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MANAGING WATER DEMAND AND SUPPLY UNDER SILTATION CHALLENGES: INTEGRATED STRATEGIES FOR THE HAMMAM DEBAGH RESERVOIR IN GUELMA PROVINCE, EASTERN ALGERIA

Berredjem A.F.
Department of Territory Planning University of Mentouri Brothers, Constantine 1 Algeria

Boumaiza A.
Department of Electronic, Badji-Mokhtar Annaba University

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ABSTRACT

This study analyses water demand management scenarios in Guelma Province, which heavily relies on the Hammam Debagh Dam, to evaluate challenges and opportunities in water security. Sedimentation in the dam significantly reduces water storage capacity, exacerbating the water crisis. The research employs a combination of hydrological modeling, scenario analysis, and stakeholder consultations. Hydrological data were used to simulate the impacts of sedimentation on water storage capacity. Various management scenarios, such as river diversion and reforestation, were modeled to assess their effectiveness in reducing unmet water demand. Stakeholder consultations provided insights into local perceptions and implementation challenges. The results project an unmet water demand of 82 million cubic meters by 2060 in the baseline scenario. Implementing river diversion could reduce unmet demand by 16%, while reforestation offers a 7% reduction. Combining these measures could achieve a 21% reduction in unmet water demand. This underscores the critical importance of integrated approaches for holistic water resources management and the urgent need for effective action.

The study highlights the necessity of an integrated approach to mitigate unmet water demand, which is essential for sustainable water management. It also advocates for proactive collaboration among stakeholders to address environmental, economic, and social challenges, ensuring the long-term resilience of water resources in the region.

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INTRODUCTION.

Water insufficiency poses a primary challenge for arid and semi-arid communities, as highlighted by Sharafatmandrad and Mashizi (2020). Water is essential for maintaining ecosystem balance and biodiversity (Rodrigues Filho et al., 2021). However, increasing population, urban development, industrial growth, and the expansion of agriculture and tourism have sharply escalated water demands (Mensah et al., 2022).

Soil erosion from precipitation and runoff is a widespread issue, particularly on slopes prone to heavy rainfall, vulnerable terrains, agricultural activities, deforestation, and land development

(Ghernaout et al., 2020). Sediment movement within watersheds and deposition in reservoirs create significant challenges for dam operators, reducing effective water storage and incurring substantial costs (Pengfeng Li et al., 2021). In Algeria, 45% of the Tellian zones face water erosion, diminishing dam storage capacity by 0.5% to 3% annually (Chebbani et al., 1999). The number of large dams has risen from about forty in the late 1970s to eighty by 2020, with a total capacity of around 9 billion cubic meters, significantly impacted by sediment deposition (Remini & Hallouche, 2005; Ouamane, 2009; Remini, 2017).

This study utilizes the Water Evaluation and Planning (WEAP) software to assess current and future water requirements in Guelma Province. WEAP's flexibility accommodates diverse data and environmental conditions, enabling effective modeling despite data accuracy challenges (Asghar et al., 2019). Previous research has extensively explored sedimentation impacts and management strategies across various regions. For instance, Pengfeng Li et al. (2021) investigated sedimentation in north-western China's rivers, using the YZD reservoir as a case study. They proposed a 'sediment avoidance diversion' concept and effective control strategies based on a comprehensive 46-year analysis, providing a theoretical foundation applicable to similar reservoirs. V. D. Vinh et al. (2014) studied the transformative effects of the Hoa Binh Dam in Vietnam, highlighting significant impacts on the Red River basin. Their findings suggest that tidal pumping may be a contributing factor to increased dry-season flow and enhanced estuarine siltation following the dam's construction. Shrestha et al. (2022) introduced the Reservoir Sediment Management (ResSMan) tool, integrated into the Soil and Water Assessment Tool (SWAT) to address sedimentation challenges in hydropower reservoirs. Validated using SedSim, ResSMan predicts a 74% trapping efficiency in the 19-reservoir Mekong system. Their coordination simulations suggest optimal flushing strategies, while also emphasizing potential ecological impacts. Louamri et al. (2013) examined the influence of rainfall variability on soil erosion and sedimentation in hydraulic dams within the semi-arid Mediterranean region of the Maghreb. Focusing on the Oued Bouhamdane basin in eastern Algeria, regulated by the Hammam Debagh dam since 1987, they found an average specific solid inflow of 257 t km^2 yr^{-1}, with substantial interannual variability. The study also highlighted the significant contribution of flood events to the overall sediment load. Remini (2017) assessed sedimentation in Algerian dams using data from a hundred bathymetric surveys conducted by the National Agency for Dams and Transfers. The study proposed a comprehensive sediment management methodology, revealing that after 160 years, 74 dams have lost 20% of their capacity due to sedimentation, totaling 1.7 billion m^3, with an annual sedimentation rate of 65 Mm^3.

This novel study applies the WEAP software to assess the sedimentation effects in the Hammam Debagh Dam, providing critical insights for sustainable water resource management in Guelma Province. By integrating current and future water requirements, this research aims to develop effective strategies to mitigate sedimentation impacts and enhance water storage capacity.

MATERIALS AND METHODS.

Description of study area.

The Province of Guelma, located at 36° 27′ 50″ north and 7° 26′ 50″ east, spans 3,686.84 km^2 and had an estimated population of 559,451 inhabitants as of 2023, based on the latest census data available from 2008, with 25% of the population concentrated in its capital. Its varied topography, abundant forest cover, and the presence of the Seybouse River are notable features. Primarily agricultural and pastoral, the province boasts a significant forest coverage of 12%, with agricultural land occupying 35% of its total area, predominantly comprising maquis and scrubland. Economically vital, Guelma houses industries encompassing agriculture, mining, and manufacturing. Agricultural activities entail the cultivation of cereals, vegetables, and fruits, employing a blend of traditional and modern techniques.

Guelma experiences a Mediterranean climate characterized by hot, arid summers and mild, humid winters. The study area is subject to this climate, displaying monthly and annual irregularities in precipitation, with an average annual rainfall of 566.8 mm/year. The mean annual temperature registers at 18.69°C. These findings delineate two distinct seasons, one dry and the other wet. Actual evapotranspiration stands at approximately 530 mm/year, with a runoff value of about 74.69 mm/year. Infiltration, on the other hand, has been estimated at 82.43 mm/year (Boudjebiour, 2022).

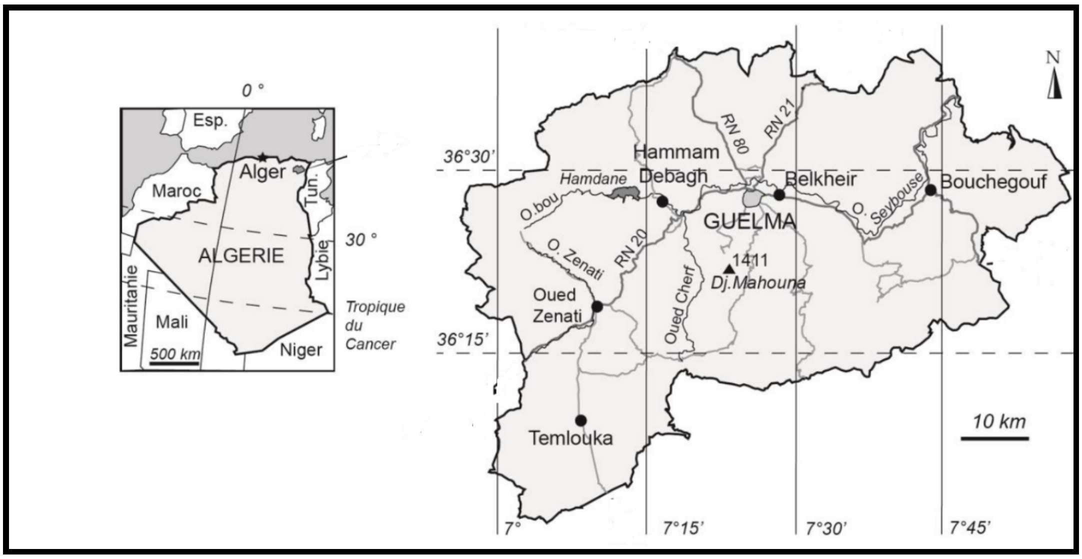

Figure 1. Map of Algeria showing the location of Guelma province (Soltani, 2019).

METHODS.

WEAP Model Application.

The WEAP water allocation model operates based on the principle of water balance accounting, enabling its application across diverse scenarios, including drinking water systems, agricultural systems, individual subbasins, and complex river systems. Essentially, WEAP functions as a simulated environment conducive to exploring different strategies for water development and management, providing a platform for evaluating alternative approaches to water resource management (Sieber and Purkey, 2015).

The model's components are structured using distinct spatial elements referred to as "nodes" and "links". Nodes in the WEAP framework represent tangible features such as demand sites, groundwater aquifers, and reservoirs, while links connect these nodes and encompass various features such as rivers, diversion links, transmission links, and return flow links. The water allocation process in WEAP is guided by demand priorities, determining the sequence in which competing entities receive their water allocations. These priorities, set by the user, dictate the distribution of available water resources within the model, encompassing competing demand sites, catchments, reservoir filling, hydropower generation, and flow requirements (S. Asadi et al., 2024).

In WEAP, three primary scenario modeling approaches are utilized: the model's baseline year, which establishes a reference scenario simulating likely developments without interventions from the Current Account; "what-if" scenarios, which enable the evaluation of the impacts resulting from changes to the reference scenario (Mensah et al., 2022). These approaches facilitate the assessment of various internal factors. In our study, the model was configured to simulate four scenarios.

Scenario 1. Reference Scenario.

The reference scenario provides a default projection, capturing trends from 2023 to 2060. It incorporates factors like population growth and economic development, establishing a fundamental baseline for analysis. This scenario specifically considers siltation, with an estimated average annual rate of 0.53 Mm^3 and an average specific solid contribution of 257 t km^{-2} $year^{-1}$, as reported by Louamri et al. in 2013. By 2023, sediment accumulation caused the dam's capacity to decrease from 220 Mm^3 to 185 Mm^3, representing a loss of 7.8% of the initial capacity, or nearly 0.5% per year, according to Zeghaba et al. (2018).

For the demand sites, three conventional user categories were considered: domestic, agricultural, and industrial water demand, illustrated in Figure 2. Domestic water demand was determined based on the most recent census data available before the current accounting year, conducted in 2008. A linear projection method was utilized to estimate population growth from 2023 to 2060 for the reference simulation, as described by Birhanu et al. (2021), assuming a theoretical water usage rate of approximately 150 liters per capita per day.

Regarding irrigation water demand, we incorporated data on irrigated areas and the theoretical annual water allocation per hectare, which stands at 5500 m^3/ha/yr, following the findings of Daifallah et al. (2017). This theoretical annual allocation signifies the volume of water designated for irrigation per hectare of land and may be influenced by factors such as crop variety, soil composition, and climatic conditions.

Scenario 2. Stream Diversion Scenario.

Through the planning of a stream diversion and the construction of a small settling dam aimed at reducing a specific amount of silt and sand by half to 50%, with an average specific solid inflow of 257 t km^{-2} yr^{-1}, our objective is to redirect the stream flow and capture sediment-laden water, thereby mitigating siltation in the main dam or reservoir. The water diverted from the water diversion project is directed towards the reservoir, serving as a source of water for consumption. Such reservoirs are known as derivation reservoirs. They offer advantages such as lower costs, low dam heights, and reduced flood control pressure. Sediment avoidance diversion prevents a large quantity of sediment from entering the reservoir during periods of high sediment concentration in the river. This not only ensures water quality standards in the water supply reservoir but also prevents capacity loss and slows sediment deposition in the reservoir.

Scenario 3. Dam Saver Reforestation Scenario.

The reforestation scenario, aimed at combating sedimentation at the Hammam Debagh dam, seeks to assess the efficacy of tree planting as a measure for sediment management to uphold the reservoir's storage capacity and enhance water supply across various sectors. It models the impact of reforestation on diminishing runoff and erosion within the watersheds that feed into the dam, resulting in a 30% reduction in sediment-laden flow. Users are empowered to designate strategic reforestation zones within the dam's watershed, allowing for the selection of suitable tree species and adjustment of planting densities.

This scenario provides an avenue for evaluating how reforestation efforts can progressively mitigate sedimentation at the dam, thereby safeguarding its water storage capacity. The resulting simulations offer insights to policymakers for implementing sustainable water resource management strategies and safeguarding critical water infrastructure such as the Hammam Debagh Dam.

Scenario 4. Integrated Scenarios: Stream Diversion, Dam Saver Reforestation.

The methodology employed adopts an integrated approach by combining two scenarios: Stream Diversion and Dam Saver Reforestation. This involves the following steps: Initially, integrating the data into the model to simulate the impacts of these scenarios on water availability and reduced sedimentation in dams. Subsequently, integrating the two scenarios to evaluate their combined effect on the overall management of water resources. This methodology offers a comprehensive understanding of the potential impacts of various water demand management strategies, facilitating informed decision-making for sustainable water resource management.

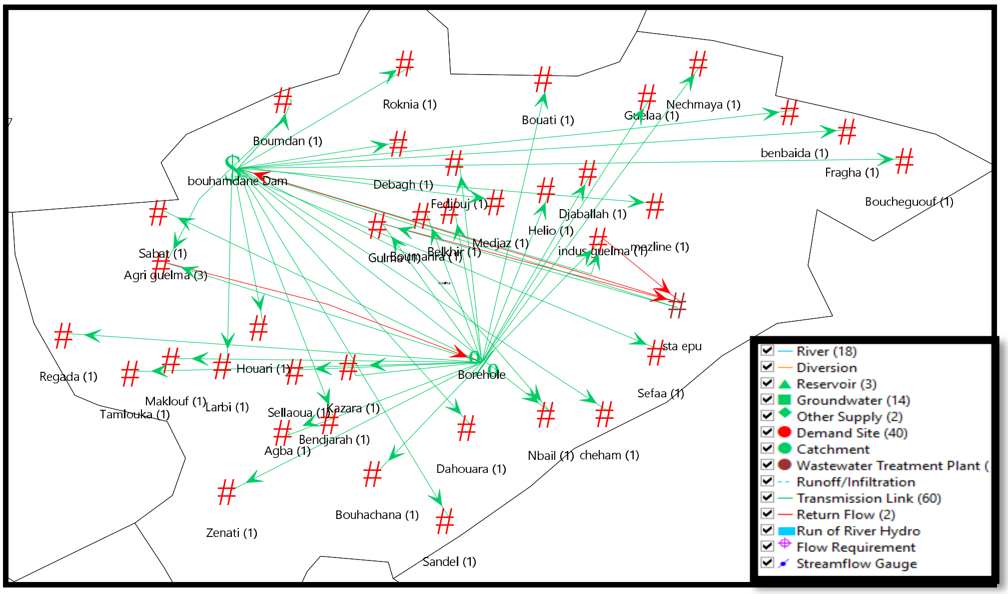

Figure 2. WEAP schematic with demands, supply nodes, transmission links, and return flows.

Current Water Supply in Guelma.

Surface Water Potential.

The Hammam Debagh dam is the first and only infrastructure in the Bouhamdane river basin, playing a crucial role in water management for the region. With a total capacity of 185 Mm³, the dam primarily serves for drinking water supply and irrigation purposes. It has an annual regulable volume (Vr) estimated at about 55 Mm³ for drinking water supply and 66 Mm³ for irrigation. The water collected by the Hammam Debagh dam is used to supply drinking water to the population and industries in the main cities of Guelma Province. Its aim is to meet the water needs of approximately 294,402 inhabitants and irrigate an area of 9,200 hectares in the Guelma and Bouchegouf perimeters (ABH CSM, 2022).

These reservoirs serve as significant surface water sources for Guelma ; however, their contribution alone falls short of meeting the city's water demand. Consequently, additional water resources, including groundwater sources, are also tapped to supplement the supply (Aoun-Sebaiti et al., 2013).

Groundwater Potential.

Groundwater is exploited by 41 wells, which are intended for use in both water supply and irrigation. These wells are distributed across different aquifers, including:

The Alluvial Aquifer of Guelma: Extending along the Oued Seybouse, this aquifer is currently tapped by 25 wells, with an actual exploitation flow rate of 195 l/s. The depth of the aquifer varies across locations, ranging from more than 30 to 40 meters below the ground surface (DRE 2018).

The Senonian Neritic Limestone Aquifer of Hammam Bradaa: The depth limits of this aquifer remain unknown. Currently, seven wells exploit it, with an actual exploitation flow rate of 165 l/s (DRE 2018).

Table 1. Summary of Well Characteristics and Flow Rates by Category (DRE and Boudjebiour, 2022).

Category	Number	Exploited Flow (l/s)
AEP Wells	32	310
Irrigation Wells	3	2
Industrial Wells	6	45

Table 1 provides information on the number of wells, the exploited flow, and the exploited flow per population for different categories of wells, including AEP (water supply), irrigation, and industrial wells.

RESULTS AND DISCUSSION.

Overall Water Demand and Future Projections.

Figure 3 depicts the projection of water demand in the reference scenario, indicating an estimated increase to beyond 128 Mm^3 by 2060.

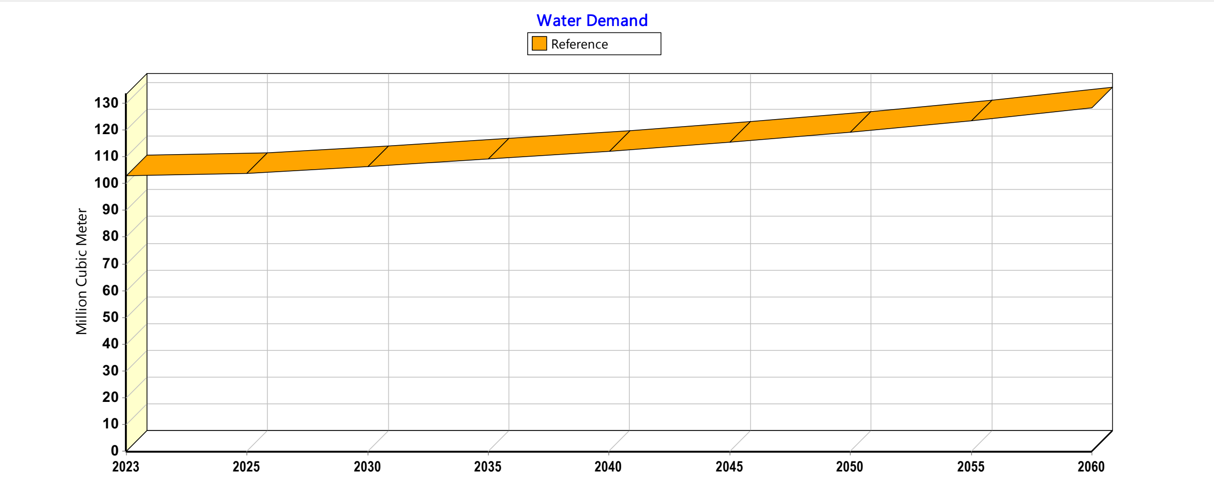

Figure 3. Total water consumption scenario 1.

The agricultural sector continues to be the primary water consumer in the province of Guelma, owing to the predominantly agricultural character of the region. With extensive farmlands and irrigation requirements, agriculture accounts for the highest water usage in the province. The cultivation of various crops, including cereals, vegetables, and fruits, along with livestock farming, contributes significantly to the overall water demand. Additionally, traditional irrigation practices and the need to sustain agricultural productivity further amplify water consumption in the area.

The household sector stands as the second-largest consumer of water resources. With population growth, particularly concentrated in urban areas, the demand for domestic and municipal water is expected to increase. This surge in demand stems from various factors such as urbanization, changes in lifestyle, and an increasing need for sanitation and hygiene services. As urban populations expand, so does the requirement for water for drinking, bathing, and other household activities, placing additional strain on water supply systems and infrastructure.

The third-largest consumer is the industrial sector. The demand for industrial water will be influenced by the types of industries present, such as agricultural processing (e.g., tomato canning, yeast manufacturing), as well as other industrial activities.

Overall Unmet Water Demand and Future Projections.

Unmet water demand, also known as water deficit, refers to the portion of water demand that cannot be fully satisfied due to constraints such as water shortages resulting from drought, inadequate infrastructure, distribution limitations, or other restricting factors (Psomas et al., 2017).

$$\text{Unmet Water Demand} = \text{Water Demand} - \text{Water Supply}$$

Scenario 1. Reference Scenario.

Figure 5 illustrates the findings of a scenario analysis conducted for the Guelma water supply. According to the graph, the analysis anticipates a shortfall in the water supply of Guelma province by 2060, with the silting of the dam being a significant contributing factor, leading to a deficit of 87 Mm^3.

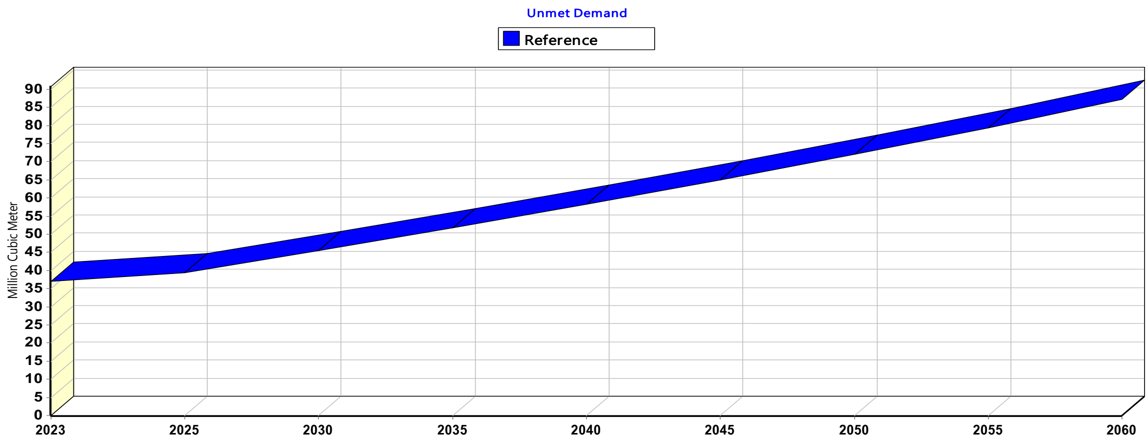

Figure 4. Future overall unmet water demand scenario 1.

Regarding unmet water demand, strategies can be implemented to either increase water supply or reduce water demand. Presently, options for boosting water supply in Guelma province are somewhat restricted, as there are no major plans for constructing dams or reservoirs. Furthermore, efforts toward enhancing the economical and efficient management of water demand are lacking.

Potential initiatives to address this issue encompass upgrading urban water networks to mitigate leakages, implementing water efficiency schemes within the industrial sector, encouraging wastewater treatment and reuse in irrigated agriculture and groundwater replenishment, promoting rainwater harvesting and water recycling practices, restricting irrigation during hot mid-days, enhancing irrigation canals and pipelines, advocating for modern irrigation techniques, adjusting water pricing to ensure greater cost recovery and incentivize water conservation, as well as conducting educational and training programs and awareness campaigns.

Haut du formulaire.

Scenario 2. Stream Diversion Scenario.

Figure 6 illustrates that the implementation of a stream diversion in the Bouhamdane River dam would decrease the unmet water demand to 76 Mm³ by 2060. This represents a 16% decrease in unmet water demand compared to the reference scenario.

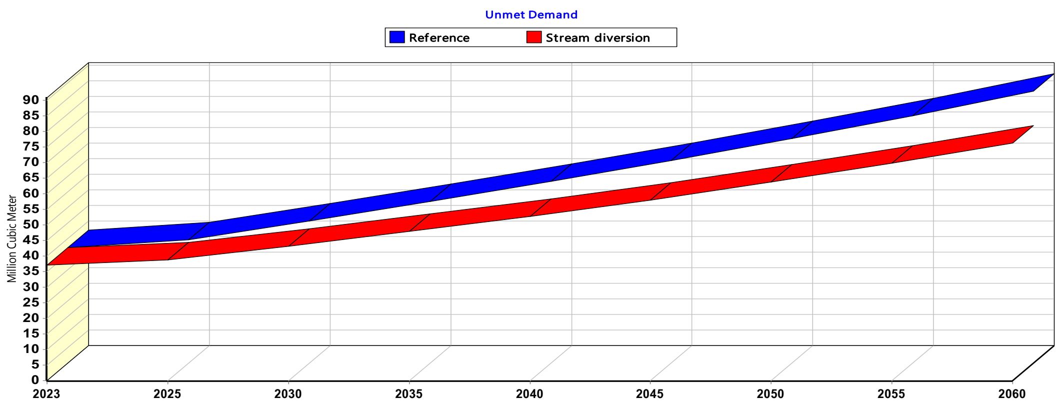

Figure 5. Future overall unmet water demand scenario 2.

To address the future water demand in the region, additional measures may be necessary, such as investing in river water diversion infrastructure to manage the significant quantities of silt reaching the dam. However, it's crucial to assess both the environmental and economic impacts to ensure regional sustainability. While the construction of such hydraulic structures requires specialized expertise and careful execution, it can potentially harm ecosystems and lead to higher water rates for consumers. Therefore, it is essential to carefully evaluate the potential economic impacts to mitigate any negative consequences. Nevertheless, drawbacks exist, including limited annual water diversion, poor self-purification functionality of reservoir water, and large project areas.

Scenario 3. Dam Saver Reforestation.

According to Figure 5, the Dam Saver Reforestation scenario has reduced the unmet water demand in Guelma to 80 Mm³ by 2060. This represents a 7% decrease in unmet water demand compared to the reference scenario.

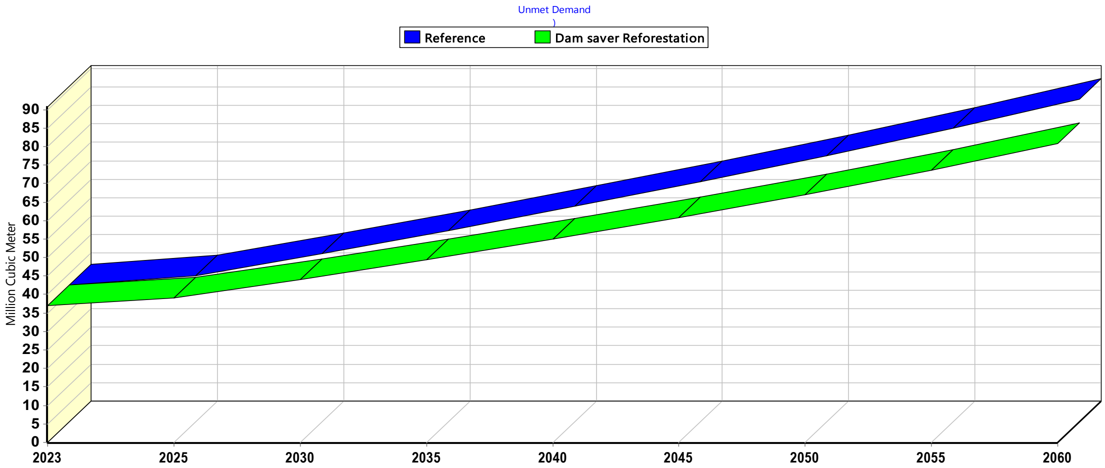

Figure 6. Future overall unmet water demand scenario 3.

Implementing reforestation strategies in the surrounding areas can effectively combat siltation by stabilizing soil, reducing erosion, and preventing sediment from entering the dam. Such efforts enhance the dam's efficiency, ensuring a sustainable water supply and mitigating the adverse effects of siltation on water resources in Guelma's arid and semi-arid zones. Nevertheless, reforestation initiatives in arid and semi-arid areas encounter challenges including increased water demand for young trees, competition for arable land, potential ecological disruptions, financial burdens, and land use conflicts. Despite these potential impacts, reforestation stands as a crucial management strategy for arid and semi-arid regions, offering significant benefits for ecosystem restoration and sustainable resource management.

Scenario 4. Integrated Scenarios: Stream Diversion, Dam Saver Reforestation.

Figure 6 illustrates that the integration of the Stream Diversion and Dam Saver Reforestation scenarios would result in a substantial reduction in unmet water demand, lowering it to 69 Mm³ by 2060. This translates to a noteworthy 21% decrease in unmet water demand when compared to the reference scenario.

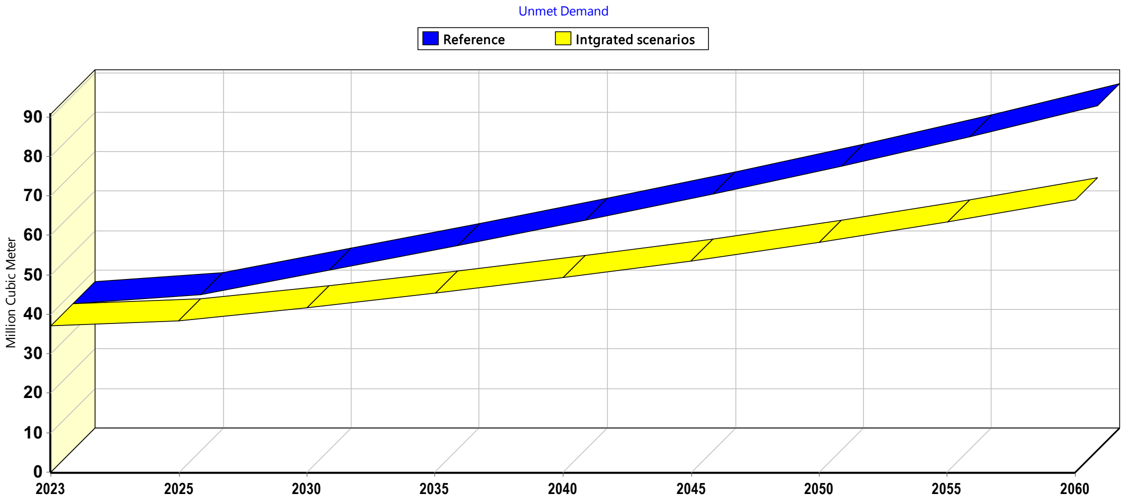

Figure 7. Integrated Scenario: Stream Diversion, Dam Saver Reforestation compared to the reference scenario.

If we integrate the two river diversion scenarios and the Dam Saver Reforestation scenario, we will have a comprehensive strategy that not only mitigates the adverse effects of dams but also fosters ecosystem restoration and resilience. By combining river diversion techniques with strategic reforestation efforts, we can effectively manage water resources while simultaneously rejuvenating degraded landscapes. This integrated approach promises multifaceted benefits, including improved water quality, enhanced biodiversity, strengthened ecological connectivity, and bolstered watershed stability. Furthermore, it presents an opportunity to engage local communities in conservation efforts, promoting sustainable livelihoods and fostering a sense of stewardship towards natural resources. As we move forward with this integrated approach, we pave the way for a more harmonious coexistence between human development and environmental preservation, ultimately contributing to the long-term sustainability of our ecosystems and societies.

Discussion on Water Demand Management Scenarios in Guelma.

This study offers a detailed analysis of water demand management scenarios in Guelma Province, focusing on the Hammam Debagh Dam. Key findings indicate that sedimentation significantly reduces the dam's water storage capacity, exacerbating water shortages. Without intervention, unmet water demand could reach 87 million cubic meters by 2060. Implementing river diversion could reduce unmet demand by 16%, while reforestation could achieve a 7% reduction. Combined, these measures could result in a 21% reduction in unmet water demand.

The agricultural sector is the largest consumer of water due to extensive irrigation needs, followed by the household sector, driven by urbanization and population growth, and the industrial sector. These results underscore the necessity for integrated water management strategies to ensure water security in regions affected by sedimentation.

Our findings highlight the challenges posed by sedimentation in reservoirs and the importance of integrated water management. The projected unmet water demand of 87 million cubic meters by 2060 aligns with concerns raised regarding water crises in arid and semi-arid regions.

The effectiveness of reforestation and river diversion as mitigation strategies. Reforestation helps stabilize soil and reduce erosion while river diversion enhances water availability. This study adds to the field by quantifying these impacts for the Hammam Debagh Dam and demonstrating the benefits of combined approaches.

Study Limitations.

Several limitations should be considered. The hydrological models used are based on historical data and assumptions that may not fully account for future environmental changes. Stakeholder consultations, while informative, might not represent all local perspectives and socio-economic impacts.

The challenges of implementing large-scale infrastructure projects, such as ecological disruptions and financial burdens, were not thoroughly explored. Similarly, reforestation efforts in arid and semi-arid areas face challenges related to water availability for young trees and land use competition.

CONCLUSION.

This study significantly contributes to the literature on water demand management and reservoir sedimentation through a detailed case analysis of the Hammam Debagh Reservoirs in Guelma Province, Eastern Algeria. Our research comprehensively evaluates multiple scenarios, including river diversion, reforestation, and their integration, highlighting the severity of sedimentation and presenting practical mitigation strategies applicable globally.

The findings show that without intervention, unmet water demand could reach 87 million cubic meters by 2060, underscoring the urgency of addressing sedimentation. River diversion could reduce unmet demand by 16%, reforestation by 7%, and their integration by 21%, demonstrating the effectiveness of combined approaches. These results enhance understanding of how integrated water management strategies can improve water security in sedimentation-affected regions.

Furthermore, this study emphasizes the importance of stakeholder collaboration and proactive engagement in sustainable water management. By advocating for an integrated approach that considers environmental, economic, and social dimensions, our research offers a blueprint for long-term water resource resilience. This holistic perspective distinguishes our study from previous research.

In conclusion, our study identifies the pressing challenges of dam sedimentation and offers actionable solutions. By providing new insights and practical strategies, this research paves the way for future studies and policy developments aimed at ensuring sustainable water supplies in sedimentation-prone regions. Future work should focus on long-term monitoring, economic analysis, advanced modelling, climate change impacts, stakeholder engagement, and policy development to further enhance the resilience of water resources and contribute to global water security.

INDEX OF NOTATIONS AND ABREVIATIONS.

DRE	Algerian Water Resources Directorate
ABHSCM	Constantine Seybouse Mellegue Basin Agency

Consent to Participate, and Consent to Publish. Informed consent was obtained from all individual participants included in the study. All authors consented to the publication of this manuscript.

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Competing Interests. Financial interests: The authors declare no financial interests to disclose. Non-financial interests: There are no relevant non-financial interests to declare.

Author Contributions. All authors contributed to the conception and design of the study. Material preparation, data collection, and analysis were carried out by Berredjem Abdel Fatah and Boumaiza Ahlem. The initial version of the manuscript was written by Berredjem Abdel Fatah, and all authors reviewed and approved the final manuscript.

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