

WATER RESOURCES VULNERABILITY AND ADAPTIVE STRATEGIES UNDER CLIMATE CHANGE IN ALGERIA

VULNÉRABILITÉ DES RESSOURCES EN EAU ET STRATÉGIES D'ADAPTATION AU CHANGEMENT CLIMATIQUE EN ALGÉRIE

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ABSTRACT

Algeria, the largest country in Africa, is facing increasing pressure on its water resources due to the combined impacts of climate change, rapid population growth, and steadily rising water demand from agricultural, domestic, and industrial sectors. The country is predominantly characterized by arid and semiarid climatic conditions, making its water resources particularly vulnerable to climatic variability and long-term climate change. Under these conditions, even modest shifts in temperature and precipitation patterns can lead to substantial impacts on water availability, drought occurrence, and overall water security. This study assesses the vulnerability of Algeria's water resources under changing climatic conditions by integrating long-term historical climate data covering the period 1951–2024 with future climate projections derived from multi-model ensembles of the Coupled Model Intercomparison Project Phase 6 (CMIP6). The analysis is conducted under five Shared Socioeconomic Pathways (SSPs), which represent a range of plausible future greenhouse gas emission trajectories and socioeconomic development pathways. The results reveal a consistent and statistically meaningful long-term decline in precipitation over large parts of the country, accompanied by increased temporal variability and more frequent deviations from historical norms. These changes have led to an intensification of drought conditions, reflected in an increased frequency and severity of drought events identified using the Standardized Precipitation Evapotranspiration Index (SPEI). At the same time, significant increases in average, maximum and minimum air temperatures are observed across the historical record, with the most pronounced warming occurring after the 1990s. Climate projections suggest that these warming trends are likely to intensify throughout the twenty-first century, particularly under higher-emission scenarios such as SSP3-7.0 and SSP5-8.5, thereby exacerbating evaporative demand and further reducing effective water availability. The combined impacts of declining precipitation and rising temperatures have placed increasing stress on both surface water systems and groundwater reserves. This growing pressure is clearly reflected in the sharp reduction in per capita water availability, which has declined from approximately 1,500 m³ in 1962 to below 450 m³ in recent years, positioning Algeria well below the internationally recognized threshold for water scarcity. Using historical data (1980–2022), four machine learning models (AdaBoost, Random Forest, SVM, and Gradient Boosting) were trained to predict water stress levels. AdaBoost achieved the best generalization (testing $R^2 = 0.967$), with total water withdrawals and urban population identified as the dominant predictors, while climatic variables (SPEI, temperature) played a supporting role. Such trends highlight the heightened vulnerability of the national water system to both climatic and demographic drivers and raise concerns regarding the long-term sustainability of existing water use patterns. In response, Algeria has undertaken a series of large-scale adaptation measures aimed at improving water supply security and reducing exposure to climate-related risks. These measures include the expansion of seawater desalination programs, the strategic mobilization and regulation of groundwater resources, and substantial investments in hydraulic infrastructure designed to enhance storage, conveyance, and distribution efficiency. While these interventions have contributed to mitigating immediate supply shortages, persistent challenges remain, particularly in terms of maintaining water quality, addressing pronounced regional disparities in water access, improving governance and institutional coordination, and ensuring the long-term financial sustainability of adaptation efforts. Overall, this study underscores the urgent need for integrated,

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climate-resilient water resource management approaches that explicitly account for future climate uncertainty. Strengthening the alignment between climate adaptation policies, water planning frameworks, and broader development strategies will be critical for enhancing resilience. The findings provide valuable evidence-based insights and transferable lessons for other arid and semi-arid countries in the Middle East and North Africa region that are facing similar climate-induced water stress and adaptation challenges.

Keywords: Water scarcity, Climate change, Algeria, CMIP6, Vulnerability, Adaptation.

RESUME

L'Algérie, le plus grand pays de l'Afrique, fait face à une pression croissante sur ses ressources en eau en raison des effets conjugués du changement climatique, de la croissance démographique rapide et de la hausse constante de la demande en eau des secteurs agricole, domestique et industriel. Le pays est essentiellement caractérisé par des conditions climatiques arides et semi-arides, ce qui rend ses ressources en eau particulièrement vulnérables à la variabilité climatique et au changement climatique à long terme. Dans le cadre de ces conditions, même des changements modestes de température et de précipitations peuvent avoir un impact important sur la disponibilité de l'eau, les sécheresses et la sécurité globale de l'approvisionnement en eau. Cette étude évalue la vulnérabilité des ressources en eau de l'Algérie dans des conditions climatiques changeantes en intégrant les données climatiques historiques à long terme couvrant la période 1951–2024 avec les projections climatiques futures issues d'ensembles multi-modèles de la phase 6 du projet d'intercomparaison des modèles couplés (CMIP6). L'analyse s'appuie sur cinq scénarios de trajectoires socio-économiques partagées (SSP), qui représentent une gamme de trajectoires plausibles d'émissions de gaz à effet de serre et de voies de développement socio-économique. Les résultats constatent une baisse à long terme constante et statistiquement significative des précipitations à long terme sur la plupart du pays, accompagnée d'une variabilité temporelle accrue et d'écarts plus fréquents par rapport aux normes historiques. Ces changements ont donné lieu à une intensification des conditions de sécheresse, reflétée par une augmentation de la fréquence et de la gravité des épisodes de sécheresse identifiés grâce à l'indice d'évapotranspiration des précipitations normalisé (SPEI). Parallèlement, on constate une hausse significative des températures moyennes, maximales et minimales de l'air à travers les données historiques, le réchauffement le plus prononcé s'étant produit après les années 1990. Les projections climatiques proposent que ces tendances de réchauffement soient susceptibles de s'intensifier tout au long du XXI^e siècle, en particulier dans le cadre des scénarios d'émissions plus élevées tels que SSP3-7,0 et SSP5-8,5, aggravant ainsi la demande d'évaporation et réduisant davantage la disponibilité efficace de l'eau. Les impacts combinés de la baisse des précipitations et de la hausse des températures ont exercé une pression croissante sur les systèmes d'eau de surface et les réserves d'eaux souterraines. Cette pression croissante se reflète clairement dans la forte réduction de la disponibilité de l'eau par habitant, qui est passée d'environ 1 500 m³ en 1962 à moins de 450 m³ au cours des dernières années, plaçant l'Algérie bien en dessous du seuil internationalement reconnu pour la pénurie d'eau. En utilisant des données historiques (1980–2022), quatre modèles d'apprentissage automatique (AdaBoost, Random Forest, SVM et Gradient Boosting) ont été entraînés pour prédire les niveaux de stress hydrique. AdaBoost a obtenu les meilleurs résultats en matière de généralisation (test $R^2 = 0,967$), avec les prélèvements d'eau totaux et la population urbaine identifiés comme les prédicteurs dominants, tandis que les variables climatiques (SPEI, température) ont joué un rôle de soutien. Ces tendances mettent en évidence la vulnérabilité accrue du système national de l'eau aux facteurs climatiques et démographiques et soulèvent des préoccupations concernant la durabilité à long terme des modèles existants d'utilisation de l'eau. En réponse, l'Algérie a entrepris une série de mesures d'adaptation à grande échelle visant à améliorer la sécurité de l'approvisionnement en eau et à réduire l'exposition aux risques liés au climat. Ces mesures comprennent l'expansion des programmes de dessalement d'eau de mer, la mobilisation et la régulation stratégique des ressources en eaux souterraines, ainsi que des investissements substantiels dans les infrastructures hydrauliques conçues pour améliorer l'efficacité du stockage, du transport et de la distribution. Bien que ces interventions aient contribué à l'atténuation des pénuries d'approvisionnement immédiates, des défis persistants subsistent, en particulier en ce qui concerne le maintien de la qualité de l'eau, la lutte contre les disparités régionales marquées en matière d'accès à l'eau, l'amélioration de la gouvernance et la

coordination institutionnelle, ainsi que la garantie de la viabilité financière à long terme des efforts d'adaptation. Dans l'ensemble, cette étude met l'accent sur le besoin urgent d'adopter des approches intégrées de gestion des ressources en eau résistantes au climat qui tiennent explicitement compte de l'incertitude climatique future. Le renforcement de l'alignement entre les politiques d'adaptation au climat, les cadres de planification de l'eau et les stratégies de développement plus larges sera essentiel pour améliorer la résistance. Les résultats fournissent des perspectives précieuses fondées sur des données probantes et des leçons transférables pour d'autres pays arides et semi-arides du Moyen-Orient et de l'Afrique du Nord qui sont confrontés à un stress hydrique d'origine climatique et à des défis d'adaptation similaires.

Mots-clés : Pénurie d'eau; Changement climatique; Algérie; CMIP6; Vulnérabilité, Adaptation.

1. INTRODUCTION

Water resources in arid and semi-arid regions are increasingly recognized as one of the most critical strategic assets for sustainable development, yet they remain highly vulnerable to both climatic and anthropogenic pressures (Amparo-Salcedo et al., 2025). Globally, the interplay between climate change, population growth, and rising water demand has intensified water security challenges, with projections indicating that by 2030, one in five countries will face severe water shortages (Mezouane et al., 2026). Algeria, the largest country in Africa, exemplifies this vulnerability. Covering approximately 2.38 million km², the country is predominantly characterized by arid and semi-arid climatic conditions, with only about 13% of its territory receiving a Mediterranean climate, while the remainder is dominated by desert and steppe environments (INDC-Algeria, 2015; MEER, 2023a). This geographical reality combined with recurrent droughts and increasing water demand, places Algeria among the most water-stressed nations in the world.

The vulnerability of Algeria's water resources to climate change is rooted in both natural and human-induced factors. Historical climate records indicate a steady rise in average temperatures and a significant decline in precipitation over the past several decades. The negative impact of climate change on Algeria's agricultural sector has been confirmed by recent econometric studies, which find a long-term negative relationship between rising temperatures and food production (Bouznit & Aïssaoui, 2024). Concurrently, annual average rainfall has declined by more than 30% over the past decades, with the most pronounced decreases observed in the western and high plateau regions (INDC-Algeria, 2015). These changes have exacerbated desertification processes, with more than 27 million hectares of steppe regions classified as highly sensitive to desertification, and have intensified the frequency and severity of both droughts and flash floods (Nichane, 2024).

The implications of these climatic shifts for water availability are profound. Per capita water availability in Algeria has declined dramatically from approximately 1,500 m³ per year at independence in 1962 to below 450 m³ in recent years, placing the country well below the internationally recognized water scarcity threshold of 1,000 m³ per capita per year (MEER, 2023a; Meskine et al., 2025). This sharp reduction reflects not only climatic pressures but also the compounding effects of rapid population growth, which reached 43.9 million in 2020 and is projected to approach 58 million by 2040, and the expansion of irrigated agriculture, which consumes over 65% of mobilized water resources (Mezouane et al., 2026). Agriculture, while contributing approximately 12% to the Gross Domestic Product, relies heavily on both surface water and increasingly overexploited groundwater reserves, with irrigated areas expanding from 350,000 ha in 2000 to over 1.3 million ha by 2020.

In response to these mounting pressures, Algeria has undertaken a series of large-scale adaptation measures aimed at securing water supply and reducing vulnerability to climate-related risks. These include an ambitious seawater desalination program, with 14 operational plants producing over 2.1 million m³ per day and contributing 17% of domestic water supply, with targets to reach 42% by 2024 and 60% by 2030 (MEER, 2023a). Additionally, the country has invested substantially in dam construction, with 80 operational dams and a storage capacity of approximately 9 billion m³, though sedimentation and silting reduce effective storage by an estimated 2-3% annually (Nichane, 2024). Groundwater resources, particularly in the Saharan regions, are also being mobilized, with the

Continental Intercalaire and Terminal Complex aquifers providing essential supplies for southern agriculture, albeit at the risk of non-renewable depletion (Mezouane et al., 2026).

Despite these efforts, significant challenges persist. Water distribution networks suffer from substantial leakages, estimated at 30-40% in some urban areas, undermining efficiency gains from supply-side investments (Meskine et al., 2025). Water quality degradation, driven by agricultural runoff, industrial effluents, and inadequate wastewater treatment, further constrains usable supplies, with approximately 60% of water sources reported to be affected by pollution (Nichane, 2024). Regional disparities in water access remain pronounced, with the northern coastal zone, comprising only 7% of the national territory, accounting for over 90% of surface runoff, while the vast Saharan regions rely almost exclusively on fossil groundwater (MEER, 2023a). Governance challenges, including fragmented institutional responsibilities and water pricing policies that do not reflect actual costs, have hindered the implementation of integrated water resource management approaches (Hamiche et al., 2017).

Understanding the vulnerability of Algeria's water resources under future climate change scenarios is therefore essential for informing adaptive strategies and ensuring long-term water security. The Coupled Model Intercomparison Project Phase 6 (CMIP6) provides a robust framework for assessing future climate trajectories under a range of Shared Socioeconomic Pathways (SSPs), enabling the evaluation of potential impacts on precipitation, temperature, evapotranspiration, and drought occurrence (Mokhtari et al., 2025). By integrating long-term historical climate data with these future projections, it becomes possible to quantify the likely changes in water availability and to identify the most effective adaptation pathways.

This study aims to assess the vulnerability of Algeria's water resources under changing climatic conditions by: (1) analyzing long-term historical climate trends from 1951 to 2020; (2) evaluating future climate projections under multiple SSP scenarios using CMIP6 multi-model ensembles; (3) developing a machine learning predictive model (using Orange3 with AdaBoost, Random Forest, SVM, and Gradient Boosting) to forecast water stress levels based on climatic, demographic, agricultural, and economic predictors, and interpreting the results using SHAP feature importance; and (4) assessing the effectiveness of current and planned adaptation measures in mitigating climate-induced water stress. The findings provide critical evidence for policymakers and water managers seeking to develop climate-resilient water strategies, not only for Algeria but also for other arid and semi-arid countries in the Middle East and North Africa region facing similar challenges.

2. STUDY AREA DESCRIPTION

2.1. Location and geography

Algeria, the largest country in Africa and the ninth-largest in the world, is located in North Africa, stretching between latitudes 19° N and 37° N and longitudes 9° W and 12° E (FAO, 2024; Oumansour, 2025). The country covers a total area of approximately 2,381,741 km² and has a Mediterranean coastline extending over 1,200 km (FAO, 2024). It shares borders with seven countries: to the east with Tunisia and Libya, to the west with Morocco and Western Sahara, and to the south with Mauritania, Mali, and Niger (Oumansour, 2025). The country's topography is dominated by two major mountain ranges, the Tellian Atlas and the Saharan Atlas, which run parallel to the Mediterranean coast and separate the coastal zone from the Saharan interior (British Geological Survey, 2024).

2.2. Climate

Algeria's climate exhibits a marked zonal gradation, ranging from Mediterranean in the north to hyper-arid desert in the south. The coastal zone and the Tellian Atlas mountains, which occupy approximately 4% of the national territory, are characterized by a Mediterranean climate (subhumid bioclimatic stage) featuring mild, wet winters and hot, dry summers tempered by sea breezes. Mean minimum and maximum temperatures range between 5 and 15 °C in winter and between 25 and 35 °C in summer, with frosts being very rare. Average annual precipitation in this region varies from 400 mm to over 1,600 mm in mountainous areas, decreasing from east to west (from 1,000 to 400 mm) and from north to south

(from 1,000 to less than 130 mm). Humid maritime winds bring rainfall from autumn to spring, more abundant in the east than in the west; however, desert influence extends to the coast through the *sirocco*, a hot, dry wind from the south that raises temperatures and desiccates vegetation. Rainfed agriculture in this zone is highly threatened by the excessive concentration of population and activities (FAO, 2026). The High Plateaus, covering about 8.4% of the total area, correspond to the arid bioclimatic stage. This region receives low and irregular precipitation (200–400 mm per year, though FAO (2026) reports 100–400 mm), with winter temperatures frequently dropping below 0 °C and summer maxima exceeding 30 °C, sometimes reaching 40 °C. Due to drought, soil fragility, water scarcity, and intensive agro-pastoral practices, the High Plateaus are subject to significant desertification processes. The Sahara Desert, which covers approximately 87% of the country, is characterized by a hyper-arid (desertic) bioclimatic stage, with exceptional and highly irregular rainfall averaging less than 100 mm per year (FAO, 2026). As one of the hottest regions in the world, the Sahara experiences mean seasonal temperatures of 15–28 °C in winter and reaches 40–45 °C in summer, with extreme maxima exceeding 45 °C, while winter nights can see temperatures drop below freezing (British Geological Survey, 2024). For the entire country, mean annual rainfall is 89 mm, and potential evapotranspiration ranges from 800 mm in the northeast to over 2,200 mm in the southeast (FAO, 2026). The rainfall regime is distinguished by two rainy seasons (dominant in winter, secondary in spring), a pronounced summer drought, and high temporal variability at daily, annual, and interannual scales. Historical records indicate a significant decline in precipitation over recent decades: studies have shown a decrease of approximately 30% in annual rainfall in the Cheliff basin and 36% in the Medjerda basin over the period 1968–2013, accompanied by a 1.3 °C increase in maximum temperature between 1980 and 2020 (Bouregaa, 2022; Khedimallah et al., 2020).

2.3. Population distribution and administrative divisions

As of 2024, Algeria's population was estimated at approximately 46.7 million inhabitants, with a growth rate of 1.52% in 2023. The population is predominantly young (nearly 60% under 30 years old) and highly urbanized, with about 75% living in urban areas, concentrated in the northern coastal region (Oumansour, 2025). The coastal zone, comprising only about 4% of the national territory, supports the majority of the population and economic activity (FAO, 2026).

Algeria is administratively divided into **69 provinces (wilayas)** and **1,541 municipalities (communes)** (République Algérienne Démocratique et Populaire, 2026). The wilayas serve as the primary administrative units for regional governance, while the communes function as the basic administrative units for local governance and service delivery, including water supply and sanitation services.

2.4. Organization of water management in Algeria

Water management in Algeria is governed by Law 05-12 of August 4, 2005 (the Water Law), which establishes the principles for the use, management, and sustainable development of water resources as a national collective good. The primary authority responsible for water policy is the Ministry of Hydraulic Resources, whose remit covers research, exploitation, storage, distribution, and sanitation. At the national level, the Ministry operates through several public institutions: the National Agency of Hydraulic Resources (ANRH) for studies and resource evaluation; the National Agency of Dams and Transfers (ANBT) for water mobilization; the Algerian Water Company (ADE) for urban potable supply; the National Office of Sanitation (ONA) for urban sanitation; and the National Office of Irrigation and Drainage (ONID) for irrigation management. At the local level, each wilaya's Hydraulic Department (DHW) executes the Ministry's functions under the administrative authority of the Wali. A National Advisory Council on Water Resources facilitates coordination among administrations, economic sectors, and users (ANRH & MRE, 2019).

The 2005 Water Law introduced key provisions, including the right to access water and sanitation for all, planning within hydrographic basins, cost-based water pricing, and the possibility of delegating public water services to public legal entities.

3. CURRENT STATE OF WATER RESOURCES

3.1. Surface water

Algeria's renewable surface water resources are estimated at 11 billion m³ (BCM) per year (Table 1), constituting two-thirds of the country's total potential (GIZ, BGE, & OSS, 2016). However, high temporal irregularity limits mobilizable volumes to 5–6 BCM annually. Most surface water is concentrated in the northern region, where approximately 7 BCM per year are captured by a network of medium and large dams. In contrast, the Saharan basin receives only 0.5 BCM per year (GIZ, BGE, & OSS, 2016). Runoff occurs as rapid floods during the short rainy season (December–February). The uneven spatial distribution necessitates significant water transfers to less endowed regions. The Cheliff River, Algeria's longest (700 km), flows from the Saharan Atlas to the Mediterranean Sea (British Geological Survey, 2015).

3.2. Groundwater

Renewable groundwater resources in northern aquifers are estimated at nearly 2.5 BCM (British Geological Survey, 2024). These shallow aquifers are recharged at 1.9 BCM per year (Figure 1), but annual withdrawals reach 2.4 BCM, creating a deficit of 0.5 BCM due to inadequate management, illegal wells, and poor coordination (Fanack Water, 2026). Nationally, total groundwater resources are estimated at 7.5 BCM. In the south, major aquifers supply 96% of water demand (Fanack Water, 2026). These southern reserves are predominantly fossil, stored in two superimposed aquifers (Complex Terminal and Continental Interlayer) forming the transboundary North-Western Sahara Aquifer System (NWSAS), holding 30,000–40,000 BCM (British Geological Survey, 2024).

Table 1. Water resource potential in Algeria (Ramli et al., 2024)

Resource category	Volume (billion m ³ /year)
Global potential	18.5
Surface water potential	11.0
Groundwater potential (Northern region)	2.5
Groundwater potential (Northern Sahara)	5.0
Unconventional resources	-
Seawater desalination	0.77
Wastewater reuse	0.9

3.3. Non-conventional water resources

To address regional deficits, Algeria mobilises seawater desalination, treated wastewater, brackish water, and artificial recharge (GIZ, BGE, & OSS, 2016).

3.3.1. Seawater desalination

Algeria operates 19 desalination plants along the coast, producing 3.7 million m³/day (APS, 2025a). The strategy aims to secure potable water for coastal cities and reallocate dam water for irrigation and transfer to the high plateaus. However, desalination carries environmental (brine) and energy penalties.

3.3.2. Wastewater reuse

The country has invested in rehabilitating and constructing treatment plants. Algeria now has 234 wastewater treatment plants with a theoretical capacity of 1.1 BCM/year; 601 million m³ are treated annually, of which 19% are used for agriculture (APS, 2025b).

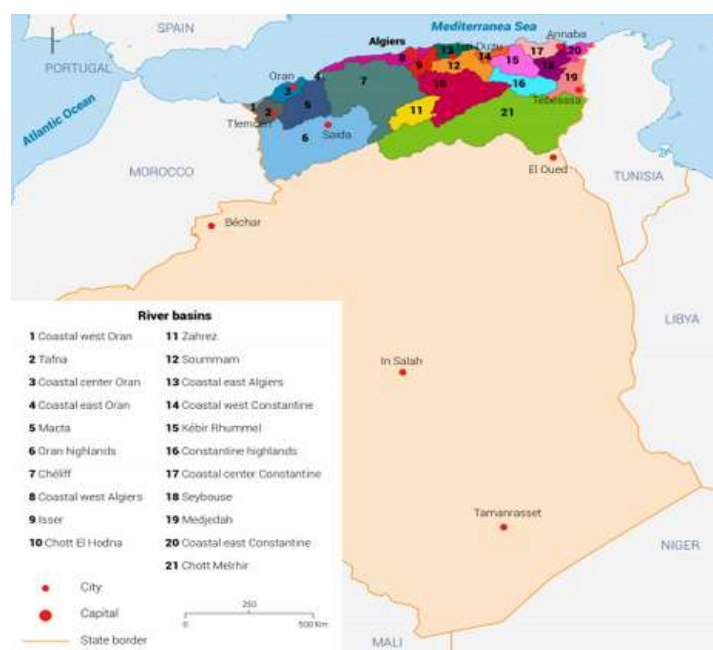


Figure 1. Algeria's major river basins (Fanack Water, 2019)

3.3.3. Water demineralisation

To treat brackish groundwater (salinity 3–6 g/L) in the Sahara, 23 demineralisation stations operate with a combined capacity of 0.25 million m³/day, serving about 950,000 inhabitants (Fanack Water, 2019).

3.4. Water infrastructure

Algeria's water infrastructure includes 81 dams (2.5 million m³/day) (Table 2), with a target of 139 dams by 2030; 19 desalination plants (3.7 million m³/day); 234 water treatment plants (3.01 million m³/day); and 23 demineralisation stations (0.25 million m³/day) (APS, 2025b; Ouamane et al., 2022).

Table 2. Water Infrastructure Capacity in Algeria (APS, 2025b)

Structure	Capacity (million m ³ /day)
81 dams	2.5
19 desalination plants	3.7
234 water treatment plants	3.01
23 demineralization stations	0.25

3.5. Water quality status

3.5.1. Surface water quality

Monitoring shows progressive physicochemical degradation of wadis from upstream to downstream, with pollution peaks near large cities (ANRH & MRE, 2019). Degradation worsens with rainfall deficits, especially in the west where self-purification is limited. Eutrophication causes algal blooms and release of ammonium, phosphates, iron, manganese, sulphides, and methane (GIZ, BGE, & OSS, 2016). Surface waters have moderate mineralisation (0.2-2 mg/L) and acceptable nitrates (<45 mg/L), but organic quality is poor in the west. Major basins (Tafna, Macta, Cheliff, Soummam, Seybouse) are

polluted, threatening drinking water supply and transfer projects (Fanack Water, 2019). Pollution stems from untreated municipal and industrial wastewater and agricultural runoff (Fanack Water, 2026).

3.5.2. Groundwater quality

Groundwater quality is generally good, though affected by natural and anthropogenic factors (Fanack Water, 2026). Northern aquifers are mostly non-saline (<1 g/L), but coastal aquifers (Mitidja, Bas Sebaou, Jijel, Annaba, Algiers) suffer from seawater intrusion (GIZ, BGE, & OSS, 2016; British Geological Survey, 2024). In the Sahara, salinity can reach 9 g/L in the Complex Terminal and near saline lakes (Fanack Water, 2026). Groundwater is often hard with high conductivity and sulphates (British Geological Survey, 2024). Anthropogenic pollution (nitrate enrichment) occurs in some northern aquifers (e.g., Mitidja) due to fertiliser leaching, agricultural effluents, and domestic/industrial discharges (GIZ, BGE, & OSS, 2016), though nitrate levels generally remain below acceptable limits (Fanack Water, 2026; British Geological Survey, 2024).

3.6. Water use

Agricultural water use dominates (67%), followed by domestic supply (31%), and industry (2%) (AQUASTAT, 2026). This pattern is typical of arid regions, though the high domestic share reflects ongoing efforts to expand potable water access.

4. DATA AND METHODS

4.1. Data sources

Historical Data (ERA5): Historical climatological data are derived from the ERA5 reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 data are presented at a spatial resolution of $0.25^\circ \times 0.25^\circ$ (approximately 25 km $\times$ 25 km) and cover the period from 1950 to 2024. This dataset includes daily-scale climate indicators, such as temperature (mean, maximum, minimum), precipitation, drought, and threshold-based indicators (e.g., number of hot days above 35°C, tropical nights above 26°C), which are particularly relevant for assessing heat stress, drought conditions, and agricultural impacts (CCKP, 2026). The ERA5 dataset has been widely applied in hydro-climatic studies across Algeria, including drought characterization in northern basins and atmospheric water vapor analysis.

Future Projections (CMIP6): Climate projections are derived from the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6), which forms the data foundation of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report. CMIP6 data are presented at the same $0.25^\circ \times 0.25^\circ$ resolution and cover the period from 1950 to 2100.

This study examines trends (1951–2024), and future projections (to 2100) of five climate variables: minimum temperature (t_{min}), maximum temperature (t_{max}), mean temperature (t_{mean}), precipitation, and the Standardized Precipitation-Evapotranspiration Index (SPEI).

4.1.1. Shared Socioeconomic Pathways (SSPs)

Projections are provided as multi-model ensembles, representing the range and distribution of plausible climate outcomes under different Shared Socioeconomic Pathways (O'Neill *et al.*, 2016; Riahi *et al.*, 2017):

- **SSP1-1.9 (very low emissions):** This scenario assumes rapid global transition toward sustainable development, with strong international cooperation, reduced material consumption, widespread adoption of clean energy, and land use change mitigation. Radiative forcing stabilizes at approximately 1.9 W/m² by 2100, consistent with limiting global warming to 1.5°C above pre-industrial levels, as targeted by the Paris Agreement.

- **SSP1-2.6 (low emissions):** This scenario follows a similar sustainable development pathway as SSP1 but achieves a radiative forcing of 2.6 W/m² by 2100. It corresponds to a likely global temperature increase of below 2°C, representing a moderate climate mitigation target. It requires net-zero CO₂ emissions by around 2070.
- **SSP2-4.5 (intermediate emissions):** This scenario represents a "middle-of-the-road" trajectory, following historical patterns of socioeconomic development without major deviations. Radiative forcing stabilizes at 4.5 W/m² by 2100, with CO₂ emissions remaining near current levels until mid-century before declining slowly. This scenario is often used as a reference for moderate climate change impacts.
- **SSP3-7.0 (high emissions):** This scenario describes a fragmented world with regional rivalry, slow technological progress, and limited international cooperation. Economic development is uneven, and population growth is high in low-income regions. Radiative forcing reaches 7.0 W/m² by 2100, driven by sustained fossil fuel use and high material intensity.
- **SSP5-8.5 (very high emissions):** This scenario assumes energy-intensive, fossil-fuel-based development with rapid economic growth and high technological progress but limited climate policy. Radiative forcing reaches 8.5 W/m² by 2100, representing the highest emission pathway.

4.1.2. Global circulation models

Future climate projections in this study are derived from an ensemble of 11 General Circulation Models (GCMs) (Table 3), selected to capture a range of plausible climate responses under the five Shared Socioeconomic Pathways (SSPs) used in CMIP6.

Table 3. General Circulation Models (GCMs) and their source institutions

Model	Institution
CAMS-CSM1-0	Chinese Academy of Meteorological Sciences
CANESM5	Canadian Centre for Climate Modelling and Analysis
CNRM-ESM2-1	Centre National de Recherches Météorologiques / CERFACS (France)
EC-EARTH3-VEG	EC-Earth Consortium (European multi-institute collaboration)
FGOALS-G3	Chinese Academy of Sciences
GFDL-ESM4	Geophysical Fluid Dynamics Laboratory (USA)
IPSL-CM6A-LR	Institut Pierre Simon Laplace (France)
MIROC-ES2L	Atmosphere and Ocean Research Institute, University of Tokyo / NIES / JAMSTEC (Japan)
MIROC6	
MRI-ESM2	Meteorological Research Institute (Japan)
UKESM1-0-LL	National Institute of Meteorological Sciences / Korea Meteorological Administration (South Korea)

4.3. Machine learning prediction of water stress

To predict future water stress levels in Algeria, a supervised machine learning approach was implemented using Orange3 data mining software (Demšar et al., 2013). Orange3 provides a visual programming environment that enables rapid prototyping and evaluation of multiple regression algorithms without extensive coding.

Target variable: The target variable was annual water stress (%), defined as total freshwater withdrawal as a proportion of total renewable freshwater resources (SDG indicator 6.4.2). Historical values (1960–2020) were obtained from the World Bank Open Database (World Bank, 2026).

Predictor variables: A set of 13 predictors was selected based on their documented influence on water stress: five climate variables (annual minimum temperature, annual maximum temperature, annual mean temperature, annual total precipitation, and the Standardized Precipitation-Evapotranspiration Index SPEI) extracted from the Climate Change Knowledge Portal (CCKP, 2026); three demographic variables (Domestic withdrawals, population growth rate, urban population percentage) from the World Bank Open Database (World Bank, 2026).

Two agricultural variables (agricultural land as percentage of total land area, and annual freshwater withdrawals for agriculture) from the same source; and three economic variables (GDP per capita, water productivity measured as US\$ GDP per cubic meter, and industrial water withdrawal percentage) also from the World Bank Open Database (World Bank, 2026). All time series were aggregated to annual resolution for the period 1980–2022.

All feature variables were normalized to a range of –1 to 1 to ensure equal contribution to the model and to prevent variables with larger magnitudes from dominating the learning process.

Machine learning models: Four regression algorithms available in Orange3 were trained and compared: Support Vector Machine (SVM), Random Forest (RF), AdaBoost, and Gradient Boosting. Each model was evaluated using 10-fold cross-validation to ensure robustness. Performance metrics included the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE).

Model training and validation: The dataset (1980–2022) was split into training (80%) and testing (20%) sets. Hyper-parameters for each algorithm were optimized manually within the cross-validation framework. Using the SHAP (SHapley Additive explanations) method, which quantifies the contribution of each predictor variable to the model's output, with variables ranked by mean absolute SHAP value.

5. RESULTS AND DISCUSSION

5.1. Climate trend in Algeria

To facilitate analysis, the time series trends in the figures are divided into three sub-periods: 1951-2024, 1971-2024, and 1991-2024, while the heat plot displays monthly anomalies for seven decadal periods, calculated relative to the monthly average of the historical reference period (1995-2014).

5.1.1. Minimum temperature trend

The figure 2 illustrates the temporal evolution of the annual average minimum surface air temperature (T_{min}) over the period 1951-2024. A clear and statistically significant warming trend is evident across all sub-periods examined. The decadal trend for the full record (1951-2024) is $+0.36^{\circ}\text{C}$ per decade, indicating a consistent increase in minimum temperatures over the past seven decades. This warming trend has accelerated in more recent periods: from 1971 to 2024, the decadal trend increased to $+0.43^{\circ}\text{C}$ per decade, and from 1991 to 2024, it reached $+0.51^{\circ}\text{C}$ per decade.

The progressive rise in decadal trends suggests an intensification of warming in the late 20th and early 21st centuries. The annual average T_{min} values support this interpretation, rising from approximately 14.8°C in 1950 to 18.0°C in 2020 (based on decadal averages), corresponding to a total increase of roughly 3.2°C over 70 years.

The minimum temperature heatmap shows that the period 1950-1980 was mainly characterized by cooler conditions, with strong negative anomalies, especially in January, April, May, and October. From the 1980s onward, temperatures gradually shifted toward warmer conditions, and the strongest positive anomalies appeared during 2000-2020, particularly between April and September. This trend is especially clear in summer months, where minimum temperatures changed from cooling to noticeable warming.

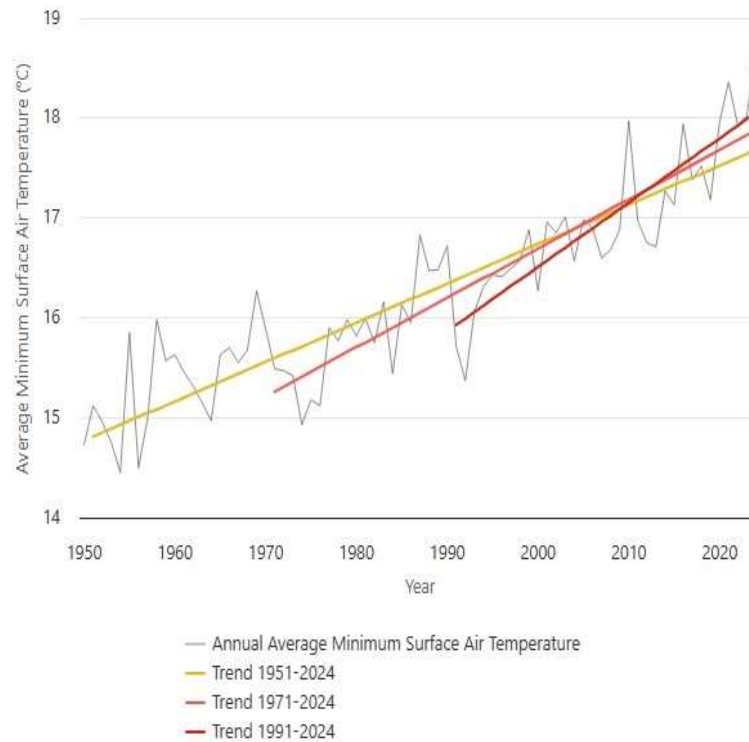


Figure 2. Minimum surface air temperature annual trends, with significance of trend/decade (1951-2024) in Algeria

5.1.2. Maximum temperature trend

The figure 3 depicts the annual average maximum temperature (Tmax) in Algeria over the 1951-2024 period, revealing a statistically significant warming trend (100% significance) across all sub-periods. The decadal trend for the full record (1951-2024) is $+0.39^{\circ}\text{C}$ per decade. This rate increases to $+0.49^{\circ}\text{C}$ per decade for the 1971-2024 sub-period and further to $+0.51^{\circ}\text{C}$ per decade for the most recent 1991-2024 sub-period, indicating a clear acceleration of maximum temperature rise in recent decades. Decadal average Tmax values support this progression: from approximately 28.22°C in the 1950s to 31.85°C in the 2020s, yielding a total increase of 3.63°C over 74 years.

The maximum temperature anomaly heatmap indicates that the earlier decades (1950-1980) were generally dominated by negative anomalies, showing cooler daytime temperatures compared to the reference baseline. The strongest cooling is observed in January, April, October, and December, where anomalies approach -2.0 to -3.0°C , particularly during winter and autumn months. From the 1980s onward, maximum temperatures gradually shifted toward less negative and more positive anomalies. The warming trend became more pronounced during 2000-2020, with several months such as January, February, March, April, May, September, October, and November showing positive anomalies. The strongest warming is especially visible in January, April, and October during the most recent decade (2010-2020), with anomalies reaching around $+0.5$ to $+1.0^{\circ}\text{C}$.

Summer months (June–August) show a more moderate transition, moving from negative anomalies in earlier decades to near-neutral or slightly positive conditions in recent decades. This suggests that warming in maximum temperatures is more evident during winter, spring, and autumn than during the summer season. The heat map reveals a clear long-term increase in maximum temperatures, although the warming pattern is less uniform than that observed for minimum temperatures. This suggests that daytime temperatures have risen over time, but with stronger seasonal variability compared to nighttime temperatures.

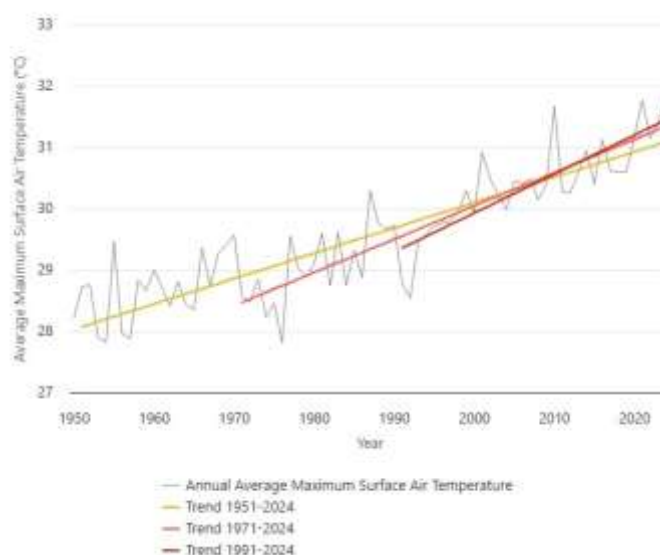


Figure 3. Maximum surface air temperature annual trends, with significance of trend/decade (1951-2024) in Algeria

5.1.3. Mean temperature trend

The figure 4 illustrates the evolution of annual average mean temperature (T_{mean}) in Algeria over the period 1951-2024. A statistically significant warming trend (100% significance) is observed across all sub-periods. The decadal trend for the full record (1951–2024) is $+0.35^{\circ}\text{C}$ per decade, increasing to $+0.44^{\circ}\text{C}$ per decade for 1971-2024 and reaching $+0.46^{\circ}\text{C}$ per decade for the most recent 1991-2024 sub-period. This progressive acceleration mirrors the patterns observed for both minimum and maximum temperatures. Decadal average T_{mean} values rose from 21.86°C in the 1950s to 25.38°C in the 2020s, corresponding to a total increase of about 3.52°C over 74 years. The consistent rise in mean temperature further confirms the intensification of warming in Algeria, with implications for evapotranspiration, water resource availability, and thermal comfort.

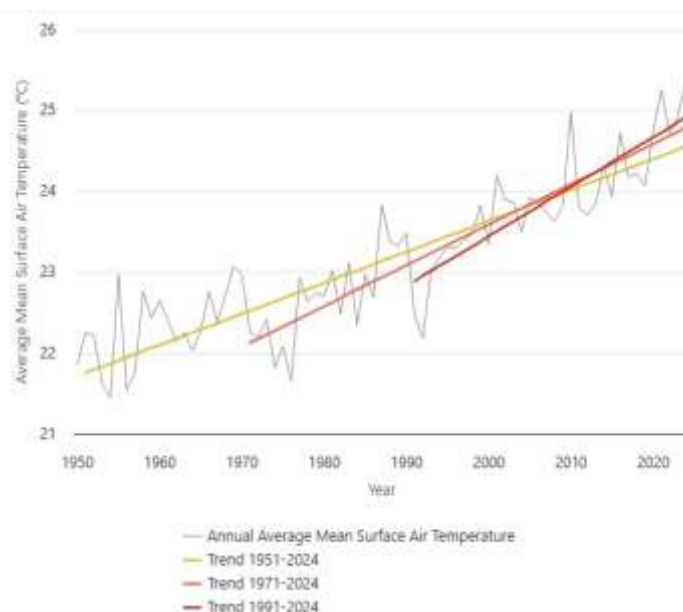


Figure 4. Mean surface air temperature annual trends, with significance of trend/decade (1951-2024) in Algeria

The heatmap shows that the early decades (1950-1980) were generally cooler than the reference baseline, with predominantly negative anomalies, especially in January, April, and October. From the 1990s onward, temperatures gradually shifted toward warmer conditions, with the strongest positive anomalies appearing during 2000-2020, particularly in winter and late summer/autumn months. Summer months (June-August) also changed from slight cooling to weak warming. The figure indicates a clear long-term warming trend with noticeable seasonal differences, where winter months warmed more strongly while some spring months, such as April, remained relatively cooler.

5.1.4. Annual precipitation trend

The figure 5 presents the annual precipitation record for Algeria at the national level over the period 1951-2024. The decadal trends are negative across all sub-periods: -1.07 mm per decade (1951–2024), -2.08 mm per decade (1971–2024), and -0.10 mm per decade (1991–2024). However, none of these trends are statistically significant, with confidence levels of 76%, 92%, and 6%, respectively, falling below the conventional 95% significance threshold. Consequently, a robust long-term decline in national mean annual precipitation cannot be established from these data alone.

Positive anomalies (e.g., >3 mm in April during 1970-1980; +3 mm in November during 2010-2020) indicate wetter than reference conditions, while negative anomalies (e.g., -2.12 mm in September during 1980-1990; and -1.62 in December during 2010–2020) reflect drier conditions. Most months and decades show anomalies close to ± 1 mm, suggesting limited long-term deviation from the baseline. However, January and September in the 1980–1990, and March in the 2000-2010 decade exhibit distinct negative anomalies. These decadal fluctuations in specific months, although not necessarily indicative of significant long-term trends at the national scale, may have localized implications for seasonal water availability.

It is important to note that national-scale aggregation may obscure substantial regional heterogeneity. Algeria's climatic gradients range from humid Mediterranean conditions in the north to hyper-arid desert in the south. Previous studies have documented contrasting regional precipitation trends: some northern basins (e.g., Cheliff, Macta) exhibit declining trends, while Saharan regions show weak or even positive signals. Therefore, the non-significant national trends reported here do not preclude the existence of locally significant changes in specific catchments or hydrological units. Regional-scale analyses are recommended to capture such variability.

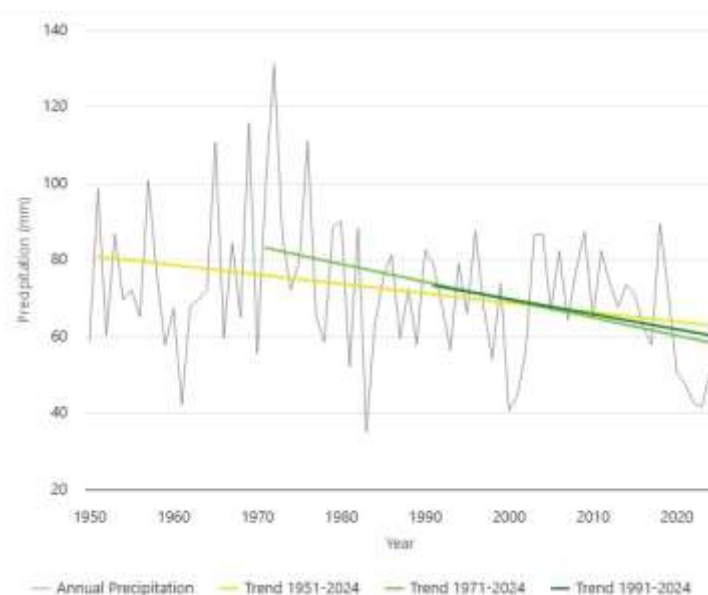


Figure 5. Annual precipitation trends, with significance of trend per decade (1951-2024) in Algeria

5.2 Future climate projections (1950–2100)

5.2.1. Projected minimum temperature changes

The figure 6 presents historical (1950–2014) and projected minimum temperatures for Algeria under five SSP scenarios (SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5). Under all scenarios, Tmin rises progressively throughout the 21st century, with the magnitude of warming strongly dependent on emission levels. By 2100, projected Tmin ranges from 17.8°C under the lowest-emission scenario (SSP1-1.9) to 23.2°C under the highest (SSP5-8.5), representing a total increase of 1.5°C to 6.5°C relative to the historical period levels. The SSP2-4.5 (intermediate) scenario yields a Tmin of 19.61°C by 2100.

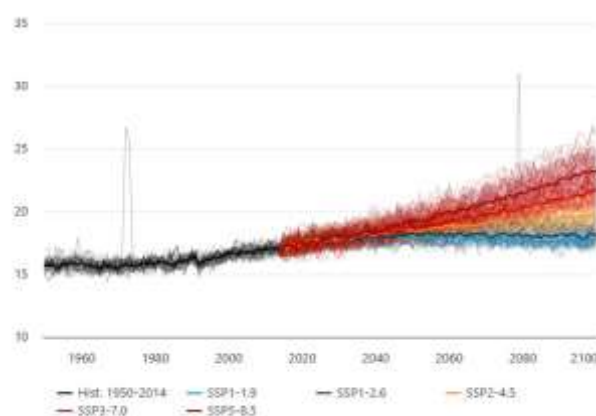


Figure 6. Projected changes in minimum temperature for Algeria (1950-2100)

5.2.2. Projected maximum temperature changes

Under all scenarios, Tmax rises progressively throughout the 21st century, with warming magnitude strongly dependent on emission levels (figure 7). By 2100, projected Tmax ranges from 31.14°C under the lowest-emission scenario (SSP1-1.9) to 36.41.0°C under the highest (SSP5-8.5), representing a total increase of 1.5°C to 6.5°C relative to the historical levels. The SSP2-4.5 (intermediate) scenario yields a Tmax of 32.93°C by 2100.

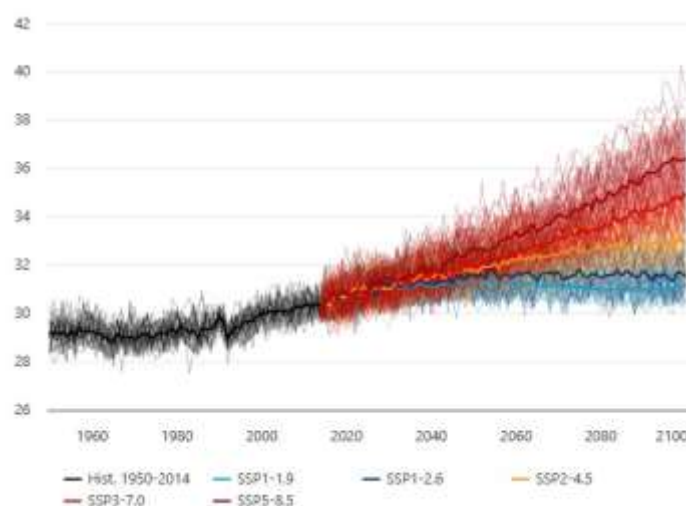


Figure 7. Projected changes in maximum temperature for Algeria (1950-2100)

5.2.3. Projected mean temperature changes

Mean temperatures in Algeria are projected to rise across all SSP scenarios (Figure 8), warming trajectories diverge significantly by 2100: the lowest-emission scenario (SSP1-1.9) reaches 24.5 °C, while the highest (SSP5-8.5) reaches 29.86°C, counterintuitively lower than intermediate scenarios. The SSP2-4.5 (intermediate) scenario yields 26.28°C by 2100, and SSP3-7.0 (high) reaches 28.44°C.

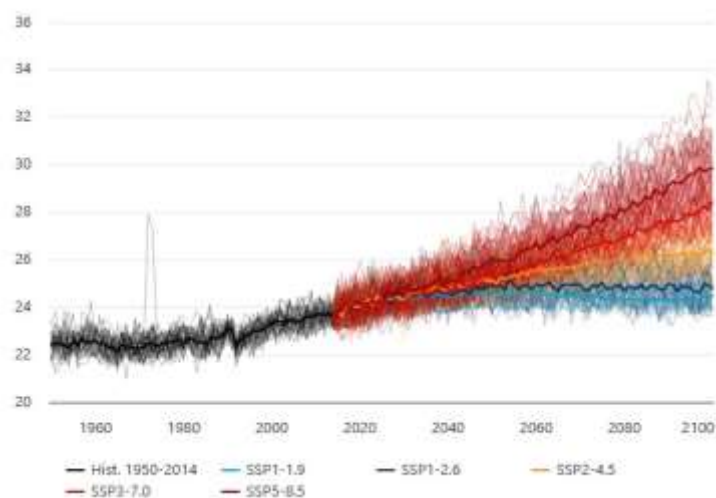


Figure 8. Projected changes in mean temperature for Algeria (1950-2100)

5.2.3. Projected annual precipitation changes

Under all scenarios, projected precipitation is consistently lower than historical levels, with the magnitude of decline directly proportional to emission intensity (Figure 9). By 2100, the highest-emission scenario (SSP5-8.5) yields the lowest precipitation (55.85 mm/year), while the lowest-emission scenario (SSP1-1.9) yields 67.11 mm/year. The intermediate SSP2-4.5 scenario projects 65.5 mm/year by 2100. These results indicate that, at the national scale, rising emissions are associated with decreasing mean precipitation, implying increased aridity and reduced water availability. However, regional assessments are necessary to capture spatial heterogeneities, such as potential wetter conditions in certain coastal areas or drier trends in the semi arid and arid regions.

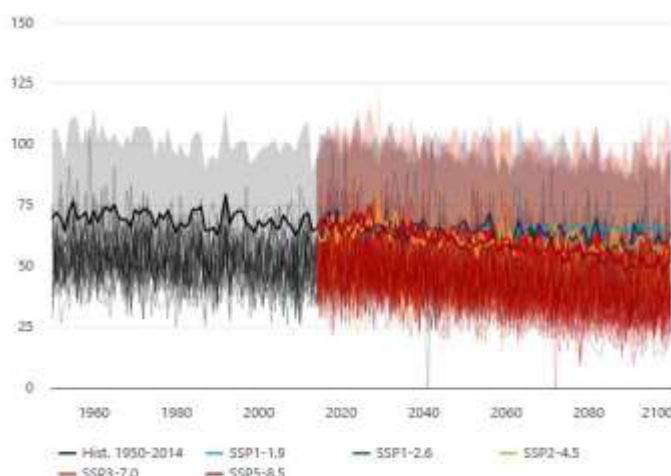


Figure 9. Projected changes in mean annual precipitation for Algeria (1950-2100)

5.2.4. Projected annual SPEI changes

Historically, SPEI declined from moderately positive values in 1960–1993 to strongly negative values by the end of the historical period (-0.94), reaching -3.0 in 2100 (Figure 10). Under future scenarios, the lowest-emission pathway (SSP1-1.9) project SPEI values near zero throughout the 21st century, suggesting a stabilization of drought conditions at near-normal levels. In contrast, higher-emission scenarios (SSP3-7.0 and SSP5-8.5) project a progressive decrease in SPEI, mirroring the historical negative trend and reaching -3.0 by 2100, indicating severe and persistent drought. These results imply that aggressive mitigation (SSP1-1.9 to SSP2-4.5) could effectively halt the long-term drying trend at the national scale, whereas unmitigated high-emission pathways would lead to extreme drought conditions. However, regional assessments are essential to capture spatial heterogeneities, such as potentially different drought evolutions in the Tellian Atlas, High Plateaus, and Sahara.

The climate projections for Algeria indicate a consistent and statistically significant warming trend across all temperature variables (minimum, maximum, and mean) under all SSP scenarios, with the magnitude of warming strongly dependent on emission pathways. By 2100, national mean temperatures under the highest emission scenario (SSP5-8.5) are projected to increase by approximately 6.5 °C relative to the historical levels. Concurrently, mean annual precipitation is projected to decline under all scenarios. The SPEI drought index, which integrates both precipitation and evapotranspiration, shows a severe negative trend under high-emission scenarios (reaching -3.0 by 2100), indicating an intensification of arid conditions, whereas low-emission scenarios stabilize the index near zero.

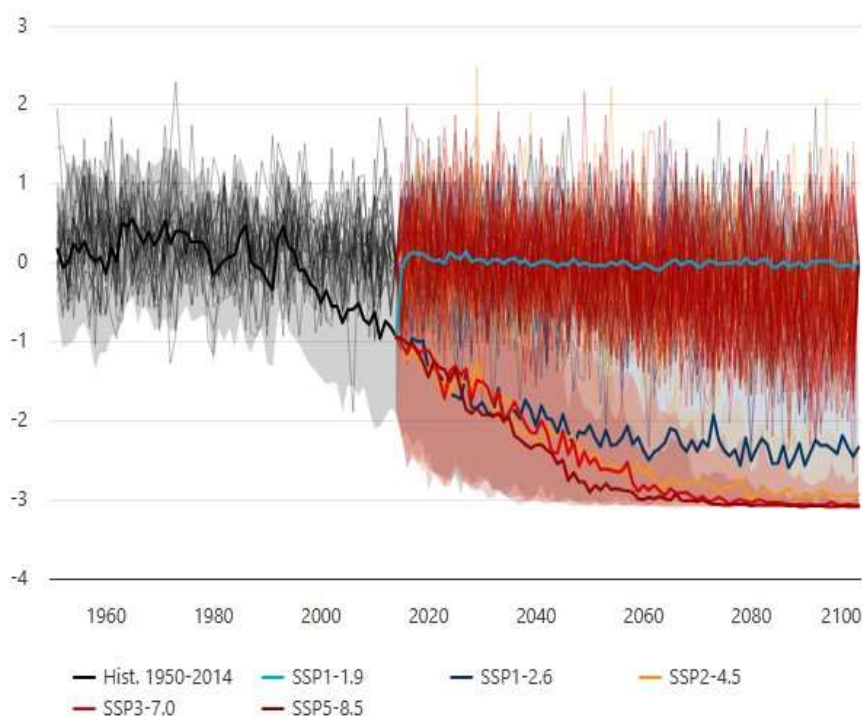


Figure 10. Projected changes in mean annual SPEI for Algeria (1950-2100)

These projected changes have profound implications for Algeria's water resources:

- **Reduced surface water availability:** Higher temperatures increase evaporation from dams and reservoirs, while declining precipitation reduces natural runoff and dam recharge. This combination will likely diminish the mobilizable surface water volume (currently 5–6 BCM out of 11 BCM potential), exacerbating existing deficits.

- **Increased groundwater stress:** Rising temperatures and prolonged droughts will increase reliance on groundwater for irrigation and domestic supply. Northern aquifers, already experiencing overexploitation (withdrawals exceeding recharge by 0.5 BCM/yr), face accelerated depletion. In the south, fossil aquifers may see increased pumping pressure, despite their low renewability.
- **Higher agricultural water demand:** Warmer minimum and maximum temperatures extend the growing season but also increase crop evapotranspiration, raising irrigation requirements at a time when water availability is declining. This threatens food security and may intensify competition between agricultural, domestic, and industrial sectors.
- **Increased drought frequency and severity:** The SPEI projections indicate that under high-emission pathways, extreme drought conditions ($\text{SPEI} < -2$) could become the new norm by 2060–2100, leading to more frequent hydrological droughts, reduced reservoir levels, and potential failure of water supply systems.
- **Strain on non-conventional resources:** While desalination and wastewater reuse are part of Algeria's strategy, these are energy-intensive and costly. Rising temperatures may increase energy demand for cooling and desalination, creating a feedback loop that exacerbates greenhouse gas emissions unless renewable energy is scaled up.
- In summary, without aggressive mitigation (following low-emission scenarios such as SSP1-1.9 or SSP1-2.6), Algeria faces a future of warmer temperatures, reduced precipitation, more severe and prolonged droughts, and consequently, heightened water scarcity across all sectors. Adaptation measures—including demand management, improved irrigation efficiency, aquifer recharge, and expansion of non-conventional resources—will be essential to offset the projected declines in renewable water availability.

5.3. Model performance evaluation

The four models were evaluated on both training and testing data (Table 4). AdaBoost achieved the best overall generalization, attaining consistently high R^2 values on training (0.988) and testing (0.967), with nearly identical RMSE (3.697 vs. 3.716) and MAE (3.208 vs. 3.492), indicating minimal overfitting. Gradient Boosting obtained the highest training scores ($R^2 = 0.993$, $\text{RMSE} = 2.873$) but showed a noticeable decline on testing ($R^2 = 0.933$, $\text{RMSE} = 5.350$), suggesting moderate overfitting. Random Forest demonstrated robust performance with a small gap between training ($R^2 = 0.972$) and testing ($R^2 = 0.921$), indicating effective regularisation. SVM delivered stable results with testing $R^2 = 0.928$ and a modest drop from training (0.962), reflecting reasonable generalisation. AdaBoost is the most generalizable model for predicting water stress in Algeria, followed by Random Forest and SVM, while Gradient Boosting, despite its high training accuracy, is less reliable on unseen data.

Table 4. Model performance evaluation

	Training			Testing		
	RMSE	MAE	R^2	RMSE	MAE	R^2
SVM	6.631	5.318	0.962	5.530	3.328	0.928
Random Forest	5.695	4.560	0.972	5.787	4.093	0.921
AdaBoost	3.697	3.208	0.988	3.716	3.492	0.967
Gradient Boosting	2.873	2.126	0.993	5.350	3.441	0.933

5.4. Observed and predicted water stress by ML models

Figure 11 presents the annual observed water stress percentages for Algeria from 1980 to 2022 alongside predictions generated by the four machine learning models: AdaBoost, Support Vector Machine (SVM), Random Forest, and Gradient Boosting. The observed data exhibit a pronounced

upward trend, increasing from 42.21% in 1980 to 144.81% in 2022, reflecting the combined effects of rising temperatures, declining precipitation, and growing anthropogenic pressures on water resources. Among the four models, AdaBoost model consistently achieves the closest alignment with observed values across all years, with deviations rarely exceeding ± 2 percentage points (e.g., 1989: 57.68% predicted vs. 60.50% observed; 2009: 104.92 vs. 102.43%).

Gradient Boosting also performs well, maintaining predictions within ± 3 points of observations. In contrast, Random Forest shows moderate deviations in the early period (e.g., 1980: 50.33% predicted vs. 42.21% observed), while SVM exhibits the largest discrepancies, particularly during the 1990s. All models successfully reproduce the inter-annual variability and the overall secular increase, indicating that the selected predictor variables adequately capture the key drivers of water stress in Algeria. On the basis of these results, AdaBoost is identified as the most reliable model for this prediction task, followed closely by Gradient Boosting.

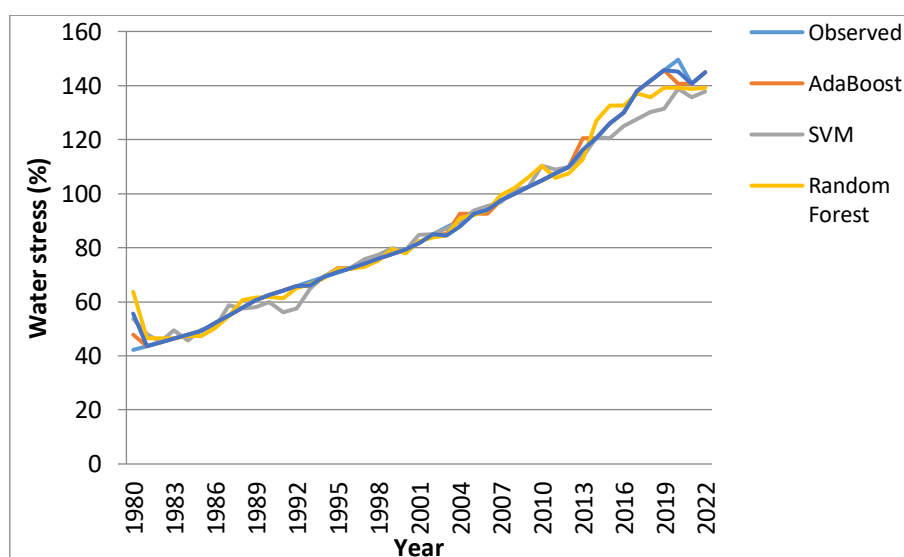


Figure 11: Observed and predicted water stress in Algeria (1980-2022)

5.5. Feature importance

The SHAP plots reveal both convergences and divergences in how the four models prioritize predictors of water stress in Algeria (Figure 12). For AdaBoost and Gradient Boosting (top panel), the most influential features are total water withdrawals, urban population, GDP per capita, and population growth rate, all of which are anthropogenic drivers. Climatic variables (precipitation, Tmin, Tmax, SPEI) appear lower in the ranking, suggesting that for boosting algorithms, socio-economic factors dominate the prediction of water stress. In contrast, the Random Forest and SVM models (bottom panel) exhibit a more balanced inclusion of climatic and hydrological variables.

For Random Forest, total withdrawals and urban population remain important, but industry and domestic withdrawals also feature prominently. The SVM model, notably, assigns relatively higher importance to water productivity, Tmin, Tmean, Tmax and SPEI, indicating that SVM captures drought-related climatic signals more sensitively than the boosting models. Across all four models, total withdrawals and urban population consistently rank among the top predictors, underscoring that human water demand is the primary driver of water stress in Algeria. However, the relatively reliance of SVM and Random Forest on climate variables suggests that ensemble or kernel-based methods may be more suitable for capturing the compound effects of drought and anthropogenic pressure. These differences in feature ranking highlight the value of using multiple interpretable models to avoid over-reliance on a single methodological perspective.

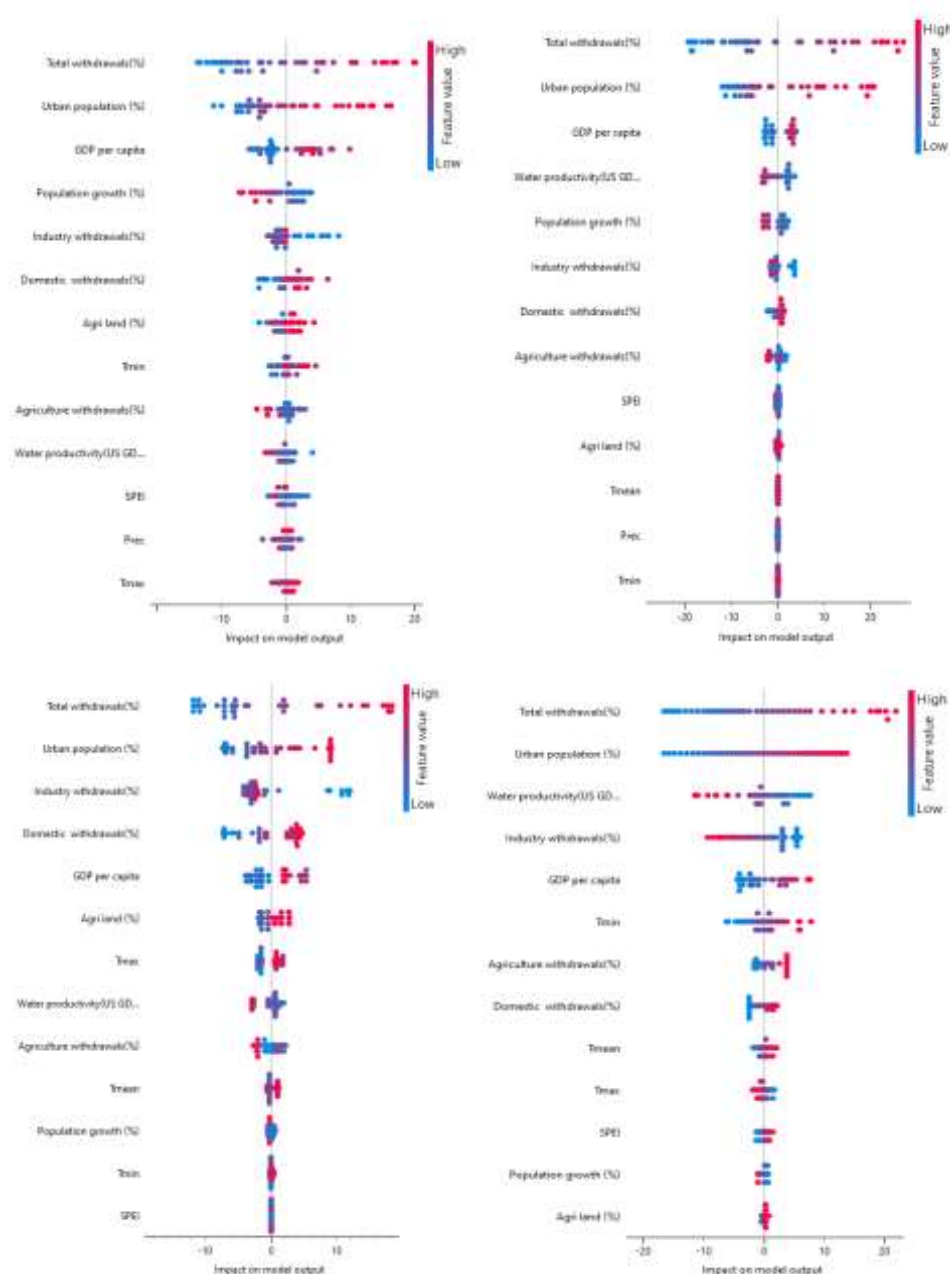


Figure 12: Variable importance for water stress prediction derived from SHAP values: AdaBoost and Gradient Boosting (top); Random Forest and SVM (bottom).

6. DISCUSSION

6.1. The role and challenges of adaptation measures

Algeria's investment in seawater desalination is a central pillar of its adaptation strategy. By 2030, desalination is expected to supply 60 % of drinking water (APS, 2025a). However, pure reverse osmosis systems face vulnerabilities: increasing turbidity events and frequent membrane replacements cause significant downtime, and the Mediterranean is warming 20 % faster than the global average, exacerbating these operational risks (Monaco Life, 2024). Hybrid MED+RO (Multiple Effect Distillation + Reverse Osmosis) systems with renewable energy integration (e.g., solar-powered electrolysis for

hydrogen) are proposed to enhance resilience, achieving 85–95 % carbon emission reductions and break-even within 16 years despite a 28 % higher capital investment (EcoMENA, 2025). Nevertheless, desalinated water remains heavily subsidized, consumers pay only 5 % of the true cost-raising questions about long-term financial sustainability and incentives for conservation (Kherbache, 2025).

Groundwater management remains another critical challenge. The NWSAS contains an estimated 40,000 billion m³, but it is largely fossil. The Tripoli Declaration (2026) is a step forward, yet many transboundary aquifers in the MENA region lack effective legal frameworks, with over-abstraction and quality deterioration continuing (BGNES, 2026). Strengthening regional cooperation and investing in aquifer recharge and demand management are essential (Noui, 2025).

6.2. Governance and institutional bottlenecks

Despite the existence of a Water Law (2005) and a National Water Plan, implementation gaps persist. At the local level, overlapping responsibilities and competing objectives among stakeholders hinder coordinated action. A multi-stakeholder analysis in western Algeria revealed that technical agencies prioritise operational targets over water quality, and disagreements due to conflicting powers threaten the sustainability of resources (Kherbache, 2025). The study recommended strengthening the role of the National Sanitation Office and enhancing collaboration between basin agencies and local stakeholders. These governance weaknesses undermine the effectiveness of both supply-side and demand-side measures.

6.3 . Limitations of the study

Several limitations should be acknowledged. First, the national-scale aggregation of climate and water stress variables masks substantial spatial heterogeneity. Algeria's strong climatic gradient, from humid Mediterranean in the north to hyper-arid in the south, means that regional (Wilaya-level) analyses are necessary for local planning. Second, the machine learning models were trained on a limited time series (1980–2022), which restricts their ability to capture long-term non-stationarities and extreme events. The observed overfitting of Gradient Boosting is a direct consequence of the small sample size. Third, uncertainty in CMIP6 projections, due to inter-model variability and downscaling methods, was not fully quantified; ensemble spread should be reported in future work (O'Neill et al., 2016; Riahi et al., 2017). Fourth, data on groundwater abstraction and quality are incomplete, limiting the accuracy of aquifer stress assessments. Finally, the analysis excluded economic and social feedbacks, such as adaptation via changes in irrigation technology or crop switching, which may alter future water demand trajectories.

6.4. Recommendations for policy and future research

Based on the findings, the following actions are recommended:

- **Integrate climate projections into infrastructure planning:** Dam design, desalination capacity expansion, and water transfer projects should incorporate the full range of SSP scenarios, including high-emission pathways.
- **Accelerate the transition to renewable-powered desalination:** Coupling desalination with solar and wind energy reduces carbon emissions and operational costs, aligning with Algeria's renewable energy targets (Energy Capital & Power, 2025).
- **Strengthen groundwater governance:** Implement the Tripoli Declaration with concrete, enforceable quotas and invest in artificial recharge schemes, particularly in coastal aquifers suffering from seawater intrusion (BGNES, 2026).
- **Improve water use efficiency:** Given the dominance of agricultural withdrawals (67%) (Our World in Data, 2022), promoting drip irrigation, deficit irrigation, and drought-tolerant crops is essential.

- **Enhance monitoring and data sharing:** Expand the hydrological monitoring network, integrate remote sensing data (Taibi, 2025), and establish open-access platforms for water resource information to support research and transboundary cooperation.
- **Advance machine learning applications in operational water management:** The high performance of AdaBoost and Random Forest suggests that these models can be used for seasonal water stress forecasting, providing early warnings for drought and supply shortages.

Future research should focus on (i) downscaling CMIP6 projections to the regional and local levels, (ii) incorporating socio-economic scenarios (e.g., SSP2 versus SSP5) into water demand modelling, (iii) integrating machine learning with process-based hydrological models to improve physical interpretability, and (iv) assessing the economic costs and benefits of adaptation options under deep uncertainty.

CONCLUSION

This study demonstrates that Algeria's water resources are highly vulnerable to the combined pressures of climate change and anthropogenic drivers. Historical climate analysis (1951–2024) reveals significant warming trends across minimum, maximum, and mean temperatures, with accelerated warming after the 1980s, while precipitation shows no statistically significant long-term national trend but exhibits increased interannual variability. Future CMIP6 projections indicate that under high-emission scenarios (SSP3-7.0 and SSP5-8.5), temperatures will continue to rise substantially (up to +6.5 °C by 2100), precipitation will decline, and the SPEI drought index will reach extreme negative values (–3.0), signaling severe aridification. Conversely, low-emission pathways (SSP1-1.9) could stabilize drought conditions near historical norms.

The machine learning analysis identifies AdaBoost as the most reliable model for predicting water stress (testing $R^2 = 0.967$), with total water withdrawals and urban population as the dominant predictors across all models. However, SVM and Random Forest also capture significant climatic signals, suggesting that drought-related variables (temperature, SPEI) are essential for accurate prediction under changing climate.

Algeria has made substantial investments in non-conventional water resources (desalination, wastewater reuse, demineralization) to offset supply deficits. Nevertheless, persistent challenges remain: overexploitation of northern aquifers, high distribution losses, water quality degradation, and pronounced regional disparities. Without aggressive mitigation following low-emission pathways, the projected increase in evapotranspiration, decline in runoff, and intensification of droughts will further reduce per capita water availability (already below 450 m³/year), threatening agricultural sustainability, food security, and socioeconomic stability.

Therefore, an integrated, climate-resilient water management strategy is urgently needed, one that combines demand-side measures (efficiency, pricing, leak reduction), supply-side diversification (renewable-powered desalination, managed aquifer recharge), and robust governance (improved coordination, data sharing, and transboundary cooperation). The findings of this study offer actionable evidence for Algeria and other arid-zone countries facing similar climate-induced water stress.

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