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Decision-support approaches for sustainable water resource management in northwest Algeria

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ABSTRACT

This study investigates water resource management in the Wilaya of Mostaganem, northwest Algeria, using the water evaluation and planning (WEAP) decision support tool in combination with the analytic hierarchy process (AHP). As water scarcity becomes increasingly critical due to population growth, agricultural demands, and climate variability, effective management strategies are essential. This research employs WEAP to simulate various water demand and supply scenarios, assessing the impacts of irrigation efficiency, industrial development, and climate conditions on water availability. Under the ASI scenario, unsatisfied water demand may reach 4.3 hm³ per year by 2027. However, improving irrigation efficiency could reduce this by up to 50% compared to the reference scenario. Seasonal variations reveal deficits reaching 3.2 hm³ per month during the summer months of July through October. Additionally, the study highlights that a significant increase in water demand, exceeding 80 hm³ by 2060, can be mitigated through improved water supply initiatives, such as constructing new dams. The integration of AHP enables the prioritization of management strategies based on stakeholder preferences, demonstrating that adapting to climate change can stabilize demand below 50 million cubic meters. This integrated approach provides valuable insights for policymakers and stakeholders in developing sustainable water resource strategies that address the challenges faced by the Mostaganem region.

Keywords: water resource management, analytical hierarchy process, WEAP model, water supply strategies, climate variability, agricultural practices.

INTRODUCTION

Freshwater resources are vital for humanity. They are essential for survival, socio-economic development, and ecosystem preservation (Koundouri et al., 2016; Mishra and Kumar, 2024; Pradinaud et al., 2019). However, in the 21st century, water resource management has become one of the most pressing challenges for policymakers, scientists, and managers worldwide (Allan et al., 2023; Heidari, 2018; Jaiswal et al., 2021). Population growth, industrial development, irrigated agriculture, and rapid urbanization are placing increasing pressure on these limited resources, particularly in arid and semi-arid regions (Alsaeed et al., 2024; Fertas et al., 2024).

Unequal access to water and inadequate management of existing resources exacerbate potential conflicts among different users, while also amplifying environmental impacts (David and Hughes, 2024; Ogunbode et al., 2024). Moreover, climate change is intensifying droughts, floods, and rainfall variability, significantly altering water availability worldwide (Ogunbode et al., 2024; Qiu et al., 2023). According to projections by the Intergovernmental Panel on Climate Change (IPCC), vulnerable regions are at risk of having their water supply severely compromised by 2050 (Allan et al., 2023; Cao and Ying, 2024).

In this context, the sustainable management of water resources is a key objective within environmental and sustainable development strategies. The need for effective, flexible, and forward-looking water resource management is increasingly evident (Doost et al., 2024; Gwapedza et al., 2024). This approach requires tools capable of integrating the complexity of hydrological systems while addressing the expectations of various stakeholders (Doost et al., 2024). Integrated water resources management (IWRM) is a systemic approach designed to coordinate the development and management of water, land, and related resources to maximize economic and social benefits without compromising ecosystem sustainability (Apostolaki et al., 2019; Ngene et al., 2021). IWRM is founded on three core principles: integrated resource management, stakeholder participation, and sustainability (Thungngern et al., 2017; Van Wilgen et al., 1999). However, implementing IWRM often encounters significant challenges (Al-Juaidi and Attiah, 2020). Firstly, hydrological basins frequently encompass multiple users, each with differing needs and priorities, such as agriculture, industry, domestic use, and environmental conservation (Benson et al., 2015; Meran et al., 2021). Managing these diverse and often conflicting interests simultaneously requires decision-support tools capable of synthesizing complex information and proposing balanced solutions (Chamberlain et al., 2013; Raseman et al., 2017).

Moreover, managers must contend with numerous variables and uncertainties, including future weather conditions, water demands from users, hydraulic infrastructure management (Olivos et al., 2024), and existing regulations (Poff et al., 2016). In this context, modeling tools such as water evaluation and planning (WEAP) and multi-criteria decision-making methods like analytic hierarchy process (AHP) are essential for supporting water resource management policies (Sardar Shahraki et al., 2018). WEAP is a simulation and modeling tool designed to assist in the planning and management of water resources. Developed by the Stockholm Environment Institute, WEAP enables the integration of data related to water supply and demand, as well as complex hydrological interactions within a given basin. It is used globally to simulate future scenarios, assess the impacts of water management policies, and analyze the interactions between water, energy systems, and ecosystems (Agarwal et al., 2019; Kandera et al., 2021).

One of WEAP's main strengths is its ability to model both water supply and demand simultaneously while incorporating management constraints and environmental impacts. It also enables the analysis of the effects of climate change, water management policies, and infrastructure projects (e.g., reservoirs, dams, canals) on water availability and demand fulfillment (Sahoo et al., 2020). WEAP offers significant flexibility in developing management scenarios, taking into account various factors such as population growth, land use changes, agricultural and industrial needs, and water pricing policies (Kandera et al., 2021).

AHP, developed by Thomas Saaty in the 1970s, is a multi-criteria decision-making method that structures complex problems into a hierarchy of criteria and sub-criteria, thereby facilitating decision-making (Saaty, 2004). This method is particularly well-suited to water resource management, where numerous variables-such as economic efficiency, environmental sustainability, and social priorities-must be considered (Cacal et al., 2023; Calizaya et al., 2010). AHP formalizes the decision-making process by conducting pairwise comparisons of different criteria and assigning weights to each based on their relative importance. This approach enables decision-makers to prioritize and guide their choices in an objective, transparent, and consistent manner. Furthermore, it ensures that decisions align with the goals and constraints of various stakeholders, including governments, farmers, industrial players, and citizens (Waheeb et al., 2023; Zerouali et al., 2024). One of the major advantages of AHP is its capacity to integrate both quantitative and qualitative data, translating them into numerical values through a rigorous process of weighting and prioritization (Saaty, 2004). This method is widely applied across various fields, from infrastructure management to urban planning and environmental policy, making it a valuable tool for water resource management. The combined use of WEAP and AHP offers a robust, integrated approach to managing water resources. While WEAP provides a framework for modeling hydrological flows, water demands, and the impacts of management policies, AHP enables the ranking and weighting of different stakeholder priorities.

The synergy of these two tools enables the exploration of various management scenarios, analysis of trade-offs among strategic choices, and support for informed, participatory, and balanced decision-making. In practice, WEAP is used to simulate multiple management scenarios, incorporating variables such as rainfall, reservoir levels, irrigation demand, and industrial consumption. The simulation results are then combined with the criteria weightings derived from AHP to identify the optimal solution that best meets water needs while minimizing environmental and economic impacts. This process generates robust solutions that account for the uncertainty and complexity inherent in water management systems.

The objective of this study document is to analyse in detail how the combination of WEAP and AHP can be utilised for water resource management, with a focus on the practical application of these tools in various contexts, particularly in regions vulnerable to climate change and increasing demographic pressures. The following sections will outline the theoretical principles of WEAP and AHP, followed by a case study demonstrating their application in regional water resource management.

STUDY AREA

The Wilaya of Mostaganem, located in the northwest of Algeria (35° 56′ N, 0° 05′ E), is a strategic region bordered by the Mediterranean Sea to the north, the Wilaya of Oran to the west, the Wilaya of Chlef to the east, and the Wilayas of Mascara and Relizane to the south. With an estimated population of approximately 935,282 inhabitants, this region is distinguished by its semi-arid climate, characterized by mild winters and annual rainfall ranging between 400 and 500 mm on the plateau, and between 500 and 700 mm on the foothills of the Dahra. Monthly temperatures fluctuate regularly, reaching an average maximum of 26 °C in August and a minimum of 10.8 °C in January, with an annual average temperature of 17.5 °C.

The choice of the Wilaya of Mostaganem as a study area is based on its unique geographical, climatic, and socio-economic characteristics, making it a relevant setting for analyzing challenges related to water resource management. Indeed, the region faces increased vulnerability to water scarcity due to its semi-arid climate and marked variability in rainfall, a situation representative of many arid and semi-arid areas in Algeria and beyond. Moreover, its agricultural importance, with high water demand for irrigation, makes it a crucial area for studying issues of food security and economic development.

Rapid urbanization and population growth in the region are exerting increasing pressure on water resources, both for domestic and industrial uses, providing a suitable context for analyzing the impacts of socio-demographic dynamics on water management. Additionally, the Wilaya of Mostaganem is highly exposed to the effects of climate change, with projections indicating a decrease in rainfall and a rise in temperatures, making it a natural laboratory for studying adaptation strategies and sustainable water management.

MATERIALS AND METHODS

Water resources and current demands

The total water demand in the Wilaya of Mostaganem is estimated at 40 hm³. Two general public irrigation (GPI) systems are operational in the region: Bordjias (5,600 ha) and Kramis Acchaacha (4,300 ha). The small and medium hydraulic (PMH) sector accounts for a significant portion of water demand, with an estimated requirement of 111 hm³.

Water resources in the wilaya consist primarily of groundwater (52 hm³) and surface water from the ESC (8 hm³). However, the over-exploitation of groundwater resources has become a critical issue. Additionally, the region draws nearly 10 hm³ annually from the BG Gargar-Oran corridor.

Three major water systems serve the Wilaya of Mostaganem:

1. The MAO transfer system (Mostaganem, Arzew, Oran),
2. The Dahra transfer system, which sources water from the Kramis Dam,
3. The SDEM system, which draws water from Chellif-Plage.

These systems collectively have a production capacity of 200,000 m³ per day, supporting both domestic and agricultural water needs in the region.

WEAP model

The WEAP model, developed by the Stockholm Environment Institute (SEI), is a powerful data processing tool that integrates a spatial database and a geographic information system (GIS) to analyze various water management scenarios within a catchment area (Figure 1). It has been widely applied in numerous regions globally, demonstrating its effectiveness in addressing water resource challenges. In this study, the WEAP model is employed to evaluate the impact of water management strategies in the Wilaya of Mostaganem. The model's implementation involves several steps, as illustrated in Figures 2 and 3, and requires diverse and detailed datasets, including hydrological data, water user information, infrastructure characteristics, and geographical data.

Using QGIS software, several ESRI shapefiles were created and integrated into the WEAP model. These include administrative boundaries (municipalities, daïras, and wilayas), 47 demand sites (35 municipalities, 9 irrigation perimeters, and 3 industrial areas), 8 watercourses, 3 dams, 10 wastewater treatment plants, 105 transmission links connecting water resources to demand sites, and 45 return links between demand sites and wastewater receiving environments (STEP and Oued). This comprehensive dataset enables the model to simulate and analyze water management scenarios accurately, providing valuable insights for decision-making in the region.

The application of the WEAP model in this study highlights its capability to support sustainable water resource management by evaluating the impacts of various strategies and interventions. By integrating spatial and hydrological data, the model offers a robust framework for addressing the complex challenges of water management in the Wilaya of Mostaganem, contributing to the development of effective and sustainable solutions for the region.

Data collection and model parameterization

The data collection process for the WEAP model involved gathering information from multiple sources to ensure the accuracy and reliability of the inputs. Climate data, including precipitation, temperature, and potential evapotranspiration (ETP), were obtained from ANRH and meteorological sources. Urban water demand was estimated using population data, a daily water allocation of 180 liters per person, and wastewater rejection rates, with adjustments for seasonal increases in consumption, particularly during the

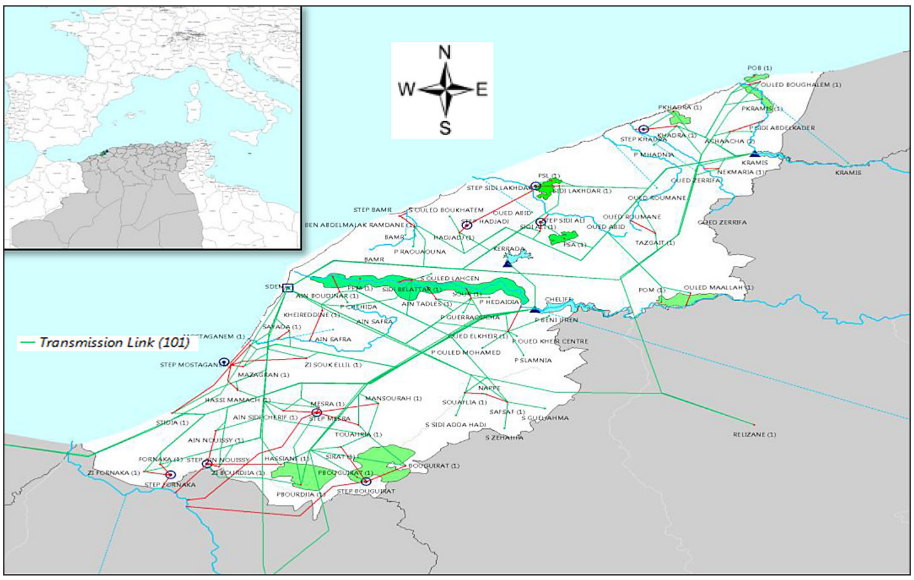

Figure 1. Localisation of the study area and WEAP model schematic

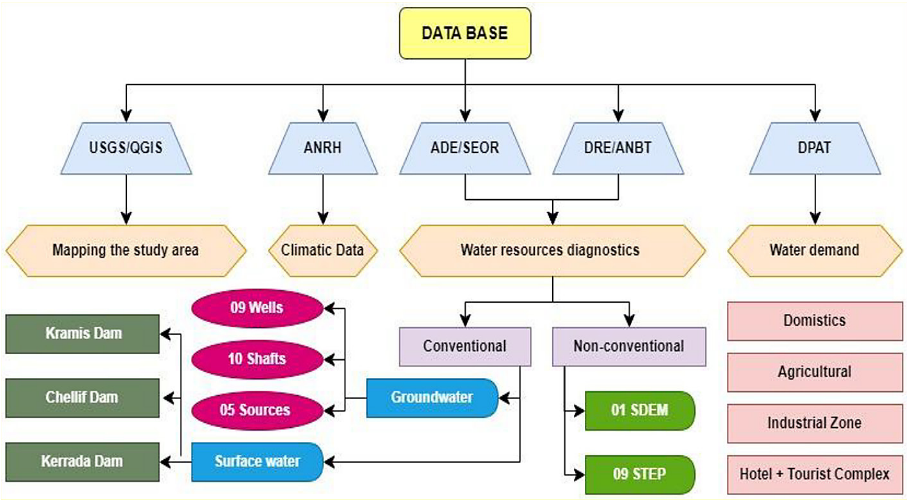

Figure 2. Input database for the WEAP water resource management model

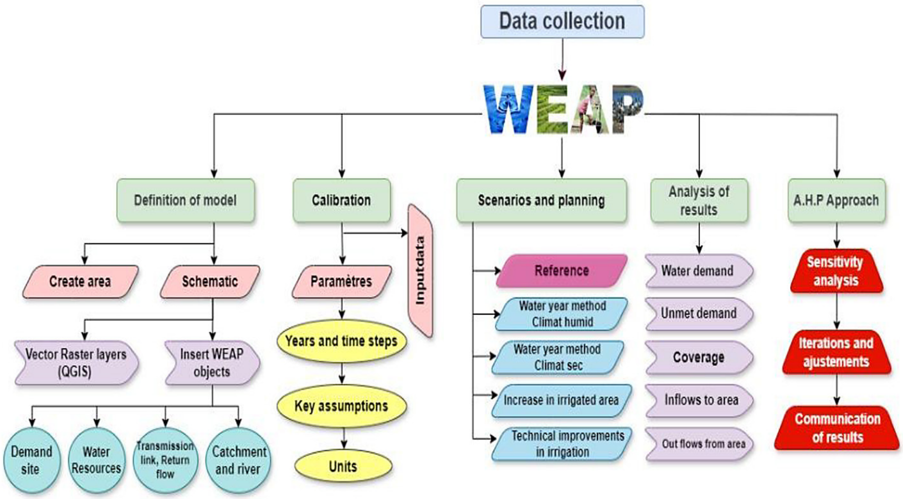

Figure 3. Flowchart of the methodology used in this study

summer months. Agricultural water demand was assessed based on land distribution data, with the Mostaganem Plateau having the largest agricultural area and the L'habra Plain the smallest, reflecting the varying agricultural capacities of these regions. Additionally, the water footprint for livestock production was evaluated, revealing that producing one kilogram of beef requires 15,415 liters of water, accounting for both direct and indirect water use.

This comprehensive data collection and parameterization process ensured that the WEAP model accurately represented the hydrological and water management dynamics of the Wilaya of Mostaganem. By integrating diverse datasets, the model provides a reliable foundation for simulating and analyzing various water management scenarios, supporting informed decision-making and sustainable resource management in the region (Figure 4).

The distribution of agricultural land across the various regions reveals significant disparities in both the total agricultural area (SAT) and useful agricultural area (SAU). The Mostaganem Plateau stands out with the largest total agricultural area at 80,579 hectares, which also corresponds to the highest irrigated area of 32,594 hectares, indicating a strong capacity for intensive farming practices. In contrast, the L'habra Plain has the smallest total agricultural area at 14,448 hectares, suggesting limitations in agricultural potential. The Dahra Mountains and Dahra Foothills present moderate total agricultural areas of 44,001 hectares and 38,282 hectares, respectively, with useful agricultural areas indicating that a substantial portion of the land is suitable for farming.

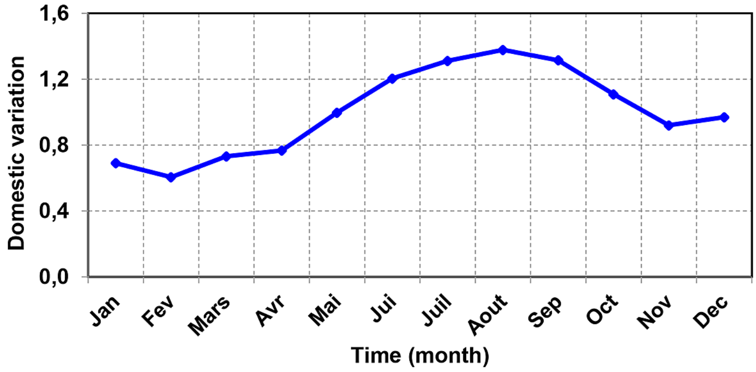

Figure 4. Monthly variation in domestic water consumption

However, irrigation levels in these regions are relatively low, particularly in the Dahra Mountains, which may impact crop yields. Overall, total wilaya data shows that while the regions vary in size and irrigation capabilities, the Mostaganem Plateau emerges as the most productive agricultural zone, likely due to better access to irrigation and larger usable land (Table 1). This analysis highlights the need for targeted agricultural policies to optimize land use and improve irrigation infrastructure, particularly in less productive areas (Figure 5).

According to the Directorate of Agricultural Services (DSA), the Wilaya of Mostaganem produced approximately 53.825 quintals of red meat and 100.765 quintals of white meat during the 2020/2021 campaign. The Water Footprint Network estimates that producing one kilogram of beef requires 15.415 litres of water, which accounts for rainwater used by plants, irrigation, animal consumption, and water pollution during production (including fertilizers, pesticides, and washing). The water footprint assesses both direct and indirect water consumption associated with

Table 1. Distribution of agricultural land (DSA, 2024)

Agricultural region	Total agricultural area (SAT) (ha)	Useful agricultural area (SAU) (ha)	Irrigated area (ha)
Dahra Mountains	44 001	25 262	2 354
Dahra foothills	38 282	26 024	3 639
L'habra plain	14 448	11 977	4 033
Mostaganem Plateau	80 579	69 005	32 594
Total wilaya	177 310	132 268	42 620

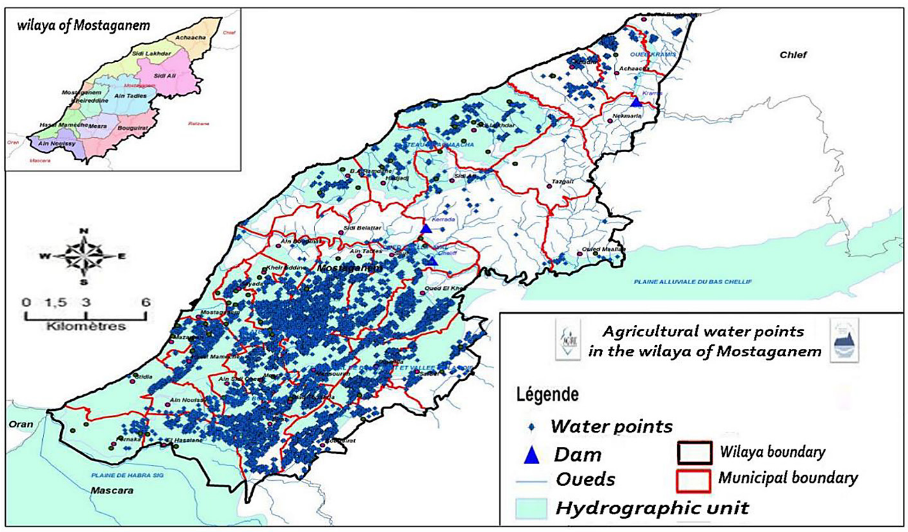

Figure 5. Map of water points for agricultural use in the Mostaganem wilaya

a process, product, company, or industry, encompassing water use and pollution throughout the entire production cycle, from the supply chain to the end consumer.

Simulation scenarios

This section outlines the various scenarios integrated into the WEAP model to evaluate the impact of different water management strategies and climate variations. The reference scenario, based on current practices and projected trends, serves as the baseline for comparison. It assumes population growth following historical trends, unchanged agricultural practices, no new water infrastructure, and stable climate conditions. Other scenarios include: improving irrigation efficiency (increasing efficiency to 65–85% and reducing agricultural water demand), expanding irrigated areas (increasing by 50% and raising water demand), increasing drinking water allocation (raising to 180 liters per capita per day to meet urban growth), simulating sequences of dry years (reducing precipitation by 20–30% and increasing evaporation) and wet years (increasing precipitation by 20–30% and reducing evaporation), and a temperature increase of 2–3 °C (raising evaporation and water demand). These scenarios aim to assess water savings, trade-offs between agricultural expansion and sustainability, resilience to droughts and floods, and the impact of climate change. The simulation results provide valuable insights to strengthen the resilience of water management strategies and support sustainable water resource management.

AHP (analytic hierarchy process) method

Analytic hierarchy process (AHP), developed by Saaty (Saaty, 1980), is a method for converting subjective assessments into a set of weights through pairwise comparisons between all criteria. Pairwise comparisons are quantified using a linear scale, as shown in Table 2 (Yilmaz and Harmancioglu, 2010). According to Table 2, the DM defines a pairwise comparison matrix P, where the entry p_{ij} represents the relative importance of the i-th criterion with respect to the j-th criterion Equation 1:

$$P = \begin{bmatrix} 1 & p_{12} & p_{1m} \\ p_{21} & 1 & p_{2m} \\ p_{m1} & p_{m2} & 1 \end{bmatrix} \tag{1}$$

In the comparison process, once the upper triangular matrix is determined, the lower triangular matrix can be defined by Equation 2:

$$p_{ji} = \frac{1}{p_{ij}} \tag{2}$$

The normalized pairwise comparison matrix X is obtained by dividing each element in P by its column sum (Equation 3). The principal eigenvector λ, defining the criterion weight vector W, is then derived by averaging the rows (Equation 4). The sum of the the criteria weights equals 1.

$$X = \begin{bmatrix} 1\Big/\sum_{m-1}^{m} p_{m1} & \cdots & p_{1m}\Big/\sum_{t-1}^{m} p_{tm} \\ \vdots & \ddots & \vdots \\ p_{m1}\Big/\sum_{m-1}^{m} p_{m1} & \cdots & 1\Big/\sum_{t-1}^{m} p_{tm} \end{bmatrix} = \begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mm} \end{bmatrix} \tag{3}$$

$$W = \frac{1}{m} \begin{bmatrix} \sum_{m-1}^{m} x_{1m} \\ \vdots \\ \sum_{t-1}^{m} x_{m1} \end{bmatrix} = \begin{bmatrix} w_1 \\ \vdots \\ w_m \end{bmatrix} \tag{4}$$

The consistency of the weights must also be verified. Saaty (1980) introduced the consistency index (CI) to quantify the inconsistency of pairwise comparison matrices, as shown in Equation 5, where λ_{max} is the largest eigenvector of the pairwise comparison matrix and n is the matrix order. Saaty (1980) also states that the eigenvector corresponding to λ_{max} should satisfy Equation 6, where $\lambda_{max} \geq n$. The consistency ratio (CR), calculated with the comparison index (RI) shown in Table 2, is then determined according by Equation 7. A CR value of less than or equal to 10% is considered acceptable, indicating an acceptable level of inconsistency in the DM's judgments.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{5}$$

$$P \cdot W = \lambda_{max} \cdot W \tag{6}$$

$$CR = \frac{CI}{RI} \tag{7}$$

Table 2. Random consistency index (Saaty and Vargas, 1984)

n	3	4	5	6	7	8	9
RI	0.5381	0.8832	1.1045	1.2525	1.3334	1.4217	1.4457

The AHP method involves stakeholder consultation to ensure that the criteria weights reflect the priorities and preferences of key stakeholders. In this study, stakeholders were identified from various sectors, including agriculture, industry, domestic water users, and environmental conservation groups. Their input was gathered through structured interviews and surveys, where they were asked to perform pairwise comparisons of the criteria relevant to water resource management in the Wilaya of Mostaganem.

The criteria considered in this study include:
- water availability under different climate scenarios (wet and dry years),
- expansion of irrigated areas,
- improvement of irrigation techniques,
- increase in drinking water supply.

The pairwise comparison matrix was constructed based on stakeholder feedback, and the weights for each criterion were calculated using the AHP method. The consistency of the pairwise comparisons was verified using the CR, ensuring that the judgments were logically consistent.

Scenario validation

To validate the scenarios generated by the WEAP model and the AHP method, the results were compared with historical data on water availability, demand, and usage in the Wilaya of Mostaganem. This comparison helped assess the accuracy and reliability of the model outputs. Historical data on rainfall, river flow, groundwater levels, and water consumption were obtained from the National Agency for Water Resources (ANRH) and the Algerian Water Company (ADE).

The validation process revealed that the model accurately captured the trends and variations in water resources and demand over the past two decades. This provided confidence in the model's ability to simulate future scenarios under different management strategies and climate conditions.

Uncertainty analysis was conducted to evaluate the robustness of the model results. This involved assessing the sensitivity of the model outputs to changes in key input parameters, such as rainfall patterns, population growth rates, and irrigation efficiency. Monte Carlo simulations were performed to generate a range of possible outcomes, accounting for uncertainties in the input data and model assumptions. The results of the uncertainty analysis highlighted the importance of adaptive management strategies, particularly in the face of climate variability and population growth. The analysis also underscored the need for continuous monitoring and updating of the model inputs to ensure the accuracy of future projections.

RESULTS

WEAP simulation results

The WEAP model was set up to simulate water resource management scenarios in the Wilaya of Mostaganem. For calibration, historical hydrological data (river flows, reservoir levels, groundwater levels) and climate data (precipitation, temperature) from 2010 to 2020 were used. Key parameters, such as runoff coefficients and infiltration rates, were adjusted to match observed data, ensuring an accurate representation of hydrological processes and the water balance in the region. For validation, an independent dataset (2021–2023) was used, evaluated using statistical metrics such as the Nash-Sutcliffe efficiency (NSE = 0.85), root mean square error (RMSE = 0.12), and coefficient of determination ($R^2 = 0.92$), confirming the model's high accuracy in simulating water availability and demand. A sensitivity analysis identified key parameters (precipitation, temperature, water demand), demonstrating the model's robustness. Finally, an uncertainty analysis using Monte Carlo simulations showed that the predictions are reliable, with a 95% confidence interval for key outputs, such as water availability and unmet demand.

The analysis of water resources in the study area highlights a diverse and multifaceted approach to water management. Groundwater plays a crucial role, with a total of 57 sources, including 10 wells, 42 boreholes, and 5 springs, collectively yielding 580 m^3/day from wells and 16.502 m^3/year from boreholes. This groundwater is primarily directed toward the potable water supply, underscoring its importance for domestic use. Additionally, the presence of three dams – Kramis, MAO, and Chéliff – producing a combined total of 183.73 hm^3/year for both potable water and irrigation, further emphasizes the region's reliance on surface water resources. The inclusion of two hill reservoirs, contributing 0.6 hm^3/year for irrigation, and a desalination plant generating 200.000 m^3/day for drinking water reflects a proactive strategy to enhance freshwater availability, particularly in areas facing scarcity. Furthermore, nine water treatment plants that manage 45,000 m^3/day demonstrate a commitment to ensuring water quality for irrigation and safe discharge into local waterways. Overall, while the study area benefits from a diverse array of water resources, it is essential to monitor their sustainability – particularly groundwater resources – to secure long-term water availability for both agricultural and domestic needs (Figure 6).

Table 3 summaries the recognized total water resource potential across four regions: the Mostaganem Plateau, Bordjias Plain, Bouguirat Syncline, and Chéliff Valley, providing insights into surface area, annual yield, and water allocations for drinking and irrigation. The Mostaganem Plateau, with the largest surface area at 700 km^2, has an annual yield of 26 hm^3, indicating a significant capacity for water resource management. In comparison, the Bordjias Plain and Bouguirat Syncline have surface areas of 250 km^2 and 240 km^2, respectively, with annual yields of 10 hm^3 and 9.5 hm^3. The Chéliff Valley, covering just 16.5 km^2, has the lowest annual yield at 6.6 hm^3, reflecting its limited water resource capacity. For drinking water, the Mostaganem Plateau again leads, allocating 16.2 hm^3, while the Bordjias Plain and Bouguirat Syncline follow with 6.6 hm^3 and 7.9 hm^3, respectively. The Chéliff Valley has the smallest allocation at 1.3 hm^3, highlighting disparities in domestic water availability. In terms of irrigation potential, the Bordjias Plain leads significantly with 31 hm^3, underscoring its importance for agricultural water use, while the Mostaganem Plateau provides 19.5 hm^3. The Bouguirat Syncline and Chéliff Valley offer offer modest irrigation allocations of 5.7 hm^3 and 1.3 hm^3, respectively. Overall, the data illustrates a clear stratification of water resource potential, emphasizing the Mostaganem Plateau's critical

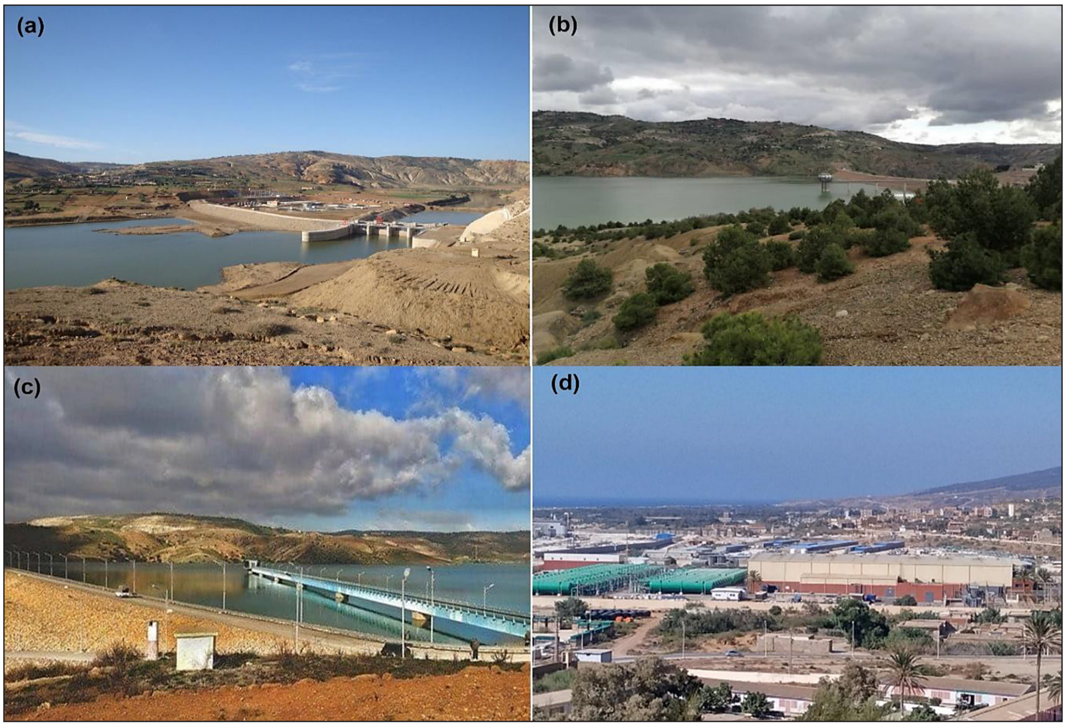

Figure 6. Dam and desalination plant in the study area: (a) Chéliff Dam, (b) Kramis Dam, (c) Kerrada Dam, and (d) Mostaganem seawater desalination plant

Table 3. Recognized total water resource potential

Label	Mostaganem Plateau	Bordjias Plain	Bouguirat Syncline	Chéliff Valley
Surface area (km^2)	700	250	240	16.5
Annual yield (hm^3)	26	10	9.5	6.6
Drinking water (hm^3)	16.2	6.6	7.9	1.3
Irrigation (hm^3)	19.5	31	5.7	1.3

role in both drinking water supply and irrigation, while the Bordjias Plain is essential for agricultural needs. Conversely, the Chéliff Valley's limited water resource potential necessitates targeted management strategies to ensure sustainable water use across the regions.

The WEAP model results from 2023 to 2060 provide a detailed view of water availability. They also show trends in irrigation efficiency, irrigated area, and economic activities under various climate conditions (Figure 7). The map offers a comprehensive spatial representation of the components that constitute the water system, including rivers, diversions, reservoirs, groundwater sources, demand sites, and supporting infrastructure. This level of detailed information is essential for the WEAP model, as it enables the integration of physical, social, and environmental factors into a unified framework for analysis.

The year 2023 serves as a reference point, with all variables held constant, allowing it to function as a baseline for future comparisons. After 2023, notable changes occur in key factors such as irrigation efficiency, water supply, irrigated area, and economic activities. These generally follow similar trends over the timeline, with some year-to-year fluctuations. Overall, these values tend to increase over time, suggesting improvements in water management and agricultural productivity. For instance, water supply shows a general upward trend with minor fluctuations, experiencing a drop in 2024 before peaking at 28.9 billion m³ in 2034. Similarly, irrigation efficiency improves over time, mirroring the trajectory of water supply, indicating a strong interdependence between water availability and irrigation practices. The irrigated area and economic activities related to crafts and industry also expand in line with these improvements (Figure 8).

Impact of irrigation efficiency on water demand

The results in Figures 9 and 10 show monthly flows and water consumption across various rivers, stations, and precipitation values for a

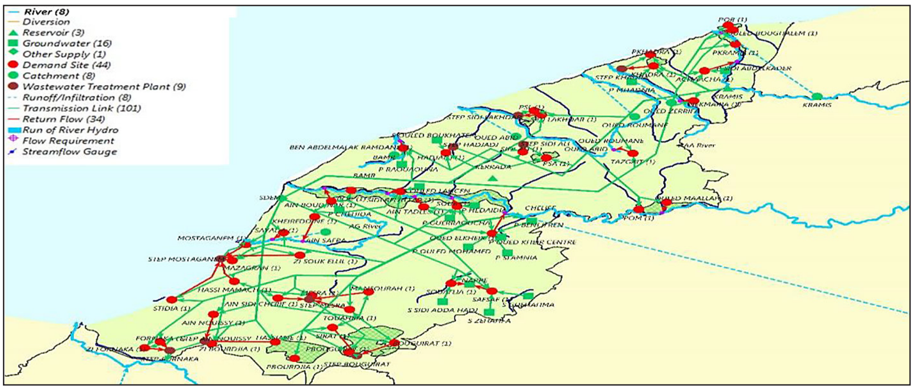

Figure 7. Spatial representation of the elements comprising the water system using WEAP model

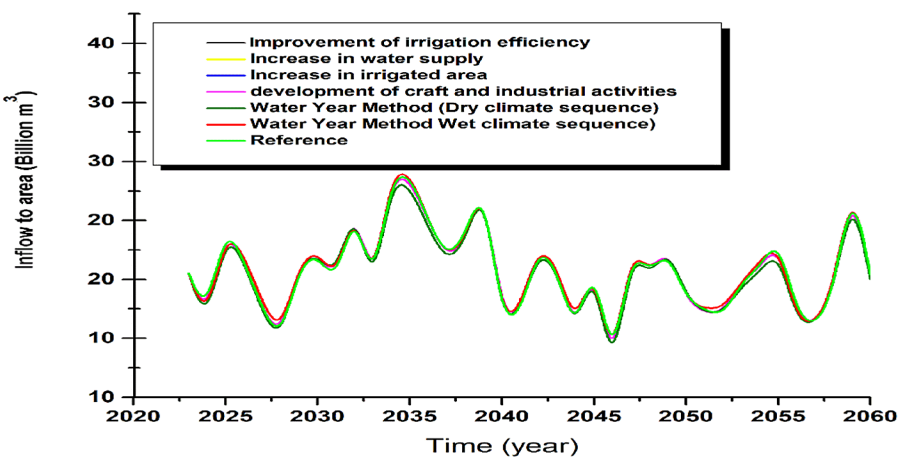

Figure 8. Inflow to area

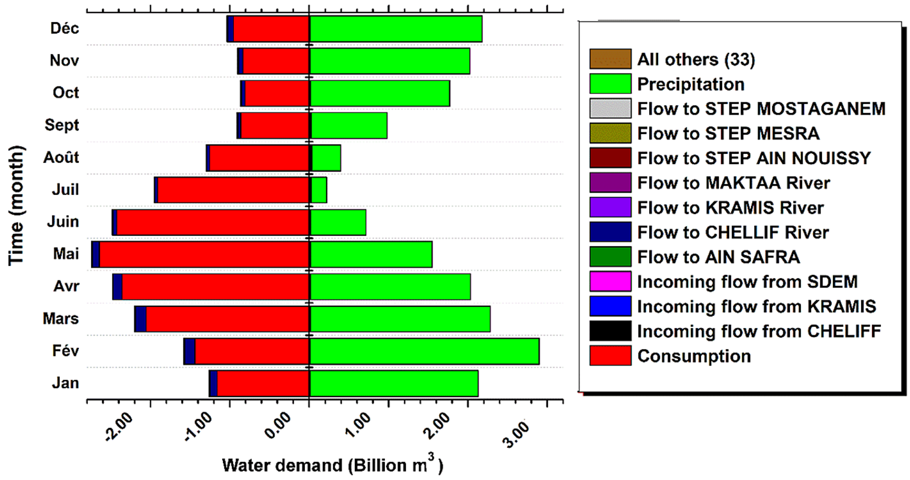

Figure 9. Monthly water demand across the water structure of the study area

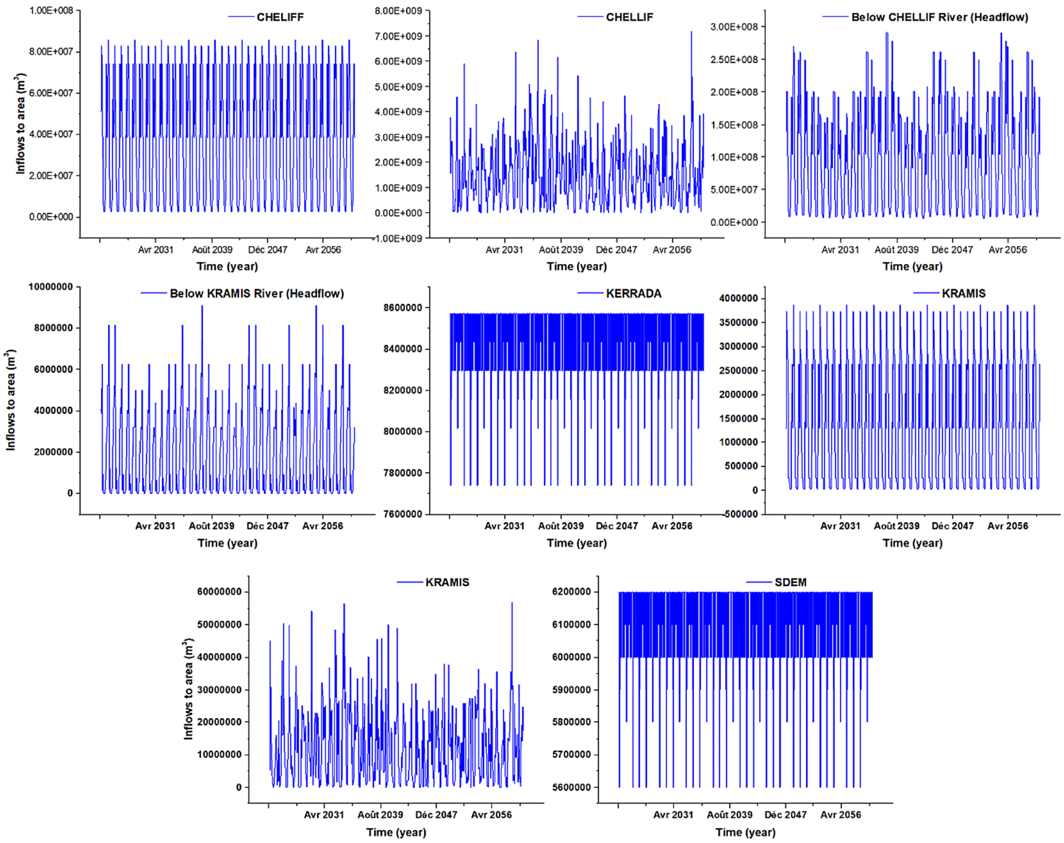

Figure 10. Fluctuation of water demand across the water structure of the study area

particular year. The negative values for "Consumption" across all months indicate the withdrawal or use of water resources, while the incoming flows from different sources (CHELIFF, KRAMIS, SDEM) demonstrate their contributions to the system. Precipitation figures provide additional water input, which, along with the inflows, supports the water balance in the region. Key observations reveal that the largest withdrawals occur in April (−2.36 billion m³) and May (−2.65 billion m³), indicating high water demand, possibly due to agricultural activities during these months, while the lowest consumption occurs in September and October. The flow from the CHELIFF River shows significant seasonal variation, peaking in April (8.48 hm³) and dropping to lower values in October (6.43 hm³) and December (5.16 h m³). Meanwhile, flows from the KRAMIS River peak in July and August, contributing more than in other months.

In terms of flow to treatment plants (STEP) and rivers, outflows to Ain Safra, the Chellif River, and other rivers vary but generally follow a similar trend, with significant outflows in May and July and smaller amounts during the winter months of January and February. Flows to treatment plants such as Ain Nouissy, Mesra, and Mostaganem remain consistent throughout the months, with a slightly increasing trend as consumption peaks.

Precipitation data reveal that the highest precipitation occurs in February (2.89 billion m^3), followed by January and March. In contrast, the months of July and August experience the least precipitation (190 and 362 hm^3, respectively), which aligns with the typical summer dryness in many regions.

In conclusion, the data highlight significant seasonal variations in both water inflow and outflow across the system. The higher consumption during the spring and early summer months corresponds with agricultural demand, while inflows from rivers and precipitation contribute to balancing the system. However, negative balances in consumption and outflows to various rivers and treatment plants indicate a heavily utilized water system, particularly during months of high irrigation demand.

Seasonal variations in water availability

The results of this study are based on simulations of a series of planning hypotheses aimed at achieving a balanced water budget in the region through the implementation of several variants:

- equilibrium with current planning,
- equilibrium with projected planning.

In the reference scenario, water demand is projected to increase from the current 180 hm^3/year to 270 hm^3/year by 2060, representing an increase of 90 hm^3/year (Figure 11). In the scenario focused on improving irrigation techniques, this demand is expected to reach 260 hm^3/year by 2060, reflecting a decrease of 10 hm^3/year compared to the reference scenario. Conversely, the scenario emphasizing the expansion of irrigated areas shows a notably high water demand, projected to reach 310 hm^3/year by the end of the scenario – an additional 40 hm^3/year compared to the baseline. This underscores the significant role agriculture plays in managing water demand. The other two scenarios – the "water year method dry climate sequence" and the "water year method wet climate sequence" – do not influence overall water demand. Instead, they primarily affect the allocation and coverage of water demand across various sectors, including drinking water, irrigation, and industry. Consequently, the water demand curves for these two scenarios are overlaid with the reference scenario for comparison.

The increase in drinking water supply (IDWS) scenario anticipates a water demand of 340 hm^3/year by 2060, corresponding to an increase of approximately 89% over the current demand of 180 hm^3/year. In comparison, the reference scenario projects a water demand of around 270 hm^3/year by 2060. The IDWS scenario thus indicates a significant increase in water demand (Figure 11), complicating efforts to secure adequate water resources, especially given the ongoing water shortages exacerbated by declining rainfall in recent years. The Mascara region, in particular, has experienced a rainfall decline of over 36%, especially in the far west (Benzater et al., 2019; Charifi Bellabas et al., 2021; Elouissi et al., 2017; Zerouali et al., 2021, 2022). This downward trend in rainfall has been evident since the mid-1970s, especially in western areas, where deficits range between 20% and 40% (Ghenim & Megnounif, 2016).

This figure illustrates the monthly unmet water demand for the scenarios examined. It is evident that the water deficit predominantly occurs during the summer months of July, August, September, and October, when irrigation activities are at their peak. Specifically, the deficit is approximately 0.5 hm^3/month for the ATI scenario, 1.5 hm^3/month for the reference scenario, and reaches around 3.2 hm^3/month for the ASI scenario (Figure 11b). Figure 11b depicts the annual unmet water demand across the examined scenarios. The deficit increases for all scenarios until 2027, when the unmet demand peaks at 2.5 hm^3 for the ATI scenario, 3.2 hm^3 for the reference scenario, and 4.3 hm^3 for the ASI scenario. After 2027, the deficit begins to decline across all scenarios, except for the ASI scenario, where the deficit continues to rise, albeit at a lower intensity compared to the earlier period (2024–2027). The reference scenario predicts a significant increase in water demand, exceeding 80 million cubic meters by 2060, driven by population growth, agriculture, and industrial expansion. In contrast,

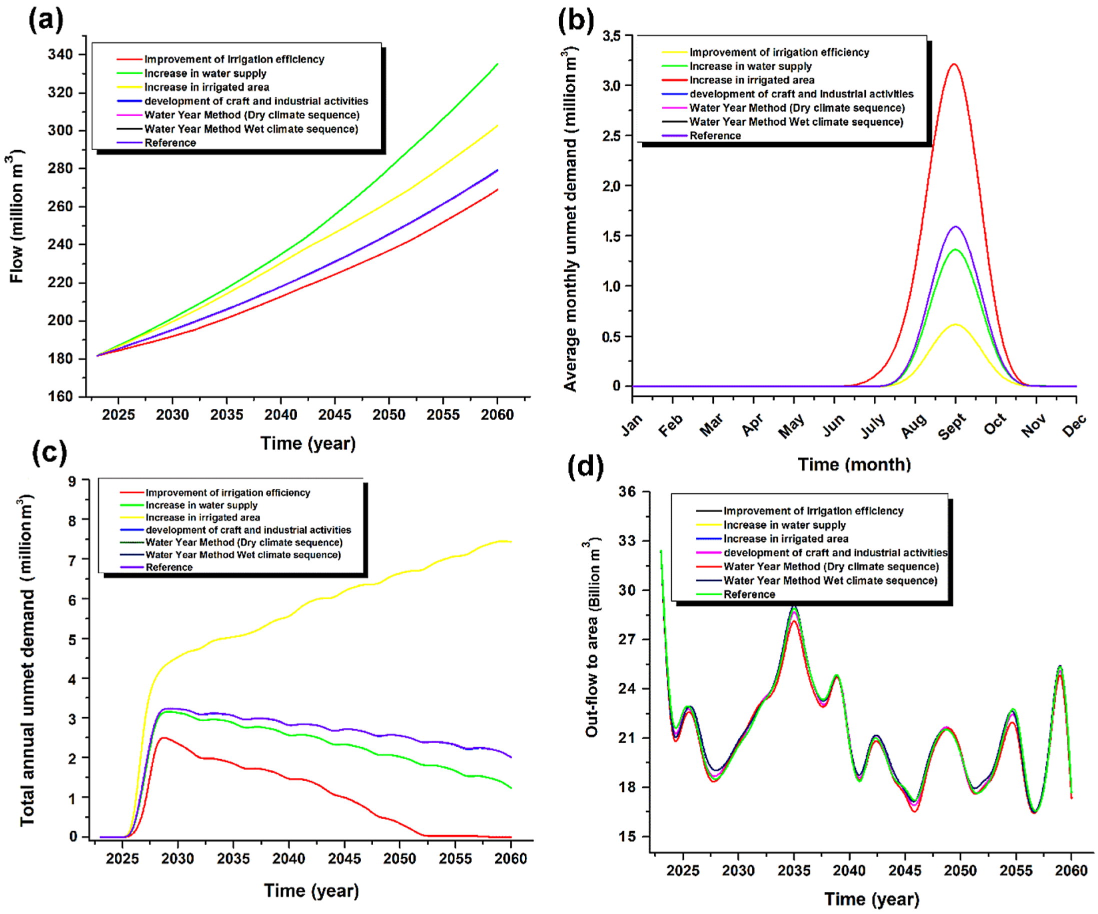

Figure 11. (a) Flow series simulation of planning hypotheses, (b) total annual unmet demand, (c) average monthly unmet demand, (d) outflow to area

implementing improvements in irrigation efficiency could reduce demand by half compared to the reference scenario, as more efficient irrigation techniques conserve water (Figure 11c). An increase in water supply through industrial development and enhancements to water resources, such as the construction of dams, would also help mitigate demand compared to the reference scenario. However, even with these improvements, demand would remain substantial, exceeding 60 million cubic meters (Figure 11d). The consideration of dry and wet years underscores the impact of climatic variability. Demand is expected to be lower during wet years and higher during dry years, with the average over multiple years remaining close to the reference scenario (Figure 11d). Ultimately, adapting to climate change could stabilize demand at levels below 50 million cubic meters by improving irrigation efficiency and increasing water supply. This scenario represents the most favourable approach for sustainable water resource management (Figure 11d).

Comparison of climate scenarios

The simulation results from the WEAP software for the Mostaganem region highlight the effects of various scenarios on runoff and water quality, particularly the Particulate Organic Matter (POM) recovery rate. Scenarios such as improving irrigation efficiency, increasing water supply, expanding irrigated areas, and enhancing industrial and urban activities, as well as the wet climate sequence, generally show an increase in runoff at different times, while the dry climate sequence and reference scenario indicate a decrease. Improved irrigation efficiency reduces runoff by decreasing water consumption, whereas increased water supply and expanded irrigated areas raise runoff due to higher water usage. Industrial and urban activities also increase runoff, underscoring the need for sustainable water management in these sectors. Climate variations significantly influence runoff, with wet conditions boosting water availability and dry conditions reducing it. The water quality analysis reveals that the wet climate sequence achieves the highest POM recovery rate (nearly 100% in June), while other scenarios, such as improving irrigation efficiency (peaking at 80%), increasing water supply, expanding irrigated areas, and developing crafts and industry, show lower peaks (20–80%). The reference scenario remains relatively flat, peaking at around 20%. These results demonstrate that climate conditions and proposed interventions significantly impact water availability and quality, with varying effectiveness across scenarios, emphasizing the importance of tailored water management strategies to address regional challenges (Figure 12).

The curve in Figure 13 illustrates the volumes of water stored in three reservoirs within the Mostaganem region: Kramis, Kerrada, and Cheliff dams. The horizontal axis represents the months of the year, while the vertical axis indicates the stored water volumes in cubic meters (m^3). Seasonal trends in stored water volumes are evident: for all dams, water volumes generally increase from January, peak in June or July, and then decline to their lowest levels in December.

A comparison of the three curves reveals that the Cheliff dam consistently holds the highest water volumes, followed by the Kerrada and Kramis dams. However, the differences between the

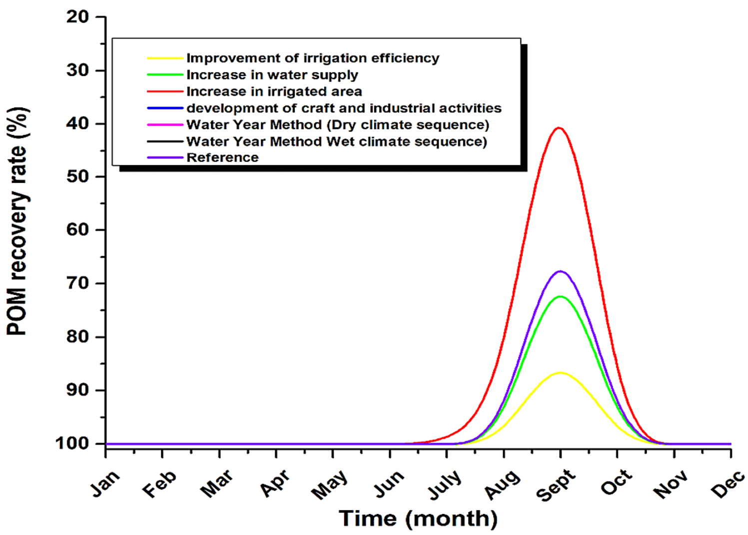

Figure 12. Flow recovery rate (%)

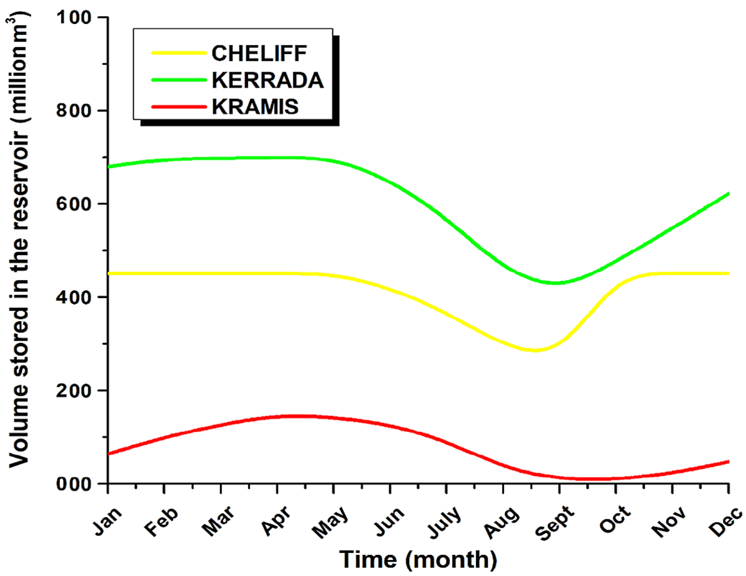

Figure 13. Monthly volume stored in the reservoirs

dams fluctuate throughout the year. This curve is a valuable tool for understanding water resource management, planning water usage, forecasting irrigation and consumption needs, and making informed decisions regarding dam construction and maintenance. It is important to recognize that several factors influence water management in these reservoirs, including precipitation, inflow and outflow rates, and evaporation losses.

AHP analysis results

The AHP was used to evaluate and prioritize five key water management criteria: water year method for wet climate sequence (WYM Wet), water year method for dry climate sequence (WYM Dry), increase in irrigated area (IIA), improvement of irrigation techniques (IIT), and increase in drinking water supply (IDWS). Through pairwise comparisons on a scale of 1 to 9, WYM Wet emerged as the most significant criterion, with a weight of 0.496 (49.63%), reflecting its critical role in decision-making. WYM Dry followed with a weight of 0.243 (24.27%), highlighting its importance in addressing climate variability. IDWS ranked third with a weight of 0.132 (13.24%), indicating its moderate significance in ensuring adequate drinking water supply. In contrast, IIA and IIT received lower weights of 0.084 (8.39%) and 0.045 (4.48%), respectively, suggesting their relatively lesser importance compared to climate-related criteria. These results emphasize the need to prioritize WYM Wet and WYM Dry in water management strategies, while also considering IDWS, to effectively address challenges posed by climate variations and optimize water resource utilization (Table 4).

This table summarizes the key parameters obtained from the AHP calculation. The count represents the number of criteria considered, which is 5 in this case. The Lambda Max value of 5.276 indicates the maximum eigenvalue of the comparison matrix, essential for deriving consistency measures (Table 5). The consistency index (CI) of 0.2256 reflects the level of consistency in the pairwise comparisons, while the consistency ratio (CR) of 0.0615 demonstrates that the judgments are reasonably consistent, as a CR value below 0.1 is generally acceptable. Finally, the constant value of 1.1045 is used in the context of consistency evaluation within AHP (Table 5).

DISCUSSION

Improving irrigation efficiency

The study highlights critical challenges and opportunities in water resource management in the Wilaya of Mostaganem, particularly during peak irrigation months (July to October), where unmet water demand is most severe. These findings align with previous research by Attar et al. (2024), Hamlat et al. (2024), and Zegait et al. (2024), which demonstrate that efficient irrigation practices can significantly reduce water demand and improve water availability. For example, our analysis shows that unmet water demand could decrease by approximately 0.5 hm^3/month under the ATI scenario and up to 4.3 hm^3/month under the ASI scenario. This underscores the importance of optimizing agricultural water use to address shortages.

Adopting modern irrigation techniques, such as drip irrigation and sprinklers, can reduce pressure on water resources while boosting agricultural productivity. This aligns with global best practices that promote technological innovations to enhance

Table 4. Pairwise comparison matrix for main criteria

Criterion	WYM Wet	WYM Dry	IIA	IIT	IDWS	Weight	Weight (%)
WYM Wet	1	3	5	7	5	0.496	49.63
WYM Dry	1/3	1	3	5	3	0.243	24.27
IIA	1/5	1/3	1	3	1/3	0.084	8.39
IIT	1/7	1/5	1/3	1	1/3	0.045	4.48
IDWS	1/5	1/3	3	3	1	0.132	13.24

Table 5. Summary of AHP parameter calculation

Parameter	Count	Lambda Max	CI	CR	Constant
Value	5	5.276	0.2256	0.0615	1.1045

water use efficiency. However, the simulation results also reveal a complex relationship between water supply strategies and demand management. While increasing water supply through infrastructure development, such as dam construction, can lead to higher runoff, this approach alone is not a sustainable long-term solution. Studies by Bhatia & Singh (2023), Nyandoro (2018), Qamruzzaman et al. (2024), and Zerouali et al. (2023) support this view, suggesting that over-reliance on supply-side measures without addressing demand-side management can lead to resource depletion and environmental degradation.

Balancing supply-side and demand-side strategies

A balanced approach that combines supply-side enhancements (e.g., new dams, desalination plants) with demand-side reductions (e.g., water conservation, efficient irrigation) is essential for long-term sustainability. For instance, the construction of the desalination plant in Mostaganem reflects a proactive effort to increase freshwater availability, but it must be complemented by demand-side measures to ensure sustainable water use.

The study also highlights the importance of adaptive management strategies to address climate variability, as seen in the differences in water demand between wet and dry years. This aligns with global best practices that advocate for integrating technological innovations and community engagement in water management. Our findings are consistent with studies in other arid and semi-arid regions, such as those by Bwire et al. (2024), Mehta et al. (2024), Tsakiris & Loucks (2023), and Yang et al. (2023), which emphasize the need for adaptive strategies to manage climate variability and rising water demand. However, the unique socio-economic and environmental context of Mostaganem requires tailored solutions that consider local conditions and stakeholder priorities.

Study contributions and future directions

This study contributes to the existing literature by providing a comprehensive analysis of water resource management in Mostaganem, integrating both supply-side and demand-side strategies. The use of the WEAP model and AHP method offers a robust framework for evaluating scenarios and identifying optimal strategies. The findings underscore the importance of a balanced approach that combines infrastructure development with demand-side measures, such as improving irrigation efficiency and promoting water conservation.

However, the study has limitations. The accuracy of the WEAP model depends on the quality of input data, such as hydrological data, water demand projections, and climate scenarios. Uncertainties in these data, especially in the context of climate change, may affect the reliability of the results. Additionally, the AHP method relies on subjective pairwise comparisons, which could introduce biases. Future studies should focus on improving data collection, validating model outputs with real-world observations, and exploring alternative decision-making methods, such as the ANP or multi-attribute utility theory (MAUT).

Implications of overlapping curves and model sensitivity

The overlapping curves in the simulation results suggest that the proposed interventions may have a limited impact on water availability or demand. This could be due to insufficient variation in input parameters, dominant external factors, or limitations in the model structure. These findings highlight the need for more robust and sensitive modeling approaches to better assess the effectiveness of different water management strategies.

To address these limitations, future scenarios should consider:
- increasing the magnitude of changes in key parameters,
- incorporating more extreme climate scenarios,
- exploring the combined effects of multiple interventions.

Improvements to model sensitivity can be achieved by:
- refining the model structure to better capture interactions between variables.
- using higher-resolution or more accurate data.
- incorporating additional variables, such as land use changes and socio-economic factors.

Policy and management implications

The limited impact of current interventions underscores the need for:
- reevaluating intervention strategies to identify more effective approaches,
- implementing adaptive management practices,

- engaging stakeholders in the development and evaluation of scenarios.

Moving forward, adaptive strategies are crucial to building resilience against climate change and increasing water demand. Key areas for future research include integrating remote sensing data for more accurate assessments, engaging local stakeholders in planning processes, and implementing long-term monitoring and evaluation of water management strategies. By combining supply-side enhancements with demand-side reductions, stakeholders can develop comprehensive plans to ensure a reliable and sustainable water supply for future generations in Mostaganem and similar regions. Ultimately, this study highlights the need for a collaborative, integrated approach to water resource management, promoting sustainable practices that enhance water security while supporting socio-economic development.

CONCLUSIONS

This study highlights the urgent need for effective water resource management in the Wilaya of Mostaganem, where rising demands due to population growth, agricultural expansion, and climate variability pose significant challenges. By integrating the WEAP decision support tool with the AHP method, the study provides a robust framework for evaluating scenarios and identifying sustainable water management strategies. The findings reveal that without intervention, unmet water demand could reach 4.3 hm^3 per year by 2027 under the ASI scenario. However, improving irrigation efficiency could reduce this demand by up to 50%, emphasizing the importance of adopting modern irrigation techniques. Seasonal analyses show critical water deficits during summer, highlighting the need for proactive planning to ensure supply during peak irrigation periods.

Infrastructure development, such as constructing additional dams, is essential to mitigate future shortages. Even with these measures, demand could exceed 80 hm^3 by 2060, stressing the importance of long-term planning and investment. Adaptation to climate change is also crucial, as it can help stabilize water demand below 50 million cubic meters. This integrated approach not only addresses Mostaganem's challenges but also serves as a model for other regions facing similar issues. Policymakers and stakeholders must collaborate to implement these strategies, ensuring the sustainability and resilience of water resources for future generations.

To address these challenges, concrete recommendations are proposed for local decision-makers. Promoting modern irrigation techniques like drip irrigation and sprinklers can enhance water use efficiency by up to 50%, and providing subsidies and training programs can encourage farmers to adopt these technologies. Constructing additional dams and reservoirs will help manage seasonal water variations, and prioritizing infrastructure investments through public-private partnerships can ensure adequate funding. Developing drought contingency plans, including water rationing and emergency responses, is essential, and establishing a regional drought task force can coordinate these efforts effectively.

Investing in water recycling and reuse technologies can reduce reliance on freshwater sources, and enforcing regulations for wastewater treatment and reuse by industries and municipalities will further support this goal. Strengthening climate monitoring and forecasting systems will provide accurate data for water management, and allocating funding for advanced equipment and early warning systems will enhance preparedness for extreme weather events. Engaging stakeholders, including farmers, industries, municipalities, and environmental groups, in water management planning ensures inclusive and sustainable strategies. Establishing advisory committees can help incorporate diverse perspectives into decision-making processes.

Implementing adaptive management strategies that adjust to changing climate conditions and water availability is crucial. Regularly reviewing and updating water management plans based on new data and insights will ensure their effectiveness over time. Supporting research and development initiatives for innovative solutions like desalination, rainwater harvesting, and aquifer recharge can provide long-term benefits. Allocating funding for research grants and partnerships with academic institutions will advance water management technologies and practices.

By implementing these recommendations, local decision-makers can address current challenges and build a resilient water management system for the future. Collaboration among stakeholders, investment in infrastructure, and adoption of innovative technologies will ensure the sustainable use of water resources, safeguarding them for future generations.

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