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Global warming in Morocco: public policy governance in the face of impacts on water resources.

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Abstract

In the context of the growing impacts of climate change, the sustainable management of water resources represents a major strategic challenge for Morocco. This study aims to empirically assess the influence of key climatic variables (temperature, precipitation, and evapotranspiration) on national water availability within a climate adapted public governance framework. Using an ARDL model applied to time series data from 2010 to 2023, the results confirm the existence of a long-term relationship between water stress and climatic factors, with effects that vary across time horizons.

The findings underline the need to strengthen adaptive capacity through proactive and flexible water policies tailored to local conditions. The study emphasizes the importance of climate responsive governance in guiding public water management decisions amid increasing vulnerability, while highlighting the relevance of further investigation into local climate water interaction mechanisms to support long term water security.

Keywords: Governance, Public policy, Morocco, Water, Global warming, ARDL.

Introduction

Public policy governance in Morocco is currently facing unprecedented challenges, among which global warming occupies a central place due to its growing impact on natural resources, particularly water. Climate change is a major disruptive factor for sustainable water resource management, especially in arid and semi-arid regions.In this context, Morocco is particularly exposed due to its strategic geographical location between Europe and Africa, as well as its challenging climatic conditions, characterised by highly variable rainfall, recurrent droughts and growing demand for water resources.

Over the past few decades, various climate indicators have confirmed a worrying trend. (Driouech et al., 2021) report a +1.1°C increase in the average annual temperature in Morocco between 1984 and 2016, which is higher than the global average. At the same time, rainfall shows a downward trend, with intensifying droughts, especially in the north of the country, as shown by climate indices such as the SPEI.

In their research on the Rheraya watershed, (Ahmed et al., 2017) project a temperature increase of +1.4°C to +2.6°C and a decrease in precipitation of -22% to -31% by 2049–2065 under RCP4.5 and RCP8.5 scenarios, leading to a reduction in runoff of up to -63%, due in particular to decreased snow cover and accelerated melting, which would increase the water vulnerability of mountainous regions.

These dynamics are also accompanied by a significant increase in evapotranspiration. In the Bin El Ouidane dam region, (El Khalki et al., 2021) estimate an increase in evapotranspiration of +15% to +36% and a decrease in precipitation of -16% to -34%, which would significantly reduce runoff (-57% to -86%) and increase pressure on water, hydroelectricity and agriculture.

This climate change is putting increasing pressure on renewable water availability, which has fallen from 2,560 m³/capita/year in 1960 to 620 m³ in 2020 (World Bank, 2021), which is below the international water stress threshold (1,000 m³) and close to the critical threshold of 500 m³, expected by 2030. This decline is the result of a combination of climate change, population growth and anthropogenic pressures.

Medium- and long-term projections reinforce the urgency of the situation.(Labaioui & Razouk, 2022) show that reference evapotranspiration (ET_0) in the Ifrane region could rise to 135 mm per month in summer by 2050, compared to 118 mm currently, according to the pessimistic RCP8.5 scenario.

At the national level, the World Bank (2021) highlights a growing decline in water resources, attributable to rising temperatures, declining rainfall and worsening droughts. It presents in detail the country's specific vulnerabilities, particularly in the areas of water security, agriculture and ecosystems. This analysis highlights the importance of coordinated adaptation policies based on solid empirical data.

Faced with this situation, the Moroccan authorities have implemented various measures such as adopting localised irrigation techniques, recycling wastewater, building new dams and developing desalination. These initiatives are part of the 2020-2027 National Programme for Drinking Water and Irrigation, with a budget of over 115 billion dirhams (Ministry of Equipment and Water, 2020). However, the effectiveness of these measures depends heavily on a thorough understanding of the mechanisms that link climate variables to water resource dynamics.

The subject of this article is therefore the impact of global warming on water resources in Morocco, analysed from the perspective of public policy governance. The objective is to empirically assess the influence of key climatic variables, namely temperature, precipitation and evapotranspiration, on national water availability. The study also seeks to clarify how these climatic pressures challenge current public water governance mechanisms and adaptation strategies.

Accordingly, the guiding question of this research is formulated as follows: **to what extent do climatic variations, particularly those linked to global warming, affect the availability of water resources in Morocco, and how do these effects challenge current public water governance mechanisms?**

This study is distinguished by its use of an ARDL (Autoregressive Distributed Lag) model, which allows for the examination of short and long-term effects between variables, while taking into account the methodological constraints associated with annual time-series data. Unlike many previous descriptive studies, this approach offers a dynamic, rigorous and integrated analysis of climate interactions, based on verified Moroccan data. It thus fills a gap in national empirical research and provides useful insights for public decision-makers seeking to improve long-term adaptation strategies within a framework of integrated and resilient water governance.

The article is structured as follows. The first section reviews the theoretical and empirical literature on the relationship between climate change and water resources. The second section presents the methodology, including the data, model specification and econometric tests. The third section presents and discusses the empirical results. The article ends with a conclusion outlining the main findings, policy implications, limitations and future research perspectives.

1. LITERATURE REVIEW

1.1. Theoretical insights

The study of the relationship between climate change and water resources is based on a multidimensional theoretical foundation that draws on hydrological, climatic, economic and social concepts.

Among the foundations of this thinking, the theory of potential evapotranspiration developed by (Penman, 1948) is an essential tool for assessing weather-related water losses. By combining temperature, wind, solar radiation and humidity, this model, which is suited to arid climates such as Morocco's, makes it possible to understand the effect of high temperatures on water availability, particularly in irrigated agriculture.

The concept of water vulnerability, introduced by (Falkenmark, 1989) , is based on the water stress index, which measures water availability per capita. In a country where this volume is below the critical threshold of 1,000 m³/capita/year, this framework highlights the growing pressure linked to demographic and climatic dynamics.

The concept of environmental justice, theorised by (Deldrève, 2013), highlights social inequalities in access to and governance of resources. In Morocco, rural or marginalised areas are more exposed to shortages, which makes an analysis incorporating social and territorial equity relevant.

The reconfiguration of the hydrological cycle proposed by (Trenberth, 2011) highlights the effects of global warming on the intensity and variability of the water cycle, including increased evaporation, changes in rainfall patterns and increased frequency of droughts and floods. These changes directly affect Moroccan watersheds.

Gleick's (1993) approach to water balance emphasises the interactions between precipitation, evaporation, runoff and infiltration. Declining rainfall and increasing evapotranspiration exacerbate imbalances between groundwater, surface water and human needs.

From an integrative perspective, the theory of complex adaptive systems developed by (Holling,1973) shows that social and ecological systems respond non-linearly to climate shocks. Applied to water, it justifies flexible, participatory and multi-level adaptation strategies.

Finally, on a methodological level, the ARDL model developed by (Pesaran et al., 2001) provides a robust empirical framework for analysing the short and long-term relationships between climate variables and water resources. Particularly suited to non-stationary time series, it allows for the assessment of the differentiated impacts of temperature, precipitation and evapotranspiration on water availability in Morocco.

In short, these different theoretical approaches provide a rich and complementary analytical foundation for addressing the issue of the impact of climate change on water resources.

1.2. Empirical insights

In Morocco, climate change is altering rainfall patterns, increasing temperatures and intensifying evapotranspiration, putting further pressure on already limited water resources. A synthesis of recent research provides a better understanding of the impact of global warming on water availability at the national and regional levels.

1.2.1. Changes in rainfall patterns

Increasing variability in rainfall patterns is one of the most visible signs of climate change in Morocco. Recent studies reveal a continuous decline in annual rainfall, accompanied by significant regional disparities. In the Oum Er-Rbia basin, for example, projections indicate a decline of up to 21% to 45% by 2100, resulting in reduced flows and increased pressure on available resources (Orfi et al., 2025). Historical analysis (1974-2017) also confirms the spatial and temporal irregularity of rainfall, marked by alternating wet phases and long dry periods (Orfi et al., 2020).

Similar trends are emerging in other strategic regions. In Souss-Massa, rainfall could decrease by 33.74% to 40.20% depending on climate scenarios, thereby accentuating seasonal irregularity (El-Yazidi et al., 2024). In the Ziz basin, analysis of climate indices shows a strong correlation between rainfall deficits and declining groundwater levels (Ben Salem et al., 2023). In the Gharb plain, rainfall instability results in alternating severe droughts and destructive floods, highlighting the fragility of water infrastructure in the face of water excesses and deficits (El Karfa et al., 2023).

Thus, climate change affects not only the amount of rainfall, but also its regularity and seasonal distribution. This instability complicates water planning and increases the risk of sudden shifts between scarcity and excess, compromising national water security.

Recent studies confirm the persistence and severity of water stress in Morocco. Boutagayout et al. (2025) show that the period 2019–2024 represents the longest recorded sequence of consecutive drought years, with an average rainfall deficit of 35%. They also underline that water management in Morocco has become a central challenge at the intersection of climate variability, agricultural modernization and resource governance. In this context, they emphasize the need for integrated water governance combining technological innovation, ecological practices and policy reforms to secure water and food resources under persistent drought and accelerating climate change.

1.2.2. Temperature variations

Rising temperatures are another major factor contributing to pressure on water resources. In the Bouregreg and Souss basins, (Mahdaoui et al., 2024; Ouharba et al., 2024), observe a steady increase in average temperatures, with projections placing this increase between +1.32 °C and +1.69 °C by 2040 according to RCP scenarios. These increases are accompanied by increased evaporation and greater demand for water, particularly in the agricultural and domestic sectors. Furthermore, global warming is disrupting the seasonal pattern of water flows. In the upper Ziz Valley, projections suggest marked seasonal variability in future temperatures, with warmer winters and springs and relatively more temperate summers and autumns (El Ouali et al., 2023). This thermal redistribution could cause early snowmelt and alter natural runoff patterns, thereby compromising water reservoir management.

By amplifying the water deficit, these changes confirm the existence of a close link between global warming and the country's increasing vulnerability to water scarcity.

1.2.3. Evapotranspiration rate

Evapotranspiration (ET), as an essential component of the water cycle, is strongly influenced by rising temperatures. In the Moulouya basin, (Amiri et al., 2022) estimate that annual evapotranspiration accounts for about 70% of precipitation, illustrating its decisive role in water loss, particularly in arid environments. Increased ET rates significantly reduce the amount of water available for agriculture, industry and human consumption.

This dynamic is exacerbated by changes in land use. In areas such as the Middle Atlas Mountains, the expansion of irrigated areas contributes to increased evapotranspiration losses, thereby exacerbating pressure on water resources (El-Bouhali et al., 2024). In addition, the gradual conversion of agricultural land to perennial crops such as olive trees, which require more water, is increasing long-term water demand. According to (Ouassanouan et al., 2022), this crop transition is placing additional pressure on regional water balances.

1.2.4. Drought and water scarcity

Drought is a recurring phenomenon in Morocco, and its intensification is widely documented. The SPI and SPEI indices, commonly used to assess the severity and frequency of droughts, highlight a continuous deterioration in water conditions in several basins. In the upper Oum Er-Rbia basin, (Mliyeh et al., 2024) identify a marked intensification of drought episodes, confirming the relevance of the SPEI as a monitoring indicator in the Moroccan context.

The pressure on groundwater in response to surface water shortages increases the vulnerability of the system. In the Ziz basin, the standardised groundwater index (SGI) indicates a continuous decline in levels, a sign of increasing stress (Ben Salem et al., 2023) . Projections based on SSP scenarios anticipate a further decrease in water availability in the most exposed areas. More recently, Lahnik et al. (2025) assessed future water resources and hydrological droughts in the Atlas Mountains of Morocco under the high-emission RCP8.5 scenario. Based on 36 mountainous basins that supply most of the country's surface water, their results show a substantial decline in future discharge, mainly driven by decreasing precipitation and increasing potential evapotranspiration. They also indicate that hydrological droughts are expected to become more frequent and prolonged, highlighting the growing vulnerability of mountain hydrological systems and the need for adaptive water management strategies adapted to basin-specific characteristics.

1.2.5. Agricultural, economic and social impacts

Agriculture, the main user of water in Morocco, is severely affected by climate change. Irregular rainfall and rising temperatures are increasing the demand for irrigation. In the Guigou depression, the expansion of irrigated areas has led to a significant increase in water abstraction, compromising the sustainability of resources(El-Bouhali et al., 2024).

The economic and social impacts are equally worrying. (Perez Cutillas & Salhi, 2024) estimate that water scarcity could reduce GDP by between 2.8% and 17.1% by 2100, with more significant losses in agricultural regions. On the social front, competition for water is exacerbating tensions, particularly in the Ziz Valley (El Ouali et al., 2023), which is already weakened by water scarcity.

2. METHODOLOGY

The literature indicates that global warming affects water resources through rising temperatures, precipitation variability, and increased evapotranspiration. However, few studies in Morocco have quantified these effects at the national level across short- and long-term horizons. This study addresses this gap using an appropriate econometric approach.

Methodologically, this research adopts a positivist empirical positioning and a hypothetico-deductive mode of reasoning. The analysis starts from relationships established in the climate-water literature and tests them empirically using Moroccan time-series data. The choice of the ARDL approach is justified by its ability to distinguish between short-term dynamics and long-term equilibrium relationships, while remaining appropriate for variables integrated at different orders, I(0) and I(1), and for relatively small samples. This makes it suitable for assessing the dynamic effects of temperature, precipitation and evapotranspiration on water resources over the period 2010–2023.

2.1. Data

The model variables are selected based on prior empirical studies to ensure economic relevance and statistical robustness. Water resources (RE), the dependent variable, measure the annual availability of surface and groundwater in Morocco and reflect climate driven changes in water security. The explanatory variables include average annual temperature (TEMP), which increases evaporation and reduces recharge; annual precipitation (PREC), the main source of water replenishment; and annual evapotranspiration (EVAP), which captures climate induced water losses in Morocco's arid context.

Table N°1 : Data description and sources

Variables	Descriptions	Sources
RE	Water resources in (Mm3/year)	High Commission for Planning (HCP)
EVAP	Annual evapotranspiration (mm/year)	
TEMP	Average annual temperature (°C)	Moroccan National Meteorological Service
PREC	Annual precipitation (mm/year)	

Source: The authors

2.2. Period studied (2010-2023)

The period 2010-2023 was chosen for several reasons. The climate and water data available for this period are relatively complete and reliable. It also corresponds to a recent phase in which the effects of global warming in Morocco have intensified, with severe droughts and a significant decrease in precipitation. Finally, this time frame is consistent with the use of the ARDL model, which is suitable for analysing short and long-term dynamics on time series of this size.

2.3. Model specification

The model to be estimated to quantify the influence of temperature, precipitation and evapotranspiration on water resources in Morocco during the period 2010-2023 is formulated as follows:

$$RE = f\,(TEMP, PREC, EVAP) \qquad (1)$$

Once the theoretical framework has been established, it must then be translated into an econometric model suitable for analysis. This transition from the abstract to the quantifiable leads to the following formulation:

$$RE_t = \alpha_0 + \beta_1 TEMP_t + \beta_2 PREC_t + \beta_3 EVAP_t + \varepsilon_t \qquad (2)$$

Equation 2 reflects a linear relationship between water resources and key climate variables. It forms the basis of an estimate, using an ARDL model, to distinguish between the short and long-term effects of each climate factor on water resources in Morocco.

2.4. ARDL Model

The ARDL model is chosen for its ability to analyze dynamic relationships regardless of variable stationarity, distinguishing short and long-term effects. It accommodates variables of different integration orders (I(0) and I(1)) and captures both immediate climate fluctuations and long-term trends, such as rising temperatures. Its robustness with small samples makes it suitable for this study, based on 14 annual observations (2010–2023).

The general equation of the ARDL model for analysing the impact of the explanatory variables (TEMP, EVAP, and PREC) on the dependent variable (RE) is as follows:

$$\Delta RE_t = \alpha + \sum_{i=1}^{p} \gamma_i \Delta RE_{t-i} + \sum_{j=0}^{q1} \delta_j \Delta TEMP_{t-j} + \sum_{k=0}^{q2} \theta_k \Delta PREC_{t-k} + \sum_{l=0}^{q3} \omega_l EVAP_{t-l} + \lambda(RE_{t-1} - \varphi_1 TEMP_{t-1} - \varphi_2 PREC_{t-1} - \varphi_3 EVAP_{t-1}) + \epsilon_t \quad (3)$$

Where :

- **ΔRE**: The variation in water resources between year t and the previous year (t−1).
- The terms ΔRE_{t-i}, $\Delta TEMP_{t-j}$, $\Delta PREC_{t-k}$, and $\Delta EVAP_{t-l}$ capture the immediate effects of short-term variations in the variables.
- Each sum (∑) represents the time lags of the variables.
- The term ($RE_{t-1} - \phi_1 TEMP_{t-1} - \phi_2 PREC_{t-1} - \phi_3 EVAP_{t-1}$) captures the equilibrium relationship between water resources and long-term explanatory variables.
- ϕ_1, ϕ_2, ϕ_3: Measure the impact of explanatory variables on water resources.
- The coefficient **λ** indicates how quickly water resources return to their equilibrium level after a shock.
- **α**: The constant measures a base effect independent of the explanatory variables.
- ε_t: The error term captures unforeseen factors.

This ARDL specification allows us to:

- ❖ Differentiate between the short-term (Δ) and long-term (ϕ_1,ϕ_2,ϕ_3) impacts of climate variables on water resources.
- ❖ Identify the speed at which water resources return to their normal state after climatic shocks (λ).
- ❖ Understand the complex interactions between climatic factors and water resources, with potentially delayed effects over time.

In order to simultaneously estimate short-term dynamics and adjustment towards long-term equilibrium, the ARDL model was reformulated in its error correction form (ECM), as represented by the following equation:

$$\Delta RE_t = \alpha + \sum_{i=1}^{p} \gamma_i \Delta RE_{t-i} + \sum_{j=0}^{q1} \delta_j \Delta TEMP_{t-j} + \sum_{k=0}^{q2} \theta_k \Delta PREC_{t-k} + \sum_{l=0}^{q3} \omega_l EVAP_{t-l} + \lambda ECT_{t-i} + \epsilon_t \quad (4)$$

Where:

- **Δ**: indicates the first differences of the variables.
- **λ**: denotes the adjustment coefficient, expected to be negative and significant to validate the long-term relationship.
- **ECT_{t-i}**: correction error term, representing the measured difference between the observed situation and the long-term equilibrium.

3. RESULTS AND DISCUSSION

3.1. Stationarity of variables

The Augmented Dickey-Fuller (ADF) test is employed to examine the null hypothesis of a unit root against the alternative of stationarity. The test results are reported in the table N°2.

Table N°2: Results of the stationarity test

Variable	Level I(0)	First difference I(1)	Integration
Water resources (RE)	-5.64 (S)	-	I(0)
Temperature (TEMP)	-2.51 (N.S)	-3.65 (S)	I(1)
Precipitation (PREC)	-4.06 (S)	-	I(0)
Evapotranspiration (EVAP)	-7.75 (S)	-	I(0)

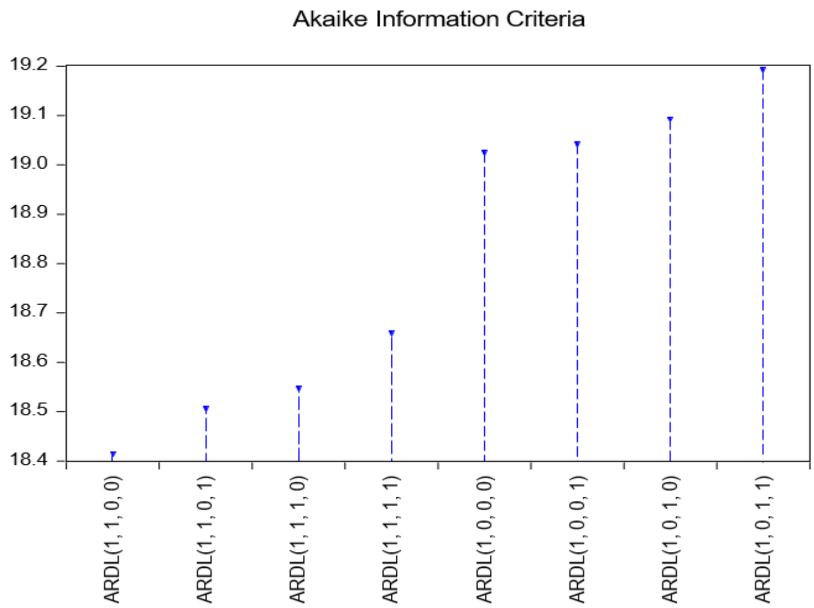
Source: The authors, (Eviews software)

We find that the RE, PREC and EVAP variables are stationary at level (I(0)) and the TEMP variable is stationary at first difference order (I(1)), which meets the conditions required for the application of the ARDL approach.

3.2. Selection of the optimal lag for the ARDL model

The Akaike Information Criterion (AIC) is used to select the optimal ARDL specification by identifying the appropriate lag structure. As shown in Figure N°1, among eight competing models, the ARDL (1,1,0,0) model with the lowest AIC value is retained.

Figure N°1: Graph of the information criterion for lags



Source: The authors, (Eviews software)

3.3. Bounds Test

The cointegration test is implemented by making the following assumptions:

- **H0**: It is postulated that there is no long-term relationship.
- **H1**: It is postulated that a long-term relationship exists.

Table N°3: Results of the cointegration test (Bounds Test)

	Significance	lower limit I(0)	upper limit (1)
F-statistic: **66.02**	10%	2.37	3.2
	5	2.79	3.67
	2.5	3.15	4.08
	1	2.65	4.66

Source: The authors, (Eviews software)

Table N°3 shows that the calculated value of F=66.02, significantly exceeds the upper limits I(1) of the critical values at the 1%, 2.5%, 5% and 10% thresholds. Consequently, the null hypothesis (H0) is rejected and the alternative hypothesis (H1) is accepted, implying the existence of a long-term relationship between the variables considered.

3.4. Estimation of results

3.4.1. Long-term result

Table N°4: Results of long-term effects

Variable	Coefficient	Std.Error	t-Statistic	Prob.
TEMP	-10302.44	2673.215	-3.853952	0.0063
PREC	9.954872	8.219168	1.211178	0.2651
EVAP	0.214733	0.050454	4.256503	0.0038
C	193166.0	50701.83	3.809842	0.0066

Source: The authors, (Eviews software)

The results in Table N°4 reveal that all variables are statistically significant at the 5% level, indicating that these variables are determinants of long-term water resources, with the exception of the Precipitation (PREC) variable, which is not significant. The estimated coefficients indicate the following:

- **Temperature (TEMP)**
  - Coefficient: **-10302.44**
  - Significant at 1% (**p = 0.0063**)

The effect of temperature on water resources is negative and highly significant. In other words, each unit increase in temperature leads to a significant decrease in water availability.

This result is not surprising: the warmer it is, the faster water evaporates, whether from the ground, rivers or dams. This leads to a direct decrease in available reserves. These results confirm the findings already mentioned in the scientific literature, according to which global warming increases evaporation and reduces the amount of water stored in the ground and aquifers.

- **Precipitation (PREC)**
  - Coefficient: **9.95**
  - Not significant (**p = 0.2651**)

The link between precipitation and water resources is positive but statistically insignificant. This means that, in the long term, variations in rainfall do not have a decisive impact on the evolution of water resources in Morocco.

This phenomenon can be explained by the irregular and seasonal nature of rainfall in the country: some areas may receive heavy rainfall in a short period of time, but this does not necessarily translate into sustainable recharge of aquifers or dams. Water management therefore becomes more complex when rainfall is unpredictable or concentrated over short periods. This observation is consistent with previous studies that highlight the difficulty of relying on rainfall as the main lever for long-term adaptation.

❖ **Evapotranspiration (EVAP)**

- Coefficient: **0.2147**
- Significant at 1% (**p = 0.0038**)

The results indicate that evapotranspiration has a positive and statistically significant effect on water availability during the period 2010-2023. An increase in evapotranspiration is associated with higher measured water resources, with an estimated coefficient of 0.2147 and a low probability of error, confirming the robustness of the relationship.

This result is noteworthy, as it contrasts with conventional interpretations in the literature. The study reports this finding as observed, without advancing causal interpretations. Such an association calls for further analysis to better understand the climate-water interactions at different regional and temporal scales. At this stage, it is sufficient to note that the relationship identified is positive and statistically significant, and therefore relevant for future research on water-climate dynamics in Morocco.

❖ **Constant**

- Coefficient: **193166.0**
- Significant at 1% (**p = 0.0066**)

The model constant represents the baseline water resources in the absence of climatic variations. The significance of this parameter shows that it contributes significantly to explaining the baseline level of water resources, independently of the climatic shocks measured by the other variables.

The model results clearly show that temperature is the most decisive climatic factor in the decline of water resources in Morocco, reinforcing the urgent need to take action against global warming. Precipitation, despite its apparent importance, has no significant long-term effect, probably due to its variability. As for evapotranspiration, its effect warrants closer examination in order to understand the local dynamics it may reflect.

3.4.2. Short-term results

Analysis of short-term effects provides a better understanding of the immediate response of water resources to climate shocks. The results of the ARDL model show two key elements: the effect of temperature variation and the adjustment behaviour towards long-term equilibrium.

Table N°5: Results of short-term effects

Variable	Coefficient	Std. Error	t-Statistic	Prob.
D(TEMP)	-4102.720	1456.730	-2.816390	0.0259
CointEq(-1)*	-1.089624	0.047842	-22.77569	0.0000

Source: The authors, (Eviews software)

The short-term equation obtained, based on the above results, revolves around the following two main variables:

- **D(TEMP)**: Temperature variation (short term).
- **CointEq(-1)**: Lagged cointegration error term, representing the speed of adjustment towards long-term equilibrium.

The results are interpreted as follows:

❖ **Temperature variation (D(TEMP))**

- Coefficient: **-4102.72**
- Significant at the 5% threshold (**p = 0.0259**)

The negative coefficient indicates that when the temperature rises sharply, even over a short period, this leads to an immediate decrease in water resources. This decrease is statistically significant, confirming that temperature changes have a tangible effect in the short term.

However, it should be noted that the effect is less pronounced than that observed in the long term (where the coefficient was more than twice as high). This is because, in the short term, the impact of a rise in temperature is felt mainly through the rapid evaporation of surface water (rivers, dams, reservoirs). On the other hand, the more profound effects on groundwater, soil and vegetation take longer to manifest themselves, resulting in a stronger long-term effect.

This result shows that even temporary increases in temperature can significantly disrupt the water balance, which is particularly worrying in regions such as Morocco, which are already subject to chronic water stress.

❖ **Equilibrium adjustment term (CointEq(-1))**

- Coefficient: **-1.0896**
- Highly significant (**p = 0.0000**)

The error correction term plays a central role in ARDL models, as it measures the speed at which the system returns to its long-term equilibrium following a short-term shock. In this case, the coefficient is negative and greater than one in absolute value ($|-1.0896| > 1$), indicating a strong and statistically significant adjustment process.

Its high level of significance confirms the existence of a robust correction mechanism, while an absolute value slightly above unity suggests a rapid adjustment with a mild overshooting of equilibrium before stabilization. This behaviour reflects the high sensitivity of water resources to climatic variations, consistent with evidence from other semi-arid contexts where hydrological equilibria are often unstable. The literature similarly shows that in vulnerable environments, water systems tend to respond quickly (sometimes in a non-linear manner) to climatic disturbances, highlighting the complexity of water resource management in Morocco.

3.5. Discussion of results

The econometric results obtained from the ARDL approach confirm the existence of a long-term relationship between certain climatic variables and water resources in Morocco. However, these results also reveal specific dynamics, sometimes distinct from those highlighted in previous studies, thus underscoring the complexity of the national water system in a context of environmental governance that is still evolving.

Firstly, the negative significance of long-term temperature, combined with its immediate short-term effect, corroborates the empirical observations of (Mahdaoui et al., 2024; Ouharba et al., 2024), which highlight the intensification of pressure on water resources as a result of global warming. These authors highlight in particular the increase in evaporation and the disruption of seasonal flows, two phenomena that compromise sustainable water management capacities. These findings are also in line with the projections of (El Ouali et al., 2023), which anticipate disruptions to the hydrological calendar in the upper Ziz Valley, illustrating the need to adapt public policies to new climatic realities.

Conversely, although precipitation has a positive effect, it is not statistically significant. This lack of significance contrasts with the findings of (El-Yazidi et al., 2024; Orfi et al., 2020), which report a marked decrease in precipitation with significant consequences for river flows and groundwater recharge. However, this divergence can be explained by the high interannual variability and erratic nature of precipitation in Morocco, as these authors point out, which makes its effect difficult to detect in an aggregated time series. These results therefore call into question the ability of institutional mechanisms to integrate this variability into water resource management strategies.

With regard to evapotranspiration, its positive and significant relationship with water resources is a surprising result. Indeed, the majority of studies, such as those by (Amiri et al., 2022; El-Bouhali et al., 2024) , consider evapotranspiration to be a major factor in water loss, particularly in arid areas. This divergence may reflect the local complexity of interactions between vegetation cover, soil moisture and water availability. It is consistent with certain field observations highlighting the influence of land use on water balances. Such results underscore the importance of territorialised governance of water policies that take into account specific local agro-ecological characteristics.

Finally, the highly significant and negative adjustment term coefficient (CointEq(-1)) highlights the marked responsiveness of the Moroccan hydrological system to climatic disturbances. This result is consistent with the work of (Ben Salem et al., 2023; Mliyeh et al., 2024) , which point to the structural vulnerability of Moroccan watersheds to sudden or prolonged droughts. The rapid adjustment observed in the model reflects systemic instability and low hydrological resilience, which has already been documented in several critical areas such as the Ziz and Oum Er-Rbia basins. These findings reinforce the idea that current water governance must better integrate climate resilience into its warning and planning mechanisms.

In summary, the empirical results obtained confirm certain major trends identified in the literature, in particular the decisive impact of temperature on water resources. However, they qualify or question other mechanisms, such as the direct influence of precipitation or evapotranspiration. This complexity highlights the limitations of purely quantitative approaches and calls for greater coordination between econometric analyses and territorial diagnostics. It also underscores the need for Moroccan public policies to strengthen water governance mechanisms, adapting them to local realities and the challenges posed by climate change.

3.6. Model robustness tests

In order to verify the validity of the ARDL model, several robustness tests were carried out. The Breusch-Godfrey test indicates the absence of autocorrelation in the residuals, with the probability of the Chi-Square(2) statistic well above the 5% threshold. The Jarque-Bera test also confirms the normality of the residuals, with a probability greater than 0.05, which validates the reliability of the statistical inferences. Finally, the Breusch-Pagan-Godfrey test reveals the absence of heteroscedasticity, with the probability obtained also being above the critical threshold. These results confirm the robustness and correct specification of the estimated model. The detailed results of these diagnostic tests are presented in Table N°6.

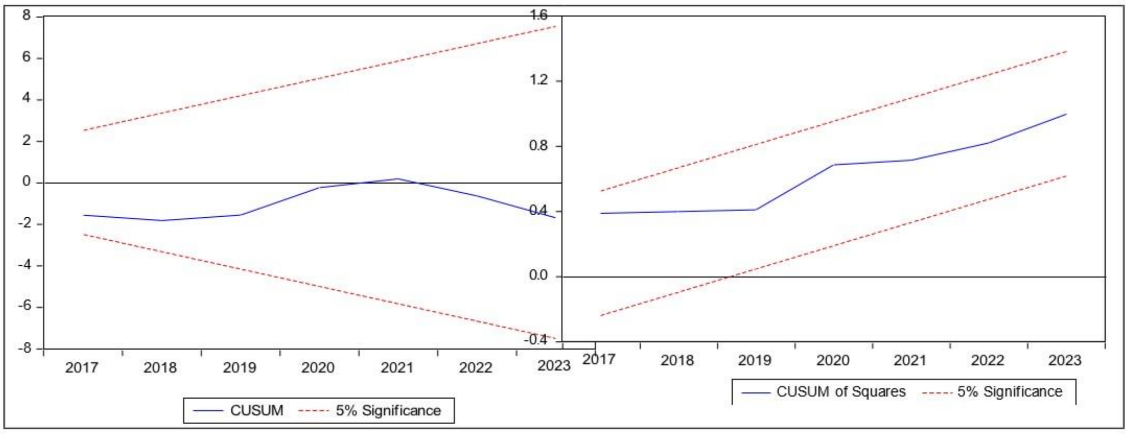
Table N°6: Summary of the various validation tests

Tests	Values (Probability)
Residual autocorrelation: Breusch-Godfrey LM	0.31
Normality of residuals: Jarque-Bera	0.60
Heteroscedasticity: Breusch-Pagan-Godfrey	0.43

Source: The authors, (Eviews software)

To complete the robustness tests, we also assessed the structural stability of the ARDL model parameters using CUSUM and CUSUMSQ tests. The corresponding figures show that the curves remain within the critical segments, confirming that the model is correctly specified and stable.

Figure N°2: Graphs of CUSUM and CUSUMQ test results



Source: The authors, (Eviews software)

Conclusion

This study, which is part of a broader reflection on public policy governance in Morocco, highlights several key lessons for understanding and managing water resources in Morocco in the context of climate change. The results show that temperature has a decisive influence on water availability in both the short and long term. This finding confirms that global warming poses a direct threat to water security and highlights the urgent need for action on several levels, including reducing greenhouse gas emissions and adapting local practices by choosing less water-intensive crops, optimising irrigation and preserving sensitive ecosystems.

Although rainfall is essential for the renewal of resources, it is too irregular to be considered a strategic lever in the long term. This uncertainty calls for greater water resilience, in particular through the diversification of sources (desalination, reuse of wastewater), the development of storage solutions, and controlled recharge of aquifers.

Furthermore, the high responsiveness of the water system to climate shocks, highlighted by the term ‘model adjustment’, indicates that rapid measures can produce visible effects. However, this sensitivity also increases the system's vulnerability to prolonged disturbances, hence the importance of continuous hydrometeorological monitoring and adaptive management mechanisms capable of responding flexibly to constantly changing contexts.

Ultimately, certain unexpected results, particularly with regard to evapotranspiration, highlight the need for further research to better understand the specific interactions between climate, vegetation and hydrology at the local level. In the face of increasing climate instability, it now seems essential to adopt an integrated, proactive and evolving approach to water management. Such a strategy will not only enable better public policy guidance, but also guarantee long-term water security in a context of persistent structural vulnerabilities.

However, this research has certain limitations that should be highlighted. First, the analysis is based on annual data at the national level, which may mask significant regional disparities. Secondly, although the ARDL model captures short- and long-term dynamics, it remains sensitive to the quality and availability of climate data, particularly in areas where records are incomplete or infrequent. Furthermore, certain structural determinants such as water governance, local agricultural practices and socio-economic dynamics could not be incorporated into the model, which limits the explanatory power of the results.

These limitations open up several avenues for future research. On the one hand, analyses disaggregated at the regional or watershed level would provide a better understanding of the local specificities of climate impacts. On the other hand, the integration of institutional, social or economic variables, such as public policies, user behaviour or infrastructure investments, would enrich the overall understanding of the phenomenon. Finally, the use of hybrid models, combining econometric approaches and climate simulations, would offer a more detailed view of possible adaptation scenarios at the Moroccan level and would provide more effective guidance for future climate governance.

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