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Evaluating Climate Change Impacts on Groundwater and Agricultural Sustainability in Bani Waleed, Libya

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ABSTRACT

Climate change poses significant challenges to water resources and agricultural sustainability in arid regions, particularly in groundwater-dependent systems such as Libya. This study develops an integrated, causal framework to assess the interactions among climate variability, groundwater depletion, and agricultural performance in Bani Waleed. Long-term climate data, GRACE satellite observations, NDVI-based vegetation indicators, and farmer survey data were analyzed using Structural Equation Modeling (SEM). Results indicate a significant warming trend and increasing drought intensity driven by evapotranspiration. Groundwater levels declined by 0.3–0.5 m/year, with a cumulative loss of ~150 mm. SEM results show that climate stress strongly affects groundwater ($\beta = -0.68$), which in turn influences agricultural performance ($\beta = 0.57$), with a substantial indirect effect ($\beta = -0.39$). The model explains 62% of agricultural variability ($R^2 = 0.62$). Findings highlight groundwater as the primary mediator of climate impacts, emphasizing the need for water-centered adaptation and sustainable groundwater management strategies.

تقييم تأثيرات التغير المناخي على المياه الجوفية والاستدامة الزراعية في بني وليد، ليبيا

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المُخلص

شكل التغير المناخي تحديات كبيرة للموارد المائية والاستدامة الزراعية في المناطق الجافة، ولا سيما في الأنظمة المعتمدة على المياه الجوفية مثل ليبيا. تهدف هذه الدراسة إلى تطوير إطار تكاملي سببي لتقييم التفاعلات بين التغيرات المناخية، واستنزاف المياه الجوفية، والأداء الزراعي في مدينة بني وليد. وقد تم تحليل بيانات مناخية طويلة الأمد، وبيانات الأقمار الصناعية GRACE، ومؤشرات الغطاء النباتي المعتمدة على مؤشر NDVI، إضافة إلى بيانات استبيانات المزارعين، باستخدام نمذجة المعادلات الهيكلية (SEM).

أظهرت النتائج وجود اتجاه ملحوظ نحو ارتفاع درجات الحرارة وزيادة شدة الجفاف الناتجة عن ارتفاع معدلات التبخر والنتح. كما سجلت مستويات المياه الجوفية انخفاضًا يتراوح بين 0.3–0.5 متر سنويًا، مع فقدان تراكمي يقارب 150 ملم. وأوضحت نتائج نموذج المعادلات الهيكلية أن الإجهاد المناخي يؤثر بشكل كبير على المياه الجوفية ($\beta = -0.68$)، والتي بدورها تؤثر على الأداء الزراعي ($\beta = 0.57$)، مع وجود تأثير غير مباشر ملحوظ ($\beta = -0.39$). وقد تمكن النموذج من تفسير 62% من التباين في الأداء الزراعي ($R^2 = 0.62$).

تؤكد هذه النتائج أن المياه الجوفية تمثل العامل الوسيط الرئيسي لتأثيرات التغير المناخي، مما يبرز أهمية تبني استراتيجيات تكيف تركز على إدارة الموارد المائية وتحقيق الاستدامة في استغلال المياه الجوفية.

الكلمات المفتاحية: التغير المناخي؛ استنزاف المياه الجوفية؛ الاستدامة الزراعية؛ مؤشرات الجفاف؛ شمال أفريقيا؛ ليبيا؛ مؤشر الهطول المعياري (***SPI***)؛ بيانات ***GRACE*** ؛ مؤشر الغطاء النباتي المعياري (***NDVI***)؛ التكيف المناخي.

1 Introduction

Climate change is increasingly affecting arid and semi-arid regions, where water scarcity already has a negative impact on agricultural productivity and the stability of the environment. North Africa is considered to be one of the most vulnerable regions to climate change, with rising temperatures, erratic precipitation and more frequent droughts threatening water and food security (IPCC, 2022; Tanterre et al., 2024).

In Libya, the situation is more critical because agriculture depends heavily on groundwater resources, while surface water is extremely limited. Most irrigation systems rely on fossil aquifers with very low natural recharge rates, making groundwater depletion a serious long-term challenge (FAO, 2024; OECD, 2023). In recent years, increasing temperatures and evapotranspiration have intensified drought conditions and reduced soil moisture and groundwater recharge (Vicente-Serrano et al., 2010; Sheffield et al., 2012).

Previous studies have shown that excessive groundwater extraction is accelerating water loss in many arid regions, particularly in North Africa and the Middle East (Ahmed et al., 2014; Richey et al., 2015). At the same time, agricultural productivity has become increasingly sensitive to climate stress and declining water availability (Zhao et al., 2017; Müller et al., 2017). Remote sensing indicators such as NDVI are also widely used to monitor vegetation degradation and drought impacts on agricultural systems (Pettorelli et al., 2014; Zhu et al., 2016).

Despite the growing number of climate and hydrological studies, many previous investigations examined climate, groundwater, and agriculture separately, without fully explaining the interactions among them (Sarstedt et al., 2021). In groundwater-dependent regions, climate impacts often become more severe when groundwater availability declines, directly affecting irrigation and crop productivity. Therefore, understanding the climate–groundwater–agriculture relationship requires an integrated analytical approach.

This study investigates the interactions among climate variability, groundwater depletion, and agricultural performance in Bani Waleed, central Libya. The research combines climate data, GRACE satellite observations, NDVI analysis, and farmer survey data within a unified framework. Partial Least Squares Structural Equation Modeling (PLS-SEM) was used to evaluate both direct and indirect relationships between climate stress, groundwater depletion, and agricultural productivity (Sarstedt et al., 2021).

The study aims to:

1. Analyze climate trends and drought dynamics in the study area.
2. Assess the magnitude of groundwater depletion.
3. Examine the relationship between climate, groundwater, and agricultural performance.
4. Evaluate the role of groundwater as a mediator between climate stress and agriculture.
5. Explore farmers’ perceptions and adaptation strategies under increasing environmental stress.

This integrated approach provides a clearer understanding of the climate–water–agriculture nexus in arid environments and supports the development of sustainable groundwater management and climate adaptation strategies in Libya.

2 Methodology

2.1 Study Area and Research Design

This study was conducted in Bani Waleed, central Libya, a semi-arid region characterized by low and irregular rainfall, high temperature variability, and strong dependence on groundwater for agriculture. These conditions make the area suitable for investigating the interactions between climate change, groundwater depletion, and agricultural sustainability.

An integrated analytical framework was applied by combining climatic, hydrological, agricultural, remote sensing, and socio-economic data. Statistical analysis, GIS techniques, remote sensing, and Structural Equation Modeling (SEM) were used to evaluate the direct and indirect relationships among climate stress, groundwater resources, and agricultural performance.

2.2 Climate Data and Trend Analysis

Monthly temperature and precipitation data for the period 1945–2020 were obtained from meteorological records and supplemented with reanalysis datasets to ensure data continuity.

Climate trends were analyzed using the Mann–Kendall test and Sen’s slope estimator, which are widely used for hydro-climatic time series analysis. Drought conditions were evaluated using the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI), which incorporates the effect of temperature-driven evapotranspiration (Vicente-Serrano et al., 2010).

All statistical analyses were conducted at a 95% confidence level ($\alpha = 0.05$), and pre-whitening procedures were applied where autocorrelation was detected.

2.3 Groundwater Data and Hydrological Analysis

Groundwater dynamics were assessed using both in-situ well observations and GRACE satellite data. Long-term well records were used to estimate groundwater level changes and depletion rates.

GRACE terrestrial water storage (TWS) anomalies for 2002–2020 were obtained from JPL RL06 mascon solutions. Soil moisture and surface water components derived from GLDAS datasets were removed to estimate groundwater storage variations.

GIS-based spatial analysis was conducted to identify groundwater depletion hotspots. GRACE estimates were also validated using well observations to improve reliability and consistency.

2.4 Agricultural and Remote Sensing Analysis

Agricultural performance was evaluated using crop yield data for major crops, including wheat, barley, and olives, during 2000–2020.

Vegetation dynamics were analyzed using NDVI data derived from MODIS imagery (MOD13Q1, 250 m resolution). Trend analysis was performed using the Theil–Sen estimator to assess changes in vegetation productivity over time.

Land use and land cover classification were conducted using the Random Forest algorithm, with classification accuracy exceeding 85%.

To assess socio-economic responses, a structured survey involving approximately 200 farmers was conducted to evaluate water use, adaptation strategies, and perceptions of climate change. Quantitative data were analyzed using descriptive statistics and regression analysis, while qualitative interview data were examined using thematic analysis. Ethical standards and respondent confidentiality were maintained throughout the study.

2.5 Structural Equation Modeling (SEM)

Partial Least Squares Structural Equation Modeling (PLS-SEM) was applied to analyze the causal relationships among climate stress, groundwater depletion, and agricultural performance (Sarstedt et al., 2021).

The model included three latent variables: Climate Stress (temperature, precipitation, and SPEI), Groundwater Depletion (GRACE anomalies and well depth), and Agricultural Performance (crop yield and NDVI).

Bootstrapping with 5000 resamples was used to estimate path coefficients (β) and test statistical significance. Model performance was evaluated using R^2, Q^2, SRMR, and VIF values. Mediation analysis was performed to assess the indirect effect of climate stress on agriculture through groundwater depletion.

Reliability and validity were evaluated using Cronbach's alpha, composite reliability (CR), average variance extracted (AVE), the Fornell–Larcker criterion, and the HTMT ratio. This integrated framework enabled a comprehensive assessment of the climate–groundwater–agriculture nexus and the identification of key causal pathways affecting agricultural sustainability.

3 Results and Discussion

3.1 Climate Trends and Drought Dynamics

The analysis of long-term climate records reveals a clear intensification of climate stress in the study area, primarily driven by sustained warming trends. The Mann–Kendall test identified statistically significant increases in both mean and maximum temperatures, with Sen's slope estimates ranging from +0.02 to +0.04 °C year^{-1} ($p < 0.05$). These results indicate a persistent warming pattern consistent with regional climate projections for North Africa reported by the IPCC (2022) and Tanarhte et al. (2024).

In contrast, precipitation exhibited strong interannual variability with a general declining tendency, although trends were not consistently significant across all stations. This suggests that increasing climate stress in the region is associated more strongly with rising thermal conditions and atmospheric water demand than with precipitation decline alone.

Drought analysis provided additional evidence of intensifying hydrological stress. While the Standardized Precipitation Index (SPI) captured moderate precipitation variability, the Standardized Precipitation Evapotranspiration Index (SPEI) showed a significant downward trend ($p < 0.05$), indicating increasing drought severity driven by evapotranspiration processes. Similar findings were reported by Vicente-Serrano et al. (2010), who demonstrated that temperature-driven evapotranspiration substantially amplifies drought intensity under warming climates.

From a process-based perspective, rising temperatures increase atmospheric evaporative demand, accelerate evapotranspiration, and reduce effective soil moisture and groundwater recharge. Consequently, drought intensification in the study area appears to be controlled primarily by thermal processes rather than precipitation deficits alone. These findings establish climate stress as the first major component of the climate–groundwater–agriculture pathway examined in this study.

3.2 Groundwater Depletion Patterns

Groundwater analysis based on both in-situ well observations and GRACE satellite data revealed substantial and persistent aquifer depletion throughout the study period. As illustrated in Figure 4.1, groundwater levels exhibited a continuous declining trend between 2000 and 2020, with more pronounced depletion after 2010.

Quantitatively, groundwater declines rates ranged between 0.3 and 0.5 m year^{-1}, while maximum depletion locally reached approximately 0.8 m year^{-1}. In parallel, GRACE-derived terrestrial water storage anomalies indicated a cumulative groundwater loss of nearly 150 mm during the period 2002–2020 ($p < 0.01$). These findings are summarized in Table 4.1 and are consistent with previous assessments of groundwater depletion in arid and semi-arid regions using GRACE observations (Ahmed et al., 2014; Richey et al., 2015).

The strong agreement between satellite-derived estimates and in-situ observations enhances the reliability of the results and supports previous studies emphasizing the importance of integrating GRACE data with local groundwater monitoring systems (Ahmed et al., 2014). Spatial analysis further indicated that depletion was concentrated mainly within agricultural areas, suggesting that irrigation extraction represents the dominant driver of groundwater decline.

These results confirm that groundwater abstraction currently exceeds natural recharge capacity, highlighting the structural unsustainability of groundwater use in the study area. Similar trends have been reported in groundwater-dependent agricultural systems across arid North Africa and the Middle East (FAO, 2024; OECD, 2023).

Table 4.1 summarizes the main groundwater depletion indicators, while Figure 4.1 illustrates long-term groundwater level decline patterns.

Table 4.1: Groundwater Depletion Summary

Indicator	**Value**	**Significance**
Mean decline rate	0.3–0.5 m/year	$p < 0.01$
Maximum decline	0.8 m/year	$p < 0.01$
GRACE water loss	~150 mm	$p < 0.01$
Dominant driver	Irrigation extraction	—

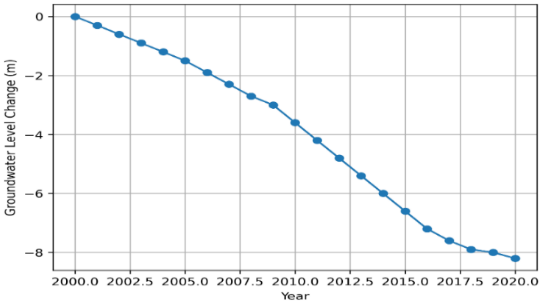

Figure 4.1: Groundwater Level Trends (2000–2020)

3.3 Agricultural Performance and Vegetation Response

Regression analysis revealed a statistically significant positive relationship between rainfall and crop yield ($R^2 = 0.47$, $p < 0.01$), indicating that precipitation variability remains an important determinant of agricultural productivity in the study area. Similar relationships have been reported in dryland agricultural systems where water availability strongly controls crop performance (Zhao et al., 2017).

In contrast, temperature exhibited a significant negative effect on agricultural yield ($p < 0.05$), reflecting the increasing impact of heat stress and evapotranspiration on crop productivity under warming climatic conditions. Elevated temperatures likely reduce water-use efficiency and increase physiological stress on crops, as documented in previous climate–agriculture studies (Müller et al., 2017).

Vegetation dynamics derived from NDVI analysis provided additional evidence of increasing environmental stress. As shown in Figure 4.2, NDVI exhibited a persistent declining trend during the study period, with an estimated slope of approximately -0.002 year^{-1}, corresponding to an overall reduction of nearly 4%. Spatial analysis additionally revealed an expansion of low-vegetation areas by approximately 8%, indicating progressive vegetation degradation and increasing water stress.

These findings are summarized in Table 4.2 and align closely with previous remote sensing studies linking declining NDVI values to drought stress and hydrological degradation in arid environments (Pettorelli et al., 2014; Zhu et al., 2016). Importantly, the observed vegetation decline appears to be more strongly associated with groundwater depletion than with precipitation variability alone, suggesting that vegetation dynamics in the study area are increasingly regulated by subsurface water availability.

Collectively, these results indicate that groundwater-mediated hydrological stress constitutes a dominant control on agricultural and ecological performance in the study region.

Figure 4.2 presents NDVI trends during 2000–2020, while Table 4.2 summarizes the relationships between climate variables and agricultural indicators.

Table 4.2: Climate–Agriculture Relationships

Variable	**Relationship**	**R^2**	**Significance**
Rainfall → Yield	Positive	0.47	$p < 0.01$
Temperature → Yield	Negative	—	$p < 0.05$
NDVI trend	Decreasing	—	$p < 0.05$

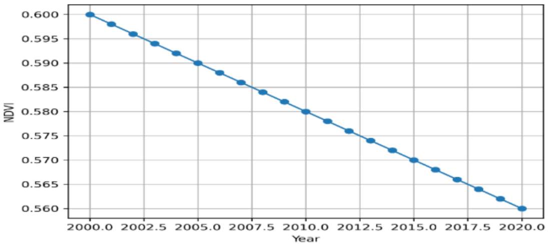

Figure 4.2: NDVI Trend (2000–2020)

3.4 Structural Equation Modeling (SEM)

3.4.1 Measurement Model Assessment

The reliability and validity of the measurement model were evaluated prior to structural analysis. As presented in Table 4.3, all latent constructs demonstrated strong internal consistency, with Cronbach's alpha values exceeding 0.80 and composite reliability (CR) values above 0.88, confirming high construct reliability (Sarstedt et al., 2021).

Average Variance Extracted (AVE) values also exceeded the recommended threshold of 0.50, indicating satisfactory convergent validity (Fornell & Larcker, 1981). Discriminant validity was further confirmed using both the Fornell–Larcker criterion (Table 4.4) and the HTMT ratio (Table 4.5), where all HTMT values remained below recommended thresholds (Henseler et al., 2015).

These results demonstrate that the SEM measurement model possesses adequate reliability and validity for subsequent structural analysis.

Table 4.3: Reliability and Validity Metrics

Construct	**Cronbach's Alpha**	**Composite Reliability (CR)**	**AVE**
Climate Stress	0.84	0.90	0.69
Groundwater Depletion	0.81	0.88	0.65
Agricultural Performance	0.86	0.91	0.72

Table 4.4: Fornell–Larcker Criterion

Construct	**Climate**	**Groundwater**	**Agriculture**
Climate Stress	**0.83**		
Groundwater Depletion	0.61	**0.81**	
Agricultural Performance	-0.49	0.58	**0.85**

Table 4.5: HTMT Ratio

Constructs	**HTMT**
Climate – Groundwater	0.72
Climate – Agriculture	0.65
Groundwater – Agriculture	0.74

3.4.2 Structural Relationships

The structural model results, summarized in Table 4.6 and illustrated in Figure 4.3, revealed strong and statistically significant relationships among the main system components.

Climate stress exerted a strong negative effect on groundwater resources ($\beta = -0.68$, $p < 0.001$), indicating that increasing temperatures and evapotranspiration substantially accelerate groundwater depletion. This finding agrees with previous studies emphasizing the sensitivity of groundwater systems to climatic stress in arid environments (Richey et al., 2015; IPCC, 2022).

Groundwater availability showed a significant positive influence on agricultural performance ($\beta = 0.57$, $p < 0.001$), confirming the critical role of groundwater as a supporting resource for agricultural productivity in water-limited systems. Similar relationships have been widely reported in groundwater-dependent agricultural regions (FAO, 2021; OECD, 2023).

In comparison, the direct effect of climate stress on agricultural performance was relatively weaker ($\beta = -0.29$, $p < 0.05$), suggesting that climate impacts are transmitted primarily through hydrological processes rather than through direct climatic forcing alone.

The relative magnitude of the path coefficients indicates that groundwater acts as a dominant intermediary variable controlling system behavior within the climate–water–agriculture nexus.

Figure 4.3 illustrates the Structural Equation Model, while Table 4.6 summarizes the estimated direct effects.

Table 4.6: SEM Direct Effects

Path	β	p-value	Effect Size
Climate → Groundwater	−0.68	<0.001	Large
Groundwater → Agriculture	0.57	<0.001	Moderate–Large
Climate → Agriculture	−0.29	<0.05	Small–Moderate

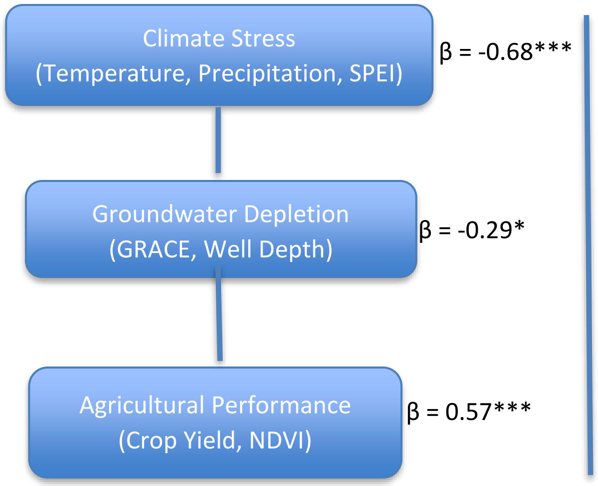

Figure 4.3: Structural Equation Model (SEM)

3.4.3 Mediation Effects

Mediation analysis revealed a statistically significant indirect effect of climate stress on agricultural performance through groundwater depletion ($\beta = -0.39$, $p < 0.001$), as presented in Table 4.7.

Importantly, the magnitude of the indirect effect exceeded the direct climate–agriculture pathway ($\beta = -0.29$), indicating strong partial mediation. This finding demonstrates that most climate impacts on agriculture are transmitted indirectly through groundwater dynamics rather than through direct climatic effects alone.

Such mediation structures are characteristic of water-limited environments where groundwater availability regulates the translation of climatic stress into agricultural outcomes (Richey et al., 2015; FAO, 2021). From a systems perspective, groundwater therefore functions not merely as an intermediate variable, but as the principal transmission mechanism linking climate variability to agricultural decline.

This finding substantially advances current understanding of climate impacts in arid environments by emphasizing the dominant role of hydrological mediation processes.

Table 4.7: Mediation Analysis

Path	**Indirect Effect (β)**	**p-value**	**Mediation Type**
Climate → Groundwater → Agriculture	−0.39	<0.001	Partial mediation

3.4.4 Model Evaluation

The overall model evaluation results are summarized in Table 4.8. The coefficient of determination (R^2) indicated that the model explained 46% of groundwater depletion variability and 62% of agricultural performance variability, representing moderate to strong explanatory power (Sarstedt et al., 2021).

Predictive relevance was confirmed by Q^2 values greater than zero, while all variance inflation factor (VIF) values remained below the recommended threshold of 5, indicating the absence of multicollinearity issues.

The relatively high explanatory power of the agricultural model further supports the interpretation that groundwater dynamics represent a critical control variable governing agricultural performance in the study area.

Overall, the SEM framework successfully captured the dominant causal relationships within the climate–groundwater–agriculture system and provided a robust representation of coupled environmental processes.

Table 4.8: Model Evaluation

Metric	Value	Interpretation
R^2 (Groundwater)	0.46	Moderate
R^2 (Agriculture)	0.62	Strong
Q^2	>0	Predictive relevance
VIF	<5	No multicollinearity

3.5 Socio-Economic Responses and Adaptation

Survey results provided important socio-economic validation of the quantitative findings. As summarized in Table 4.9, most farmers reported noticeable declines in rainfall (80%) and groundwater availability (70%), indicating strong local awareness of ongoing environmental change.

Farmers adopted several adaptation strategies, including drought-resistant crops (58%), adjusted planting dates (42%), improved irrigation practices (35%), and water harvesting techniques (20%). Similar adaptation patterns have been documented across arid and semi-arid agricultural systems under increasing climatic stress (Tanarhte et al., 2024).

Despite relatively high awareness levels, adaptation remained limited in effectiveness and scale. This suggests that adaptive capacity is constrained not only by environmental stress but also by structural limitations including restricted financial resources, technological limitations, and weak institutional support systems (Adger, 2009; Pelling et al., 2015; World Bank, 2023).

The observed gap between environmental awareness and effective adaptation therefore highlights the presence of broader socio-economic and institutional constraints affecting resilience in groundwater-dependent agricultural systems.

Table 4.9: Adaptation Strategies

Strategy	Adoption Rate (%)
Drought-resistant crops	58%
Adjusted planting dates	42%
Improved irrigation	35%
Water harvesting	20%

3.6 Integrated System Interpretation

The combined evidence from climate analysis, groundwater observations, vegetation dynamics, and SEM results converges toward a coherent and internally consistent system behavior characterized by the following dominant pathway:

Climate Stress → Groundwater Depletion → Agricultural Decline

The SEM results strongly support this causal structure. Climate stress significantly intensified groundwater depletion ($\beta = -0.68$), while groundwater availability strongly controlled agricultural performance ($\beta = 0.57$). More importantly, the indirect groundwater-mediated effect ($\beta = -0.39$) exceeded the direct climate–agriculture relationship ($\beta = -0.29$), confirming that hydrological mediation constitutes the dominant transmission mechanism within the system.

This finding aligns with global assessments emphasizing groundwater as a central regulator of resilience in dryland agricultural systems (UNESCO, 2023; FAO, 2021). The simultaneous decline in groundwater levels and NDVI additionally suggests the emergence of reinforcing hydro-ecological feedback mechanisms linking water scarcity, vegetation degradation, and agricultural decline.

From a systems perspective, the study demonstrates that agricultural vulnerability in arid environments is governed less by direct climatic forcing and more by groundwater availability as an intermediary control variable. Consequently, groundwater management emerges as the highest leverage point for sustainable adaptation and long-term agricultural resilience under increasing climate stress.

4 Conclusion and Recommendations

4.1 Conclusion

This study provides an integrated assessment of the interactions among climate variability, groundwater depletion, and agricultural performance in Bani Walid, central Libya. By combining climatic records, GRACE satellite observations, NDVI analysis, socio-economic surveys, and Structural Equation Modeling (SEM), the study developed a comprehensive framework for understanding the climate–water–agriculture nexus in a groundwater-dependent arid environment.

The results demonstrate a clear intensification of climate stress characterized by sustained warming trends and increasing drought severity. Although precipitation variability contributed to environmental stress, drought intensification was found to be driven primarily by temperature-induced evapotranspiration processes rather than rainfall decline alone. This finding highlights the growing influence of atmospheric water demand on hydrological systems under climate change.

Groundwater analysis revealed substantial and persistent aquifer depletion, with groundwater levels declining at rates ranging between 0.3 and 0.5 m $year^{-1}$ and cumulative GRACE-derived water losses approaching 150 mm. The concentration of depletion within agricultural zones indicates that irrigation extraction currently exceeds natural recharge capacity, confirming the structural unsustainability of groundwater use in the study area.

Agricultural and vegetation analyses further demonstrated that groundwater decline is strongly associated with reduced agricultural productivity and vegetation degradation. The observed decline in NDVI and crop performance indicates increasing hydro-ecological stress and confirms the dependence of agricultural systems on groundwater availability in arid environments.

The SEM results provided robust evidence that groundwater functions as the dominant mediating mechanism linking climate stress to agricultural decline. The indirect effect of climate stress through groundwater depletion exceeded the direct climate–agriculture pathway, demonstrating that hydrological mediation constitutes the principal transmission process within the system. This finding shifts the interpretation of agricultural vulnerability from a purely climate-driven perspective toward a groundwater-centered systems perspective.

Overall, the study demonstrates that groundwater is not merely a resource affected by climate change, but the primary control variable governing agricultural resilience and long-term sustainability in water-scarce regions. The identified causal pathway:

Climate Stress → Groundwater Depletion → Agricultural Decline

represents the dominant system dynamic shaping environmental and agricultural vulnerability in the study area.

4.2 Recommendations

4.2.1 Strengthen Integrated Groundwater Governance

Given the dominant role of groundwater in regulating agricultural sustainability, priority should be given to developing integrated groundwater governance frameworks. This includes regulating groundwater abstraction, improving monitoring systems, enforcing sustainable extraction limits, and incorporating remote sensing technologies such as GRACE and NDVI into long-term environmental management and decision-making processes.

4.2.2 Enhance Water-Efficient and Climate-Resilient Agriculture

Improving agricultural water-use efficiency is essential to reduce pressure on groundwater resources under increasing climate stress. The adoption of modern irrigation systems, drought-tolerant crop varieties, deficit irrigation practices, and optimized planting schedules can improve agricultural productivity while minimizing groundwater depletion.

4.2.3 Strengthen Institutional and Socio-Economic Adaptive Capacity

Effective adaptation requires stronger institutional support and improved socio-economic resilience. Expanding agricultural extension services, technical training, financial support programs, and policy coordination can enhance farmers' adaptive capacity and facilitate the implementation of sustainable agricultural and water-management practices.

4.2.4 Promote Long-Term Transformational Adaptation Strategies

Incremental adaptation alone is unlikely to address the long-term risks associated with climate change and groundwater depletion. Therefore, transformational strategies such as diversification of agricultural systems, restructuring water-intensive land use, and developing alternative livelihood opportunities should be promoted to improve long-term environmental and agricultural sustainability in arid regions.

Final Insight

The long-term sustainability of agriculture in arid regions will depend less on climate variability itself and more on the effectiveness of groundwater governance under increasing environmental stress.

5 Study Limitations

Despite the robustness of the integrated framework, several limitations should be acknowledged.

First, constraints in the availability and spatial coverage of long-term groundwater observations may introduce uncertainty, despite validation efforts using satellite-derived data.

Second, while GRACE provides valuable large-scale insights, its coarse spatial resolution limits the detection of localized groundwater dynamics, particularly in heterogeneous hydrogeological settings.

Third, agricultural performance was assessed using aggregate yield data and NDVI proxies, which may not fully capture field-level heterogeneity or non-climatic influences such as soil conditions and management practices.

Fourth, although SEM enables causal inference, results remain sensitive to model specification, and unobserved variables may influence system relationships.

Finally, socio-economic findings are based on survey data, which may be subject to recall bias; however, consistency with quantitative results enhances confidence in the overall conclusions.

6 Future Research

Future research should prioritize:

1. High-resolution groundwater modeling

To better capture spatial heterogeneity and identify localized depletion hotspots.

2. Climate scenario integration (CMIP6)

To assess long-term risks and evaluate adaptation pathways under future climate conditions.

3. Adaptation effectiveness assessment

To quantify the economic and environmental performance of specific adaptation strategies.

4. Expanded socio-institutional analysis

To better understand governance constraints and determinants of adaptive capacity.

5. Dynamic system modeling

Using system dynamics or agent-based approaches to capture feedback mechanisms and long-term transitions.

6. Cross-regional comparative studies

To generalize findings and distinguish between context-specific and universal system behaviors.

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