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Water Banking as a Strategy for the Management and Conservation of a Critical Resource: A Case Study from Tunisia's Medjerda River Basin (MRB)

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Abstract: The increasingly adverse impacts of climate change (e.g., rainfall patterns, droughts, and floods), coupled with the ever-increasing water demands, are often translated into a contingent liability for water users' communities. Additional complexities arise due to competing priorities, water rights, and transboundary water sources. Therefore, conventional water management practices should shift toward more comprehensive and responsive integrative approaches, even for systems with limited data. Furthermore, water managers must prioritize dynamic and interactive management techniques for existing systems. One such management technique is water banking, which is the focus of this study. Herein, a dynamic interactive water allocation model, which encompasses the water managers and heterogeneous parties with competing demands, is developed. The voluntary sales of water shares between parties are illustrated through the specific case of the Medjerda River in Tunisia, an excellent example of a transboundary basin with limited hydrologic data and conflicting water use requirements between its upstream and downstream sectors. A set of scenarios is developed for the first analysis with this model: two management scenarios that include the no-water trade and the water banking option; three demand scenarios that include a combination of steady-, low-, and high-water demand conditions; and two hydrologic scenarios that include dry and wet conditions. Based on an economic model, the economic impacts of water banking are calculated using estimates of the costs of water shortages brought to users that illustrate the magnitude. The results show that the water banking technique can improve water resource availability by optimizing the management, operation, and conservation of natural and artificial water storage systems and water distribution infrastructure. Specifically, water banking can offset users' profit losses during severe conditions (i.e., drought), even with limited hydrologic data. This water management technique would allow the Tunisian government to minimize the economic impacts on farmers from drought and to plan for future uncertainties by optimizing the water storage potential in years of abundant rainfall.

Keywords: competing priorities; water allocation; hydro-economic model; drought

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1. Introduction

Population growth and urban development continue to place severe pressure on water infrastructure planning and management due to short-term variations in water availability and demand, and due to long-term climate uncertainties [1,2]. Climate change is expected to accentuate thermal stress (drought, heatwaves), increase warming, change air and water quality, alter rainfall patterns and distribution, increase the frequency of floods and extreme snowstorms, and affect food availability [3–6]. This is worsened in regions where water scarcity is an existing concern [7,8], which would increase as temperatures rise, rainfall trends become less predictable, and pollution of water bodies becomes more sporadic [9,10]. Moreover, the water supply and demand are not constant inputs and requirements; rather, they are functions in which the overall and marginal economic values of different quantities of used or stored water vary during different periods [11,12].

These dynamic risks present a major threat to humans and ecosystems; therefore, water management practices must consider these risks if they are to be effective, thus motivating a shift toward integrative approaches [13–17]. Moreover, communities commonly desire more sustainable and reliable water distribution, thus future water management must shift the focus from building new systems and making emergency repairs to maintaining and optimizing existing systems [18,19]. All of this entails a change in the priorities' scale, and appropriate instrumentation that facilitates the acquiring of hydrologic datasets for improved operation and management becomes of primary importance [11,20–22]. In this context, integrating advanced geostatistical and image-processing models for water resource monitoring, management, and forecasting further enhances decision-making capabilities. These models combine historical and real-time data, and they enable the implementation of new schemes for water management and analysis. Proactive measures may also be adopted to anticipate seasonal stresses, droughts, floods and shifting drought–flood patterns [23–25].

For instance, a systems approach based on simulation, optimization, and multi-objective analyses in deterministic, stochastic, and fuzzy forms has proven to be extremely effective in supporting sustainable water resources management. Throughout the last half of the 20th century, these approaches helped to explore the benefits of managing environmental systems as interdependent integrated units [26–28], and they have demonstrated the benefits of detailed hydrologic data. However, limited historical records or limited instrumentation raise the question of the suitability or feasibility of interactive management techniques. Moreover, despite the recognition of the potential economic benefits and the increased interest in developing marketing instruments, the application of systems analysis in water markets has remained less common and slower to evolve in response to political decisions, institutional constraints, and the increasing water scarcity driven by the aforementioned factors [29]. Water markets are often challenged and influenced by the long-standing institutional rules and regulations, historical agreements and colonial legacies that govern the allocation of water across users [30,31].

This is especially evident in areas experiencing population growth with limited water availability, such as the Middle East and North Africa (MENA) region, where water markets face their own unique set of challenges, primarily driven by historical water rights and geopolitical complexities. An exemplar case highlighting the allocation of water resources along the Nile River reveals the enduring influence of longstanding agreements and treaties, which historically governed the distribution of water among riparian states. Rooted in historical usage patterns, this allocation framework has ensnared countries in complexities related to water, energy, and national security stemming from disputes over equitable utilization. However, fostering sustainable cooperation along this shared waterway holds promise in addressing the challenges posed by climate change and in alleviating contemporary conflicts between Ethiopia and Egypt, as well as other nations within the region [32]. An additional well-known situation is the one concerning water rights in the Western USA, where the oldest shareholders are given priority and a "use it or lose it" rule governs the more efficient modern management practices. Another robust example of water rights is the case of the Tigris and Euphrates rivers, which flow through several countries, including Turkey, Syria, and Iraq. These countries have historically disputed their water rights and allocations, which has been a source of ongoing political tension and conflict. However, the lack of a comprehensive water-sharing agreement has led to inequitable access and water scarcity issues. The upstream country, Turkey, has constructed dams and infrastructure that allow it to control the flow of these rivers, impacting the downstream nations like Iraq and Syria. The potential benefits of water markets, which enable the reallocation of water from low-value to high-value users (thereby increasing economic efficiency) are well documented in economic research, including the concept of a water bank, which is a specific mechanism within water markets for managing and distributing water rights [33].

Water market models integrate the complex interrelationships between hydrologic and economic systems, and they reflect the regional-scale features of the hydrologic, engineering, environmental, and economic dimensions of water resources management. The idea is to operationalize economic concepts by including them at the heart of water resource management models [11,34]. These simulations have emerged as a privileged tool for conducting integrated water resources management (IWRM). They represent spatially distributed water resource systems, infrastructure, management options, and economic values in an integrated manner, in which the water allocations and management are either driven by the economic value of water or economically evaluated to provide policy insights and reveal opportunities for better management [35,36]. This research paper endeavors to investigate the optimal water management strategies for shared resources within a critical context. It achieves this by utilizing a dynamic, interactive water allocation model, even in the face of limited hydrologic data constraints.

For this purpose, a direct application considered the Medjerda River under future variations in supply and demand. The choice of the Medjerda River holds significant relevance as it is a river that traverses the international boundaries between two countries, Algeria and Tunisia, and influences nine states within Tunisia. In attempting to meet community expectations, the questions have been narrowly interpreted as follows. (1) How can water-marketing arrangements, such as water banks, provide a balancing strategy between users' satisfaction and resource sustainability? (2) How can the water-banking management mitigate the impacts of the worst-case hydrological and water demand scenarios?

Also included herein for contextual value is background material that covers the current water allocation and management in the study region. This material covers underlying data on how the Medjerda water system is managed, who makes the water allocation calls, how and why. The answers to these questions were revealed through several interviews and meetings with the main water actors in the region, and through drawing from the latest available scientific research and data reports.

2. Background on the Medjerda Water Management: Drivers and Challenges

Since 1954, Tunisia has implemented a centralized approach to managing its water resources, encompassing various aspects such as collection, storage, transfer, and allocation across sectors and regions [37]. The Ministry of Public Works (MPW), a federal ministry, bears overall responsibility for constructing dams, related structures, conveyance canals, and channels. The Ministry of Agriculture, specifically its Directorate of Studies and Hydraulic Works (DEGTH), oversees the operation, maintenance, and policy-related studies concerning water resource utilization. Furthermore, the Office for the Development of Medjerda Valley and Irrigation Public Perimeters (OMVVM-PPI) is tasked with designing, constructing, operating, and maintaining the irrigation networks, as well as with fostering agricultural development within the Medjerda Valley [38].

This centralized management approach became a particular concern in light of the region's varying rainfall and temperatures from north to south. Similar to the western Mediterranean, the majority of the rainfall in the region occurs between October and May, primarily due to the impact of extratropical weather systems from Europe and the Atlantic Ocean. The severe climate, characterized by prolonged droughts and intense heavy downpours, presents significant challenges for the centralized water management approach. These weather patterns hinder effective water absorption by the soil, leading to an increased risk of floods. This highlights the critical importance of an efficient water resources management system [39,40].

Furthermore, the geographical distribution of the water resources and consumption patterns adds complexity to the management approach. The uplands and sources of water are primarily situated in the northern and eastern portions of Tunisia. However, the coastal areas, where water consumption is highest, are located at a distance. The majority (about two-thirds) of the population is located in the low plains of the Mediterranean coast, and one-third of the manufacturing industries are situated around the capital "Tunis", with the remaining spread along the northern and southern coastline [41,42].

The northern coastal plains and valleys boast the richest and most fertile soils, supporting the cultivation of high-demand crops such as wheat, barley, tomatoes, and grapes. In this context, a "high-demand crop" refers to a type of agricultural product that is in significant and consistent demand in the market. Another fertile sector is the Cap-Bon Peninsula, which in addition to the aforementioned crops, also produces oranges [43]. To address the spatial and structural challenges, regional and inter-regional water conveyance systems are linked to a network of dams and conveyance channels [41,44]. These systems must store and transfer excess water to coastal regions that have insufficient local resources, thus mitigating the risk of significant water deficits during times of drought. Additionally, the rigid structure of the water distribution network reflects the direction and quantity of the water flow [43,45].

To further illustrate, the west–east transfer subsystem of Tunisia is organized around the Sidi Salem Reservoir (upstream), the Laroussia Diversion Dam, and the Medjerda/Cap Bon Canal (MCB Canal) (downstream). During 1996–1997, it was delivering 163 MCM from the Sidi Salem Reservoir, of which 72.6 (44.5%) were allocated to the irrigated perimeters of the lower valley and 90.4 (55.5%) were transferred to Tunis, Cap Bon, the Sahel, and Sfax. The north–south transfer subsystem extends upstream to the Sejnane and Joumine dams and downstream to the Medjerda transfer system. Sejnane serves a dual purpose similar to the Sidi Salem dam: it collects water from the Wadi Sejnane watershed and other storage reservoirs in the far north, such as Sidi El Barrak, Zerga, and Moula [46]. As is not uncommon, these systems have instrumentation and means of estimating water release and conveyance, but with limited corresponding historic records. Also, there is a lack of adequate weather stations and of sufficient geographic coverage throughout the region to provide comprehensive hydrologic datasets.

The abovementioned challenges facing water managers in North Tunisia are exacerbated by various factors. The arid and semi-arid climate prevalent in the area heightens its vulnerability to water stress, aggravating the growing demand for water. The excessive pumping for agriculture, industry, and domestic use has resulted in declining groundwater levels, saltwater intrusion in coastal areas, and land subsidence. The water quality degradation due to pollutants from agricultural runoff, industrial activities, and improper wastewater management contributes to water pollution in North Tunisia. The inefficient water management practices, including outdated irrigation techniques and water distribution systems, contribute to wastage and inefficiencies as well [10]. Addressing these challenges requires effective governance, institutional coordination, and a good management strategy, including strengthened frameworks, improved data collection and monitoring, and investments in water infrastructure.

3. The Medjerda River Basin (MRB) and Water System

As previously noted, the Medjerda River Basin (MRB) (Figure 1) is a transboundary basin with contradictory water use requirements between its upstream and downstream sectors. The river originates west in Algeria and crosses the north of Tunisia in the SW and NE directions toward the Gulf of Tunis, with an approximate length of 460 km and a drainage area of 22,000 km^2 [39]. About 20% of the Medjerda basin resides within Algeria (less than 20% of the consumption of water); the majority of the water demand comes from Tunisia, as illustrated by the average annual volume of 1000 MCM recorded at the Medjez el Bab station compared to that of nearly 130 MCM recorded at the Algerian border [39].

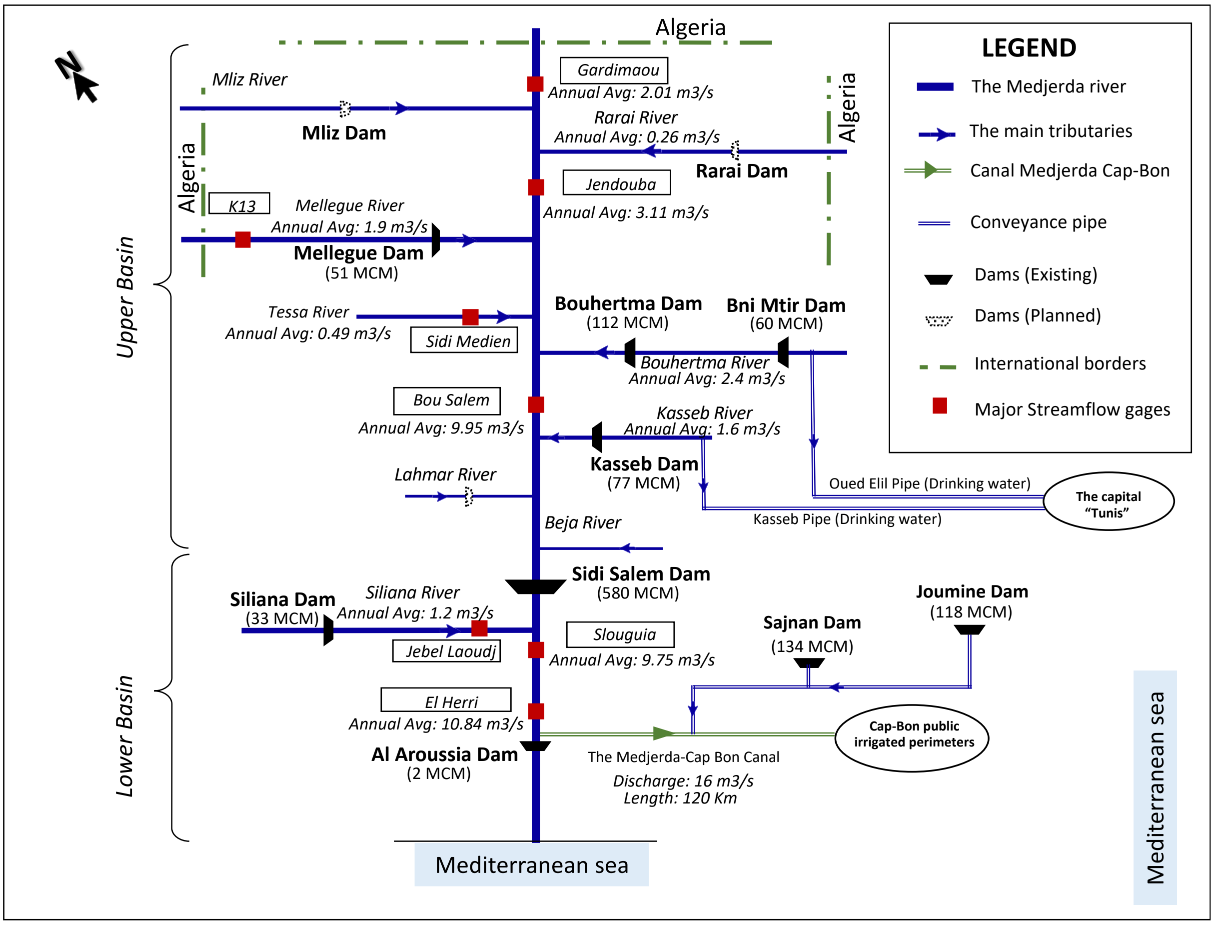

Figure 1. Representation of the Medjerda River water system use and distribution.

The MRB involves 10 Tunisian states, where Beja, Jendouba, and Kef represent the upper basin, and Tunis, Siliana, Ariana, Ben Arous, Bizerte, Nabeul, and Zaghouan represent the lower basin. The lower basin represents only about 8.5% of the surface area of Tunisia but includes about 45% of the urban population, 49% of industrial jobs, 36% of tourist capacity, and 30% of irrigable land [43]. The MRB is managed with an upstream-to-downstream approach accounting for the satisfaction of demands, releases, uses, spills, deficits, failures, and determination of the final state of the reservoirs (Figure 2). At the top of the upstream basin, the Mellegue dam was constructed on the Mellegue River and provides water to the irrigation systems in the El Kef and Kasserine states. The management strategy prioritizes water supply to the large-scale irrigation systems of El Kalaa, Tajerouine, and Sebitla, which are the biggest users of water in the region, with a total average of 20 MCM per year. Besides supplying the capital, Tunis, with drinking water via the Oued Elil and Kasseb pipes, the Bni Mtir, Bouheurtma, and Kasseb dams provide around 312 MCM of water to the large-, medium-, and small-scale irrigation systems located in the north-east states of Jendouba and Beja. Before the construction of the Sidi Salem dam, the public-irrigated perimeters of the lower basin were also irrigated via the Mellegue dam. The standing state of management is that Sidi Salem provides 160 MCM of water to irrigation users downstream, including the large-scale systems of Manouba, Ariana, and the vineyards of Grand Morneg. In addition, a supply obligation of 45 MCM per year is delivered to the Cap-Bon region to protect the existing orange trees, and an additional 171 MCM for the fruit trees and vegetable crops. This delivery is made possible via the 120 km Cap-Bon canal, which is the country's largest open channel system [43].

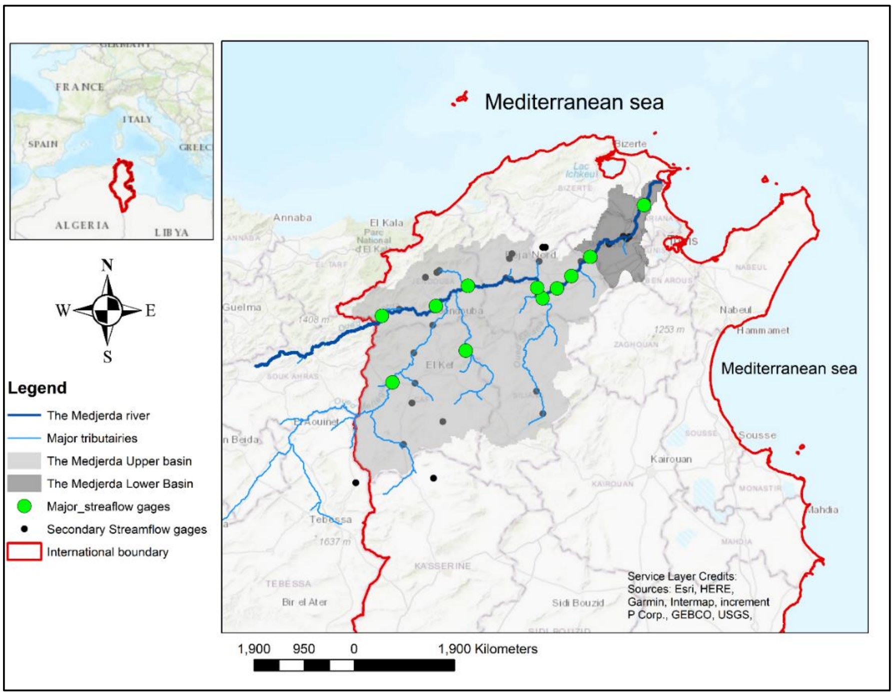

Figure 2. Delineation of the Medjerda River Basin, the Medjerda River, the main tributaries, and the major flow gages considered in this study.

These details of the Tunisian water system provide several key priorities and challenges to water managers. First, the significant spatial variability in the water demand has resulted in water being the decisive factor in spatial management, planning, and socio-economic development. Modern water management approaches would, therefore, be a beneficial and fundamental component of the Tunisian space and regional development. Secondly, major transfers are essentially made for the benefit of the most dynamic regions, particularly those which form the coastal fringe of the country. Water flow networks have thus reinforced the asymmetric character of the national territory. Thirdly, climate change and variability have exacerbated, and will continue to exacerbate, the severe economic and social issues presently confronting water management. Although some aspects of the climatic changes, such as the increased precipitation, may have some localized advantages, there will also be a range of foreseen repercussions, such as reduced water availability, heat waves, and more frequent extreme weather events. These climatic events further exacerbate the challenges faced by water managers, emphasizing the urgent need for effective water management strategies to mitigate the consequences of diminished water availability, extreme weather events, and other consequences of climate change [5].

Droughts and floods are common in the region and their frequency appears to be on the rise, a trend expected to continue with the effects of climate change. For instance, the Medjerda River Basin experienced droughts in several years, including 1994, 1995, 2000, 2001, 2008, 2010, 2011, and 2015. The most severe drought in 50 years spanned from 2008 to 2011. Additionally, the region witnessed severe floods in 1969, 1982, 1990, and 2003. In 1969, rainfall persisted continuously for 38 days in September and October, resulting in the most devastating flood in the Medjerda River Basin. The flood claimed the lives of 600 individuals, displaced 300,000 people, and caused extensive damage to 70,000 homes, as well as to streets, roads, bridges, and power supply lines.

4. The Hydro-Economic Model

4.1. The Model

This study focuses on the water use decisions that refer to the choices and actions taken by water managers, communities, governments, and other stakeholders regarding water resources management, allocation, and use. To examine the hydrologic and economic impacts of water management, we developed a dynamic, numerical, and nonlinear model that does not require extensive and detailed hydrologic records. It can simulate the water diversion, allocation, and water decisions made by heterogeneous users/parties under each scenario that considers the management, water demand, and a range of hydrologic or water availability conditions.

The heterogeneity among users arises from several sources. Tunisia's water users differ in their water rights, which specify the water source and priority. In this context, users also differ concerning the size of their land base, location, water use, and productivity of their land (in terms of the crop yields per unit of land area). The model framework of water banking requires creating an account for each party or group of users and dividing the yearly transboundary inflows, the reservoir evaporation, and the available water reservoir storage. In reality, configuring water user accounts and dividing their appropriate shares would be a negotiated and political decision that may provide an opportunity to add efficiency and possibly even add stakeholders to management. A straightforward division is to allocate each user the current balance in their water reservoir. Therefore, the concept would divide the inflows and the remaining reservoir storage among parties (expanding the pie) rather than negotiating ever-larger cutbacks and mandatory conservation targets (shrinking the pie).

The Interactive Dynamic Water Allocation concept is built on a series of tasks (Figure 3): (a) observe the reservoir inflow (either prior years or forecast), (b) appropriate inflows among the parties, (c) estimate each party's share of the reservoir evaporation proportional to their account balance, and (d) calculate each party's available water as their beginning of year account balance plus a share of inflow minus a share of evaporation. Next, (e) parties decide, based on their respective water amounts and motivations, the volume they will sell or if they wish to purchase additional volume, and then (f) the parties will decide the consumptive use or conservation/storage, (g) calculate an end-of-year account balance and (h) transfer the balance to the beginning of the next year.

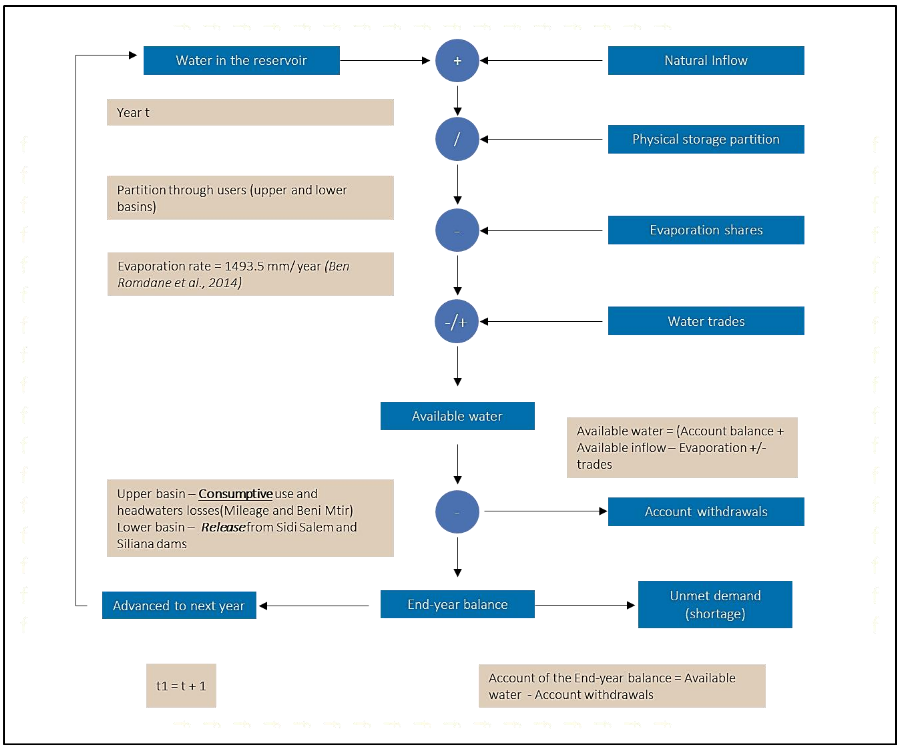

Figure 3. Diagram of the model; where: (+) symbolizes addition; (−) s substruction; and (/) division [47].

No Water Trade Management Option

A water manager should reflect on how to optimize the amount of water that has to remain in the end-of-year account balance π, which is calculated according to the rule:

$$\underset{u,s,i}{Max}\,\pi = \sum_{u,i} B_{ui} + I_i - E_{si} - \sum_{u,s,i} w_{usi} \tag{1}$$

where $u = 1, \ldots, u$ indexes the user, $s = 1, \ldots, s$ indexes the source of water, and $i = 1, \ldots, I$ indexes the year. In Equation (1), B_{ui} is the beginning of the year (i) balance per user (u), I_i is the natural inflow to the system per year (i), W_{us} is the amount of water diverted (withdrawn) from source s and allocated to user u, and E_{si} is the yearly share of evaporation per source s. We specify evaporation as a fixed proportion of volumes every year over the simulation period and within the general setup of the model. The evaporation was calculated as the product of the evaporation rate from the reservoir and the wet surface of the water storage. However, when calibrating the model, evaporation should account for various factors, including the change in the wet surface area of water storage, temperature, wind, etc. As a result, this approach illustrates an opportunity for Tunisia to consider weather stations at critical locations for improved hydrologic records and forecasting.

A water manager will also decide how much water to withdraw, with the proviso that it should not exceed the amount of water that is currently in the account. This is achieved based on factors that include the size of their land, location, water consumption, and productivity of their area (in terms of the crop yields per unit of land area). Constraint (2) ensures that the total water withdrawal by each manager should not exceed the account available water that each user is permitted to divert from the source, D_{us}.

$$\sum_{u,s,i} w_{usi} \leq D_{usi} \tag{2}$$

The amount of water remaining in the account of each party is determined by adding the balance at the beginning of the year to the yearly share of the natural inflow I, minus the portion of annual evaporation for each party E. Constraint (3) limits the water manager to not having a negative end-of-year balance account.

$$\sum_{u,s,i} \pi_{usi} > 0 \tag{3}$$

Drought reduces the surface water availability, W_{us}, which results in allocating the available water to the most prioritized water right, which means that the permanent irrigated crops (i.e., olive and citrus trees) are going to be awarded first their full or partial water entitlement. Constraint (4) limits the minimum amount of water that should be withdrawn from the sources, which should respond to the water requirements for permanent crops R_u.

$$\sum_{u,s,i} w_{usi} \leq R_u \tag{4}$$

As long as a user u account's available water $\sum_{u,s,i} (D_{usi})$ exceeds the total water requirement downstream $wr_{ui,}$ the user is awarded the full right entitlement of selling or saving for next year whatever is left over after allocating the downstream needs. If the water requirement $wr_{ui,}$ exceeds $\sum_{u,s,i} (D_{usi})$, the user will then only be able to purchase water to cover the deficit in his account, with the selling option being restricted.

In this model, we assumed that water managers are operating under a range of future uncertainties, which implies that they cannot anticipate the severity of any event, such as drought, flood, and high demand, or whether the water right(s) will be curtailed in each management scenario or not. The present research is based on scenario analysis since it can be a powerful illustrative and planning tool for managers facing deep uncertainties and varying stakeholder concerns. Uncertainty is prevalent in both economic and hydrologic systems and is, therefore, a potential element in this Interactive Dynamic Water Allocation concept. The natural inflow, reservoir sedimentation, and future demand, in particular, constitute the most important sources of uncertainty for users and managers that are considered in this study. The reservoir sedimentation uncertainty and other complexities were abstracted from the analysis due to a lack of data.

One source of dynamics is that the model focuses on water managers' decision-making during a consistent long-term period. The model thus centers on long-run responses to changes such as the purchase or sale of water as well as to sudden events (i.e., drought, flood, or high demand).

4.2. Calibration

The model was calibrated to the Medjerda River Basin (MRB). The first step considered the 20th and early 21st centuries' historical data on the water demand and natural inflows (1997 to 2016). This set of data was the basis on which the hydrologic scenarios were constructed, as it is the most accurate and confident data in our depiction of the occurrences that have previously been recorded. The wet decade scenario was inspired by the period between 2002 and 2005, in which the records showed the highest levels of water inflows in the region (Figure 4). The dry decade scenario was inspired by the period between 2006 and 2011, in which the natural inflows recorded a 50% drop with respect to the average records (Figure 4). The model considered all the water reservoirs within the same area as one shared source (the concept of a "shared reservoir"). Therefore, the Mellegue, Bouhertma, Kasseb, and Bni Mtir dams, with a total active storage of 333 Mm^3, were assumed to be one unique source providing water to the upper Medjerda basin, while the Sidi Salem, Siliana, and Al-Aroussia dams, with a total active storage of 582 Mm^3, were managed as one unique source providing water to the lower Medjerda basin and the Cap-Bon Medjerda Canal. This reflects the management of a single system with multiple reservoirs; however, if desired, additional resolution could be added to the model to consider individual reservoirs. The second phase of the calibration required creating an account for each party and dividing the yearly inflow, the reservoir evaporation, and the available water reservoir storage. Although the system is quite complex, it is clear that three main users can be considered in the partition: the upper basin, the lower basin, and the Cap-Bon region, knowing that the model treats water companies and irrigation districts as an individual decision-maker. It is, therefore, more appropriate to aggregate across irrigators, districts, and canal companies than to separately model each party, although the current model could consider individual parties and additional complexity. The third step was to calculate the shares of evaporation proportionally to the account balance, i.e., the product of the average evaporation rate from the reservoirs (1493.5 mm/year) and the wet surface of the water storage [47]. Then, the evaporation was simulated as a constant fraction each year, and the model and scenarios were designed to account for its temporal and spatial variation, so as to mitigate uncertainties and manage the limitations imposed by the data constraint.

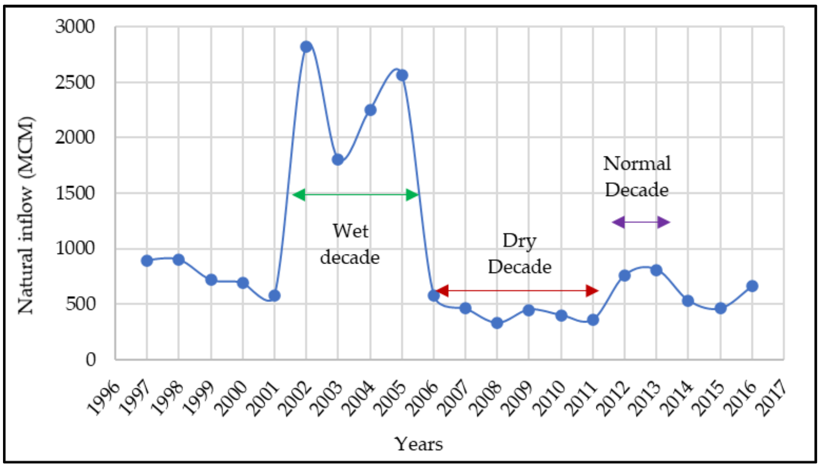

Figure 4. Historical natural inflow in the Medjerda River (1997–2016) (Slouguia station).

4.3. Scenario Analysis: Exploring the Interplay of Climate, Management, and Demand in Water Allocations

In the present study, we explored a comprehensive set of scenarios encompassing various climatic, management, and demand conditions to assess the water allocations. Two management strategies were examined: no water trade and the water-banking technique. Additionally, three demand scenarios were considered, representing steady, high, and low water demand conditions. Furthermore, we incorporated three hydrologic scenarios, including dry, normal, and wet conditions (Figure 5). By considering this combination of scenarios, we accounted for the serial correlation in weather patterns and demand fluctuations, enabling more robust and realistic water allocation assessments.

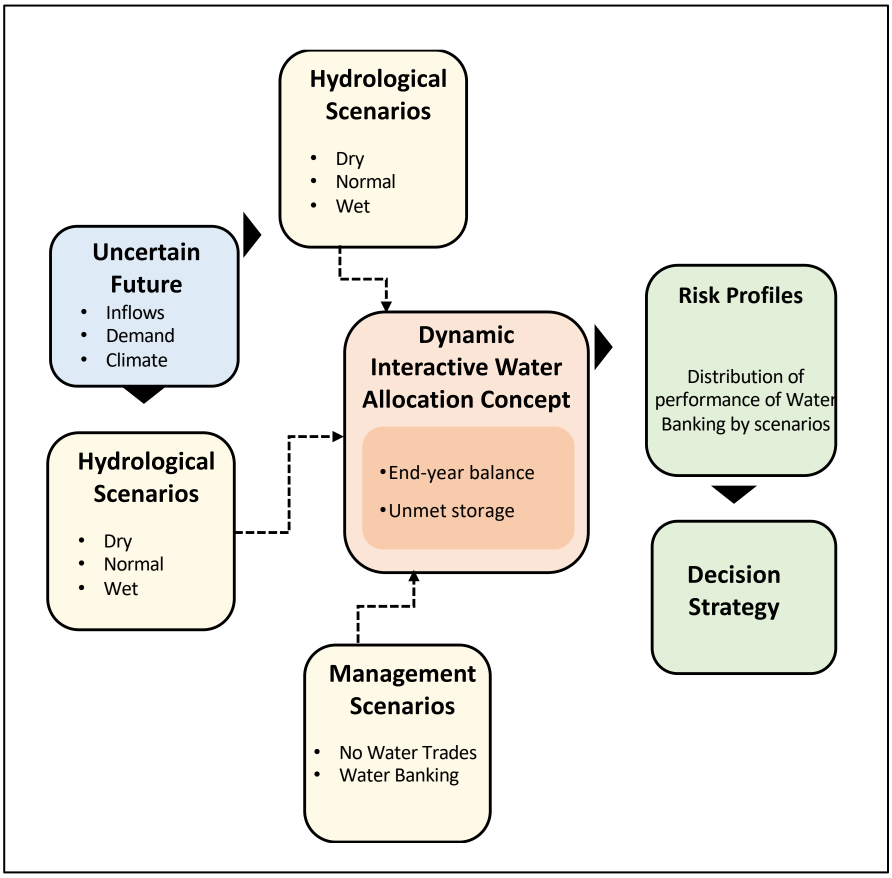

Figure 5. Explanatory schematic.

It is important to note that the institutional rules governing water allocations across users were not applied in these scenarios. Instead, this study focused on a single institutional scenario where the surface water and groundwater were managed separately (a non-conjunctive system). As such, the investigation primarily centered on surface water management. By employing this diverse range of scenarios, our study provides valuable insights into how different factors, such as climate, management approaches, and demand patterns, influence water allocations. The findings from these simulations will contribute to more informed decision-making and the formulation of effective water resource management strategies to ensure sustainable and equitable water allocation practices.

First, the simulation of the current situation as the baseline serves as a crucial reference point in the scenario analysis. By replicating a no-drought condition with current water demands and water release data obtained from Medjerda water managers, the baseline scenario provides a snapshot of the existing water allocation and management practices in the region. This baseline helps establish a benchmark against other scenarios, allowing for a clearer understanding of the impacts of different factors on the water allocations.

Additionally, simulating the current management strategy, which prioritizes the lower basin and the Medjerda canal over the upper basin with headwaters, provides valuable insights into the existing water management approach and its implications for various regions.

Second, in Scenarios 1 and 2, the simulation attempts to replicate the dry decade experienced during the period of 2006 to 2011, using an average of 550 MCM (million cubic meters) of natural inflow over a 10-year period. In the first scenario, a management strategy of no water trades (NWTs) is assumed, meaning that there are no water transfers between different regions. Secondly, water banking (WB) is incorporated as a management strategy, allowing users to voluntarily save their excess water or sell it to other users. Simulating a dry decade with a low water demand is of utmost importance as it allows the assessment of the impacts of prolonged water scarcity and drought conditions on the water management system, highlighting regions vulnerable to water shortages. Understanding the consequences of extended periods of low water availability for agriculture and public consumption is vital for planning, setting realistic water allocation targets, and developing strategies to cope with water scarcity challenges.

Third, in Scenarios 3 and 4, the simulation attempts to replicate the wet decade experienced during the period of 2002 to 2005, using an average of 1150 MCM (million cubic meters) of natural inflow over a 10-year period. The management strategy assumed in Scenario 3 is no water trades (NWTs), while water banking (WB) is incorporated in Scenario 4. Simulating a wet decade with a high water demand in the scenario analysis serves multiple critical purposes. Firstly, it stress tests the water management system, revealing its robustness and resilience under increased water demands during periods of high water availability. The derived information will help decision-makers identify vulnerabilities and limitations for improved planning. Secondly, it allows for better long-term planning and resource allocation.

Finally, in Scenarios 5 and 6, the simulation aims to replicate a normal decade inspired by the period of 2012 and 2013, with the inclusion of two successive dry years during the fifth and sixth years. The average inflow during these dry years is set at 480 MCM (million cubic meters), based on the natural inflow experienced in the dry years of 2006 and 2011, over a 10-year period. Once again, no water trades (NWTs) is assumed in Scenario 5, while Water Banking (WB) is incorporated in Scenario 6 as a management strategy. By simulating a normal decade with two successive dry years, the analysis provides insights into the impacts of sustained drought conditions on the water management system and allows for the examination of the system's performance under the most challenging and stressful conditions, revealing vulnerabilities that may not be evident in less severe scenarios. Comparing the results of the scenarios with different management strategies (NWTs and WB) allows for the evaluation of the effectiveness of water banking in mitigating the impacts of drought and ensuring a more resilient water supply in the face of the challenging hydrological conditions.

5. Results and Discussion

The model defines how much water is available in the end-of-year balance and how much water should be allocated to users in each period based on the current state variables. The allocations will, in general, vary over time and depend on the realization of the uncertain conditions. The end-of-year balances illustrate how, for the complex water systems of Tunisia, the model can provide value to water managers as they meet demands despite diverse challenges.

To evaluate the vulnerability of current and future operational policies and management strategies, seven scenarios were explored, and the findings are presented below.

5.1. Scenario 0—Baseline

The baseline scenario (Figure 6) simulates a no-drought condition, incorporating current water demands and water release data obtained from Medjerda water managers. Additionally, the scenario replicates the current management strategy, which prioritizes water allocation to the lower basin and the Medjerda canal over the upper basin with headwaters. The simulation reveals that users in the upper basin are at risk of facing water curtailment within 7 years, as the cumulative volume of unmet storage reaches ~221 MCM. Consequently, approximately 29,368 hectares of irrigated lands are left unserved, leading to a reduction in irrigation activities and productivity. These outcomes align with the provisions of the Priority Action Programs of the National Irrigation Plans (PAPNIPs) for the Medjerda River Basin, which have directed significant governmental investments and support toward irrigation development and management in the lower basin and the Cap-Bon region, covering around 32,800 and 6000 hectares, respectively, with a focus on protecting citrus trees. Conversely, the upper basin has received comparatively less attention, as reported by the Ministry of Agriculture, with 20% of equipped irrigated areas remaining unexploited (ref: 2019 annual report [38]) and most irrigated lands performing below their potential. These simulations indicate that the model effectively replicates the current situation, reflecting the current disparities in the water allocation and irrigation management in the Medjerda River Basin.

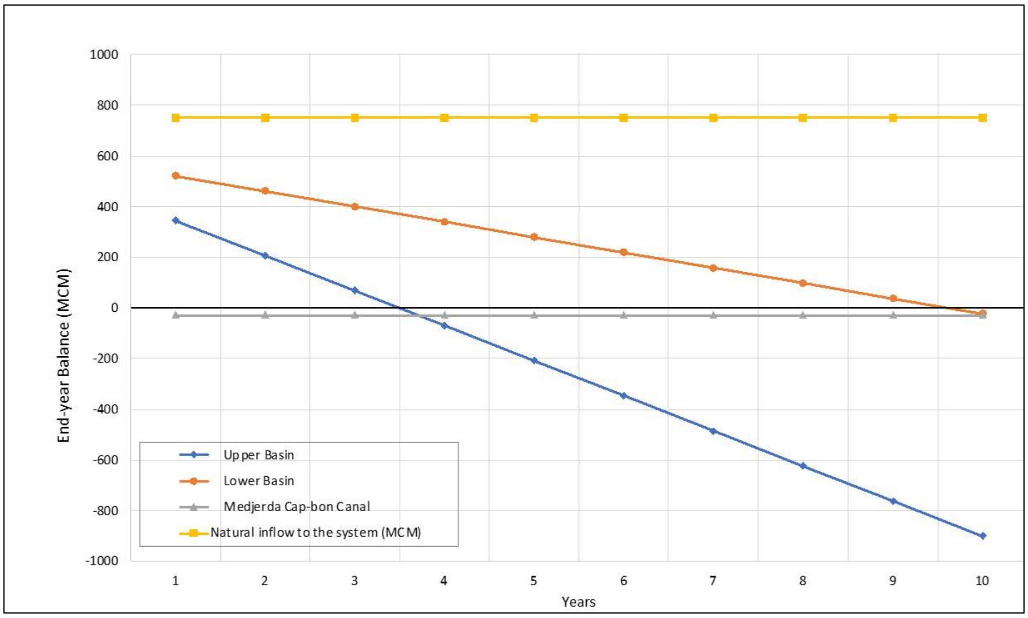

Figure 6. Baseline no-drought scenario that reproduces the current water allocation strategy.

5.2. Scenarios 1–6

The results of Scenario 1 show that the upper basin will experience water curtailment during the fifth year of the simulation period, with a negative account accumulation of −1139.62 MCM by the end of the tenth year. The Cap-Bon region, which is subject to a fixed number of supplies, experiences a negative end-of-year balance of −85 MCM during the tenth year. These significant depletions of water resources in the upper basin and Cap-Bon regions, attributed to drought conditions, can lead to adverse effects on agricultural productivity with implications for food production, local economies, and the livelihoods of farmers in the regions. On the other hand, the lower basin does not show a reduction in its end-of-year account balance over the 10-year period and registers an average of 348 MCM. This is because the current water development policies do not impose any usage restrictions on the lower basin, indicating that the region has sufficient water supply to meet its demands, even during drought conditions.

To address these water scarcity issues, it is crucial to draw from the lessons learned during the 2006–2011 drought period. Mitigation strategies and policy recommendations can help enhance water resource management and resilience. Water banking, which involves strategically reallocating water from low-value to high-value users, might have a crucial role in diversifying water sources and ensuring a more reliable water supply in regions prone to drought.

In contrast, the results of Scenario 2, which incorporated water banking, show how this management technique improves the availability of water resources for all the users. The upper basin and Cap-Bon users exhibit a reduction of their negative accounts from −1139.62 and −85 MCM as in first scenario to −250.13 and −24 MCM in the second scenario (Figure 7b). This reduction directs a more balanced and equitable distribution of water resources and demonstrates the positive impact of water banking over water availability.

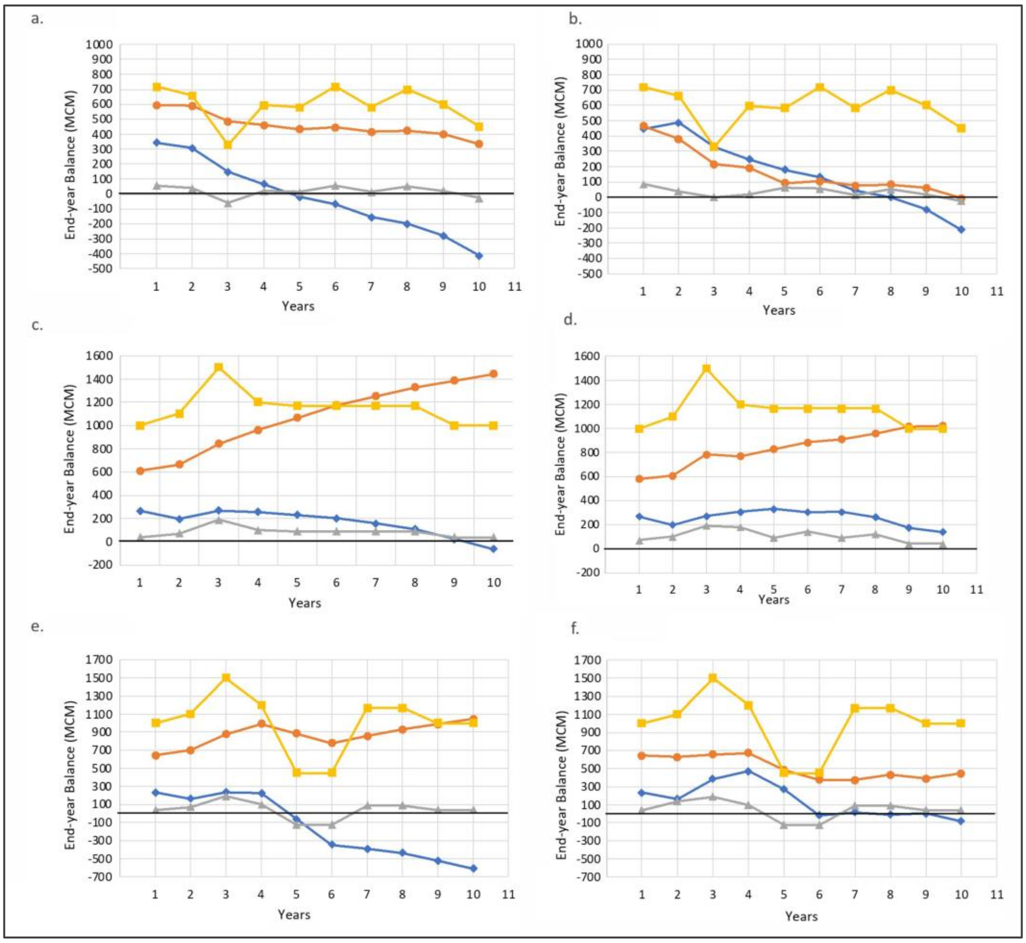

Figure 7. End-of-year balance for each scenario: (**a**) Scenario 1; (**b**) Scenario 2; (**c**) Scenario 3; (**d**) Scenario 4; (**e**) Scenario 5; and (**f**) Scenario 6.

In Scenarios 3 and 4 (Figure 7c,d), the wet decade experienced between 2002 and 2005 is replicated, assigning an average natural inflow of 1150 MCM (million cubic meters) over a 10-year period. The simulation results of a wet decade with a high water demand in Scenario 3 provide valuable insights into the dynamics of water allocation and management in different regions of the Medjerda Basin. Despite the abundance of water, the upper basin is projected to experience a negative end-of-year account in the ninth year (−50 MCM). This indicates that the water demand in the upper basin outstrips the available water supply, leading to potential water shortages and unmet needs. The reasons for this imbalance could be multifaceted, including increased agricultural and industrial activities or population growth, coupled with inadequate water management practices in the upper basin. In contrast, the lower basin and Cap-Bon regions show resilience in the face of a high water demand, as they do not face water shortages during the wet decade. This resilience could be attributed to their larger water storage capacity or to the water allocation policy. The water-banking technique again proves to be a promising solution that empowers users in the upper basin, allowing them to save or sell excess water. It contributes to a more flexible water system and ensures a more equitable distribution of the resource. As a result, the negative end-of-year account balance for the upper basin turns positive, indicating a successful mitigation of water scarcity. This demonstrates the effectiveness of the water-banking strategy in optimizing water allocation and meeting water demands during a wet decade with high demand. The results underscore the importance of implementing efficient water management practices to ensure sustainable water supply and resilience in the face of varying hydrological and demand conditions.

Simulating a normal decade, interrupted by two successive dry years inspired by the period between 2012 and 2013, along with a high demand, provides valuable insights into the water allocation dynamics and the impact of management strategies. In Scenario 5, during the first dry year (fifth year of the simulation), the upper user is expected to face a negative end-of-year account, indicating water scarcity and potential water curtailment. By the end of the simulation period, both the upper basin and the Cap-Bon regions have accumulated significant negative end-of-year accounts of −1375.00 MCM and −200 MCM, respectively, suggesting water shortages and challenges in meeting water demands during the two successive dry years. These negative accounts are substantially enhanced in Scenario 6, which introduces water banking, allowing users to actively manage their water accounts and providing flexibility to save or sell excess water during different segments of the simulation period. This strategic approach has a transformative effect on the upper basin and the Cap-Bon regions, bringing their end-of-year accounts closer to a positive balance. Specifically, for the upper basin, the negative end-of-year account is significantly reduced to −50 MCM, while the Cap-Bon region's account improves to −150 MCM.

The findings highlight the effectiveness of water banking in mitigating water scarcity challenges during dry periods with high water demand. Water banking empowers users to dynamically manage their water resources, thereby boosting the water allocation efficiency and promoting a more equitable distribution. Ultimately, this strengthens the resilience of both the upper basin and the Cap-Bon regions.

These results underscore the importance of implementing innovative and flexible water management strategies to effectively address water scarcity issues, even during challenging periods of drought and high demand.

5.3. Decision Analysis: Risk Profiles

The decision analysis estimates the cost of water shortages based on the hydro-economic model to evaluate the seven scenarios over a ten-year management period. For instance, a monetary penalty for shortages does not currently exist in Tunisia. However, the cost of water shortages that will be brought to the users' community (farmers) illustrates the magnitude of the expected economic damages. The severity of water shortage can therefore be interpreted as the water manager's degree of risk aversion to climate conditions and water supply fluctuations. Certainly, incorporating the distinction between small- and large-scale farmers is crucial when addressing the socio-economic impacts of severe climate conditions, particularly considering the varying scales and geographical distributions observed in the study area. For instance, small farmers are predominantly situated in the upper basin and partially in the lower basin, such as in the Manouba schemes. In contrast, big farmers are typically located in the lower basin and the Cap-Bon region. By acknowledging these socio-economic disparities and geographical distributions, we should recognize the differential impact that water shortages may have on different farmer groups. Small farmers often have limited resources and rely on rain-fed agriculture, and consequently, they will face heightened vulnerability to water scarcity. Their agricultural practices, typically less mechanized and reliant on natural rainfall, render them more susceptible to the adverse effects of water shortages. On the other hand, big farmers, situated in areas with better access to irrigation systems and potentially larger financial reserves, will have greater capacity to mitigate the impacts of water scarcity. Their operations, often more extensive and commercially oriented, may exhibit varying degrees of resilience to fluctuating water availability. The expected shortage cost is calculated in the present research using the following function:

$$E\ [\text{Shortage}Cost_i] = [Penalty \times WaterShortage_i] \tag{5}$$

where *E* denotes the expected value; *i* is the choice scenario; Shortage*Cost* is the total cost of the shortage incurred in the selected scenario over the planning period; *WaterShortage* is the volume of unmet water estimated from the end-of-year balance of the model, also interpreted as the water supply vulnerability; and *Penalty* is a cost incurred by the decision-makers for each MCM of water shortage during the year of the shortage. In this research, we referred to the water productivity in Tunisia (USD 9.3 per cubic meter), which is the total constant 2015 USD GDP per cubic meter of total freshwater withdrawal [48] (World Bank, 2022 [49]).

Figure 8 summarizes and graphically illustrates with boxplots the decision analysis results for the cumulative water shortage costs of each scenario. These plots show the distribution of the cost and water supply risk faced because of the different management strategies under different climatic conditions.

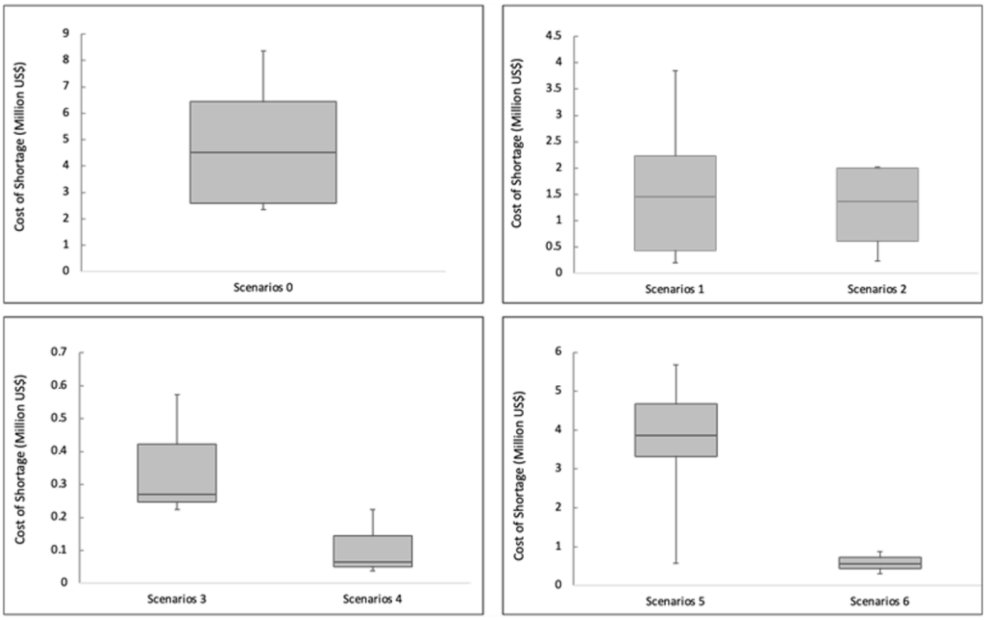

Figure 8. Decision analysis visualizing the water shortage risks according to different scenarios.

Figure 8 shows the distribution analysis in Scenario 1 (NWT), which reveals a positively skewed pattern, evidenced by a median that is situated closer to the upper quartile (USD 1.5 million) and a longer whisker on the top end of the box (skewed right). This skewness indicates a higher frequency of highly valued scores, with most of the shortage cost falling around USD 4 million. In contrast, Scenario 2 (WB) presents a distribution with a negative skew, suggesting more variation among the smaller values that tend to fall below USD 0.5 million. This negative skewness indicates that in Scenario 2, there is greater diversity in the smaller shortage cost values, with some instances of lower costs below the median. The comparison of these distribution characteristics highlights the impact of the different management strategies (NWT and WB) on the cost of water shortages. Scenario 1 (NWT) tends to have higher shortage costs clustered around a specific value, while Scenario 2 (WB) shows a wider range of shortage costs with more variability among the lower values. Such insights gleaned from the distribution analysis are instrumental in informing decision-makers about the potential financial risks and variations associated with different water management strategies, guiding them toward adopting measures that effectively mitigate economic losses and ensure sustainable water allocation.

In Scenario 3 (NWT), the distribution analysis reveals a positively skewed pattern, as evidenced by the median's proximity to the first quartile at approximately USD 0.3 million and a whisker that extends closer to the maximum score of around USD 0.6 million. This skewness suggests the higher frequency of the fourth quartile, which ranges from USD 0.4 to 0.6 million. In other words, Scenario 3 shows a concentration of shortage costs in the higher range, with most instances falling within the upper quartile. On the other hand, Scenario 4 (WB), incorporating the water-banking option, also exhibits a positively skewed distribution. However, in this case, the median is situated closer to the first quartile, at USD 0.1 million, while the whisker extends toward the maximum score of USD 0.2 million. This indicates that the distribution in Scenario 4 is more compact around the lower range, with a higher frequency of lower shortage costs falling between USD 0.1 and 0.2 million. Despite the similar positive skewness, the difference in the positioning of the median and whisker in Scenario 4 suggests a higher concentration of lower shortage costs compared to Scenario 3. These findings from the distribution analysis offer crucial insights into the impact of adopting the water-banking (WB) strategy in managing shortage costs.

In both Scenario 5 (NWT) and Scenario 6 (WB), the distribution analysis demonstrates a normal distribution pattern, as indicated by the similarity of the whiskers on both sides of the boxes. These scenarios reveal medians that are closely positioned to the interquartile range, with values around USD 4 million and USD 0.5 million, respectively. In Scenario 5 (NWT), which does not include the water-banking technique, the median shortage cost remains relatively stable at USD 4 million, indicating consistent and expected costs during the normal decade. However, in Scenario 6 (WB), where the water-banking option is introduced, the median shortage cost reduces significantly to USD 0.5 million. This implies that the water-banking strategy effectively offsets shortage costs and mitigates profit loss during the normal decade, even when facing two successive dry years.

The simulation of the decision analysis by calculating the estimates of the cost of water shortages across the seven scenarios over a ten-year management period showcases the water manager's degree of risk aversion to climate conditions and water supply availability. By understanding the potential economic consequences of different scenarios, water managers can make more informed decisions and prioritize innovative water management strategies to ensure optimal water allocation and utilization. The importance of adopting innovative water management strategies, such as water banking, is underscored by the simulation's results. Regions prone to droughts or experiencing increasing water demand due to population growth and economic development can benefit significantly from these adaptive approaches. Climate change has intensified the challenges of water scarcity and unpredictability, making it even more crucial to implement forward-thinking strategies like water banking. The findings highlight water banking's ability to provide flexibility in managing water accounts and facilitating water exchanges between users, which can play a crucial role in mitigating water shortages during challenging times.

These findings are at the very core of the Sustainable Development Goals (SDGs 6 and 13) that address water use efficiency and water stress and integrate climate change measures into national policies, strategies, and planning. First, this targets the SDG indicator number 6.4 Horizon 2030, which aims to substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity. This work explicitly tracks progress toward the SDG target 6.4.1, which monitors the change in water-use efficiency over time, measured as the ratio of the USD value added to the volume of water used. Second, this targets the SDG indicator number 6.5 Horizon 2030, which aims to implement integrated water resources management at all levels, including through transboundary cooperation as appropriate. Third, this targets the SDG indicator number 6.6 Horizon 2030, which aims to protect and restore water-related ecosystems, including wetlands, rivers, aquifers, and lakes. Fourth, this targets SDG indicator 13.2, which integrates climate change measures into national policies, strategies, and planning. In particular, SDG target number 13.2.1 involves several countries with nationally determined contributions to set long-term strategies, national adaptation plans, and adaptation communications.

Given the multiple dimensions of this study and the model capabilities, it is appropriate to also illustrate the limitations of this work. First, the information gaps in Tunisia. However, a lack of data is not uncommon in many water systems, such as a lack of hydrologic data to characterize flow regimes, natural flows, and an understanding of current management strategy. Indeed, insufficient information can be problematic in conducting a thorough and more detailed study. This is worsened when dealing with developing countries where data scarcity is a serious issue. However, it is worth noting that our model's capabilities were designed to precisely address these types of data gaps, potentially offering an opportunity to improve water resource management in regions with data scarcity. Second, the present work addressed the main statistical uncertainties, while other dimensions of uncertainty such as the location of uncertainty during a decision-making process, as well as structural and observational uncertainties, are not addressed. Third, it is important to recognize that scenario analysis is not explicitly probabilistic, although the choice of certain values for the released volumes does assign some implicit probability to the outcomes of this analysis.

Future opportunities are to be considered to improve and extend the approach of water banking as a management strategy to conserve water resources. It is important to focus on the seasonal water balance and to include the entire summer/winter water cycle within the hydro-economic model. Particular attention should also be paid to the governance aspects to understand and deal with the issues of multi-functionality in water use and distribution, improving water network efficiency, avoiding water losses, and optimizing the water storage potential. Finally, centralized water management in Tunisia always involves government arbitration. The shift toward decentralized system management or maybe a hybrid management system is a gradual process that should be built over the years. Further research should delve into innovative concepts, such as crafting a revitalized water strategy reorganization plan that spans from the national to the local level. This plan involves a socio-economic "reconstruction" of water management, which, although it may present short-term socio-economic and environmental challenges, harbors substantial potential for long-term efficacy. The Tunisian government could revise its current integrated drought management strategy into a more formal integrated drought management policy. This was previously recommended by the United Nations (UN) Food and Agricultural Organization (FAO), the World Meteorological Organization (WMO), and other international organizations. Taking these actions will help Tunisia reduce the contingent liability from drought and achieve greater and more sustainable results for farmers and the national economy.

6. Conclusions

The adverse impacts of climate change, particularly droughts and floods, are translated into a contingent liability for the community of users, notably farmers, who rely on water availability. This study explored water resource management aspects by specifically dealing with water storage and water allocation challenges through an innovative water management solution that considers the impacts of climate change. This study mainly focused on water decisions made by water managers and sometimes by heterogeneous users/parties under a range of hydrological, water demand, and management scenarios. We developed a dynamic interactive model to address the challenge of allocating scarce surface water among competing users, while ensuring the sustainability of the natural resource. We introduced a new management method based on the annual water balance over a run period of 10 years and developed a set of scenarios where the management options included no water trade and water banking; the water demand conditions encompassed a combination of the three levels of steady, low, and high; and the hydrological scenarios considered dry, normal, and wet conditions. To examine the hydrological and economic impacts of water management, we calculated the estimates of the cost of water shortages that will be brought to users (farmers) to illustrate the magnitude of the expected economic damages based on the economic model. Scenarios 1 and 2 simulated dry conditions and low demand, but they assumed the different management conditions of no water trade (NWT) and the water banking option (WB). The results of the shortage cost showed that the banking technique can alleviate the cost of shortage from USD 1.5 million to USD 0.5 million. Similarly, Scenarios 5 and 6 simulated different conditions of drought by including two successive dry years and a high demand, but they assumed the different management conditions of no water trade (NWT) and the water banking option (WB). The estimates of the cost of water shortages showed that the banking technique can alleviate the cost of shortage from USD 4 million to USD 0.5 million. This study mainly proved that allowing banking across sources along with management–administration and drought scenarios introduces flexibility in water exchange that improves the producer welfare outcomes. The findings of this research align with the Sustainable Development Goals (SDGs), specifically SDG 6 and 13, which focus on water use efficiency and water stress and integrating climate change measures into national policies. The water-banking technique emerges as a valuable tool for enhancing long-term water resource availability by optimizing management and allocation, conserving natural water storage systems, and improving equitable distribution.

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