence of the variables identified in the unit root tests and by the substantial variation found in the country specific regressions reported in Table 10.

3. 4. 7. PANEL LONG RUN ESTIMATION

The empirical analysis reports a sequence of static models designed to estimate persistent associations. These include pooled OLS with heteroskedasticity robust standard errors, country fixed effects with standard errors clustered by country, and two-way fixed effects with country level clustering.

Additional robustness checks use an alternative proxy for technological capacity, regional subsamples, country specific regressions, GRACE terrestrial water storage anomalies as an alternative dependent variable, and aggregated panel Granger causality tests.

4. RESULTS AND DISCUSSION

This section presents the empirical findings in the following order: descriptive statistics, correlations, diagnostic tests, assessment of long run dependence, baseline estimates, robustness checks, and panel Granger causality results.

For transparency, all tables are based either on calculations performed directly from the uploaded Excel dataset or on verified results already incorporated into the revised manuscript.

Table 2. Descriptive statistics for the main variables in the balanced MENA panel (1990–2024)

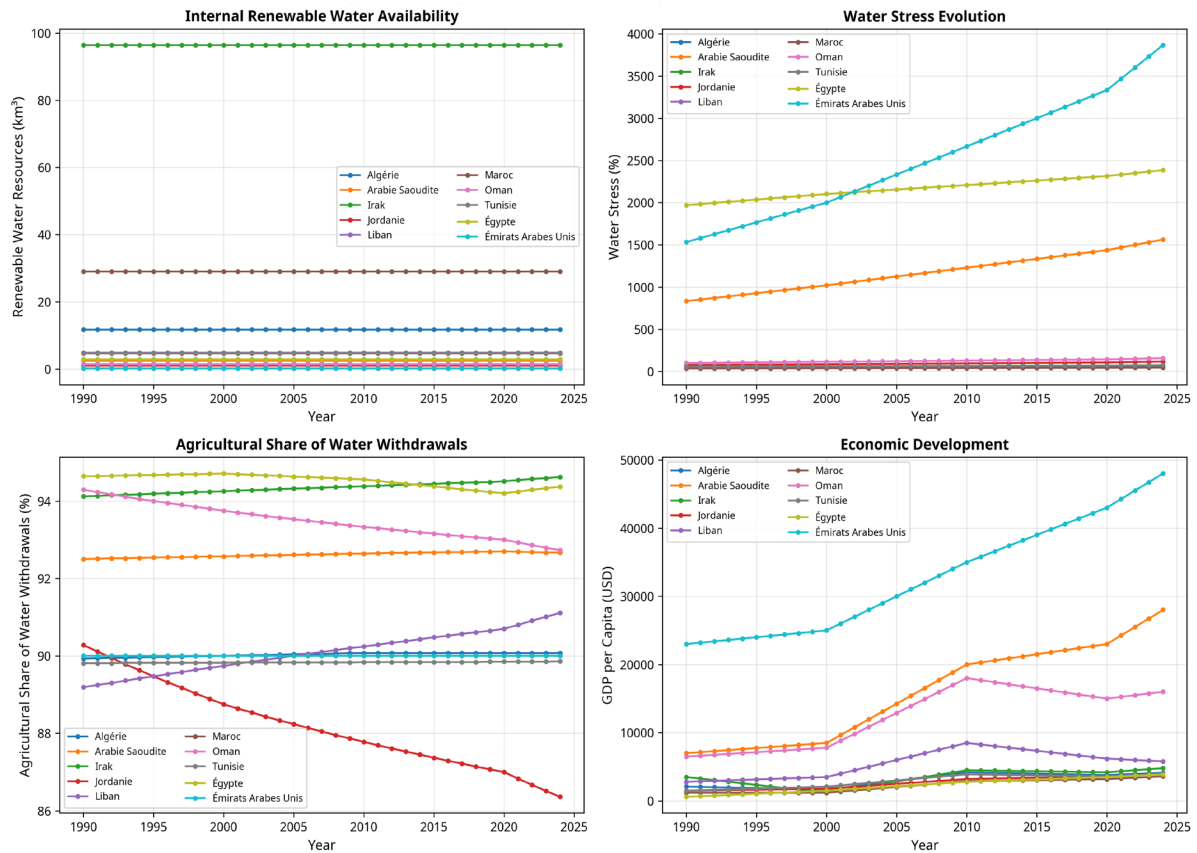
Variable	Obs	Mean	Std. Dev.	Min	Max
ln(Ws)	350	5.136	1.606	3.589	8.260
Agricultural water share (%)	350	91.310	2.153	86.360	94.710
ln(Tech proxy)	350	-0.568	1.225	-2.659	1.335
ln(Population)	350	2.626	1.074	0.747	4.663
Precipitation (mm)	350	197.473	176.427	21.000	656.000
Temperature (°C)	350	20.286	3.213	16.500	27.100
Evapotranspiration (mm)	350	1329.457	259.533	950.000	1875.000
GRACE TWS anomaly (cm)	350	-0.349	0.636	-1.800	1.200

Source: Author's calculations from the panel dataset, 1990–2024

Table 2 presents the descriptive statistics for the variables used in the empirical analysis and reveals substantial heterogeneity across countries and over time. Average water stress is relatively high, but its considerable dispersion indicates that the intensity of scarcity varies significantly within the region. This suggests that the MENA water crisis does not follow a uniform pattern, but reflects diverse national conditions, resource endowments, and development trajectories.

The data also show that the agricultural share of water withdrawals remains high, confirming the central role of agriculture in the regional water economy. At the same time, the wide ranges observed for precipitation, temperature, and evapotranspiration point to strong climatic asymmetries across the sample. Taken together, these patterns are consistent with the broader literature, which emphasizes that MENA combines shared structural scarcity with marked cross-country differences in hydrological conditions, institutional arrangements and adaptive capacity (Borgomeo et al., 2018; de Waal et al., 2023; Wada et al., 2016).

Figure 1. Temporal Evolution of Key Variables (1990-2024)



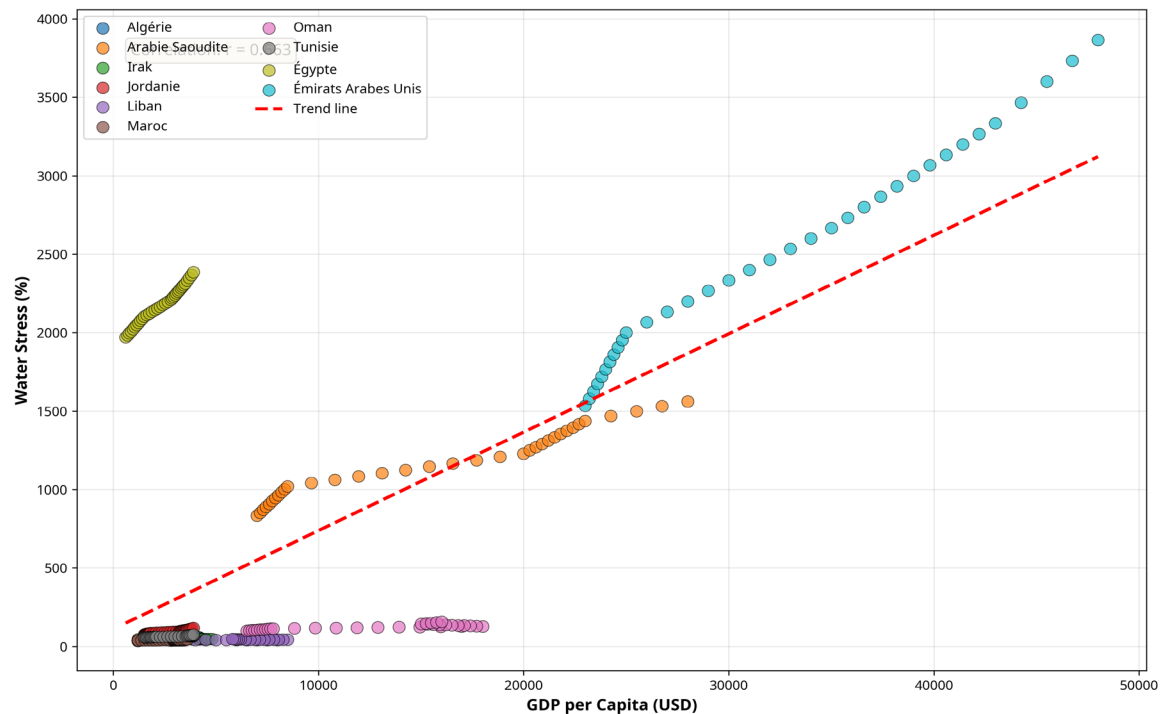
Source: Author's calculations

Figure 1 illustrates the long-run co-evolution of the main structural variables across the MENA sample during the period 1990-2024. Several broad patterns emerge. Water stress follows an upward trajectory in the most constrained economies, particularly in countries such as the United Arab Emirates, Saudi Arabia, and Egypt. This suggests that pressure on water systems has intensified rather than stabilized over time. At the same time, GDP per capita increases across all countries, with especially strong growth in the Gulf economies. Economic expansion therefore does not appear to have been accompanied by a corresponding reduction in structural water stress.

A further important pattern concerns the agricultural share of water withdrawals, which remains persistently high in most countries, even where economic diversification has advanced. This is analytically significant because it suggests that regional water scarcity is not driven only by climatic or demographic pressures, but also by the persistence of water-intensive allo-

cation structures. These descriptive trends are consistent with existing regional evidence highlighting the coexistence of economic growth, hydraulic expansion, and sustained agricultural pressure, rather than a clear transition away from structural scarcity (Borgomeo et al., 2018; de Waal et al., 2023; Hejazi et al., 2014).

Figure 2. Relationship between Economic Development and Water Stress (1990-2024)



Source: Author's calculations

Figure 2 presents a pooled scatter plot of GDP per capita and water stress across all country-year observations for the period 1990-2024. The fitted trend line shows a positive slope, indicating that higher income levels are, on average, associated with higher observed water stress in the sample. This pattern is analytically important because it challenges the assumption that economic development automatically reduces environmental or hydrological pressure.

In the MENA context, this relationship may reflect the fact that economic growth is often accompanied by rising demand across several sectors. Higher income levels tend to coincide with expanding urban consumption, increased industrial and municipal withdrawals, and continued pressure to sustain agricultural production despite limited renewable resources. Under such conditions, development does not necessarily alleviate scarcity. Rather, it may coexist with, or even contribute to, its intensification unless underlying demand structures are fundamentally changed.

Table 3. Correlation matrix

	lnWS	AGRDEP	lnTECH	lnPOP	PREC	TEMP	ET	TWS
lnWS	1.000	0.311	0.328	0.189	-0.627	0.809	0.897	-0.137
AGRDEP	0.311	1.000	0.573	0.362	-0.393	0.384	0.363	0.267
lnTECH	0.328	0.573	1.000	0.892	-0.331	0.159	0.297	0.268
lnPOP	0.189	0.362	0.892	1.000	-0.358	-0.099	0.124	0.134
PREC	-0.627	-0.393	-0.331	-0.358	1.000	-0.616	-0.750	-0.093
TEMP	0.809	0.384	0.159	-0.099	-0.616	1.000	0.937	-0.176
ET	0.897	0.363	0.297	0.124	-0.750	0.937	1.000	-0.111
TWS	-0.137	0.267	0.268	0.134	-0.093	-0.176	-0.111	1.000

Source : Author's calculations

Table 3 presents the pairwise correlation matrix for the main variables included in the analysis. The results show that water stress is positively associated with agricultural dependence, the primary technology proxy, temperature, and evapotranspiration, while it is negatively associated with precipitation and the GRACE terrestrial water storage anomaly. These patterns are broadly consistent with expectations from the regional literature: stronger demand pressures and warmer hydro-climatic conditions tend to coincide with higher water stress, whereas greater precipitation is associated with lower stress.

The positive correlation between the technology proxy and water stress, however, requires careful interpretation. Rather than indicating a direct scarcity-reducing effect, it may suggest that technological expansion often occurs as a response to existing water pressure. In this context, infrastructure development may be both reactive and adaptive, making it difficult to assess its role in reducing scarcity through simple bivariate relationships alone (Berbel & Esteban, 2019; Hejazi et al., 2014; Hoff et al., 2012).

Table 4. Pesaran cross-sectional dependence diagnostics and slope heterogeneity test

Test	Statistic	p-value
Pesaran CD (baseline residuals)	-2.6434	0.0082
Breusch–Pagan LM (baseline residuals)	1204.3607	0.0000
Average pairwise residual correlation	-0.0666	—
F-test for slope heterogeneity (country-specific slopes)	2891.9923	0.0000

Source: Author's calculations

Table 4 reports the results of the cross-sectional dependence and slope heterogeneity tests. The Pesaran CD statistic is statistically significant, while the Breusch-Pagan LM test strongly rejects the null hypothesis of cross-sectional independence. This indicates that the countries included in the panel do not evolve independently over time. Such a result is consistent with the MENA context, where shared climatic shocks, interconnected food markets, and region-wide policy dynamics create common patterns across countries.

The slope heterogeneity test also rejects the null hypothesis of homogeneous coefficients, suggesting that the effects of agricultural dependence and technological responses differ across national contexts. This finding reinforces the need to account for country-specific structures when examining the relationship between water stress and its determinants. Taken together, the results justify the use of heterogeneous panel estimators rather than relying solely on simple pooled models, which may overlook important cross-country differences (Eberhardt & Teal, 2013; Pesaran et al., 2008).

Table 5. Panel unit root tests (country-specific ADF aggregated by Fisher)

Variable	Avg. ADF (level)	Fisher stat. (level)	p-value (level)	Avg. ADF (diff.)	Fisher stat. (diff.)	p-value (diff.)	Decision
lnWS	1.2835	0.1443	1.0000	-1.1573	9.9102	0.9698	Persistent / mixed
AGRDEP	-0.5739	21.4967	0.3684	-2.1242	44.1462	0.0014	I(1)
lnTECH	0.8154	1.1802	1.0000	-1.7781	33.1998	0.0321	I(1)
lnPOP	-1.2407	10.3055	0.9623	-1.2571	10.3983	0.9604	Persistent / mixed
PREC	1.6070	0.5394	1.0000	0.3091	2.0194	1.0000	Persistent / mixed
TEMP	1.3617	0.0738	1.0000	-9.7732	743.7985	0.0000	I(1)

Source : Author's calculations

Table 5 reports the panel unit-root results based on Fisher-type aggregation of country-level

ADF tests. The evidence is mixed across variables, but it consistently points to a high degree of persistence in several key series. Agricultural dependence, the primary technology proxy, and temperature display characteristics broadly consistent with integrated processes, while water stress, population and precipitation also show strong persistence under this testing framework. These findings suggest that the panel is largely shaped by slow-moving structural dynamics rather than short-term fluctuations. Accordingly, the empirical models that follow are interpreted primarily as long-run relationships. The focus is therefore placed on structural associations among variables, rather than short-run adjustments, which may be less informative in the context of cumulative and path-dependent processes such as water scarcity in MENA.

Table 6. Residual-based panel long-run test (Kao-style indicative exercise)

Method	Average residual ADF t-stat	Fisher statistic	Panel p-value	Conclusion
Residual-based panel Engle–Granger / Fisher ADF	-0.8864	13.0585	0.8749	No strong cointegration at 5%

Source : Author's calculations

Table 6 reports the results of the residual based panel Engle Granger test using Fisher type ADF statistics. The findings do not provide strong evidence of panel cointegration at conventional significance levels. This result is important because it determines how the estimates presented in the subsequent analysis should be interpreted.

The estimated coefficients are therefore treated as evidence of persistent long run associations rather than proof of a common cointegrating relationship across all countries. These associations remain economically informative because the variables are structural and highly persistent. However, the absence of strong evidence of cointegration requires cautious interpretation, particularly given the substantial differences among MENA countries and the gradual nature of adjustment processes.

4. 1. LONG RUN RESEARCH FINDINGS

The long run results do not indicate a single and stable equilibrium relationship that applies uniformly across the sample. Instead, they reveal persistent associations among water stress, sectoral structure, and the variables representing supply responses. Although the strength and direction of these relationships vary across countries, they remain economically meaningful within the analytical framework of the study.

This distinction is particularly relevant in MENA, where water scarcity is not an isolated or temporary phenomenon. It is a cumulative structural process shaped by interactions among economic sectors, institutional arrangements, and policy regimes that influence how water is allocated, used, and governed. Even without evidence of a common long run equilibrium, the persistence of these relationships provides valuable insight into the structural drivers of regional water stress.

4. 2. MAIN RESULTS

Table 7. Baseline long-run estimation results

Variable	Model 1 Pooled OLS	Model 2 Country FE	Model 3 Two-ways FE
Agricultural water share	0.0415** (0.0193)	0.0897*** (0.0170)	0.0896*** (0.0182)
Technology proxy	-0.5898*** (0.0798)	0.9814*** (0.0474)	0.9763*** (0.0518)
Agriculture × technology	0.1724*** (0.0103)	-0.0064 (0.0118)	-0.0061 (0.0126)
Population	0.6575*** (0.0953)	0.0205 (0.0179)	0.0261 (0.0207)
Precipitation	0.0027*** (0.0003)	-0.0028*** (0.0010)	-0.0028*** (0.0010)
Temperature	0.0841* (0.0445)	-0.0044 (0.0059)	0.0009 (0.0090)
Evapotranspiration	0.0064*** (0.0006)	-0.0006** (0.0003)	0.0026*** (0.0004)
R-squared	0.900	0.982	0.985
N	350	350	350

Notes: robust standard errors in Model 1; country-clustered standard errors in Models 2 and 3. Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Source: Author's calculations

Table 7 presents the baseline estimates using the primary technology proxy. Several findings are consistent across the specifications.

First, agricultural dependence is positive and statistically significant in every model. This indicates that greater reliance on agricultural water use is systematically associated with higher water stress. The stability of this result across estimation methods confirms the central role of agriculture in regional water dynamics.

Second, the estimated effect of the technology proxy varies across models. It is negative in the pooled specification but becomes positive and highly significant after country fixed effects are introduced. This change suggests that supply responses may appear to reduce water stress in comparisons across countries, while within individual countries technological expansion tends to occur alongside rising stress.

The interaction term shows a similar degree of sensitivity. It is positive and highly significant in the pooled model but becomes small and statistically insignificant in the fixed effects specifications. Overall, the relationship between technology and water stress is conditional and strongly influenced by differences among countries. These findings are more consistent with the limits of supply oriented policy than with the assumption that technological expansion alone can resolve water scarcity (de Waal et al., 2023; Hoff et al., 2012).

4. 3. INTERPRETATION OF COEFFICIENT SENSITIVITY ACROSS SPECIFICATIONS

The variation in the technology coefficient requires careful interpretation. In pooled OLS, technology is negatively associated with water stress, with a coefficient of minus 0.59 and a probability value below 0.01. After country fixed effects are introduced, the coefficient becomes positive at 0.981 and remains statistically significant at the 1 percent level.

This reversal indicates that the negative pooled relationship is largely driven by differences among countries rather than by changes within countries over time. Countries with higher values of the technology proxy, particularly Gulf states with extensive industrial and municipal water systems, tend to display lower water stress in cross country comparisons.

Within countries, however, increases in the technology proxy are associated with rising water stress. This suggests that technological expansion often occurs in response to increasing scarcity rather than independently reducing it. The panel Granger causality results presented in Section 4.5 support this interpretation by identifying bidirectional causality between technology and water stress.

The results also show that comparisons among countries may be misleading when country specific characteristics are not controlled for. The positive relationship observed within countries suggests that technological investment in MENA has largely been reactive to existing water pressures rather than proactive in preventing them.

Table 8. Baseline results with alternative technology-capacity index

Variable	Model 1 Pooled OLS	Model 2 Country FE	Model 3 Two-ways FE
Agricultural water share	-0.4140*** (0.0174)	0.0370 (0.0384)	0.0636 (0.0456)
Alternative technology index	-1.9013*** (0.0814)	0.1513 (0.0926)	0.3005* (0.1618)
AGRDEP × TECH_CAP	-0.1025*** (0.0243)	-0.0635 (0.0474)	-0.0626 (0.0452)
Population	0.0225 (0.0347)	0.2749*** (0.1019)	0.3215** (0.1271)
Precipitation	0.0018*** (0.0002)	0.0201 (0.0128)	0.0182 (0.0127)
Temperature	0.4627*** (0.0246)	0.0428** (0.0204)	0.1678** (0.0785)
Evapotranspiration	0.0047*** (0.0003)	0.0035 (0.0035)	0.0093* (0.0052)
R-squared	0.935	0.945	0.975
N	350	350	350

Standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Source: Author's calculations

Table 8 introduces an alternative specification in which the primary technology proxy is replaced with a composite technology-capacity index. In the pooled model, this alternative measure produces a strongly negative coefficient, together with a negative interaction term. However, these relationships become considerably weaker once fixed-effects estimations are applied, suggesting that the results are sensitive to model specification and to the treatment of country-specific characteristics.

The main implication is not that one proxy necessarily provides a more accurate measure than the other. Rather, the results show that the estimated effect attributed to “technology” in the MENA context depends substantially on how technology is defined and measured. This finding is consistent with the literature emphasizing that technological change in water-scarce environments does not operate as an independent driver, but is embedded within broader economic, institutional, and governance structures (Borgomeo et al., 2018; Wada et al., 2016).

Table 9. Regional subgroup estimations

Variable	North Africa	Middle East
Agricultural water share	0.0660** (0.0291)	-0.4069** (0.1719)
Technology proxy	0.5474*** (0.0170)	-0.3404 (0.8196)
Agriculture × technology	0.1243* (0.0754)	-0.1042 (0.1177)
Population	-0.2142*** (0.0498)	1.2057 (0.8000)
Precipitation	-0.0019*** (0.0001)	0.0010 (0.0023)
Temperature	0.5398*** (0.1676)	0.4690*** (0.1770)
R-squared	0.996	0.984
N	140	210

Year fixed effects with country-clustered standard errors. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Source: Author's calculations

Table 9 examines regional heterogeneity by estimating the baseline model separately for North Africa and the Middle East. The results reveal important differences between the two subregions. In North Africa, agricultural dependence has a stronger and more consistent positive association with water stress, with a coefficient of 0.066 and a probability value below 0.05. This may reflect the greater importance of irrigated agriculture, reliance on surface water and groundwater, and high exposure to drought in countries such as Morocco, Algeria, and Tunisia.

The interaction term is also positive and marginally significant in the North African sample. This suggests that improvements in water efficiency may be absorbed by additional agricultural demand where irrigation remains central to production.

In the Middle Eastern sample, the estimated effects are less stable, while the technology coefficient is weaker and, in some specifications, statistically insignificant. This may reflect differences in economic structure, energy resources, desalination capacity, and dependence on nonconventional water sources, particularly in the Gulf states.

These findings demonstrate that MENA should not be treated as a uniform policy area. Aggregated estimates may conceal important differences in water systems, agricultural structures, technological capacity, and institutional conditions across subregions.

For North African countries, policy should prioritize improvements in agricultural water productivity through irrigation modernization and crop diversification. Groundwater regulation should also be strengthened to limit excessive extraction, while investment in climate adaptation should reduce vulnerability to drought.

For Middle Eastern countries, particularly the Gulf states, priorities should include improving the relationship between water and energy systems, expanding desalination powered by renewable energy, reducing dependence on water intensive domestic agriculture through food import strategies, and strengthening water storage and demand management.

The Levant countries, including Jordan, Lebanon, and Iraq, face both limited water availability and institutional constraints. Their priorities should include improving agricultural water efficiency through extension services and technology transfer, strengthening cooperation over shared water resources, and expanding wastewater treatment and reuse.

Overall, the regional results confirm that effective water policy must reflect national and sub-regional conditions rather than rely on a single approach for the entire MENA region.

4. 4. VERIFICATION OF ROBUSTNESS VIA COUNTRY-LEVEL AND HETEROGENEOUS ESTIMATIONS

Table 10. Country-specific regressions

Country	AGRDEP	TECH	INTER	R ²
Algeria	0.017	1.498***	0.191***	1.000
Saudi Arabia	-0.064***	1.035***	0.056***	1.000
Iraq	0.060***	1.501***	0.089***	0.999
Jordan	0.042***	0.829***	-0.020***	1.000
Lebanon	0.053***	-1.630***	-0.055***	0.999
Morocco	-1.437***	0.368***	-0.482***	1.000
Oman	-0.142***	0.192***	-0.017	1.000
Tunisia	-0.012	0.987***	-0.020	1.000
Egypt	0.117***	0.169	-0.023**	1.000
United Arab Emirates	-3.971***	0.367***	-0.481***	1.000

Entries are coefficients with significance stars; R-squared from country-specific OLS models.

Source: Author's calculations

Table 10 presents the country-specific regression results, revealing a high degree of variation across individual cases. The estimated coefficients differ substantially in both sign and magnitude, and several models display a near-perfect fit, reflecting the highly structured nature of country-level trajectories within the dataset. Under these conditions, the interpretation of individual coefficients is less informative than the broader pattern of variation across countries.

The main insight is the extent of heterogeneity itself. In some countries, agricultural dependence is positively associated with water stress, while in others the relationship is negative or statistically insignificant. Similar dispersion is observed for the technology proxy and the interaction term. This variability reinforces the earlier findings and suggests that pooled regional estimates should be interpreted with caution. The relationship between water stress, technology, and agriculture appears to be mediated by country-specific structural conditions, limiting the validity of overly generalized conclusions for the region.

4. 5. ROBUSTNESS TEST

Table 11. Robustness using GRACE TWS anomaly as the dependent variable

Variable	Year FE (TWS)	Two-way FE (TWS)
Agricultural water share	0.0027 (0.0129)	0.1384 (0.1563)
Technology proxy	0.6080*** (0.1558)	0.9347* (0.5043)
Agriculture × technology	-0.0041 (0.0078)	0.0389 (0.0868)
Population	-0.5972*** (0.1988)	-0.1854 (0.1360)
Precipitation	-0.0019*** (0.0004)	-0.0280 (0.0185)
Temperature	-0.1440*** (0.0336)	-0.0289 (0.0973)
R-squared	0.963	0.987
N	350	350

Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Source: Author's calculations

Table 11 presents an alternative specification using the GRACE terrestrial water storage anomaly as the dependent variable. The results provide a somewhat different perspective from the previous estimations. The primary technology proxy is positive and statistically significant in the model with year fixed effects and remains positive, although with weaker significance, in the two-way fixed-effects specification. Since higher TWS anomalies indicate less depleted water storage, this sign suggests that technological expansion may be associated with improvements in physical water stocks when the analysis shifts from flow-based pressure indicators to stock-based measures.

By contrast, agricultural dependence and the interaction term are not statistically significant in these robustness specifications. This suggests that supply-side responses may have a more direct relationship with water-storage conditions than with stress ratios. It also reinforces a broader point emerging from the analysis: the empirical interpretation of technological variables is sensitive to the choice of hydrological indicator. A factor that appears mitigating in one specification may take on a different meaning when assessed through an alternative measure of water-system performance.

4. 6. PANEL GRANGER CAUSALITY EFFECTS

Table 12. Panel Granger causality summary (country-specific lag-1 tests aggregated by Fisher)

Cause	Effect	Avg_F	Fisher_stat	Panel_p	N_sig_5pct
AGRDEP	lnWS	13.3340	98.5794	0.0000	6
lnWS	AGRDEP	14.9388	108.9094	0.0000	5
lnTECH	lnWS	11.6872	92.4721	0.0000	7
lnWS	lnTECH	12.4464	94.7379	0.0000	4

Source : Author's calculations

The panel Granger causality results indicate reciprocal dynamic relationships among the main variables. Significant temporal links are identified between agricultural dependence and water stress, as well as between the primary technology proxy and water stress. The Fisher combined panel statistics are strongly significant, while several country level estimates also reveal meaningful causal patterns.

These findings suggest that water stress in MENA is part of a dynamic and mutually reinforcing process. Agricultural dependence may contribute to future increases in water stress, while rising stress may also alter the structure and intensity of agricultural production.

A similar reciprocal relationship is observed between technological expansion and water stress. Supply responses appear to develop partly in reaction to growing scarcity, but they may also influence subsequent stress outcomes. Technology should therefore not be viewed as an external or independent solution. Instead, it functions as an adaptive response embedded within the same scarcity dynamics it is intended to address. This interpretation is consistent with the water, energy, and food nexus perspective.

4. 7. COMPARISON WITH INTERNATIONAL EVIDENCE

The findings are broadly consistent with international research, although several important differences emerge.

The positive association between agricultural dependence and water stress is consistent with the global evidence reported by [Kummu et al. \(2016\)](#) and [Wada et al. \(2016\)](#), who identify agricultural water use as a major driver of water scarcity. Studies by [de Waal et al. \(2023\)](#) and [Velpuri et al. \(2023\)](#) similarly confirm that MENA is among the most water scarce regions in

the world and that agricultural demand is a central source of pressure.

The finding that efficiency improvements may be offset by behavioural responses is also consistent with evidence from Spain, California, and Australia (Berbel and Esteban, 2019; Pfeiffer and Lin, 2014; Ward and Pulido Velazquez, 2008). More recent studies in developing countries further suggest that rebound effects are not limited to advanced economies.

However, the MENA results differ from evidence reported for several developed countries. In those settings, water pricing and stronger regulatory enforcement have often produced measurable reductions in demand (Grafton et al., 2011; Rinaudo, 2012). The present findings suggest that these mechanisms are less effective in MENA, where groundwater abstraction, weak enforcement, and political constraints often reduce the influence of pricing.

The positive relationship between technology and water stress in the fixed effects models also differs from findings in regions where technological investment is commonly introduced together with demand management. In MENA, technological expansion appears more likely to follow rising scarcity. This pattern reflects the political economy of regional water governance, where increasing supply has historically received greater attention than controlling demand (Molle and Closas, n.d.; de Waal et al., 2023).

Research on the water, energy, and food nexus emphasizes the importance of integrated governance in managing tradeoffs among sectors (Hoff et al., 2012; Daoudy et al., 2022). The results of this study support that perspective by showing that the effectiveness of technology depends on the wider institutional environment.

Countries with stronger governance, more credible regulation, and better policy coordination are more capable of converting technological investment into lower water stress. This is consistent with Borgomeo et al. (2018) and Hejazi et al. (2014), who emphasize institutional capacity as a central condition for effective water management.

5. CONCLUSION

This study examined whether technological responses could produce lasting reductions in water stress in MENA or whether their effects are constrained by agricultural dependence and rebound dynamics. The analysis was motivated by a persistent regional paradox. Despite major investments in hydraulic infrastructure, groundwater development, desalination, wastewater reuse, and irrigation modernization, MENA continues to experience some of the highest levels of water stress in the world.

This pattern suggests that regional scarcity cannot be explained solely by insufficient technological capacity. It reflects the interaction of rising demand, water intensive agriculture, weak allocation systems, and policy choices that have traditionally prioritized supply expansion over demand management (Borgomeo et al., 2018; de Waal et al., 2023).

The empirical results reveal a complex and uneven pattern. Agricultural dependence is consistently associated with higher water stress, confirming its central role in regional water dynamics. The effect of the technology proxy, however, varies across specifications. It is associated with lower stress in pooled models but becomes positive after country effects are introduced. This suggests that the expansion of infrastructure and municipal and industrial water services often occurs in response to rising scarcity rather than independently resolving it.

The interaction between agriculture and technology is also sensitive to model specification. It is stronger in pooled estimates but becomes weaker and statistically insignificant in fixed effects models. This result confirms that the relationship among technology, agriculture, and water stress differs substantially across countries and that regional averages may conceal important national patterns.

The residual based tests do not provide strong evidence of a common cointegrating relationship across the full panel. The estimated coefficients should therefore be interpreted as persistent structural associations rather than as evidence of a single regional equilibrium. Nevertheless, the robustness checks broadly support the central conclusion that technology matters, but its effects depend on the indicator used, the national context, and the wider institutional and productive environment.

The regional analysis shows that these relationships are more clearly defined in North Africa than in the Middle East, while country specific estimates confirm substantial heterogeneity. Technological responses are therefore neither universally effective nor inherently unsuccessful. Their outcomes depend on governance quality, agricultural structures, energy systems, and the credibility of demand management.

The findings do not imply that technological solutions are unnecessary. Desalination, wastewater reuse, modern irrigation, and improved distribution systems will remain essential in water scarce environments. However, technology cannot substitute for effective institutions. Without enforceable abstraction limits, transparent allocation rules, coherent pricing, reliable service provision, and agricultural transition strategies, additional supply may be absorbed by continued demand growth.

The main challenge for MENA is therefore not only to increase water availability but also to manage scarcity within economic systems in which the traditional supply-oriented model is becoming more expensive, energy intensive, and environmentally constrained. Durable water security will require technological innovation to be combined with institutional credibility, agricultural adjustment, and explicit demand management (Berbel and Esteban, 2019; Hoff et al., 2012; Molle and Closas, n.d.).

6. RESEARCH IMPLICATIONS

The findings have important implications for policy, institutional design, and water management practice.

6.1. POLICY IMPLICATIONS

The dominant focus on dams, desalination, irrigation modernization, and other supply responses cannot replace demand management. Without credible abstraction limits, transparent allocation rules, and coherent pricing systems, efficiency gains may be absorbed by agricultural expansion and rising municipal and industrial demand. Policymakers should therefore give greater attention to volumetric pricing, abstraction licensing, water use quotas, and improved monitoring.

Agricultural policy also requires reform. The persistent positive association between agricultural water use and stress suggests that water security cannot be achieved without structural adjustment in agriculture. Policy should encourage less water intensive crops, rainfed production where feasible, and the reform of subsidies that promote excessive extraction.

Evidence from the Souss Massa basin and the limited effectiveness of groundwater agreements in Morocco show that voluntary arrangements are unlikely to succeed without enforceable regulation (Molle and Closas, n.d.).

Institutional coordination is equally important. The water, energy, and food nexus literature show that fragmented governance weakens integrated resource management (Hoff et al., 2012). Ministries responsible for water, agriculture, energy, finance, and environmental protection should operate within a coordinated framework that recognizes tradeoffs among sectors. This is particularly important because desalination affects energy demand, public budgets, and carbon emissions.

6. 2. PRACTICAL IMPLICATIONS

Water utilities and irrigation agencies should combine technological investment with monitoring, enforcement, and user education. Drip irrigation and wastewater reuse can improve water management, but their success depends on the regulatory environment.

Where groundwater extraction remains unmonitored, improved irrigation efficiency may encourage agricultural expansion and accelerate aquifer depletion. Desalination projects should therefore be evaluated not only according to production costs but also in relation to energy security, environmental impacts, and long-term financial sustainability.

International development organizations should link infrastructure financing to institutional reform. Technical assistance should strengthen water accounting, regulatory enforcement, administrative capacity, and participatory governance.

The substantial differences among MENA countries also mean that a uniform policy approach is unlikely to be effective.

For the Gulf states, including the United Arab Emirates, Saudi Arabia, and Oman, the main priority is improving the relationship between water and energy systems. Policy should support desalination powered by renewable energy, strategic water storage, source diversification, and a gradual reduction in water intensive domestic agriculture through carefully designed food import strategies. Pricing reform and conservation measures should also be strengthened while recognizing the political sensitivity of water subsidies.

For North African countries, including Morocco, Algeria, Tunisia, and Egypt, policy should combine irrigation modernization with enforceable abstraction limits. Groundwater licensing, metering, and monitoring are essential for reducing excessive extraction. Food imports may relieve pressure on domestic water resources, but they should be balanced against food security concerns. Drought preparedness and early warning systems are also increasingly important.

For Jordan, Lebanon, and Iraq, priorities include improving agricultural water efficiency through extension services and technology transfer, strengthening cooperation over shared water resources, and expanding wastewater treatment and reuse. Institutional reforms should also improve cost recovery, reduce distribution losses, and strengthen regulatory enforcement.

Across all countries, common priorities include stronger coordination among ministries, better data collection, improved monitoring, investment in administrative capacity, and greater international cooperation on demand management.

7. RESEARCH LIMITATIONS

Several limitations should be acknowledged.

First, the measure of technological capacity is indirect. Consistent annual data on desalination capacity, wastewater reuse, and modern irrigation adoption are unavailable for the full period from 1990 to 2024. The primary proxy captures the scale of municipal and industrial water systems but does not directly measure investment in specific water saving technologies.

Second, the analysis is conducted at the national level. National averages may conceal important regional and basin level differences, including informal groundwater extraction, local aquifer depletion, and conflicts over allocation. Water stress varies considerably within countries such as Morocco, Egypt, and Saudi Arabia.

Third, the sample contains only ten countries. This limits statistical power and restricts the use of advanced panel estimators that require a larger number of cross-sectional units. The exclusion of Syria, Yemen, and Libya also limits the applicability of the findings to countries affected by severe conflict and institutional disruption.

Fourth, climate variables are included as controls, but the analysis does not model future climate scenarios. The period from 1990 to 2024 captures historical climatic variation, but future policy assessment will require projections of temperature, rainfall, drought, and extreme events.

Fifth, the model does not fully capture conflict, geopolitical instability, and transboundary water relations. These factors may influence water availability, infrastructure investment, and institutional performance in ways that are not adequately represented.

Sixth, the study relies on FAO AQUASTAT data, which are reported by national authorities and may contain measurement error, particularly for groundwater withdrawals and informal water use.

Seventh, the analysis does not examine the distributional and social consequences of water reform. Pricing, abstraction restrictions, and agricultural adjustment may affect small farmers, rural households, and vulnerable groups differently. These issues lie beyond the scope of the macro panel approach but remain important for policy design.

Despite these limitations, the study provides useful evidence on the structural determinants of water stress and the conditions under which technological responses are more likely to succeed.

8. DIRECTIONS FOR FUTURE RESEARCH

Future research should develop more precise indicators of technological capacity. Detailed data are needed on desalination capacity, energy sources, production costs, wastewater treatment and reuse, and the adoption of drip, sprinkler, and precision irrigation. Satellite data and facility level surveys could complement national statistics and provide more accurate measures of technological diffusion.

Further analysis should also move from the national to the basin and subnational levels. Hydrological boundaries rarely correspond to administrative borders. Basin level studies could better capture groundwater depletion, return flows, informal extraction, and local allocation conflicts.

Future models should explicitly incorporate climate projections. Panel econometric analysis could be combined with climate scenarios and hydrological simulations to assess how changes in temperature, rainfall, and extreme events may influence water stress and policy effectiveness.

The political economy of water reform also requires greater attention. Research should examine the influence of interest groups, the political feasibility of pricing and allocation reforms, the effectiveness of participatory governance, and the conditions required to build institutional credibility.

Rebound effects should be examined at several spatial levels. Plot level measures of irrigation efficiency should relate to basin level water accounting to determine whether local savings reduce total withdrawals or are offset by land expansion, crop intensification, or increased pumping. Quasi experimental methods and agent-based models could provide stronger causal evidence.

Finally, future studies should examine virtual water and trade more directly. Food import dependence, agricultural trade balances, and global price volatility could be incorporated into panel models to assess how external adjustment affects domestic water stress and economic vulnerability over time.

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