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PERFORMANCE AND ASSESSMENT OF FUTURE WATER MANAGEMENT USING THE WEAP AND RRV INDICATORS IN MAGHNIA MUNICIPALITY, NORTHWESTERN ALGERIA

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ABSTRACT

The municipality of Maghnia is experiencing increasing pressure on its water resources due to rapid socio-economic development and agricultural expansion. The growing imbalance between supply and demand raises concerns regarding the long-term sustainability of the local water system. To address these challenges, an integrated approach based on the Water Evaluation and Planning (WEAP) system was implemented to simulate water supply-demand dynamics through 2050, incorporating various management options and operational policies affecting municipal demand. Three performance indicators, namely reliability, resilience, and vulnerability (RRV), were employed to evaluate unmet water demand under both anthropogenic and optimized management scenarios. These indicators were subsequently integrated into a composite Sustainability Index (SI) to provide a comprehensive assessment of system performance. Results indicate that under the anthropogenic scenario, agricultural expansion generates substantial unmet demand, leading to low sustainability levels (SI ≈ 0.30-0.40). The domestic and public services sectors exhibit moderate stress, while the industrial sector remains comparatively less vulnerable. In contrast, the optimized scenario significantly reduces unmet demand across all sectors and improves system sustainability (SI ≈ 0.65-0.75), particularly through combined demand management and supply enhancement measures. The findings demonstrate that integrated intervention strategies are essential to mitigate future water deficits and strengthen adaptive capacity. This work provides a robust decision-support framework for sustainable water resource management under increasing anthropogenic pressures.

Keywords: Anthropogenic pressures; WEAP system; Water deficits; Optimized scenarios; Performance indicators; Sustainability Index.

INTRODUCTION

Water is a vital resource, indispensable for socio-economic development, no society today can claim to grow or even survive without adequate quantities of this natural wealth (Zella and Smadhi, 2010; Aroua, 2018; 2022; 2023; Binaya et al., 2021; Rouissat and Smail, 2022). Current trends in global water resources align with assessments from the World Report on Water Resources Development, indicating that the world faces multiple and increasingly complex challenges that are expected to intensify in the future (WWAP, 2018). We live in an increasingly interdependent world. The impacts of economic, financial, security, health and natural crises are spreading faster than ever before, affecting more people (Faye, 2017; Baba Hamed, 2021; Ihsan and Derosya, 2024; Chadee et al., 2024). All these global issues affect the satisfaction of water needs (GWP, 2005).

Global water demand has risen by approximately 1% annually, driven by population growth, economic development, and changing consumption patterns, with further significant increases projected over the next two decades. Although agriculture remains the largest water consumer, industrial and domestic water demands are growing more rapidly. The majority of this demand growth is expected in developing and emerging countries (Katerji and Hoflack, 2004). Water resources are increasingly vulnerable due to various pressures, including climate change and intensified competition among users, recognized as critical global issues (Hugonin, 2011; Milano, 2012). Climate change is projected to exacerbate the vulnerability of populations and water resources, particularly through extreme events such as droughts and floods (Hugonin, 2011; Assemian et al., 2021; Chadee et al., 2023; Hafnaoui et al., 2023; Baudhanwala et al., 2023; Remini, 2024; Ben Said et al., 2024; Koussa, 2025; Ezz, 2025; Do et al., 2025).

Demographic factors have a profound impact on water resources. While the world population tripled during the 20th century, water use increased sixfold (Hugonin, 2011). Climate influences water availability but often plays a lesser role compared to rising water demand due to demographic pressures (UNECE, 2010). The global population is expected to increase from 7.7 billion in 2017 to between 9.4 and 10.2 billion by 2050, with two-thirds living in urban areas and more than half of this growth occurring in Africa (Katerji and Hoflack, 2004). Agriculture, industry, and demographic growth are interdependent pressures on water, threatening its sustainability by increasing demand for food and other essential uses (Khemmoudj et al., 2016; Hugonin, 2011; Jelisavka et al., 2019; Qureshi et al., 2024).

Water management remains a persistent challenge in West Africa, particularly in Algeria (Boudjadja et al., 2003; Boutebba et al., 2014; Faye, 2016; Berrezel et al., 2023). Due to its location in an arid to semi-arid zone, Algeria is exposed to unfavorable hydro-climatic conditions, including recurrent droughts, water shortages, and occasional floods (Remini, 2020; Zegait and Pizzo, 2023; Remini, 2023). These natural constraints are further exacerbated by demographic and economic growth, which continue to increase demand for drinking water, irrigation, and industrial use (UNDP, 2019). Classified among the 17 African countries experiencing water stress, Algeria's water availability falls below the World Bank's scarcity threshold of 1000 m³ per capita per year. To safeguard critical sectors such as agriculture and industry, it is essential for Algeria to strengthen its water sector's resilience to climatic hazards while improving overall resource management (Bouchentouf and Benabdeli, 2021; Jayasena et al., 2021; Kezzar and Souar, 2024). In response to the growing imbalance between limited water resources and increasing, diversified demands, Algeria is shifting away from traditional water management systems toward a new national policy based on integrated and rational water resource management, inspired by international water governance frameworks (Benslimane et al., 2011; Chohin-Kuper et al., 2014).

In this context, this study focuses on the municipality of Maghnia, a strategic border region with Morocco, where water demand has risen sharply. Stakeholders have sought to understand the scale, causes, and consequences of the issue, and to identify strategies to mitigate impacts. Current efforts emphasize demand management policies aimed at reducing or slowing demand growth, optimizing the use of limited resources, and adapting demand to supply conditions (Dutreix et al., 2014). Prospective tools are critical for projecting future demand scenarios and uncertainties to inform adaptation measures (Graveline et al., 2010).

Methodologically, this research employs an integrated approach using the Water Evaluation and Planning (WEAP) system. The model describes the current water situation in Maghnia, evaluates resource availability, and forecasts future demands under anthropogenic pressure scenarios. Supply and demand side management scenarios are applied to optimize water management and reduce unmet demand by 2050. The evaluation focuses on system performance through reliability, resilience, and vulnerability indicators, which are aggregated to compute the sustainability index.

These results aim to support decision-makers in assessing the relevance of their strategic choices under uncertainty, encouraging reflection on current projects and policies to prevent future structural deficits (COGESAF, 2011).

MATERIAL AND METHODS

Study area

Maghnia is one of the most important urban centers in the far west of Algeria. Geographically, it is bounded to the north by the Traras Mountains, which separate it from the Mediterranean Sea, to the south and east by the Tlemcen Mountains, and to the west and southwest by the border with Morocco. Its strategic location within the Tafna basin, combined with its significant demographic and economic weight, gives the municipality a particular importance in the region. The geographical position of Maghnia within Algeria is illustrated in Fig. 1.

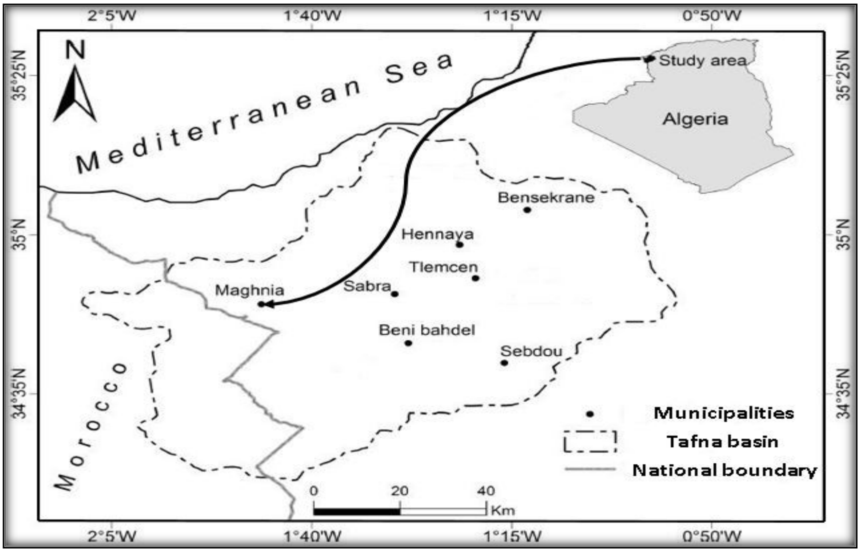

Figure 1: Geographical location of the municipality of Maghnia within Algeria, showing its position in the Tafna basin

The municipality of Maghnia, located in the Tafna basin in western Algeria, is a major urban center in Tlemcen province, with a population exceeding 150,000 inhabitants. It includes the main town of Maghnia as well as secondary urban areas such as Akid Lotfi, Bettaim, Ouled Charef, Akid Abbes, Legfaf, Bekhata, Djerabaa, Chébikia, and Messamda. This region exhibits a spatial contrast between densely populated urban centers and sparsely inhabited rural zones. The concentration of population and socio-economic activities exerts significant pressure on local water resources.

Maghnia plays a central role in regional agricultural production, with a highly diversified and economically important agricultural sector. Following the closure of the border with Morocco, agricultural activity intensified within the irrigated agricultural basin. This initiative, now considered both economically and socially significant, contributes substantially to regional food production. However, the expansion of irrigated areas, coupled with increasingly dry climatic conditions, is projected to cause a 150% increase in agricultural water withdrawals in Algeria (Milano, 2012). Consequently, the Maghnia aquifer is heavily overexploited, particularly within the large irrigation perimeter. Many unauthorized boreholes have been drilled to compensate for the Beni Behdel dam's reallocation from irrigation to domestic water supply (MRE, 2014a). Recently, reductions in cultivated areas have been reported due to water shortages, negatively affecting agricultural output. In addition to agriculture, Maghnia hosts several industrial activities, including textile, agri-food, and construction material sectors. Industrial water supply depends primarily on boreholes, with supplementary sources from dams and, less frequently, desalination. Seasonal water scarcity, especially during summer, has prompted some industries to implement water-saving measures, on-site boreholes, and recycling systems.

The region falls within Algeria's Mediterranean basin, one of the areas that is most vulnerable to hydrological impacts of climate change. A decline in precipitation, combined with increased evapotranspiration, is expected to reduce available water resources by over 50%, particularly in semi-arid regions like the Tafna basin (Milano, 2012). Maghnia is especially exposed due to its location in a semi-arid zone, characterized by chronic droughts, high desertification risk, and increasing anthropogenic pressures all of which threaten water security and the sustainability of agricultural and industrial activities.

Water supply sources and distribution system in the municipality of Maghnia

The drinking water supply system in the municipality of Maghnia is divided into two main zones: East and West. Each zone is served by a primary drinking water storage and distribution reservoir with a total capacity of 10,000 m³ (two reservoirs of 5,000 m³ each). These reservoirs are supplied by three main sources: the Souk Tleta seawater desalination plant, the Hammam Boughrara Dam along with its affiliated treatment plant, and the Bouhlou drinking water production plant fed by the Beni Behdel Dam. Following a 2024 survey, the Hammam Boughrara Dam reservoir has maximum storage capacity of 75 million cubic meters (Mm³). The Hammam Boughrara facilities capture surface water for treatment and distribution to consumers. The Bouhlou plant has a current production capacity of 28,000 m³/day and supplements the supply from the Beni Behdel Dam. Groundwater exploitation primarily relies on the Beni Boussaid Aquifer, which is the most significant underground water resource in the region. Consequently, the municipality's water supply comes from surface water sources (Beni Behdel and Hammam Boughrara Dams) and groundwater resources (Beni Boussaid Aquifers), and the Souk Tleta desalination plant, which represents the only non-conventional water source serving the area. Water from these resources is distributed to meet domestic, public service, industrial, and agricultural demands within Maghnia.

Data collection and processing

The methodology adopted in this study relies on field campaigns and data collection from various official agencies involved in water resources management. The primary institutions consulted include the National Agency for Dams and Transfers (ANBT), the Directorate of Agricultural Services (DSA), the National Sanitation Office (ONA), the National Office of Irrigation and Drainage (ONID), the National Statistics Office (ONS), the Oranie Chott Chergui Water Basin Agency (ABH-OCC), and the Integrated Water Resources Management Agency (AGIRE). Additional field surveys and interviews were conducted with stakeholders and officials from the Algerian Water Authority (ADE), specifically the Maghnia unit.

The data series compiled include annual volumes of water produced and consumed in the municipality of Maghnia over a period of 17 years (2006–2023), which served as the system is monitoring period. In 2023, for instance, the Algerian Water Authority (ADE) reported a total production of 13.9 Mm³ of potable water to meet urban demand. The surface water of the Hammam Boughrara treatment plant contributed approximately

96.4% (13.4 Mm³) of this volume, while the Souk Tleta seawater desalination plant provided 506,504 m³, accounting for 3.6% of the total production or an average of 1,387.68 m³/day. Furthermore, historical data on water supply between 2019 and 2023 were analyzed (Table 1) to evaluate the consistency of the current situation. Demographic trends, expansion of irrigated areas, and the development of industrial zones were also tracked, as these represent key variables for estimating future water demand in the region.

Table 1: History of water supply volumes in the municipality of Maghnia (ADE, 2023)

Year	Surface water resource			Groundwater Resource	Unconventional Water Resource
	Hammam Boughrara Dam	Beni Behdel Dam		Beni Boussaid Water Table	Mediterranean Sea
	Hammam Boughrara Treatment Plant	Bouhlou Filtration Plant	Beni Behdel Dam	Beni Boussaid Water Table Drillings	Souk Tleta Sea Desalination Plant
2019	10,959,659	596,836	1,000,000	726,461	961,832
2020	10,295,187	26,053	0	1,084,713	175,560
2021	10,101,653	397,964	0	1,165,690	8
2022	9,304,969	404,765	0	1,224,925	812,288
2023	8,001,825	361,154	0	1,092,948	506,504
Use	Domestic and Public Services + Industrial		Agricultural	Domestic and Public Services + Industrial	

Methodology

As illustrated in Fig. 2, the methodological framework of this study is structured around four main components. The first dimension focuses on the quantitative assessment of available water resources. The second dimension evaluates water demand across various sectors, including domestic and public services, agriculture, and industry. To support this analysis, the WEAP21 (Water Evaluation and Planning System) model was employed as an integrated tool for simulating water supply and demand dynamics over long-term planning horizons in the municipality of Maghnia. This includes socio-economic development projections to assess the intensity and evolution of pressure on water resources. The third dimension aims to generate comprehensive scenario-based analyses. It compares anthropogenic pressure scenarios with optimized scenarios incorporating adaptation measures such as rational water consumption, increased water reuse, and improved irrigation techniques for the period 2022–2050. The fourth dimension integrates performance evaluation through the application of RRV (Reliability, Resilience, and Vulnerability) indicators, derived from simulations of unmet water demands under different scenarios (Hall et al., 2012; Jahanshahi and Kerachian, 2019). These indicators are further synthesized into a Sustainability Index (SI), providing a holistic measure of the system's capacity to meet future water demands sustainably

(Aydin, 2014). This framework enables comparative analysis of policy alternatives and supports informed decision-making under uncertainty. Fig. 2 presents an overview of the modeling approach and methodological steps adopted in the study.

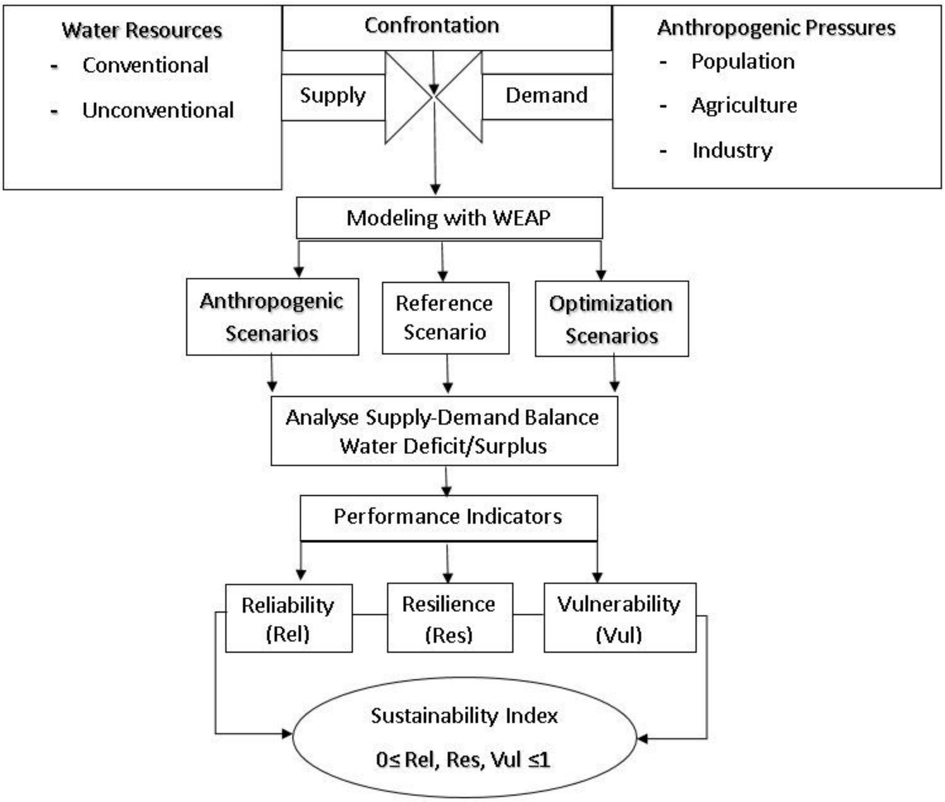

Figure 2: Methodological framework of the study

WEAP model

As an initial step, the WEAP (Water Evaluation and Planning) model, developed by the Stockholm Environment Institute, was adopted as an integrated water resource management tool. WEAP belongs to a new generation of modeling tools designed to address both natural and anthropogenic challenges at the watershed level, facilitating assessment and forecasting of water resource availability (Yates et al., 2005). Its integrated approach provides water planners with a comprehensive perspective on the multiple factors involved in managing water resources for current and future demands (Osoro George et al., 2018). Globally recognized for its flexibility, user-friendly interface, compatibility, and scalability, the WEAP model is widely used for complex water systems. Additionally, it enables the construction and evaluation of multiple future scenarios based on varying assumptions related to water demand and supply policies (Kou et al., 2018).

WEAP21 is a conceptual model that employs a schematization approach to represent both physical and hydrological processes within a watershed (Bouznad et al., 2016). It integrates natural system components (e.g., catchments, aquifers, rivers, lakes) and technical system elements (e.g., reservoirs, boreholes, diversions, treatment plants, desalination plants, irrigation farms) as a network of interconnected model elements without explicit geographical referencing (Psomas et al., 2017). The model requires extensive input data for each network component, with customizable data structure and detail level to suit specific analyses or data availability constraints (Yates et al., 2005). In this study, a Geographic Information System (GIS)-based map of the Maghnia municipality was used to schematize the river network, demand sites, reservoirs, and other physical elements within WEAP21, for annual time steps spanning 2022 to 2050. The schematization represents groundwater and surface water sources, treatment plants, a wastewater treatment plant, and desalination plant nodes linked to geographically distributed demand sites. Water allocation priorities for each demand site were established following the local Water Resources Development Master Plan (PDARE). Nodes representing demand, treatment, and desalination were interconnected with transmission and return flows, enabling the simulation of water distribution and usage dynamics. Fig. 3 illustrates the constructed WEAP model interface.

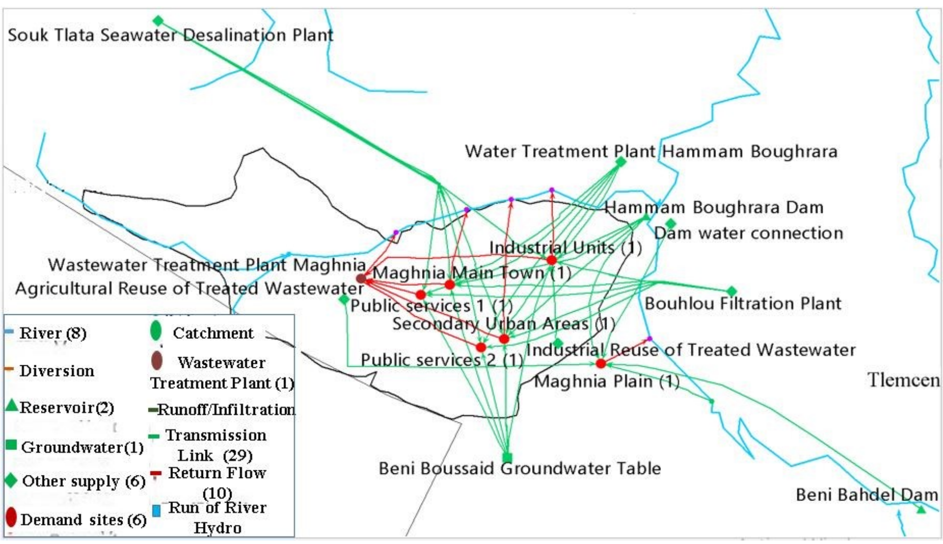

Figure 3: Schematic illustration of the municipality of Maghnia in the WEAP application

Future possible scenarios

This scenario-based modeling approach allows for the integration of projection assumptions, political decisions, and their technical or financial implications. It also enables a more rigorous interpretation of projection results by quantifying the scale of emerging challenge particularly those linked to anthropogenic pressures through defined numerical ranges. Furthermore, key variables within the model can be adjusted to test adaptation measures and develop alternative optimization scenarios, with the ultimate goal of achieving a sustainable water balance in the Maghnia municipality by 2050.

Building upon this framework, the scenarios developed in this study are grounded in the same core assumptions as those used in regional water use planning. They draw upon the PDARE, national strategic reports, and the ongoing development programs of the Ministry of Water Resources (MRE, 2014b). Additionally, the scenarios reflect a comprehensive view of climate change adaptation, socio-economic dynamics, water supply and demand management, as well as prevailing economic trends and technical parameters specific to the Algerian context. Fig. 4 provides a summary of the different scenarios developed in this study, highlighting their main assumptions.

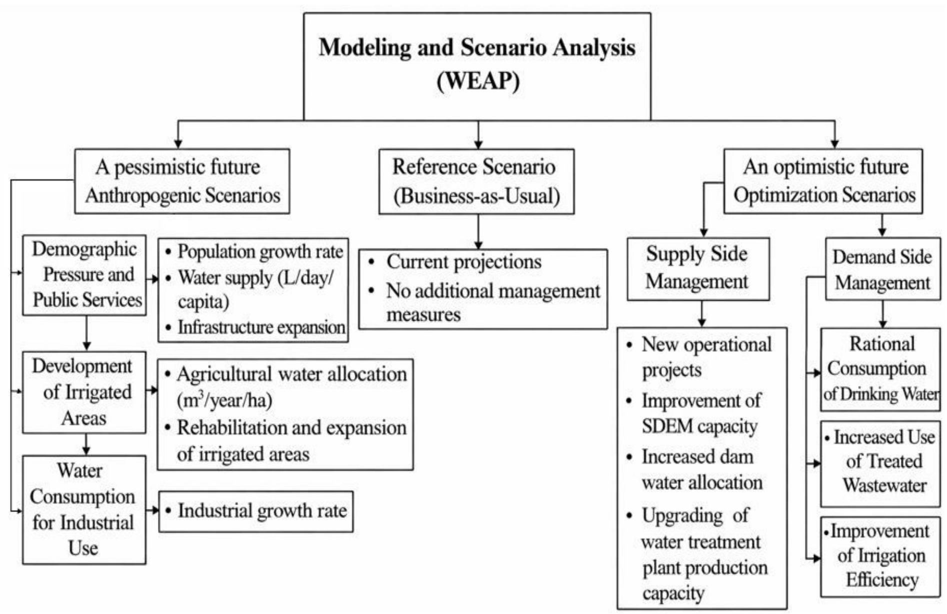

Figure 4: Study an image showing the workflow of the anthropogenic scenarios and the optimization scenarios with the key assumptions used in the study

Reference Scenario (RS)

The reference scenario, considered as the baseline (alternative zero), reflects current socio-economic trends and assumes constant per capita water demand over the simulation period. It spans from 2022 to 2050, with 2021 serving as the baseline year, representing the existing water supply conditions in the Maghnia municipality. This scenario projects future demand based solely on population growth, without changes in water use or supply practices.

Scenario of pressures of anthropogenic activities on water resources

This scenario, denoted PAAWR, is structured around three essential components, which serve as key assumptions integrated into the model framework.

Component 1: Demographic pressure and public services

Population growth, driven by rising demand for improved living standards, remains a major factor challenging the ability to meet future water needs in the Maghnia municipality. Demographic analysis, based on historical data from national censuses by the National Statistics Office (ONS), provides insights into past trends and informs projections of future population changes. This scenario assumes an elevated annual population growth rate of 2.8% to evaluate demographic pressure on water resources. Additionally, water consumption for public services is projected to grow by 1% annually, increasing from 0.84 m^3 per capita in 2022 to 16.4 m^3 by 2050, reflecting expanding service demands.

Component 2: Development of irrigated areas

In the reference scenario, agricultural activity in the Maghnia basin covers approximately 4,823.5 ha annually. Driven by demographic pressure, the demand for arable land has increased, leading to intensified water withdrawals from the supply canal. Trends from census data, the Directorate of Water Resources (DRE), Tlemcen Province, and the Directorate of Agricultural Services (DSA) programs indicate a continued expansion of irrigated areas, with projections reaching 7,000 ha and an estimated annual growth rate of 3.3%. Consequently, water demand is expected to rise gradually by an average of 1.4 Mm^3 per year. This scenario assumes no climate change impacts during the study period.

Component 3: Water consumption for industrial use

Industrial water consumption in the model was estimated using a proportionality coefficient, representing the ratio between industrial and domestic/public water use. With projected development of the Ouled Bendamou industrial park and planned supply from the Hammam Boughrara treatment plant or the Souk Tleta desalination plant, industrial demand is forecast at 5.2% for 2025 and 2030, and 8.6% by 2035. An annual growth rate of 0.4% is assumed thereafter, reaching 9%, 9.4%, and 9.8% in 2040, 2045, and 2050 respectively.

Optimization scenarios (OS)

The optimization scenarios explore adaptation measures aimed at reducing unmet water demands in Maghnia by 2050, focusing on both supply enhancement and demand reduction. Supply-side measures include increasing dam outputs and expanding seawater desalination capacity. On the demand side, scenarios target urban water conservation, improved irrigation techniques in agriculture, and the reuse of treated wastewater, reflecting a comprehensive approach to sustainable water resource management.

Scenario of Rational Consumption of Drinking Water (RCDW)

This scenario focuses on rationalizing water consumption by assuming a 5% reduction in drinking water use in both the main town of Maghnia and secondary urban areas over the simulation period. The projected decrease is attributed to public awareness campaigns led by the Integrated Water Resources Management Agency (AGIRE), aiming to promote responsible water use and reduce waste.

Scenario for Improving Irrigation Techniques (IIT)

This scenario prioritizes the enhancement of irrigation techniques to optimize agricultural water use within the Maghnia irrigation perimeter. It proposes transitioning from traditional gravity irrigation operating at 50–70% efficiency to advanced methods such as sprinkler and drip irrigation, which can achieve efficiencies up to 90%. The scenario aims for a 35% reduction in water consumption by 2050, lowering annual usage to 4,550 m^3/ha across existing and planned irrigated areas. This approach addresses water demand challenges posed by the region's semi-arid climate and potential variability in climatic conditions throughout the study period.

Scenario of Increased Treated Wastewater (ITW)

This scenario aims to reduce discharges into the Tafna River and optimize water use through wastewater treatment and subsequent reuse. Emphasis is placed on agricultural reuse of treated wastewater, with projections assuming significant growth linked to the completion of irrigation area connections to the Maghnia wastewater treatment plant. Reused wastewater volume is estimated to increase linearly to 8.5 Mm^3 by 2050. Additionally, industrial water reuse is expected to rise by 30% compared to baseline scenarios. Reused water is primarily allocated to irrigation, industrial activities, and non-potable uses.

Supply Side Management Scenario (SSM)

This scenario builds upon the baseline scenario of anthropogenic pressures on water resources and explores future supply-side enhancements for the Maghnia municipality. Given the absence of planned major reservoirs, efforts focus on rehabilitating the Souk Tleta desalination plant, aiming to restore its production to 15 Mm^3/year. Additionally, the scenario considers the construction of a new seawater desalination facility in Marsa Ben M'hidi with a projected capacity of 100,000 m³/day dedicated to Maghnia. To strengthen agricultural supply, it also proposes connecting the Maghnia irrigation perimeter to the Hammam Boughrara dam, with an estimated allocation of 20 Mm³/year. These measures reflect a strategic shift towards securing water availability in the context of increasing demand and limited conventional resources.

Performance criteria RRV

The application of Reliability, Resilience, and Vulnerability (RRV) indices has become standard in evaluating water supply system performance (Hall et al., 2012). These indices, first introduced by Hashimoto et al. (1982), provide a flexible and robust framework for assessing system behavior under varying demand and supply conditions (Hashimoto et al., 1982). Their strength lies in the ability to adapt threshold criteria to context-specific definitions of satisfactory performance. Combined into a Sustainability Index (SI), these metrics allow for an objective comparison of different water resource management scenarios (Fowler et al., 2003). In this study, the RRV approach is applied to the municipal water supply system of Maghnia, Algeria. System performance is characterized through three dimensions: reliability (failure frequency), resilience (recovery speed), and vulnerability (failure impact) (Rodding Kjeldsen and Rosbjerg, 2004). The evaluation uses discrete time intervals to compare water demand $X_{D,t}$ and supply $X_{S,t}$, with deficits D_t calculated as the cumulative unmet demand according to Eq. (1). This method supports data-driven decision-making for sustainable urban water management under variable supply conditions.

$$D_t = \begin{cases} X_{D,t} - X_{S,t}, & \text{if } X_{D,t} > X_{S,t} \\ 0, & \text{if } X_{D,t} < X_{S,t} \end{cases} \quad (1)$$

When $X_{S,t} > X_{D,t}$ the system is in a satisfactory (non-failure) state, meaning water supply meets or exceeds demand; conversely, when $X_{S,t} < X_{D,t}$, the system is in a failure (unsatisfactory) state, meaning water demand is not fully met. The RRV indicators for variable i are estimated based on the extracted series of failure durations and deficit volumes, using both descriptive and mathematical definitions, as detailed in several studies (McMahon et al., 2006; Hunter et al., 2015; Golmohammadi et al., 2021; Nair and Indu, 2021).

Reliability (Rel)

Reliability (Rel^i) is one of the most established and widely utilized performance criteria for evaluating water resource systems (Hunter et al., 2015). Originally introduced by Hashimoto et al. (1982), this metric quantifies the ability of a system to consistently satisfy water demand without experiencing deficits over a defined analysis period (Loucks, 1997; Hashimoto et al., 1982; Comair et al., 2013; Maestro et al., 2014; Palop-Donat et al., 2020; Hong et al., 2022; Moudi, 2022).

Mathematically, reliability represents the probability (P) that the system remains in a satisfactory, non-failure state ($X_t \in S$) throughout the simulation (Kundzewicz and Kindler, 1995; Hashimoto et al., 1982; McMahon et al., 2006; Hall et al., 2012; Biglarbeigi et al., 2020). In the context of water management, it reflects the frequency with which the system successfully meets demand requirements. It is computed as the ratio between the number of time steps (n_s) where no deficit occurs ($D_t = 0$), and the total number of simulated periods (n), as expressed in Eq. (2). (Holling, 1973; Hashimoto et al., 1982; Ostfeld, 2001; McMahon et al., 2006; Hall et al., 2012; Mays, 2013; Ahmadaali et al., 2018; Al-Juaidia and Attiahb, 2020; Palop-Donat et al., 2020; Golmohammadi et al., 2021):

$$Rel^{i} = P[X_t \in S] = \frac{n_S(D_t = 0)}{n} \tag{2}$$

Resilience (Res)

Resilience, originally conceptualized by Holling (1973), characterizes a system's capacity to recover its core functions following a disruption (Shuang et al., 2019). In the context of water resource management, this criterion quantifies the speed at which a system transitions from a failure state (F), such as an unmet water demand, back to a satisfactory state (S) (Kundzewicz and Kindler, 1995; Biglarbeigi et al., 2020). Specifically, resiliency (Res^i) is defined as the conditional probability (P) that a satisfactory condition ($X_t \in S$) occurs in the time step immediately following an unsatisfactory one ($X_{t-1} \in F$) (Hong et al., 2022).

A higher resilience value indicates better recovery capacity and system adaptability. This metric is especially relevant for assessing how water systems respond to disturbances and adapt to changing conditions (WHO, 2009; Sandoval-Solis et al., 2011; Asefa et al., 2014; Wied et al., 2020; Leštáková et al., 2024).

Mathematically, it is calculated as the ratio between the number of successful transitions from deficit to non-deficit, $n_s(D_t = 0 \cap D_{t-1} > 0)$, and the total number of periods where the system was in a state of deficit, n_d ($D_{t-1} > 0$), as expressed in Eq. (3) (Ostfeld, 2001; Aydin, 2014; Palop-Donat et al., 2020; Golmohammadi et al., 2021):

$$Res^{i} = P[X_t \in S | \; X_{t-1} \in F] = \frac{n_S(D_t = 0 \cap D_{t-1} > 0)}{n_d(D_{t-1} > 0)} \tag{3}$$

Vulnerability (Vul)

Vulnerability (Vul^i) provides a critical measure of the average magnitude and severity of consequences caused by failure events (unsatisfactory scenarios) in water resource systems (Hashimoto et al., 1982). Unlike reliability, which focuses on the frequency of events, vulnerability quantifies the intensity and extent of water shortages during deficit periods (Kundzewicz and Kindler, 1995; Ostfeld, 2001; McMahon et al., 2006; Zimmermann 2011; Hunter et al., 2015; Hong et al., 2022). This criterion accounts for the cumulative impact of failures over a given time series, enabling more reliable comparisons between alternative management scenarios (Fowler et al., 2003).

Mathematically, vulnerability is quantified as the ratio between the sum of all daily or monthly deficits ($\sum D_t$) recorded throughout the simulation and the total number of time steps where a deficit actually occurred, $n_d(D_t > 0)$, as expressed in Eq. (4) (Hashimoto et al., 1982; Loucks, 1997; Kufeld et al., 2012; Maestro et al., 2014; Hunter et al., 2015):

$$Vul^{i} = \frac{\sum_{t=1}^{n} D_t}{n_d(D_t > 0)} \quad (4)$$

Sustainability Index (SI)

Loucks (1997) introduced the Sustainability Index (SI) by integrating the reliability, resilience, and vulnerability (RRV) metrics, each informative individually, to evaluate the long-term performance of water resource systems (Ostfeld, 2001; Aydin, 2014; Palop Donat et al., 2020; Golmohammadi et al., 2021). The SI aids in assessing and comparing water management policies, reflecting the system's adaptive capacity to reduce vulnerability (Ostfeld, 2001; Golmohammadi et al., 2021). A critical step in computing the Sustainability Index (SI) consists of normalizing vulnerability into a dimensionless relative vulnerability measure (Vul^{i}_{rel}) to ensure comparability with reliability and resilience indicators (Aydin, 2014).

The relative vulnerability is calculated as the ratio between the mean vulnerability (Vul^{i}) and the maximum observed deficit (D_{max}) during the assessment period, as expressed in Eq. (5). This normalization ensures that all performance criteria vary within the interval [0,1], where higher reliability and resilience values indicate better system performance, while lower vulnerability values reflect reduced system risk (Zimmermann, 2011; Hall et al., 2012; Kufeld et al., 2012; Nair and Indu, 2021).

$$Vul^{i}_{rel} = \frac{Vul^{i}}{D_{max}} \quad (5)$$

Traditionally, the Sustainability Index is obtained by aggregating multiple normalized performance criteria, typically reliability, resilience, and vulnerability, into a single composite indicator (Zimmermann, 2011; Aydin, 2014; Golmohammadi et al., 2021). However, in the present study, the SI formulation was adapted to specifically reflect the system's capacity to mitigate the impact of water shortages. To maintain consistency with the specific operational constraints of the evaluated system and to preserve a high comparative analytical capacity, the Sustainability Index (SI^{i}) is expressed as a direct function of relative vulnerability (Vul^{i}_{rel}). This approach emphasizes the severity of deficits as the primary driver of system risk, as presented in Eq. (6):

$$SI^{i} = 1 - Vul^{i}_{rel} \tag{6}$$

RESULTS AND DISCUSSION

This section presents the key findings from our 29-year simulation. Using the WEAP model, several components of the water system were analyzed across six different scenarios. Each scenario has a distinct impact on the municipality's water resources. The analysis is structured into three main parts to capture the various dimensions of water demand. First, we examine the demands projected by WEAP under the reference scenario, taking into account anthropogenic activities as well as selected optimization strategies. Second, we assess the overall unmet demand across all sectors, using performance indicators to compare the scenarios. Finally, we conduct a comparative analysis of the results to highlight the implications of each scenario for future water resource planning.

Reference scenario "Business as Usual"

Under the baseline scenario, projections indicate a significant increase in water abstraction at all withdrawal points throughout the system. The primary water demand nodes considered in this analysis include domestic and public services, industry, and irrigation, all of which exert considerable pressure on available water resources. In particular, the municipality of Maghnia is expected to experience a steady rise in demand due to population growth and socio-economic development, posing a substantial challenge for future water resource planning. Fig. 5 illustrates the current distribution of water demand across each demand site in the municipality. Total water demand is projected to increase from 27 Mm^3 in 2021 to 37 Mm^3 by 2050, a dramatic escalation compared to the baseline year. If water availability remains unchanged, the municipality will face significant challenges in meeting the rising daily water needs across all sectors. In 2021, water demand was distributed as follows: 20 Mm^3 for irrigation, 6 Mm^3 for domestic and public services, and 1 Mm^3 for industrial use. By 2050, this demand is projected to grow to 37 Mm^3, with irrigation accounting for 27 Mm^3, domestic and public services 8 Mm^3, and industry 2 Mm^3. Agricultural demand represents the largest share, comprising 73% of the total projected water needs, reaffirming the agricultural character of the municipality.

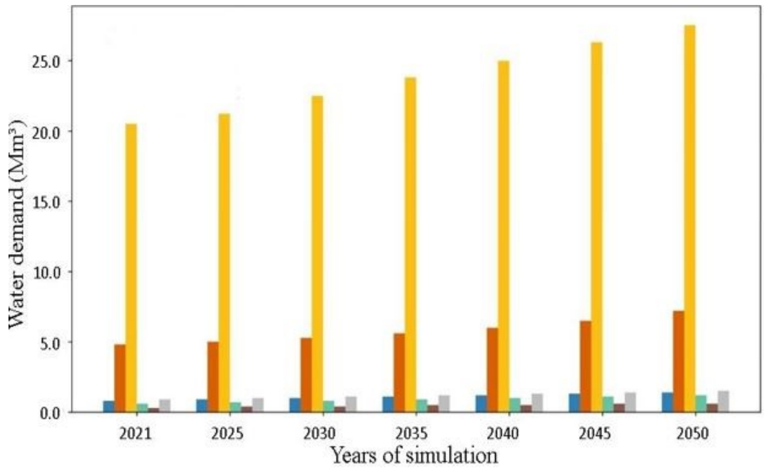

Figure 5: Evolution of water demand across different sectors in the Maghnia municipality (2021–2050): Maghnia Plain (yellow bar), Maghnia Main Town (orange bar), Secondary Urban Areas (grey bar), Industrial Units (blue bar), Public Services 1 (green bar), and Public Services 2 (brown bar)

Unmet water demand in various sectors and future scenarios

Domestic and public services

The proposed water conservation strategy aims to reduce overall water consumption by promoting rational water use among households and public institutions. This approach is represented by the RCDW scenario and evaluated using the WEAP model in comparison with two additional scenarios, namely PAAWR and SSM.

The simulation results indicate that a slight unmet water demand persists under all scenarios throughout the projection period (2021–2050) (Fig. 6). However, the magnitude of this deficit remains limited and increases only gradually over time. The SSM scenario produces the lowest deficit values, followed by RCDW, while PAAWR exhibits relatively higher unmet demand. Nevertheless, in all cases, the deficit remains small in comparison with total water demand, indicating a relatively stable supply–demand balance.

These findings confirm that demand management measures, particularly those focused on rational drinking water consumption, contribute significantly to mitigating water stress in the municipality of Maghnia. Although the simulations do not demonstrate a complete elimination of deficits, the projected shortages remain within acceptable limits, suggesting that improved planning and conservation-oriented policies can enhance system performance and sustainability.

Given the strategic importance of drinking water in the study area, these results are particularly relevant. Despite demographic growth and increasing pressure from urban and public service sectors, the projected deficits remain moderate. However, the persistence of a residual unmet demand highlights existing structural pressures within the system. Future challenges are therefore expected to be more closely linked to agricultural water use, which remains comparatively high and less responsive to optimization measures. This aspect will be further analyzed in the following section.

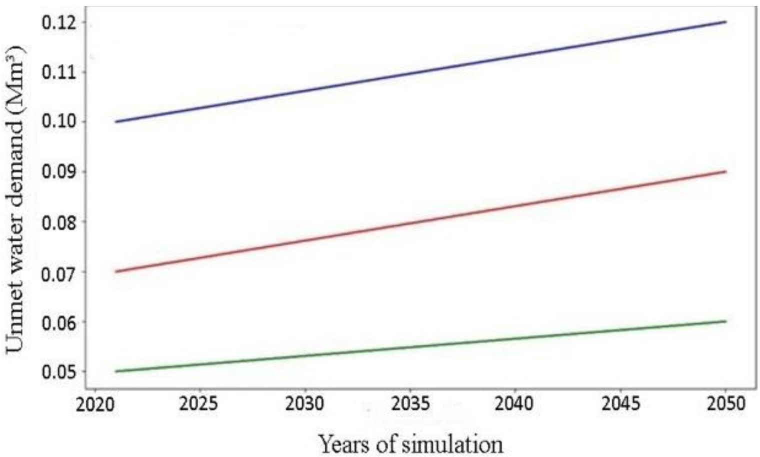

Figure 6: Evolution of unmet water demand in the domestic and public services sector under three simulation scenarios (2021–2050): Pressures of Anthropogenic Activities on Water Resources (blue line), Rational Consumption of Drinking Water (red line), and Supply Side Management (green line)

Agricultural activities

The municipality of Maghnia is projected to experience a gradual increase in unmet water demand in the agricultural sector by 2050. This is mainly due to the rehabilitation and planned expansion of the irrigated area in the Maghnia plain, posing a significant challenge for future water planning. Irrigation thus exerts considerable pressure on water resources and could severely impact the agricultural sector unless mitigated. This trend is illustrated in Fig. 7, which compares projected unmet agricultural water demand under various scenarios.

In the PAAWR scenario, the Maghnia plain is expected to face persistent water deficits throughout the simulation period, rising from 8 Mm³ in 2021 to 40 Mm³ by 2050. These shortfalls are attributed to several factors, including reduced river flows, lower reservoir levels particularly in the Beni Behdel dam, which irrigates around 4,250 hectares and broader climatic pressures, as Maghnia lies within a semi-arid zone. Additionally, water transfers from the Hammam Boughrara dam to surrounding areas such as Hammam

Boughrara village, Beni Boussaïd district, Nedroma town, and the Tafna plain, further strain local supplies.

To address these challenges, a set of demand-side management (DSM) measures was introduced, aiming to reduce consumption and optimize water use. These strategies were embedded in the IIT (Improved Irrigation Techniques) and IRTW (Increased Reuse of Treated Wastewater) scenarios.

The IIT scenario, which incorporates improved irrigation techniques aiming at water savings in large irrigated areas, significantly mitigates this pressure. Although deficits are not eliminated, they remain substantially lower than in PAAWR. After a temporary increase in the mid-projection period, unmet demand stabilizes below 10 Mm^3 by 2050. This confirms that irrigation modernization reduces water stress but does not fully offset the effects of agricultural expansion.

The IRTW scenario introduces the reuse of treated wastewater to supplement irrigation supply. The results show a moderate reduction in unmet demand compared to PAAWR; however, deficits persist throughout the simulation period. This indicates that wastewater reuse improves water allocation efficiency but remains insufficient as a standalone solution to balance supply and demand.

The SSM scenario provides the most effective mitigation among the evaluated strategies. Although unmet demand is not completely eliminated, it remains consistently below 4 Mm^3 over the entire projection period. This demonstrates that supply-side reinforcement, including enhanced infrastructure and diversification of water sources, substantially improves agricultural water security.

Overall, Fig. 7 clearly indicates that agricultural expansion is the dominant driver of future water imbalance in Maghnia. While demand-side measures and reuse strategies significantly reduce deficits, integrated supply and demand management remains essential to ensure long-term sustainability.

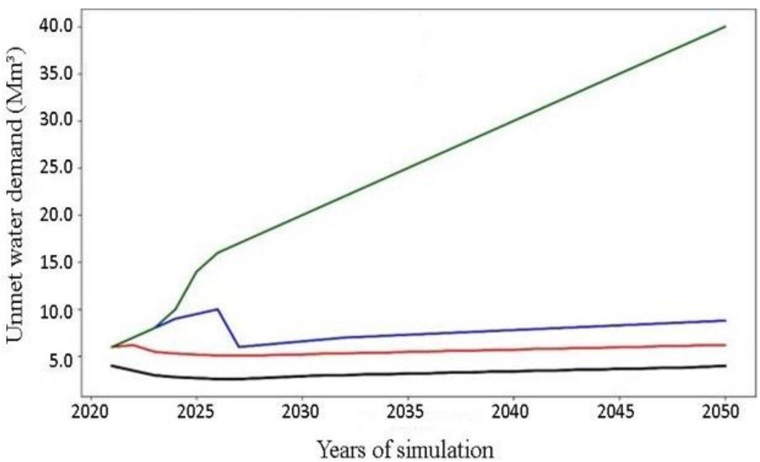

Figure 7: Evolution of unmet water demand in the agricultural sector under four simulation scenarios (2021–2050): Pressures of Anthropogenic Activities on Water Resources (green line), Improvement of Irrigation Techniques (blue line), Increased Reuse of Treated Wastewater (red line), and Supply Side Management (black line)

Industrial use

Fig. 8 compares the evolution of unmet water demand under the IRTW scenario (increase in industrial reuse of treated wastewater to 30%) and the SSM scenario, relative to the PAAWR scenario. The objective is to evaluate the extent to which industrial water reuse and supply-side management can mitigate pressures induced by increasing industrial demand.

The results indicate that unmet water demand persists under all scenarios throughout the simulation period. Although industrial water reuse contributes to reducing pressure on conventional water sources, the IRTW scenario does not eliminate the deficit and exhibits higher unmet demand compared to SSM. In contrast, the SSM scenario consistently produces the lowest deficit values, highlighting the effectiveness of supply-side optimization measures.

These findings suggest that while industry represents a significant water user, the overall water balance is more strongly influenced by demographic growth and structural demand pressures. Increasing treated wastewater reuse in the industrial sector contributes to improved resource efficiency; however, it is not sufficient on its own to fully stabilize the supply–demand balance. Consequently, integrated strategies combining supply management, demand regulation, and reuse optimization are required to mitigate future water stress and reduce the risk of allocation conflicts, particularly in water-intensive industrial activities.

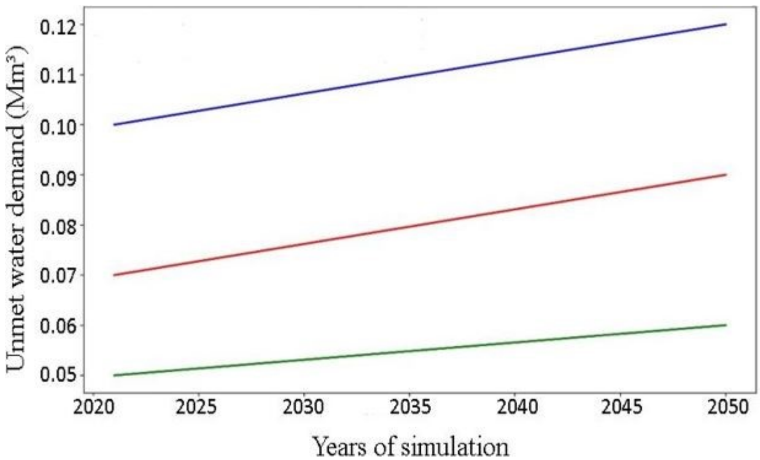

Figure 8: Evolution of unmet water demand in the domestic and public services sector under three simulation scenarios (2021–2050): Pressures of Anthropogenic Activities on Water Resources (blue line), Increased Reuse of Treated Wastewater (red line), and Supply Side Management (green line)

Performance criteria

Table 2 presents the key results of the water demand assessment across different sectors based on the performance criteria applied to all the scenarios described earlier. The WEAP model was used to generate numerical outputs for each scenario, enabling a comparative analysis of the different alternatives. Using equations (2), (3), (4), (5), and (6), the Reliability, Resilience, Vulnerability (RRV) performance criteria, along with the Sustainability Index (SI), were calculated.

Table 2: Reliability, resilience, vulnerability, and Sustainability Index of water supply in Maghnia municipality under various future water use scenarios

Sectors	Scenarios	Number of times		Performance criteria			
		$D_t = 0$	$D_t > 0$	Rel	Res	Vul	SI
Domestic and Public Services	PAAWR	0	29	0	0	1.000	0.000
	RCDW	0	29	0	0	0.727	0.273
	SSM	0	29	0	0	0.500	0.500
Agricultural	PAAWR	0	29	0	0	1.000	0.000
	IIT	0	29	0	0	0.303	0.697
	IRTW	0	29	0	0	0.223	0.777
	SSM	0	29	0	0	0.141	0.859
Industry	PAAWR	0	29	0	0	1.000	0.000
	IRTW	0	29	0	0	0.727	0.273
	SSM	0	29	0	0	0.500	0.500

Domestic and public services

Over the 29-year assessment period, the domestic and public services sector exhibits permanent deficit conditions under all investigated scenarios. The reliability indicator is equal to 0.000, indicating the absence of any deficit-free year. Similarly, resilience remains null, since no transition from deficit ($D_t > 0$) to equilibrium ($D_t = 0$) occurs during the simulation horizon. This structural persistence of deficit reflects a chronic imbalance between domestic demand and available supply capacity.

Under these conditions, system performance differentiation depends exclusively on vulnerability levels. Vulnerability ranges from 0.500 under SSM to 1.000 under PAAWR. The increase of 45.4% between SSM (0.500) and RCDW (0.727) corresponds to a proportional degradation of the Sustainability Index (SI), which decreases from 0.500 to 0.273.

The PAAWR scenario reaches the critical threshold Vul = 1.000, implying that the mean annual deficit equals the maximum observed deficit. This represents an extreme structural stress condition, leading to null sustainability performance (SI = 0.000) .Therefore, domestic sustainability improvement is quantitatively associated with deficit magnitude reduction rather than deficit occurrence frequency, since reliability remains unchanged across scenarios.

Agricultural activities

Despite reliability and resilience remaining at zero, the agricultural sector exhibits markedly different vulnerability dynamics across various management scenarios. Vulnerability begins at a relatively low level of 0.141 under SSM, rises to 0.223 under IRTW, and further increases to 0.303 under IIT, before ultimately reaching a critical peak of 1.000 under PAAWR, representing a state of maximum exposure.

The transition from SSM (0.141) to PAAWR (1.000) represents an 85.9% reduction in normalized deficit severity when adaptive management is applied. Even between SSM and IIT, vulnerability increases by 115%, demonstrating high sensitivity to management strategy. This significant variability translates into Sustainability Index values ranging from 0.859 (SSM) to 0.000 (PAAWR). The agricultural sector thus achieves the highest SI among all sectors under adaptive scenarios.

Unlike domestic and industrial sectors, where vulnerability stabilizes around 0.5 under SSM, agricultural vulnerability is reduced to 0.141, indicating that deficit intensity mitigation is considerably more effective in this sector. This confirms that regulating agricultural demand is the main lever for improving sustainability in the municipality of Maghnia.

Industrial use

The industrial sector demonstrates a strictly analogous structural behavior. Reliability and resilience are both equal to 0.000 for all scenarios, confirming the persistence of annual deficits over the entire period. Vulnerability evolves from 0.500 (SSM) to 0.727 (IRTW) and reaches 1.000 under PAAWR. The 45.4% increase between SSM and IRTW indicates a substantial amplification of deficit severity. Under PAAWR, the system attains maximum normalized deficit intensity, resulting in SI = 0.000.

The absence of reliability and recovery mechanisms implies that industrial sustainability performance is solely governed by deficit amplitude control. The proportional relationship between Vul and SI confirms that industrial water demand intensification directly translates into structural system stress without buffering capacity. Compared to the domestic sector, industrial vulnerability follows the same quantitative pattern, suggesting similar sensitivity to scenario assumptions.

Comparative analysis and discussion of different scenarios

The water resources assessment provides a quantitative framework for evaluating the impact of anthropogenic pressures and future development strategies on the water balance of Maghnia municipality. The scenarios are derived from structured regional planning documents (e.g., PDARE) and integrate progressive policy assumptions, ranging from demand expansion (PAAWR) to optimized management and supply reinforcement (SSM).

The comparative results reveal a clear structural differentiation among scenarios in terms of deficit magnitude rather than deficit occurrence. Over the 29-year simulation period, all sectors experience persistent annual deficits (Rel = 0; Res = 0), indicating that the system operates under chronic stress conditions. Therefore, scenario performance is primarily governed by vulnerability levels.

The PAAWR scenario produces the highest cumulative agricultural deficit over the simulation horizon, largely exceeding those of the optimization scenarios, reflecting the combined effect of agricultural expansion and climate-induced pressure. This scenario systematically produces maximum vulnerability (Vul = 1.000), indicating that the mean deficit approaches the maximum observed deficit. Such behavior characterizes a structurally unsustainable trajectory.

In contrast, optimization scenarios (RCDW, IIT, and IRTW) substantially reduce annual agricultural deficits compared to PAAWR, although structural imbalance persists. These strategies incorporate wastewater reuse, irrigation efficiency improvement, and demand regulation. Although they significantly mitigate deficit intensity, they do not eliminate structural imbalance, as reliability remains null.

The SSM scenario demonstrates the most effective performance. By integrating ambitious supply-side measures, particularly seawater desalination and infrastructure reinforcement it considerably reduces vulnerability across sectors. In agriculture, vulnerability decreases to 0.141, representing an 85.9% reduction compared to PAAWR. This confirms that combined supply augmentation and demand management provide the most balanced improvement.

Domestic and industrial sectors show relatively controlled deficit severity under optimization scenarios due to conservation measures and wastewater reuse in industry. However, agricultural demand exhibits the strongest growth, increasing from 20 Mm^3 in 2021 to 27 Mm^3 in 2050, primarily driven by irrigation expansion and climate variability. This growth explains why agricultural vulnerability dominates overall system performance.

Overall, the comparative analysis indicates that expansion-oriented policies without compensatory supply reinforcement led to structural deficit amplification. Conversely, integrated strategies combining supply enhancement and demand management significantly improve sustainability conditions, even though complete reliability recovery remains unattained.

CONCLUSION

This study provides an integrated assessment of water resource system performance under increasing anthropogenic pressures in the municipality of Maghnia. By applying a scenario-based WEAP modeling framework combined with standardized performance indicators (Reliability, Resilience, Vulnerability, and Sustainability Index), the analysis offers a structured evaluation of future water management strategies across domestic, industrial, and agricultural sectors.

The results reveal a structurally deficit-driven system, characterized by persistent annual shortages throughout the simulation period. Reliability and resilience remain null across all scenarios, indicating that future water management challenges are not associated with the frequency of deficits, but rather with their magnitude.

Among the evaluated strategies, expansion-oriented policies such as PAAWR generate the most critical conditions, particularly in the agricultural sector, where vulnerability reaches its maximum level. This confirms that uncontrolled demand growth under climatic stress leads to structural unsustainability.

Optimization scenarios incorporating wastewater reuse (IRTW), rational consumption (RCDW), and irrigation improvement (IIT) significantly reduce deficit severity but do not fully restore system equilibrium. Although domestic and industrial demands remain comparatively more stable under these strategies, agricultural demand continues to exert dominant pressure on basin-scale performance.

The Supply Side Management (SSM) scenario demonstrates the most balanced outcome. By combining supply augmentation (desalination and infrastructure reinforcement) with demand-side efficiency measures, it achieves the lowest vulnerability levels and the highest Sustainability Index values among all scenarios. However, even under SSM, complete deficit elimination is not achieved, highlighting the structural limitations of the current resource base.

These findings emphasize that agricultural water demand constitutes the principal driver of future system vulnerability and confirms the need for integrated and adaptive water management strategies in water-scarce regions.

Recommendations

Sustainable water management in Maghnia requires an integrated approach that simultaneously enhances supply capacity and improves irrigation efficiency, particularly under projected demographic growth and climate variability.

From a strategic perspective, medium- and long-term planning is essential to optimize infrastructure investments and ensure timely implementation of adaptive measures. The limited capacity of the Hammam Boughrara treatment plant necessitates reinforcement or expansion, while the progressive integration of seawater desalination, specifically with the official launch of the Aïn Adjroud desalination plant in the commune of Marsa Ben M'hidi (Tlemcen), represents a key structural solution to guarantee future supply and strengthen water security in the commune of Maghnia.

In addition, increasing the reuse of treated wastewater, especially from the Legfaf treatment plant, for agricultural and industrial purposes can substantially alleviate freshwater stress, while the adoption of efficient irrigation technologies, including drip and sprinkler systems, is strongly recommended to maximize water productivity, reduce agricultural vulnerability, and improve the overall resilience of the water management system.

Finally, the use of standardized performance indicators should be systematically encouraged in future studies and water planning processes to support evidence-based decision-making and enhance the long-term sustainability of water resource management systems.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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