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Enhancing Water Management and Disaster Resilience under Extreme Events via Integrated Multi-Dam Operations and Inter-Basin Transfers

Case Study SPIK Water Production System Beni Amrane-Hamiz-Keddara Algiers

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I, Safia ZENAGUI, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all the information, material and results from the other works presented here have been fully cited and referenced in accordance with academic rules and ethics.

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This thesis represents the original scholarly contribution of the candidate, developed under our supervision and guidance. It has been prepared in accordance with the academic standards required by our institution and is submitted for examination with our full endorsement as the candidate's appointed University Supervisors.

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DEDICATION

To my little Lyna, gone too soon never forgotten ….

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ACRONYMES

AEP: Drinking Water Supply

AGIRE: Nationale Agency for Integrated Water Resources Management

ANBT: National Agency for Dams and Transfers

ANRH: National Agency for Water Resources

DRE: Water Resources Directorate

DSS: Decision Support Systems

DZD: Algerian Dinar

GDP: Gross domestic product

HEC-ResSim: Hydrologic Engineering Center – Reservoir System Simulation

IBTs: Inter-basin water transfers

IPCC: Intergovernmental Panel on Climate Change

IWRM: Integrated Water Resources Management

MAO: Mostaganem-Arzew-Oran

MCM: million cubic meters

ONID: National Office of irrigation and Drainage

ONM: National Meteorological Office

PSO: Particle swarm optimization

RN05: National Road 05

SEAAL: Algiers Water and Sanitation Company

SEI: Stockholm Environment Institute

SDEM: Sesalination Plant

SPIK: Production system Isser-Keddara

SWOT: Strengths, weaknesses, opportunities, and threats

USD: United States Dollar

WEAP: Water evaluation and planning

RRV: Reliability, Resiliency, and Vulnerability

SAA: Securing Water Supply - Algiers

Abstract

This study investigates the operational dynamics and coordination mechanisms among the interconnected reservoirs of the SPIK system in Algiers, Algeria, namely, Keddara, Hamiz, and Beni Amrane, which are critical for securing the drinking water supply through interbasin transfers. This research explores how extreme hydrological events, such as floods and droughts, impact reservoir performance and highlights the importance of integrated, resilient management strategies. An integrated approach combined hydrological modeling (HEC-ResSim and WEAP) with quantitative data gathered through structured questionnaires targeting dams operators to improve institutional collaboration, enhance real-time data sharing, and integrate predictive tools. The questionnaire results provided insight into operational challenges, coordination gaps, and institutional readiness in handling extreme events. Simulations via HEC-ResSim revealed inconsistencies in coordination and highlighted the importance of prerelease strategies for flood mitigation. During 2012 flood event, release-based scenarios showed a 30% reduction in peak flow attenuation, while scenarios focused on transfer operations demonstrated an even greater reduction, achieving 45% peak flow attenuation. During the drought period, the performance of the SPIK system showed a reliability of 31%, which improved to 50% using demand-based optimization allocation. Which emphasized the importance of demand-based water allocation in conserving water for drought periods. Recommendations are proposed regarding developing a clear protocol for flood control among the system and a clear contingency plan for drought periods. Suggestions for implementing data sharing dashboards or online platforms and DSS tools such as HEC-ResSim and WEAP can enhance coordination and reservoir operation within the system to ensure water security and build system resilience.

Keywords: Multireservoir operation, Interbasin transfer, SPIK, HEC-ResSim, WEAP, Extreme events, Water supply resilience, Reservoir coordination, Decision support system (DSS)

1. Introduction

I.1 Background

Algeria faces significant challenges in managing its water resources, exacerbated by climate variability and inefficient infrastructure. The renewable water resources in the country have experienced a gradual decline, dropping from 784.5 m^3/capita/year in 1971 to 266.1 m^3 per capita in 2020 (World Bank, 2020). This decline is worsened by temporal rainfall variability, characterized by seasonal fluctuations and interannual variations. In Algiers, the capital city, over 50% of the water supply depends on surface water sources (Aoudia, 2014), making it vulnerable to fluctuations. Dams, the primary infrastructure for storing and distributing water, are essential for managing surface water in a region. However, these structures face significant challenges, particularly sedimentation, which has substantially reduced reservoir capacity with silting rates in Algeria's 57 major dams of 45 million cubic meters, translating to a 0.65% reduction in capacity each year (Remini B., 2017). Additionally, dam evaporation losses are significant, with an average annual loss of 250 million cubic meters, equivalent to 6.5% of their maximum capacity (Remini B., 2017).

In addition to these issues, Algeria has experienced severe droughts, particularly in the northern regions. Since 1881, the country has faced two major drought periods, one from 1943 to 1948 and the other starting in 1977 (Loayza, 2012). These droughts significantly impact water resources, which are unevenly distributed across the country. In response to water supply challenges, Algeria has turned to nonconventional water policies, including the widespread use of desalination plants. However, despite their desalination efforts, Algiers faces persistent water challenges due to climate variability, population growth, and inefficient water distribution systems.

Reservoirs and dams are crucial in regulating water flow, ensuring sufficient water is available for irrigation, hydropower generation, and urban water supply (Yazdi & Moridi, 2017). However, dam operation has become increasingly complex due to changing climate patterns, population growth, and rising water demand across various sectors. In February 2024, an incident in Ammal, south of Boumerdès, highlighted the importance of coordinated dam operations. Following heavy rains, the Oued Isser River threatens to flood the region, and the Beni Amrane dam must release water quickly to avoid disaster. However, the release of water was delayed because of inefficiencies in the coordination between dam operators and authorities

(Kebbabi, 2024). This incident highlights the crucial need for better coordination in dam management, particularly in response to changing hydrological conditions such as floods and droughts. Effective management is essential for optimizing water release schedules, minimizing adverse impacts, and ensuring water security.

Interbasin water transfers (IBTs) have also become central to addressing water scarcity in Algeria. These transfers, including the Système de Production Isser-Keddara (SPIK) and TAKSEBT, are vital for improving the water supply in regions facing water stress. However, IBTs face challenges such as water loss—12% in transfers and 30% in distribution (Benblidia, 2011). While IBTs provide a solution to water shortages, they must be carefully assessed for their environmental and ecological impacts, particularly regarding the sustainability of water resources across upstream and downstream areas (Shiklomanov, 2000; Yevjevich, 2001; Liu, 2002).

Effective reservoir and dam management is crucial for optimizing water allocation, particularly as climate change and increasing water demand place additional pressure on water resources. Dams regulate water flow and serve as vital infrastructure for flood control and drought mitigation, ensuring that water resources are managed efficiently across seasons. Despite these challenges, reservoir operation is central to Algeria’s water security strategy. The coordination between dam operators and other stakeholders must be enhanced to manage the complex dynamics of water availability, demand, and environmental considerations.

I.2 Problem statement

Algeria grapples with the pressing issue of water scarcity, a challenge exacerbated by many factors, including population growth, climate change, and inefficient water management practices. With predominantly arid to semiarid climates, Algeria's water resources are inherently limited, further strained by erratic rainfall patterns and prolonged droughts.

The water supply system in Algiers, the capital of Algeria, is intricately dependent on three types of sources: surface water, groundwater, and desalination. Notably, surface water sourced from various dams contributes to 51% of the total water supply in Algiers (Aoudia, 2014). However, this reliance renders the system particularly susceptible to fluctuations in rainfall patterns, increasing its vulnerability. Three primary transfer systems play pivotal roles in sustaining the city's water needs: SPIK (Système de Production Isser-Keddara), which has been operational since 1987, ensures a steady water flow. SAA (Sécurisation de l’Alimentation en eau d’Alger), established in 2002, reinforces the water supply network.

Additionally, TAKSEBT, which was introduced in 2008, is another vital component of the complex web of water distribution infrastructure (Naimi-Ait-Aoudia, 2017).

The SPIK system comprises three primary dams, two of which (Beni Amrane and Hamiz) collectively supplying the Keddara dam, which is responsible for a significant portion of Algiers' water supply. However, the operation and management of this dam complex pose multifaceted challenges, particularly concerning its response to extreme events such as flooding or drought. The interconnected nature of this dam system, coupled with interbasin transfers, introduces complexities in its operation and coordination, especially across different administrative and institutional boundaries. To ensure effective responses and optimal water resource utilization, coordinating various agencies and institutions responsible for managing these dams is crucial, particularly during extreme conditions.

In this context, it is imperative to analyze the current operational practices of dams and assess their resilience and efficiency during extreme events. Additionally, understanding the coordination mechanisms among diverse stakeholders in managing dam complexes under such conditions is essential for enhancing overall performance and resilience.

I.3 Research Objective

I.3.1 Main objective:

This research aims to assess the coordinated operation of multiple dams during interbasin water transfer and alternative water management in Algiers. Additionally, it aims to conduct a stakeholder analysis during extreme events to improve a region's water supply security and resilience.

I.3.2 Specific objectives:

- To analyze the current operation and diversion strategies employed for the multi-dam system Hamis, Beni Amrane, and Keddara, with a focus on the water supply performance and disaster resilience in response to extreme hydrological events such as floods, droughts.
- To understand the coordination and management practices between dam operators and other stakeholders under normal and extreme conditions.
- To evaluate the impact of operational strategies of dam complex on water availability and disaster resilience under extreme events using reservoir operation model HEC-ResSim and illustrate the role of decision support system tools.

- To assess the Performance of SPIK supply system under optimistic and pessimistic scenarios using WEAP model
- To and provide actionable insights for policymakers to inform decision-making processes and improve the overall management of water resources in Algiers.

I.4 RESEARCH QUESTIONS AND THE WORKING HYPOTHESIS

I.4.1 Questions

- What are the current operation and diversion strategies used in the multi-dam system of Hamis, Beni Amrane, and Keddara?
- How is coordination managed between dam operators and other water stakeholders in the multi-dam system of Hamis, Beni Amrane, and Keddara?
- How do the operational strategies and interbasin transfers of the multi-dam system impact water availability and disaster resilience under both normal and extreme hydrological conditions?
- How do the operational strategies of the dam complex and interbasin transfers impact water availability and disaster resilience during extreme events, and what role do decision support system tools, play in enhancing reservoir system performance?
- How does the SPIK supply system perform under different water demand and supply scenarios (optimistic and pessimistic)?
- What actionable insights can be derived from the analysis of the multi-dam system to inform policymaking for better water resource management in Algiers?

I.4.2 Working Hypothesis

The operational strategies of the Hamis, Beni Amrane, and Keddara dams, in combination with effective stakeholder coordination, significantly impact water availability and disaster resilience in the catchment area during extreme hydrological events. It is hypothesized that integrating HEC-ResSim and WEAP modeling and a comprehensive reservois coordination assessment will provide actionable insights that can enhance water supply system performance and disaster resilience, and inform infrastructure decisions, leading to more sustainable water resource management in Algiers.

I.5 RELEVANCE OF THE STUDY

The significance of this study lies in its contribution to enhancing water security and disaster resilience in the Algiers region by addressing the critical need for integrated and adaptive management of interconnected reservoirs. As climate change intensifies the frequency and severity of extreme hydrological events such as floods and droughts, the coordinated operation of multi-dam systems becomes increasingly vital. This research identifies operational inefficiencies and institutional coordination gaps within the SPIK system and provides practical insights through hydrological modeling and stakeholder engagement. This study bridges the gap between technical planning and real-world implementation by incorporating field-based data from dam operators and water managers. These findings can inform policy reforms, improve emergency response mechanisms, and support the development of decision-support systems tailored to Algeria's specific water management context. Ultimately, this work offers a replicable framework for other regions facing similar challenges in managing complex water infrastructure under climate stress.

I.6 Scope of the study

The scope of this study is centered on the SPIK water production system in Algiers, Algeria, which comprises the interconnected reservoirs of Keddara, Hamiz, and Beni Amrane. Geographically, the research covers the hydraulic infrastructure spanning the Isser, Hamiz, and Keddara subbasins, focusing on their role in ensuring water supply security for the capital region. This study addresses the operation and coordination of multi-reservoir systems, particularly under conditions of hydrological extremes such as floods and droughts, and evaluates the effectiveness of interbasin water transfer. The research integrates hydrological modeling via HEC-ResSim and WEAP with qualitative insights from structured questionnaires administered to dam operators and water management stakeholders. These tools assess current operational performance, coordination challenges, and institutional preparedness. This study also considers temporal aspects by simulating reservoir behavior under historical conditions and simulated scenarios that influence climate variability.

2. Literature Review

2.1 Overview of Water Challenges in Algeria

Algeria faces significant water resource challenges driven primarily by climatic, demographic, and management factors. The country's geographic diversity, which spans from the Mediterranean coastline to the Sahara Desert, exacerbates the complexity of water availability and management. These challenges are compounded by climate change, population growth, pollution, and inefficient water governance.

Algeria faces significant water resource challenges driven primarily by climatic, demographic, and management factors. The country's geographic diversity, which spans from the Mediterranean coastline to the Sahara Desert, exacerbates the complexity of water availability and management. These challenges are compounded by climate change, population growth, pollution, and inefficient water governance. Algeria is among the most water-scarce countries globally, with per capita water availability declining from 784.5 m^3 in 1971 to only 266.1 m^3 in 2020 (World Bank, 2020). This scarcity is exacerbated by decreasing rainfall, prolonged droughts, and desertification, particularly in the western regions. Algeria's complex topography also presents physical barriers that further hinder equitable water distribution. The increasing need for integrated water management strategies, including interconnected reservoir systems and interbasin transfers, is critical to mitigating supply shortages and adapting to climate variability (GIZ report, 2016).

Water demand has increased fourfold over the past four decades, with urbanized northern regions, where 90% of the population resides, experiencing the most pressure. The over-extraction of coastal aquifers to meet domestic, agricultural, industrial, and tourism demands has resulted in seawater intrusion and pollution (Haouchine et al., 2015). Groundwater overexploitation in northern China has reached alarming levels, with an extraction rate of 91.15% of total groundwater reserves (Slaimi, 2014). The Setif Province exemplifies this challenge, where growing domestic water demand exceeds the available supply despite infrastructure improvements (Hadj & Chenni, 2020). The situation is further aggravated by climatic factors that intensify water scarcity, highlighting the urgent need for integrated solutions to address population growth and environmental constraints.

The expansion of urbanization and industrial activities has significantly increased wastewater discharge into natural water bodies, surpassing the self-purification capacity of rivers. Major rivers such as Tafna, Macta, Cheliff, Sébaou, Soummam, and Seybouse suffer from severe pollution due to untreated industrial and municipal wastewater (GIZ report, 2016). Additionally, microbial contamination of shallow aquifers has been observed due to leaks from sewage systems and septic tanks. The annual volume of wastewater discharged into the environment is estimated at approximately 1,200 million cubic meters. This pollution degrades water quality and threatens human health and agricultural productivity.

In the Algerian context, climate change exacerbates aridity and seriously threatens sensitive environments, particularly high plateaus and steppe areas. The intense and persistent drought observed over the past 20 years, characterized by a 10% deficit in rainfall, has harmed river flow patterns, the filling levels of dam reservoirs, and the replenishment of underground aquifers, leading to severe consequences for the country's overall socioeconomic activities. Preliminary quantitative estimates, although still approximate, suggest a potential reduction in river flow rates by an average of 15% by 2030. The total volume of surface water resources that can be harnessed (via dams), estimated at 6.4 billion m3 per year, may be reduced to a maximum of 5.5 billion m3 per year (Benblidia, 2010).

Algeria’s water management approach prioritizes resource mobilization over efficiently utilizing existing supplies. The current policy framework focuses more on increasing the water supply than optimizing usage through demand-side management (Benblidia, 2010). Despite efforts to develop hydraulic infrastructure, pollution control and efficient allocation remain secondary concerns. A more comprehensive water management strategy is needed, integrating demand management policies, improved distribution efficiency, and sustainable governance structures to ensure long-term water security.

2.2 Water Resource Challenges in Algiers

In Algiers, the capital city of Algeria, the reliance on surface water exceeds 50% (Aoudia, 2014), making it susceptible to significant fluctuations. Dams are the primary infrastructure for storing and supplying water from surface sources to Algiers. However, these vital structures face numerous challenges, with silting or sedimentation ranking among the most pressing concerns for water management in Algeria (Remini B. &., 2009). Assessments conducted in 2006 reveal alarming statistics: the annual silting rate of the 57 major Algerian dams amounts to 45 million cubic meters (Remini B. , 2017). This situation translates to an annual reduction in capacity of 0.65%. Evaporation poses another significant issue, with measurements conducted across 39 major dams indicating an average annual loss of 250 Mm^3, equivalent to

6.5% of their maximum capacity (Remini B. , 2017). Uncontrolled water seepage through banks and foundations is estimated to reach 40 Mm^3 annually for 22 large dams.

Algiers relies on three main interbasin transfers for their water supply system: SPIK (Système de Production Isser-Keddara), which has been operational since 1987 and ensures steady water flow. Inaugurated in 2008, TAKSEBT is another vital component of the complex web of water distribution infrastructure. However, the loss rates in these transfers are approximately 12% (Benblidia, 2011) and 30% in distribution networks, according to SEEAL, the company in charge of water management in Algiers.

Various forms of drought (meteorological, hydrological, and agricultural) have also been observed in Algeria, particularly in the northern part. Since 1881, the country has experienced two major drought periods: the first from 1943 to 1948, which significantly impacted crops and livestock, and the second, which has been observed since 1977 (Loayza, 2012). Droughts have negatively impacted water resources and are limited and unevenly distributed across the country. In response to water supply challenges and severe periods of drought, the government adopted a nonconventional alternative policy. The implementation of water desalination has emerged as a strategic solution to meet the drinking water needs of Algiers. Many desalination plants have been established for this purpose. The primary sources of desalinated water for Algiers are two plants located in Hamma and Fouka, which have been operational since 2008 and 2011. The Hamma plant has a theoretical daily production capacity of 200,000 m^3, whereas the Fouka plant can produce up to 120,000 m^3 per day, with only half of its output allocated to Algiers, owing to its location outside the city’s boundaries. The SDEM system, comprising five mono-bloc stations, also supplements the supply with an additional capacity of up to 12,500 m^3 per day (Aoudia, 2014).

Despite efforts to improve the water supply through desalination and supplementary systems, Algiers continues to face persistent water challenges. Factors such as climate variability, population growth, inefficient water distribution, and aging infrastructure exacerbate the ongoing strain on water resources in the region. These challenges underscore the critical need for effective management strategies to safeguard Algiers' water supply and infrastructure.

2.3 Reservoir operation and interbasin transfers

2.3.1 Contribution of reservoirs to water security

Reservoirs are essential for securing water resources, particularly in regions vulnerable to droughts and variable water availability. For example, the Sterkfontein Dam in South Africa has been a crucial component of the Vaal River system, supporting the water security of a socioeconomically important region for over four decades (Muller, 2016). The dam demonstrates how effective storage systems can help mitigate the impacts of droughts by regulating the water supply during dry periods. Furthermore, the design and operation of such dams are continually adapted to meet emerging challenges, such as climate change and population growth, highlighting the evolving role of reservoirs in securing water resources. In line with this, the construction of reservoirs globally has been linked to increasing demand for water, food, and energy, as demonstrated in a study by (Insannul et al., 2019), which emphasized the interrelationship between water consumption, energy consumption, and dam construction. Dams, therefore, ensure a steady water supply and contribute to energy production food security through irrigation, and flood control.

Developing extensive reservoir networks has improved water security in regions historically plagued by droughts, such as Northeast Brazil. (Neto. et al., 2024) analyzed the evolution of water security in the Upper Jaguaribe Basin, where a dense network of reservoirs has mitigated the impact of meteorological droughts. However, their study also highlights that while larger reservoirs provide greater security, smaller reservoirs play a crucial role in distributing water resources, emphasizing the need for a balanced approach to reservoir capacity. In China, the joint operation of local reservoirs with the Three Gorges Reservoir has proven effective in mitigating the impacts of hydrological droughts in Poyang Lake, further illustrating how reservoir management can reduce drought severity and improve water availability (Xianghu, 2023). These examples underscore reservoirs' importance in managing water resources, supporting regional water security, and adapting to changing environmental conditions.

In Algeria, following the severe 2001-2002 hydrological year, when water reserves reached their lowest recorded levels, the country redefined its approach to water management. As a response, Algeria’s water policy has concentrated on increasing water mobilization efforts and facilitating interregional transfers to mitigate shortages in regions with limited water availability (Ouamane et al., 2022).

In line with this effort, large-scale dam construction and water transfer projects were initiated as part of the 2000-2004 plan and continued through the 2015-2019 plan. During this period (2000--2019), thirty large dams were built, collectively providing a total capacity of 4.14 billion m^3. Since 1962, more than 60 dams with capacities exceeding 10 million m^3 each have been constructed, increasing Algeria's storage capacity from 1 billion m^3 in 1962 to over 9 billion m^3 by 2019—nine times the capacity available in 1962 (Ouamane et al., 2022). (Ouamane, Sekkour, & Athmani, 2022) The national strategy also involves interconnecting storage facilities into regional systems. For example, the Keddara, Taksebt, and Koudiat Acerdoune dams are part of a network that supplies water to Algiers, Boumerdes, and Tizi-Ouzou, and the Mao (Mostaganem-Arzew-Oran) network connects dams to supply water to the urban centers of northwestern Oran (Mozas & Ghosn, 2013).

2.3.2 Reservoir operation and stakeholder coordination

Effective coordination in multi-reservoir systems is essential to modern water management, particularly as communities face evolving risks associated with floods and droughts. Large-scale hydrological models, critical for forecasting and managing these risks, are increasingly refined to incorporate reservoir interactions' complexities. In response to the challenges posed by these extreme events, hydrological models need to operate at high resolutions, both spatially and temporally. As highlighted by (Bierkens, 2015), managing and forecasting flood and drought risks requires models that can accurately represent these events and their interactions across large geographic scales. In the case of multiple reservoirs within a basin, these models do not treat the reservoirs as a single entity but instead account for their contributions to system dynamics (Shin et al., 2019). This nuanced approach ensures that each reservoir's distinctive roles, such as their individual capacities, release schedules, and responses to changing conditions, are accurately modeled.

A significant area of focus is incorporating human management practices in hydrological models, especially given their influence on water distribution across multiple reservoirs. (Wu et al., 2024) (Chen et al., 2024) underscore the need for better representations of how human activities—particularly mismanagement—impact water systems, including basins. Despite advances, many state-of-the-art models yield mixed results when modeling extremes such as monthly releases (Zaherpour et al., 2018). As a result, considerable scope remains for research to determine which aspects of human water management are most crucial for inclusion in multi-reservoir models. One such aspect, frequently recognized as a cornerstone of effective water management, is the coordination between reservoirs ((Wang et al., 2018); (Jeuland et al., 2014); (Ajudiya et al., 2024)).

Coordination in multi-reservoir systems involves the interaction between different reservoirs within a basin, where decisions made at one reservoir, such as the timing and volume of water release, are influenced by the conditions in other reservoirs. This concept is crucial because reservoirs are rarely isolated; the actions of one reservoir, particularly in terms of water release, can significantly affect water availability in other parts of the system. However, as (Rougé et al., 2021) and other studies have noted, this interconnected behavior has not yet been fully integrated into release rules in large-scale hydrological models. The challenge lies in implementing effective coordination strategies that account for the dynamic nature of water systems. For example, (Masaki et al., 2017) reported discrepancies between different models when attempting to represent flows across large reservoir cascades, illustrating the difficulty of ensuring model accuracy when multiple reservoirs are involved. Similarly, as highlighted by (Chen et al., 2024) in their study, reservoir storage dynamics are shaped by a complex interplay of natural and anthropogenic factors, which vary significantly across regions. In Northeast China and Northwest China, natural inflow variations have emerged as key drivers that strongly influence both interannual and intra-annual fluctuations in reservoir storage. Moreover, human interventions, such as outflow regulation for flood control, hydropower generation, and ice jam prevention, predominantly dictated storage dynamics in the Yellow River Basin, Eastern China, and Southwest China. This intricate balance highlights reservoir management challenges' regional specificity and multifaceted nature.

In practice, managing a multi-reservoir system involves a combination of technical, political, and economic considerations. (Adigüzel & Coşkunoğlu, 1984) discuss how decision-making processes in interconnected reservoir systems often span multiple jurisdictions and administrative boundaries. The complexity of coordinating these systems lies in the competing demands for water and the interdependencies between reservoirs. Water release from one reservoir can affect the water availability downstream, necessitating a careful balance of water distribution to ensure that the needs of all users are met while maintaining system reliability. This is particularly challenging in regions where water resources are limited or subject to fluctuating climatic conditions.

Given these complexities, an adaptive management approach has become a promising solution. Adaptive management, which involves iterative decision-making and continuous adjustments on the basis of system feedback, is crucial for responding to the dynamic nature of multireservoir systems (Adigüzel & Coşkunoğlu, 1984). As water inflows, demand patterns, and environmental conditions change, the coordination strategies must be regularly updated to reflect new information and conditions. This approach, which combines real-time data with long-term planning, can improve system performance and resilience to extreme events such as floods and droughts.

Coordinating multiple reservoirs is a critical aspect of water resource management, particularly in the context of growing risks related to climate change. While advances in hydrological modeling have improved the representation of individual reservoir dynamics, challenges remain in integrating the interactions between reservoirs. Future research must focus on developing models that better capture these interdependencies and refining coordination strategies that account for human management and environmental variability. Only through continuous adaptation and better integration of these factors can multi-reservoir systems effectively meet the water management needs of diverse stakeholders while maintaining ecological and operational sustainability.

2.3.3 Challenges of Coordinated Reservoir Operations: Insights from Global Incidents to Local Incidents

Reservoirs are vital in developing and managing integrated water resources (Zhou, 2015). Dams are crucial in regulating water flow and storing water for various purposes, such as irrigation, hydropower generation, and urban water supply (Yazdi & Moridi, 2017). Understanding dam operation and coordination is paramount for ensuring efficient water management and mitigating potential risks. The coordinated operations of multiple reservoirs aim to optimize water storage, flow, and release across interconnected systems. Operators can minimize conflicts and maximize the system's overall performance by considering the reservoirs as part of a larger system rather than managing each independently (Shen et al., 2018). However, dam operation and management have become increasingly challenging due to changing climate patterns, population growth, increasing water demand from various sectors, environmental concerns, regulatory requirements, and competing interests for water allocation (Larson, 2013) (Ghashghaie, 2014). In February 2024 (Kebbabi, 2024), it was reported that a disaster was narrowly averted in Ammal, south of Boumerdès, due to heavy rains that hit the region. Five houses in the village of Thinoukline were flooded, and approximately thirty others were isolated because of the rising waters of the Oued Isser, one of the largest rivers in the region. The phenomenon took many by surprise, and opening two wall valves of the Beni Amrane dam, located 6 km away, was necessary to avert the danger. However, this was not a simple operation. The dam employees had to wait for authorization from higher authority, which acted on instructions from its supervisory authority following an alert issued by the Wilaya authorities. This incident highlights the operational constraints in reservoir management. The delay in opening the dam valves points to inefficiencies in the response system. Moreover, the situation was exacerbated by the accumulation of mud in the riverbed, which had not been dredged. If the river had been cleaned, the waters would not have risen to the national road RN05, nearly blocking traffic and isolating part of the village (Kebbabi, 2024). This incident emphasized that coordinated dam operations are vital for responding to changing hydrological conditions, including floods and droughts, to enhance water security and resilience, which can be achieved by fostering stakeholder collaboration and communication.

Thus, effective coordination among dam operators is essential for optimizing water release schedules, balancing conflicting demands, and minimizing adverse impacts on downstream ecosystems and communities (Annys, 2020).

2.3.4 Extreme events and their impact on reservoirs

Climate change poses a significant threat to reservoir operations worldwide, and Algeria is no exception. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events substantially affect water storage, quality, and availability in reservoirs. According to the IPCC (2021), one of the most critical impacts of climate change on reservoirs is the alteration in inflow patterns. Reduced precipitation and increased evaporation rates contribute to declining reservoir levels, leading to water shortages during dry seasons (Masson-Delmotte et al., 2021). In arid and semiarid regions such as Algeria, the decrease in annual rainfall exacerbates this problem, reducing the reliability of reservoirs for water supply, agriculture, and hydropower generation (Kundzewicz et al., 2008).

One figure of extreme events consists of a long drought, one of the most critical impacts of climate change on reservoirs. It consists of alterations in inflow patterns. Reduced precipitation and increased evaporation rates contribute to declining reservoir levels, leading to water shortages during dry seasons (Masson-Delmotte et al., 2021). Various forms of drought (meteorological, hydrological, and agricultural) are observed in Algeria, particularly in the northern part. Since 1881, the country has experienced two major drought periods: the first from 1943 to 1948, which significantly impacted crops and livestock, and the second, which has been observed since 1977 (Loayza, 2012). Droughts have negatively impacted water resources, are limited, and are unevenly distributed across the country.

Another figure of extreme events is floods. Algeria is highly exposed to natural disasters, 61% of which are floods (WorldBank, 2023). From 1965 to 2013, Algeria recorded 1,306 flood events, with 607 events resulting in human casualties, 27 of which caused more than ten casualties each. The period between 2000 and 2011 was particularly devastating, with floods causing 1,014 human mortalities, accounting for more than 77% of the total human casualties (Boutaghane, 2021). The frequency of floods in Algeria has increased in recent years, with the highest number of floods recorded in 2015 (14 floods), followed by 2018 (11 floods) and 2019 (10 floods). While this increase may not necessarily indicate greater precipitation, it can be attributed to urban expansion and settlement on the edges of wadis (Hafnaoui M.A., 2023).

These floods have resulted in significant fatalities, damage to buildings, and the loss of roads and urban infrastructure. The economic impact of floods in Algeria is substantial. Between 1954 and 2022, the estimated economic loss was $1,543.917 million (WorldBank, 2023). The Algerian government estimates that annual spending over the past 15 years to respond to floods, earthquakes, and forest fires averages approximately USD 255 million (DZD 35.14 billion), with approximately 70% allocated to floods. Disaster losses related to earthquakes, floods, and forest fires could average approximately 0.7% of the country's GDP per year, with average annual losses related to floods amounting to $178.37 million, which slows the GDP growth rate of the country (WorldBank, 2023).

Algiers, the capital city, experienced the most disastrous flood in Algeria's history on October 11, 2001, resulting in 900 human casualties, 423 injuries, and catastrophic material damage estimated to exceed US$ 300 million (Boutaghane, 2021). The floods that occurred in Algiers in 2001 and 2011 are among the ten deadliest (921 deaths) and most costly (USD 0.89 billion) hydrometeorological disasters on the African continent over the past 50 years (WorldBank, 2023).

Climate change is expected to exacerbate flood risk in Algeria. It is estimated that by 2050, Algeria could experience an approximately 41% increase in exceptional storms capable of causing floods, landslides, and significant damage. The main flood risks are concentrated in northern Algeria, where a large portion of the population and economic activity are located (WorldBank, 2023). These figures highlight the significant impact of floods on Algeria's economy and the need for effective flood mitigation strategies. Effective reservoir operation strategies and adaptive management are crucial in mitigating these risks.

2.4 Interbasin water transfer IBT:

2.4.1 Overview of IBT

Interbasin water transfer represents a significant strategy for addressing water stress and is defined as the transfer of water between geographically distinct river catchments or basins (Davies, 1992). IBTs have gained considerable attention in water resource management. The literature on IBTs underscores this approach's complexity and multifaceted nature in mitigating water scarcity. Analysis reveals that the effectiveness of IBTs is contingent upon various factors, including topography, population distribution, and intricate upstream water connections. These connections encompass a range of dynamics, such as stream flows, water withdrawals, and return flows, significantly influencing the outcomes of IBTs (Kai Duan, 2022). IBTs have historically been critical in securing freshwater supplies in regions facing water deficiencies. Studies by (Shiklomanov, 2000), (Yevjevich, 2001), and (Liu, 2002) (Kai Duan, 2022) underscore the importance of IBTs in addressing water scarcity challenges. However, the apparent solution provided by IBTs to water shortages must be carefully evaluated in light of potential environmental and ecological impacts. While IBTs may seem to offer a straightforward solution to water scarcity, extensive research, as highlighted by (Wang, 1999) (Zhuang, 2016), suggests that the environmental and ecological consequences could be significant and complex. IBTs present both opportunities and challenges in water resource management. While they offer a potential solution to water scarcity, carefully considering their environmental, ecological, and socioeconomic impacts is essential. Therefore, comprehensive evaluation and consideration of upstream and downstream implications are imperative for informed interbasin water transfer decisions.

2.4.2 Contribution of interbasin water transfer to alleviating water disparities

Improving access to and equitable sharing of water resources across regions is a key focus of the Algerian government's water policy. To address geographic disparities, a program of regional water transfers has been gradually implemented to promote fairer access to water. Major initiatives have been undertaken in the last decade under the supervision of the National Agency for Dams and Transfers (ANBT). These water transfers also align with Algeria's food security strategy, supporting regions with high agricultural potential. For example, by channeling large-scale water transfers to the wilayas of Sétif and Djelfa, the government aims to turn these areas into cereal production zones expected to meet 20% of the nation's demand by 2014 (Mozas & Ghosn, 2013).

The initiative also seeks to interconnect water resources across regional systems around major urban centers, supplying nearby towns through smaller infrastructure projects. For example, Constantine is linked to the Béni Haroun dam in Mila, whereas hydroelectric dams in the Sétif region now supply southern areas instead of generating electricity. In Algiers, the Taksebt and Koudiat Acerdoune dams are part of a transfer network reaching Tizi Ouzou, Médéa, and M'sila, and the MAO system (Mostaganem-Arzew-Oran) serves the northwestern part of the country.

A landmark project in southern Algeria is the Ain Salah-Tamanrasset water transfer from the Ain Salah aquifer (in northern Tamanrasset) to Tamanrasset city, covering a distance of over 750 km. Inaugurated in April 2011, it is among Algeria's largest hydraulic achievements over the past decade, comparable to the Beni Haroun and MAO systems. The Ain Salah-Tamanrasset transfer initially supplies 50,000 m^3/day, potentially reaching 100,000 m^3/day. The project is valued at $3 billion and includes 48 wells, two parallel pipelines, six pumping stations, two large 50,000 m^3 reservoirs, and a 100,000 m^3 demineralization station. While expected to increase economic growth, the project's environmental impact raises concerns about long-term sustainability, with fossil water usage simulations analyzed through 2040 (Mozas & Ghosn, 2013).

2.5 Multi-Reservoir Operation and the Role of Models in Decision Support Systems

The operation of multi-reservoir systems is a critical component of integrated water resource management. Reservoirs are vital in balancing the water supply, flood control, irrigation, hydropower generation, and environmental sustainability. The complexity of managing interconnected reservoirs has increased due to the dynamic nature of hydrological processes, climate variability, and competing stakeholder demands (Labadie, 2004). To address these challenges, sophisticated modeling tools such as HEC-ResSim have been developed to assist decision-making by simulating reservoir operations under varying conditions (Labadie, 2004).

Hydrological modeling is crucial for understanding and managing water resources within a watershed or river basin, particularly when dealing with interconnected reservoir systems. These models simulate the movement and distribution of water across the landscape, accounting for factors such as precipitation, runoff, infiltration, evaporation, and groundwater flow(Beven, 2006). By representing these processes, hydrological models provide insights into how reservoirs interact and how water storage and release patterns impact water availability, flood control, and overall system efficiency (Beven, 2012; Lamb, 2006). In multi-reservoir systems, hydrological models help optimize the management of water resources by forecasting water inflows, predicting reservoir behavior under varying conditions, and evaluating the effectiveness of different operational strategies (Beça et al., 2023). Such models are invaluable for supporting water management decisions, ensuring a reliable water supply, mitigating flood risks, and enhancing resilience to droughts and climate variability (Beça et al., 2023; Dash et al., 2023). Furthermore, hydrology allows for the simulation of extreme events such as floods and droughts (Lamb, 2006; Xianghu, 2023), enabling predictions under different climatic conditions. This capability aids in better preparedness and decision-making, reducing the adverse impacts of natural disasters on communities.

HEC-ResSim (Hydrologic Engineering Center – Reservoir Simulation) and WEAP (Water Evaluation and Planning System) are widely employed to simulate reservoir behavior and water demand and serve as critical decision-support tools for water resource management. By integrating these tools, water managers can comprehensively understand reservoir operation and long-term management strategies to ensure water security (SEI, 2008; USACE, 2000).

2.6 Generalized Computer Models in Decision Support Systems (DSS)

2.6.1 HEC-ResSim

The integration of computer models in decision support systems (DSSs) has revolutionized water resource management. The DSS provides an analytical framework that combines hydrological models, optimization tools, and real-time data to enhance decision-making (Şensoy et al., 2018). Several studies highlight the role of the DSS in reservoir management, and it has been widely used in conjunction with decision support systems (DSSs) to improve operational coordination among reservoirs. For example, in the Mekong Basin, a DSS that integrates HEC-ResSim with land-use models helps decision-makers better understand the effects of various operational strategies on local communities (Mccartney et al., 2011). Additionally, the combination of simulation models such as HEC-ResSim with optimization algorithms such as particle swarm optimization (PSO) has led to enhanced water allocation strategies, particularly in interbasin transfer systems (Peng et al., 2017). Furthermore, HEC-ResSim has proven effective in real-time decision-making. A study conducted in India demonstrated how HEC-ResSim, when coupled with forecasting tools, optimized reservoir release to mitigate flood risk and improve flood management in real time (Chandel et al., 2022). Generalized computer models such as HEC-ResSim remain a preferred choice because of their detailed rule-based structure and ability to handle multireservoir operations effectively (Wurbs, 2012).

2.6.2 Application of the water evaluation and planning model (WEAP)

WEAP is a system model pioneered by the Stockholm Environment Institute (SEI). As a hydrological model, it simulates the natural water balance within a basin by integrating data on precipitation, evaporation, runoff, and reservoir operation. It allows for the estimation of water availability and demand under various scenarios, enabling users to assess the impact of different water management practices. WEAP offers an integrated methodology for simulating the natural and engineered hydrological elements concerning both demands and supplies within a water system (Sieber, 2015). Recognized as an IWRM tool, the WEAP model is distinguished by its water-focused approach (Tena, 2019). The WEAP model has emerged as a versatile tool extensively employed to assess water demand and supply dynamics across diverse geographical contexts (Amisigo, 2015). (Dlamini, 2023) applied WEAP to simulate the effects of climate change on water resources and agricultural demand in Ghana and South Africa, respectively, demonstrating the model's applicability in addressing complex environmental challenges. (Mourad & Alshihabi, 2016) extended this exploration by developing five distinct future scenarios, ranging from technological advancements to regional cooperation and conflict, thereby demonstrating WEAP's capability in scenario planning. In the (Sandoval-Solis, 2022) study, WEAP was used within a regional water planning framework to evaluate the interactions between water supply and demand in the Aragvi River Basin. Rajosa (2021) (2022) employed WEAP to assess future water supply and demands in the Medjerda River Basin. Their investigation into the impact of climate change on water resources within the basin under different climatic scenarios exemplified the model's utility in climate change adaptation planning. (Gao, 2017) utilized the WEAP model to evaluate the potential impacts of development activities on local water resources in a typical arid/semiarid area in China. In regions such as Iran, WEAP has been employed to evaluate the performance of interbasin transfer projects. In one study, a simulation-optimization framework was developed via WEAP to support the Bashar-to-Zohreh interbasin water transfer project. The model helps optimize water allocation for agricultural lands in Iran's semiarid Kohgiluye and Boyer-Ahmad Provinces, achieving acceptable reliability levels for land development (Mousavi et al., 2017).

Similarly, in Turkey's Yesilirmak Basin, WEAP was used to evaluate the operational performance of reservoirs, considering different water demand scenarios. The model successfully identified areas of vulnerability and helped design operational strategies that could better meet the region's water supply needs during periods of scarcity (Pinarlika & Seleka, 2024). These studies underscore the importance of the WEAP model as a valuable tool for assessing water resource dynamics, facilitating informed decision-making via future scenarios, and addressing complex challenges such as climate change and sustainable development.

As a decision support system (DSS), WEAP goes beyond hydrological simulation to provide valuable insights into water management decision-making. For example, WEAP was used in Greece to assess the impact of short-term droughts combined with high water competition from rural and tourist activities on two multipurpose reservoirs. This DSS framework enables the simulation of future scenarios, helping policymakers better understand how the water supply might be affected by seasonal demand fluctuations and droughts (Demertzia et al., 2013). The model also facilitated the development of strategies for improving water management in a semiarid environment with limited irrigation infrastructure. In semiarid regions, WEAP is particularly valuable in scenarios involving climate change. The model has been used to simulate the impact of changing precipitation patterns and increasing water demands on regional water resources. By running multiple climate scenarios, WEAP has supported decision-makers in planning for the long-term sustainability of water resources, helping to optimize water distribution and minimize the risks of shortages (Hussain, 2023). In regions such as China's arid and semiarid areas, WEAP has been used to assess water management strategies' environmental and agricultural sustainability under climate change, integrating future water demand predictions with the available supply (Hussain, 2023).

Furthermore, the flexibility of WEAP allows it to be applied across a wide range of water management contexts, from urban areas to agricultural regions. In Nigeria, for example, WEAP was applied to analyze water allocation from Tiga Dam, addressing conflicts between agricultural and urban water demands. The model predicted future water shortages and identified strategies for growing demand, including wastewater recycling and better irrigation efficiency (Mohammed et al., 2020). Moreover, WEAP was employed in Morocco to assess water demand and supply in the Middle Draâ Valley, predicting significant reductions in available water resources due to climate change (Hussain, 2023). In Iran, a study on water resource allocation in the Bakhtegan catchment used the WEAP to evaluate the performance of a dam series, highlighting the challenges of meeting agricultural and drinking water needs during drought periods. The model provided insights into how combining surface and groundwater resources could improve water availability (Karimi & Khorshidi, 2025). Similarly, in Turkey, WEAP was applied to five reservoirs in the Yesilirmak Basin to assess operational performance via reliability, resilience, and sustainability indices.

HEC-ResSim and WEAP are powerful tools in decision support systems (DSSs) for water resource management, each offering unique strengths. HEC-ResSim stands out for its detailed rule-based structure, making it the preferred choice for complex multi-reservoir operations, particularly flood management and hydropower optimization (Wurbs, 2012). On the other hand, WEAP excels in simulating water allocation scenarios under changing conditions, integrating economic, environmental, and social factors to provide comprehensive insights for decision-making. Together, these models support informed and adaptive management, enabling policymakers to address water security challenges, mitigate risks from extreme events, and plan for climate change adaptation across diverse regions.

2.7 Previous studies on multi-reservoir operation and the application of HEC-ResSim

Numerous studies have focused on optimizing multi-reservoir operations to improve efficiency and sustainability. Traditional methods rely on rule curves and empirical approaches but advances in computational modeling have introduced simulation-based and optimization-based approaches. (Labadie, 2004) reviewed optimization techniques for multi-reservoir systems, emphasizing their role in improving operational decision-making. Many optimization models incorporate mathematical techniques such as linear programming, dynamic programming, and heuristic algorithms (Wurbs, 2012). These methods have been applied in various case studies, including the Eastern Nile Basin, where investment scenarios for different subbasins were analyzed via simulation models such as HEC-ResSim (Belachew & Mekonen, 2014). Interbasin water transfer also plays a crucial role in ensuring water security. Studies have examined interbasin transfer strategies for optimizing water allocation among interconnected reservoirs (Gu et al., 2017). In China, an interbasin water transfer system was analyzed via simulation-optimization models to determine the optimal diversion strategies, minimizing water shortages while balancing hydropower and irrigation needs (Wan et al., 2018).

HEC-ResSim, developed by the U.S. Army Corps of Engineers, is widely used for simulating reservoir operations. The model provides a flexible rule-based framework that allows users to define operating policies, constraints, and optimization scenarios (Meshkat & Klipsch, 2018). It has been successfully applied in various settings. HEC-ResSim has proven to be an effective tool for optimizing reservoir operations for various applications, including hydropower generation, flood management, and climate change adaptation. Studies have shown that HEC-ResSim can increase power production regarding hydropower and water supply. For example, in the Nyumba ya Mungu reservoir system, the model was used to simulate alternative operational strategies, which resulted in a 13% increase in power generation compared with previous strategies (Mulungu, et al., 2011).

Additionally, HEC-ResSim has been applied to flood management, such as in the Chemung River watershed, where it was used to simulate the complex bidirectional flow of a multi-reservoir system. This highlighted its ability to handle intricate hydrological interactions, improving flood management outcomes (Meshkat & Klipsch, 2018). Furthermore, HEC-ResSim has been incorporated into climate change adaptation strategies. For example, a study in Turkey integrated machine learning techniques with a model to assess the impacts of future climate scenarios on reservoir inflows and operations, predicting a potential reduction in water availability of up to 37% under severe climate conditions (Eskişehir et al., 2022). The adaptability of HEC-ResSim makes it a valuable tool for reservoir managers, enabling them to test various scenarios and adjust operations based on real-time data and long-term planning objectives (Abdelkader et al., 2023).

While numerous studies have explored multi-reservoir operation strategies and the application of decision-support models such as HEC-ResSim in various hydrological and institutional contexts worldwide, a notable gap in the literature regarding their use in the SPIK system remains. The existing body of research has focused predominantly on well-documented river basins, where long-term data availability and model integration into water governance systems are well established. In contrast, despite its strategic importance in securing a water supply for Algiers, the SPIK system has received little to no attention in the scientific literature, both in terms of hydrological modeling and operational coordination analysis. This lack of localized studies on reservoir operation and the limited application of models such as HEC-ResSim in Algeria highlight a critical knowledge gap. Addressing this void presents a valuable opportunity to advance the understanding of integrated reservoir management in data-scarce and institutionally fragmented environments. This study, therefore seeks to contribute original insights by applying HEC-ResSim to an underresearched system while simultaneously exploring the operational and institutional dynamics that shape water resource resilience in the region.

2.8 Conclusion

Despite significant advancements in reservoir operation modeling, most research has focused on flood control, with few studies addressing the complexities of multi-reservoir systems and interbasin water transfers under extreme events. Most existing works simulate single reservoir operations or multi-reservoir interactions, leaving a gap in the comprehensive study of interconnected reservoirs operating under climate-induced extremes such as prolonged droughts or extreme precipitation events. Moreover, while mathematical functions, optimization algorithms, and machine learning techniques have been extensively used in reservoir operation studies, few works have focused on utilizing existing simulation models that provide simple, practical, and user-friendly decision support for reservoir operators. Many of these advanced methods require specialized knowledge in mathematical optimization or machine learning, making them less accessible for real-world applications by reservoir managers and decision-makers.

The primary aim of reservoir operation modeling should be to provide practical and implementable decision support systems that do not require extensive expertise in specific computational fields. This gap highlights the need for research that focuses on developing and adapting simulation models such as HEC-ResSim and WEAP to handle complex reservoir networks and interbasin water transfers intuitively and user-friendly. Future studies should prioritize model design that simplifies operators' decision-making while maintaining reliability and accuracy in predicting and managing water resources under extreme conditions.

3. Research Data and Methodology

3.1 Description of the study area

3.1.1 Location

The study covers the area of the SPIK (Système de Production Isser-Keddara), which forms a critical component of the water supply infrastructure in Algiers. It is one of three primary water transfer systems in Algiers, along with SAA and Taksebt transfers. Given that surface water contributes to 51% of the total water supply in Algiers, these systems are vital to water security in the region(Ait-Aoudia & Berezowska-Azzag, 2016). SPIK encompasses a network of dams and interbasin water transfers to harness surface water resources, particularly from the Isser region to the Keddara region. It spans two basins, namely, Cotier Algerois 02a and Isser 09, which are part of the great basin Algerois-Hodna-Soumam. The system primarily comprises the Keddara, Hamiz, and Beni Amrane dams, with the Koudiet Acerdoune dam supplementing the supply during water shortages in the capital. The Keddara and Beni Amrane (through transfer) dams are exclusively dedicated to the drinking water supply (AEP). In contrast, the Hamiz Dam serves a dual purpose: providing drinking water and irrigation with a regulated water volume of one million cubic meters per year (Ait-Aoudia & Berezowska-Azzag, 2016).

3.1.2 Geographical context

The SPIK spans two basins, Cotier Algérois 02a and Isser 09, both of which are part of the great Algerois-Hodna-Soummam hydrological basin located in the North Central part of Algeria, one of Algeria's major basins with an area of 47.43 km^2 and a surface water potential of 1.69 billion cubic meters (Hamiche et al., 2015). It encompasses four primary basins: the Cotier-Algérois basin (02), which is subdivided into two smaller coastal basins, Cotier-Algérois 02a, and Cotier-Algérois 02b; Isser (09); Soummam (15); and Hodna (05), each contributing significantly to regional water supply and management strategies. The Côtiers Algérois (02a) and Isser (09) basins are particularly vital, as they serve as the primary catchment areas supporting the SPIK system (Figure 3.1).

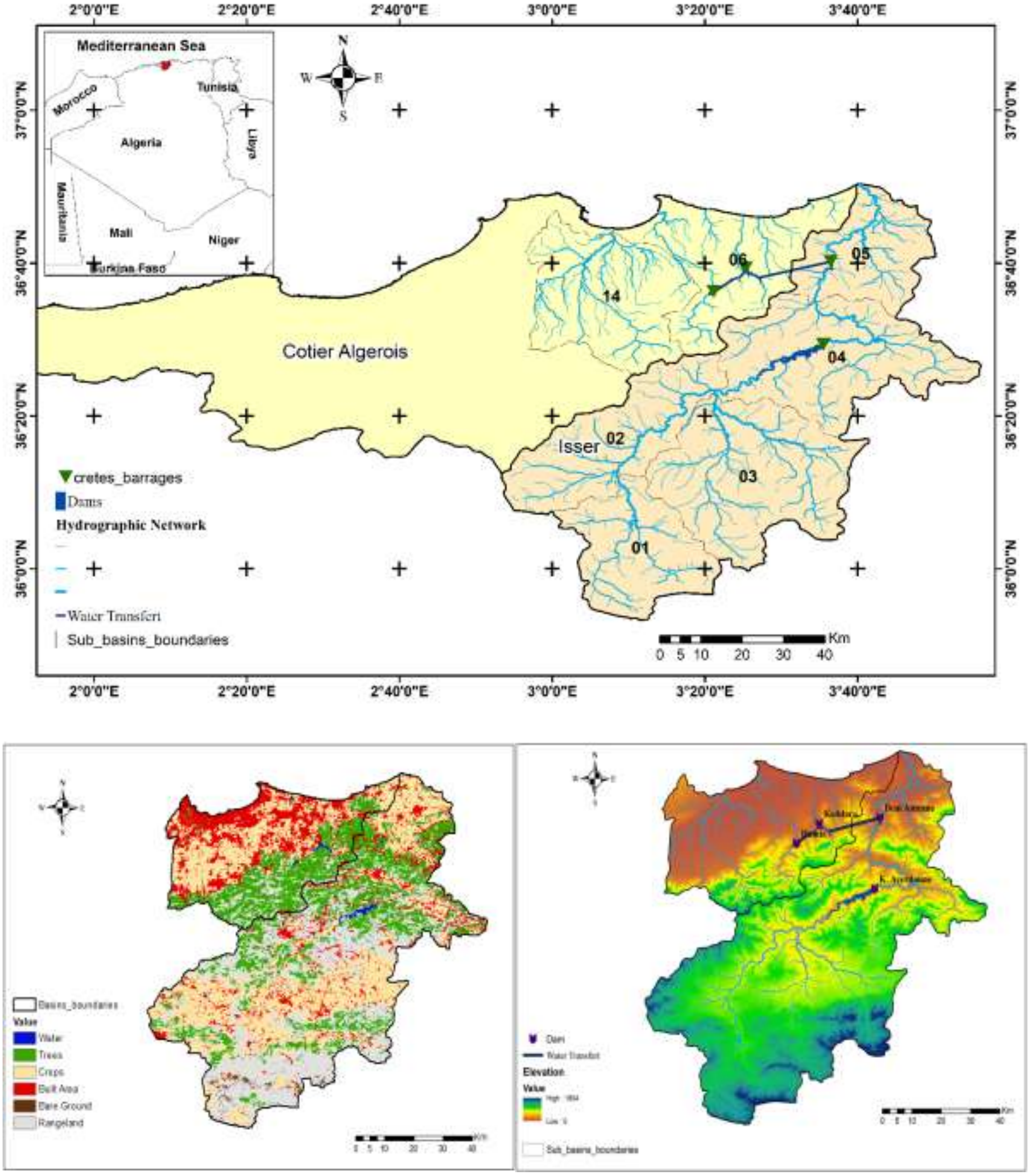

Figure 3.1: a) Spatial representation of the SPIK system and its subbasins, b) land use/land cover of the study area, and c) elevation model of the study area

Cotier-Algérois 02a

Cotier-Algérois 02a contributes significantly to the region's hydrological dynamics, with an annual water yield of 847 Hm³/year**,** representing 22.99% of the overall water contribution of the Algérois-Hodna-Soummam Basin (Benmihoub & Akli, 2020**).** It encompasses five subbasins**:** Mazafran**,** El-Harrach**,** Côtier Ouest**,** Côtier Centre**,** and Côtier Est. The basin spans 4,570 km²**,** with approximately 70% of the area covered by two main catchments: the Mazafran and El-Harrach rivers (Benmihoub & Akli, 2020). These river basins play crucial roles in the area's overall hydrology and water management.

The Keddara and Hamiz reservoirs are located in subbasin 06 of the Côtier Algerois Basin. Keddara is built on Oued Boudouaou, which is 35.2 km long and drains the Boudouaou basin. Hamiz spans Oued Arbatache. Although reservoirs are located in the same subbasin, they are not connected hydrologically and have different streams and outlets. Instead, reservoirs are linked with water transfer from Hamiz to Keddara in closed channels.

Isser 09

The Isser Basin is located in the north-central region of Algeria, with a total area of 4,149 km², representing 8.72% of the total area of the Algiers-Hodna-Soummam Basin. Concerning the geological and structural context, the Isser basin is divided into three main parts: the Upper Isser, Middle Isser, and Lower Isser. The Upper Isser features two main watercourses: the Oued Mellah and the Oued Isser. The Oued Isser is formed by the confluence of the Oued El Hammam and the Oued Mellah, which drains one-third of the basin's area. The Middle Isser is drained by three streams: Oued Djemaa in the east, Oued Bou-Hammoud in the west, and Oued Isser in the center. The Oued Isser crosses the Lower Isser along with several east and west tributaries (Hahi, n.d.) Beni Amrane is located downstream of the subbasin along the Oued Isser River (05).

3.1.3 Socioeconomic Impact of SPIK

The SPIK system is pivotal in ensuring water security and driving socio-economic development in northern Algeria. Keddara primarily supplies drinking water to Algiers and its surrounding areas, corresponding to 1 097 466 residents by providing 400 000 cubic meter per day, while fostering economic diversification through integration into inland fisheries investment initiatives. The Hamiz Dam contributes significantly by regulating Oued Hamiz flow and supporting agricultural activities in the eastern Mitidja plain with 11 million cubic meter per year during the low flow period spanning from May to September. Similarly, the Beni Amrane Dam is instrumental in meeting the drinking water needs of Greater Algiers and neighboring towns, with its transfer system providing a direct link to ensure efficient water distribution. Together, these dams underpin regional water management, safeguard livelihoods, and promote sustainable development through improved access to water for domestic, agricultural, and economic uses.

3.2 Description of the SPIK Infrastructure

3.2.1 Overview

The SPIK (Système de Production Isser-Keddara) is a critical water production and distribution system designed to supply water to Algiers and surrounding regions. It integrates three major dams—Beni Amrane, Keddara, and Hamiz. SPIK was initiated in the mid-1980s and has been operational since 1987; it was developed in response to the increasing water demands of a rapidly growing urban population and the limitations of relying solely on groundwater sources.

The interconnectedness of these reservoirs plays a critical role in meeting the region's water demands. The Hamiz and Keddara Dams are linked by a gravity-fed transfer system through an underground gallery of 3.1 km, enabling efficient water movement between the two reservoirs. On the other hand, the Beni Amrane Reservoir provides Keddara with water via a pumping system, which transfers water over 31 kilometers. The chart (Figure 3.2) below highlights the interconnection of these reservoirs and the end use of water from each reservoir.

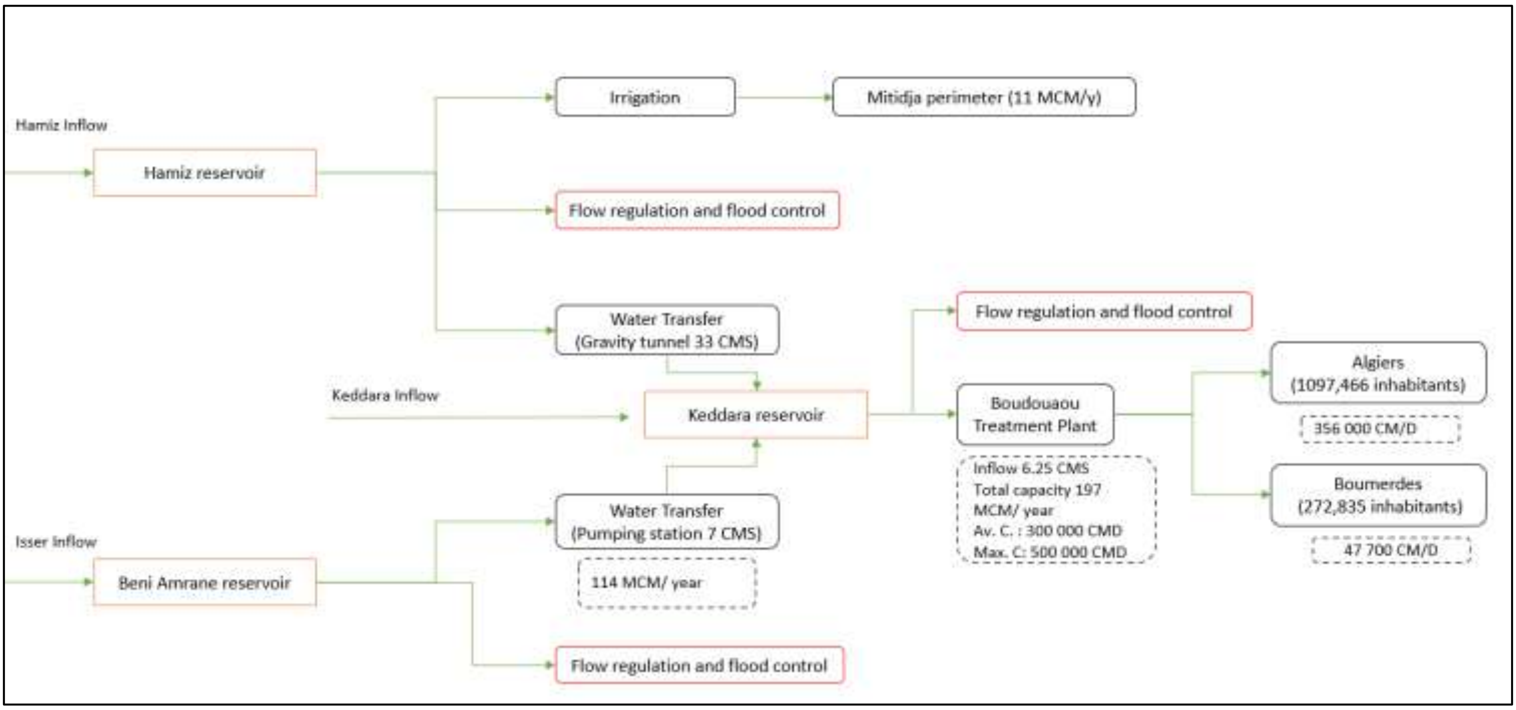

Figure 3.2: Interconnections and water transfers within the SPIK reservoir system

3.2.2 Reservoirs

The SPIK system is a network of four interconnected reservoirs, three of which, namely, Hamiz, Beni Amrane, and Koudiat Acerdoune, contribute to one main reservoir, Keddara, and supply other regions for various purposes. Table 3.1 summarizes the infrastructure information and parameters related to these reservoirs.

- **Keddara**

The Keddara Dam is located in Boumerdès Province, 8 km south of Boudouaou and 35 km east of Algiers. It is part of the Isser-Keddara water management system, which is designed to meet the drinking water needs of the Algiers metropolitan area. Its reservoir is fed by inflows from the Keddara and El Haad rivers and a transfer gallery from the Hamiz Dam.

The dam features a rock-fill embankment with a central clay core. It has a storage capacity of 145.6 hm^3 and covers an area of 5.2 km^2 at its maximum water level. Built primarily to ensure a steady drinking water supply to Algiers and its surroundings, it has recently been incorporated into activities supporting inland fish farming (ATTOU & ARAB, 2010, in ATTOU, 2014).

- **Hamiz**

Hamiz Dam is situated in Arbatache in Boumerdès Province. The dam covers a watershed area of Oued Hamiz (ex-Oued Larbatach) of 140 km^2. With a storage capacity of 15.53 million m^3 at its normal retention level, the dam is designed to regulate floods from the Hamiz River and support irrigation in the eastern Mitidja plain.

- **Beni Amrane**

The Beni Amrane Dam is located on the Oued Isser in Boumerdes Province and is part of the SPIK. The watershed covers an area of 3,710 km^2, with an average annual inflow of approximately 400 hm^3. Its primary purpose is to supply drinking water to the Greater Algiers area and towns within the Mitidja region, which is situated between Algiers and Oued Boudouaou. The dam has a storage capacity of 11.85 million m^3 at its normal retention level.

Table 3.1: Reservoir information and key parameters (ANBT Report)

Input Data	**Keddara**	**Hamiz**	**Beni-Amrane**
Location coordination			
Basin	Cotier Algerois 02a	Cotier Algerois 02a	Isser 09
Subbasin	Cotier Algerois 0206	Cotier Algerois 0206	Isser 0905

Province	Boumerdes	Algiers	Boumerdes
Construction Period	1982-1986	1979/1935*	1984-1988
1st-year Operation	1989	1979/1935*	1988
Type	Rockfill	Buttress	zone embankment with a clay core
Catchment Area (km^2)	93	140	3710
Initial Capacity Mm³	145.791	21	15.6
Height (m)	106	53	39.5
Length (m)	468	161.7	156
Source	Oued Boudouaou Hamiz Dam Beni Amrane	Oued Hamiz (Ex Oued Arbatache)	Oued Isser
Use purpose	municipality	Municipality Irrigation	Municipality
Spillway Discharge	735	750	10000
Normal Water level	145	174.10	63.5
Dead water level	77	151	54
Crest level	147.32	175	77

(Hamiche et al., 2015)

3.2.3 Water transfer

Water transfer in the SPIK system is a critical operational mechanism for optimizing the water distribution among interconnected reservoirs and ensuring a reliable supply to Algiers and surrounding regions. These transfers involve monitoring the volume, timing, and pathways of water conveyed between reservoirs (Table 3.2). The Hamiz–Keddara–Beni Amrane production system features two distinct water transfer routes. The first is a gravity-fed transfer that channels water from the Hamiz Reservoir to the Keddara Reservoir through a 3.2 km tunnel. The second transfer involves a 31.1 km pipeline with a 2-meter diameter that transports water from the Beni Amrane Reservoir to the Keddara Reservoir. This system is powered by a pumping station equipped with six pumps—four operational pumps and two standby pumps—capable of delivering a flow rate of 7 m³/s.

Table 3.2: summarizes information about these three water transfers.

Input Data	Hamiz-Keddara	Ben-Amrane-Keddara
Structure Type	Tunnel	Pipe
Conveyance type	Gravity	Pumped
pumps	/	8
Material	Concrete	steel
Length (km)	3.2	31.3
Diameter (m)	2	2
Flow capacity (m3/s)	33	7

3.3 Data collection

3.3.1 Hydrological data

For the hydrological data collection, daily inflow, rainfall, and pool evaporation data were gathered from the reservoirs, covering the period from 1990 to 2020. The inflow data represent the amount of water entering the reservoirs daily, whereas the rainfall data were obtained from onsite rain gauges at the reservoirs. Additionally, pool evaporation, which accounts for water loss due to evaporation from the reservoir surface, was recorded. These data sets are crucial for understanding the dynamics of water availability, as they directly influence the operational management of reservoirs. The data were collected daily, ensuring that temporal variations in inflows, rainfall, and evaporation were captured in detail. This long-term data collection provides valuable insights into trends, seasonal patterns, and the overall variability of water resources, which are essential for modeling and analyzing reservoir operations under varying climatic conditions.

3.3.2 Operational data

The operational data collected for this study include key measurements related to the daily reservoir operations of Keddara, Hamiz, and Beni Amrane. These data are crucial for reservoir operation simulations in the HEC-ResSim model, as they provide essential information for managing water storage, release, and transfer. The data collected include the following:

- Reservoir daily elevation
- Reservoir daily storage
- Surface variation

- Hypsometric Curve (HC Curve): The characteristic curve of a reservoir, also known as the storage-elevation curve, represents the relationship between the elevation and storage volume of the reservoir. This curve is essential for HEC-ResSim, as it allows the model to determine the volume of water at any given elevation, helping to guide operational decisions such as water release and storage management.
- Water allocated to the drinking water supply: These data are related solely to the Keddara reservoir since it is the only reservoir providing water for the drinking water supply to Algiers and Boumerdes.
- Water allocated to irrigation: These data are related to Hamiz Reservoir only since it is the only reservoir providing water for irrigation to the Mitidja Plain.
- Water was transferred from Hamiz Reservoir to Keddara Reservoir.
- Water was pumped from the Beni Amrane Reservoir to Keddara.

3.3.3 Questionnaire-Based Data Collection: Operational Practices and Coordination among SPIK System Operators

The data were collected through questionnaires to gather information regarding reservoir operation practices and the level of coordination among the operators of the SPIK system. The primary objective was understanding how different operational strategies are applied under various conditions. The questionnaire was structured into three main sections, each corresponding to a different operational scenario: normal conditions, heavy precipitation, and drought.

Each section of the questionnaire focused on several key aspects of reservoir management, including communication among operators and with high-level authority, decision-making processes, data-sharing practices, and decision support systems (DSSs) and prediction tools. These parameters are crucial for assessing how well operators collaborate and make informed decisions under varying operational contexts. During extreme events, questions regarding resilience have been added to assess the strategies to ensure a continued water supply without compromising infrastructure and downstream safety.

- Normal conditions: This section focuses on standard operational practices during typical conditions, gathering insights into how communication flows, decisions are made, and data are shared between operators, in addition to water practices during normal conditions.
- The heavy precipitation conditions section examines the management of extreme precipitation events, focusing on how operators adapt their decision-making and

response strategies during high rainfall, including the DSS and prediction tools for forecasting and managing risks.

- The drought conditions section was dedicated to drought conditions and explored how water management practices are adjusted when water availability is limited.

3.4 Methodology

The research methodology follows a structured approach (Figure 3.3) to assess the coordination among SPIK operators and the operational dynamics of the system, combined in two parts respectively Part I and Part II.

The Part I adopts a quantitative approach, employing self-administered structured questionnaires to collect data from key stakeholders responsible for managing and supervising the SPIK multi-reservoir system. The first step involved identifying the main actors directly involved in system operations. A total of four respondents are selected: three reservoir operators and one high-level authority representative from the National Agency for Dams and Transfers (ANBT). Two distinct questionnaires are developed to address the specific roles and expertise of the participants. The questionnaire addressed to the reservoir operators consists of 81 questions divided into three thematic sections: normal operating conditions, heavy precipitation, and drought conditions. This design allowed for a structured exploration of decision-making practices under different hydrological scenarios. The second questionnaire, addressed to the ANBT official, comprised 26 questions focusing on strategic oversight, inter-reservoir coordination, and institutional mechanisms.

The use of structured questionnaires instead of in-depth interviews is based on the nature of the study, which required comparable and structured insights from all respondents. Multiple-choice and guided response formats ensured that all operators responded to the same set of operational themes, and enables a comparative analysis of their practices and viewpoints. This uniformity is essential for identifying patterns, inconsistencies, or alignments in operational behavior across the reservoirs. Moreover, the standardized nature of the responses facilitated easier integration of findings into the modeling framework for reservoir operations.

The responses are analyzed quantitatively, and the results informed a SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats), used to assess the effectiveness of existing operational coordination and to highlight potential areas for improvement in managing extreme hydrological events within the SPIK system.

The Part II of the study focuses on modeling the operational dynamics of the SPIK system via the HEC-ResSim model. HEC-ResSim uses an original rule-based approach to mimic the decision-making process that reservoir operators must use to meet operating requirements for flood control, power generation, water supply, and environmental quality. This model is set up through three main modules. First, key data, such as stream and reservoir locations, are incorporated into the watershed setup. The reservoir network module configuration includes parameters such as outlets, diversions, and junctions. The model is then calibrated and validated via observed elevation and storage data to ensure that it accurately simulates the system's behavior, which is the third module of the model. The baseline scenario is established, which will serve as a reference point for future simulations and comparisons.

Different operational scenarios are simulated via the WEAP (Water Evaluation and Planning) model following model validation. These scenarios assess various aspects of water management, including water demand during drought conditions, identifying water-stressed areas, and exploring alternative water sources for improving water allocation. Furthermore, the capacity of the SPIK system to manage water flow under normal conditions is evaluated, and optimization techniques are applied to ensure efficient flow regulation.

Finally, the results of these simulations are analyzed to assess the system's performance under different conditions. This analysis aims to optimize the system's operational strategies, ensuring that water is allocated efficiently and the system is resilient to drought events. By integrating both qualitative data from the surveys and quantitative data from the modeling process, the methodology comprehensively evaluates the SPIK system's performance and offers recommendations for improving water management practices and operational coordination.

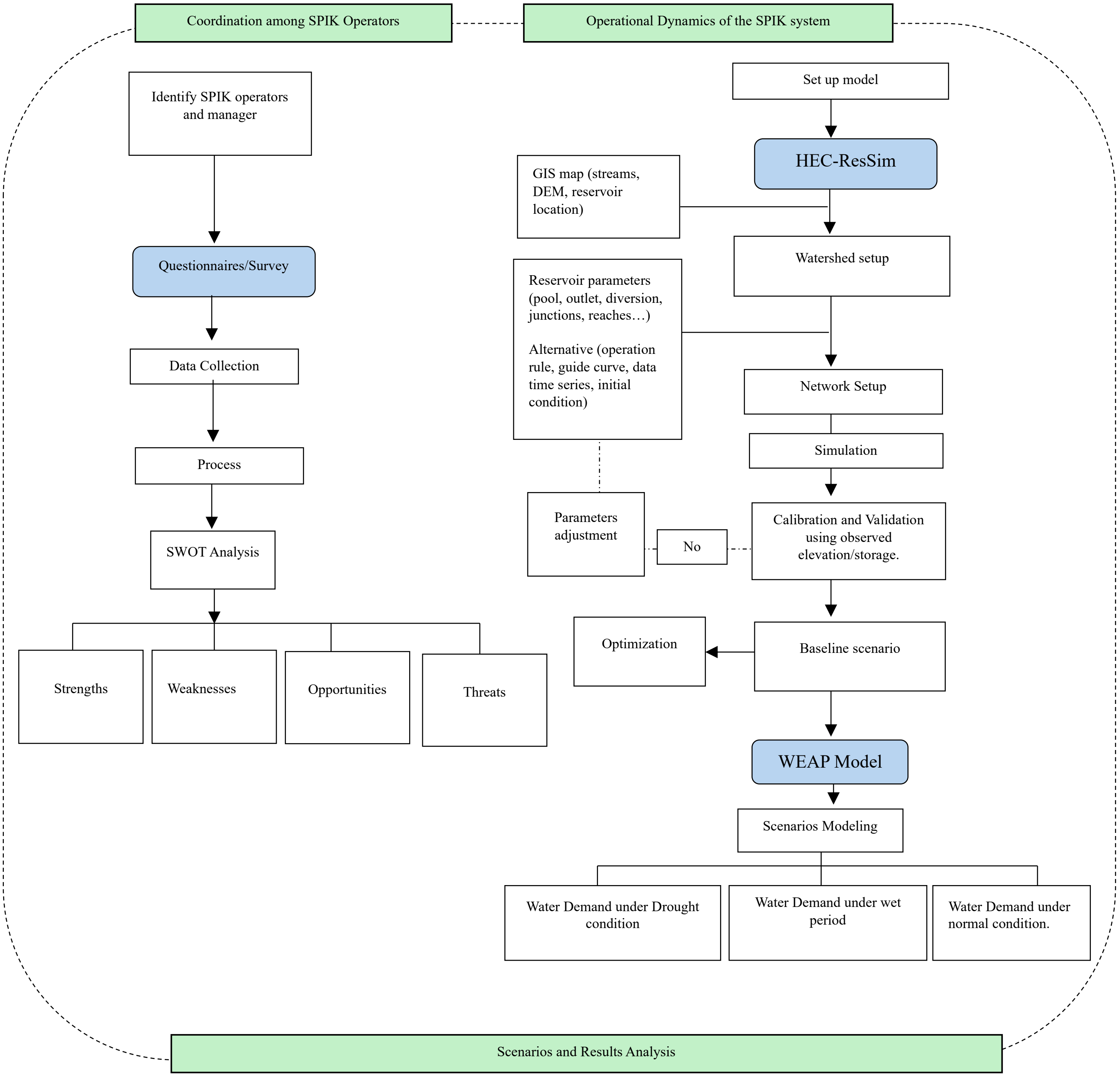

Figure 3.3: Methodology flow chart

3.5 Operational data visualization and interpretation

The collected data were visualized and represented to understand the operational dynamics of the reservoirs. The yearly and monthly operational data were organized and displayed as water budget diagrams, which helped illustrate key parameters such as elevation, storage, and water allocation. Various plots were created to show the variation in these parameters over time, allowing for a better understanding of the changes in reservoir conditions across different periods. This approach provides insights into water management practices and the operational performance of reservoirs, highlighting trends and patterns that are essential for further analysis.

3.5.1 Reservoir water budget

"You cannot manage what you do not measure" holds for water budgeting. A water budget is a systematic assessment of the hydrologic components of the water cycle, including their interactions and relative contributions within a given system. It provides insight into water availability, usage, sources, and replenishment rate. At its core, a water budget quantifies the balance between water entering and exiting a system, helping to evaluate overall water dynamics and sustainability (Stanton et al., 2011). It tracks inflows (deposits) and outflows (withdrawals) over a set period to assess changes in storage. When inflows exceed outflows, storage increases; when outflows surpass inflows, storage declines. Surpluses from previous periods can balance occasional deficits, but prolonged negative balances can lead to long-term water depletion and resource stress. Monitoring these trends is essential for sustainable water management and planning (Laird & Cowin, 2016).

Reservoirs play a crucial role in managing water resources. They are particularly vital in semiarid and arid regions where water availability fluctuates significantly (Healy et al., 2007). Reservoir operators must carefully determine release rates to balance water supply needs with flood control. Releasing too much water too soon could lead to shortages later, whereas releasing too little water could result in uncontrolled flooding during periods of high inflow. Effective reservoir management requires a thorough understanding of the water budget, which considers stored water, expected inflows, and various demands, such as irrigation, water for municipalities, power generation, and environmental requirements (Healy et al., 2007). The water budget plays a crucial role in reservoir operations by providing a comprehensive understanding of storage variations, inflows, and outflows, which can provide reservoir operators with valuable information to make informed decisions on water releases. Moreover, understanding the water budget helps evaluate the impacts of human activities and natural processes on a reservoir's water balance (Laird & Cowin, 2016). This approach ensures efficient water management, balanced supply demands, flood control, and environmental sustainability (Healy et al., 2007).

In the SPIK reservoir system, we focus on a water budget analysis emphasizing the balance between inflows and outflows to assess the system's hydrological performance. The primary inflows are water entering rivers and transferring from other reservoirs. The outflows include evaporation losses, water withdrawals for municipalities and irrigation purposes, reservoir losses, controlled releases, and water discharged through the spillway. By quantifying these components, we aim to understand the reservoir's water balance, essential for effective water resource management. This analysis helps evaluate the reservoir's capacity to meet its intended purpose, such as water supply and flood control and informs decision-making processes to ensure optimal operation.

The water budget equation used in this study is as follows:

Inflow (a, b, c) - Outflow (a, b, c) = Change in Storage (Laird & Cowin, 2016)

Considering the key parameters that influence the water budget in SPIK

WB = Inflow (river+transfers)− Outflow (Evaporation + Withdrawal+Reservoir losses + Release + Spillway)

where WB = Water Budget

3.5.2 Monthly water budget

The monthly water budget analysis provides a detailed assessment of how water is distributed and managed within each reservoir over time. By evaluating inflows, outflows, and storage variations on a monthly scale, seasonal patterns can be better understood, imbalances can be detected, and the efficiency of reservoir operations can be assessed. This analysis is crucial for identifying periods of surplus or deficit, optimizing water allocation, and improving resilience to extreme hydrological events. The following section presents the monthly water budget for each reservoir, highlighting key trends and variations that influence the overall performance of the SPIK system.

Monthly water budget of the Keddara reservoir

The monthly water budget analysis of the Keddara Reservoir (Figure 04) reveals distinct seasonal trends, highlighting the reservoir's reliance on external support from Hamiz and Beni Amrane. The system consistently experiences a negative water balance from May to November, where outflows exceed inflows, indicating higher water demand or reduced replenishment during these months. The most critical deficits occur in July and August, with extreme cases such as 2020, where the deficit exceeded 15 million cubic meters, while the average deficit is approximately 10 million cubic meters. Conversely, the period from December to April generally has a positive water balance, reflecting increased inflows from precipitation and upstream contributions. Notably, significant water budget peaks surpassing 60 million cubic meters were observed in February 2003, February 2012, **and** March 2014, suggesting extreme hydrological events or management strategies to maximize storage. These fluctuations underscore the importance of coordinated operation between Keddara and its supporting reservoirs to optimize water availability and mitigate seasonal deficits.

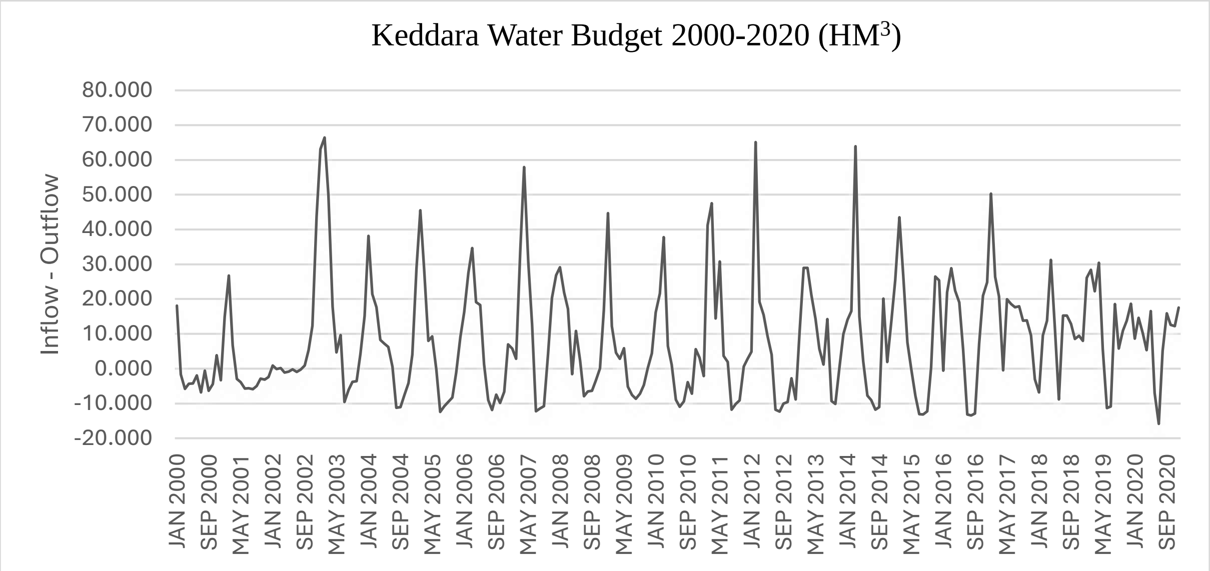

Figure 3.4: Keddara water budget.

Monthly water budget of Hamiz Reservoir

The monthly water budget analysis of Hamiz Reservoir (Figure 05) highlights notable fluctuations and seasonal patterns influenced by its inflow and outflow dynamics. Between January 2000 and October 2002, the reservoir experienced persistent negative to near-zero water budgets, with an extreme deficit reaching 6 million cubic meters in January 2001. Beyond this period, a clear seasonal pattern emerges, with deficits occurring from May to October and occasionally extending to November. During these deficit months, outflows consistently surpass inflows, with monthly extreme deficits reaching approximately 4 million cubic meters. In contrast, the wet season (November to April) generally has a positive water budget, averaging 5 million cubic meters, with notable peaks in February 2006 (7 million cubic meters), March 2007 (8 million cubic meters), and January 2017 (7.6 million cubic meters). Since the Hamiz Reservoir relies solely on streamflow as its inflow source, its ability to sustain the water balance depends heavily on natural hydrological conditions. Additionally, its role in supporting the Keddara Reservoir through gravity transfer further influences its monthly variability, emphasizing the need for efficient reservoir management to maintain stability within the system.

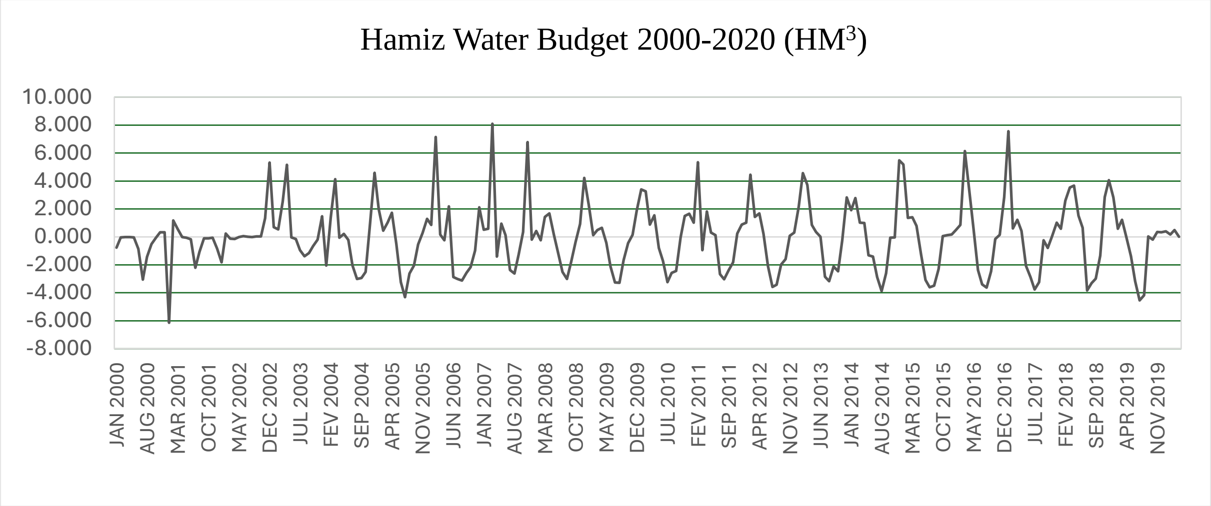

Figure 3.5: Hamiz Water Budget

Monthly water budget of the Beni Amrane Reservoir

Unlike Hamiz and Keddara, which exhibit a recognizable seasonal pattern with deficits generally occurring between May and September, the Beni Amrane Reservoir (Figure 06) shows no clear seasonal or regular variability in its water budget. The fluctuations between positive and negative values appear erratic, making it difficult to predict periods of surplus or deficit based on typical hydrological cycles. From 2002 to 2004, the reservoir maintained a consistently positive water budget, suggesting a period of stable inflows and controlled releases. However, starting in January 2004, a noticeable shift occurred, introducing a high degree of variability in the reservoir’s water balance, which coincides with the period when the reservoir started transferring water to Keddara. Two significant water budget peaks stand out: January 2003 (17.70 MCM) and March 2006 (17.46 MCM), indicating periods of exceptionally high inflows or reduced outflows. Conversely, June 2007 recorded an extreme deficit of 8.28 MCM, suggesting a substantial outflow relative to incoming water.

The most striking feature of Beni Amrane’s water budget is the inconsistency in positive and negative balances. For example, April 2013 had a deficit of 6.5 MCM, yet May 2013 saw a surplus of 5.9 MCM, demonstrating a sudden shift within a short time. Similarly, in what is typically a dry period, July 2013 recorded a positive balance of 5.8 MCM; in August 2020, the budget reached 6.25 MCM. Even months that usually have comparable conditions show inconsistencies, as seen in February 2014 (-3 MCM) versus February 2017 (-5.6 MCM). Another unusual occurrence occurred in July 2017, with a positive water budget of 5.81 MCM.

The absence of direct municipal, irrigation, or hydropower demand suggests that the erratic nature of Beni Amrane’s water budget is primarily linked to its role in transferring water to the Keddara Reservoir. The irregularity may stem from operational decisions, where transfer volumes fluctuate depending on the conditions and requirements of Keddara rather than following a predictable seasonal pattern. Sudden shifts between surpluses and deficits could be attributed to management strategies, emergency transfers, or variations in upstream inflows.

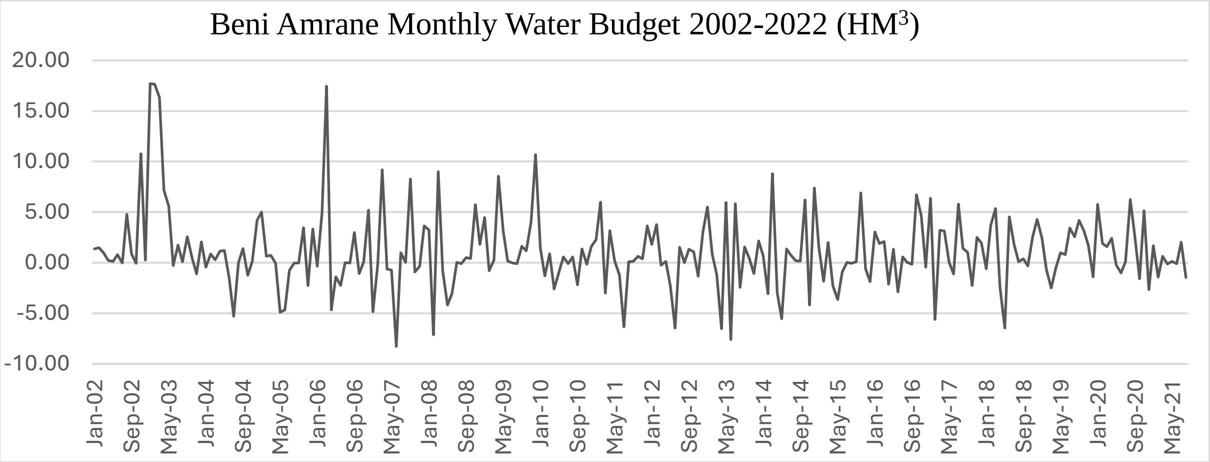

Figure 3.6: Beni Amrane Monthly Water Budget

3.5.3 Annual Water Budget

Analyzing the annual water budget data for the Hamiz, Keddara, and Beni Amrane reservoirs from 2002--2022 reveals significant interannual variability, reflecting the complex interplay of hydrological factors influencing each reservoir's storage dynamics (Figure 7).

The Keddara Reservoir's water budget data display significant variability. Positive water budgets are observed in 2003, 2007, 2009, 2011, 2013, 2014, 2015, 2017, and 2021, suggesting periods of net water gain. In contrast, years such as 2004, 2005, 2006, 2010, 2012, 2016, 2018, 2020, and 2022 have negative water budgets, indicating net water loss.

The Hamiz Reservoir exhibited notable fluctuations in its water budget over the two-decade period. Years such as 2003, 2007, 2011, 2012, 2014, 2018, and 2021 presented positive water budgets, indicating that inflows surpassed outflows, leading to increased storage levels. Conversely, years such as 2002, 2005, 2009, and 2010 experienced negative water budgets, where outflows exceeded inflows, resulting in decreased storage.

The water budget of the Beni Amrane Reservoir has distinct trends. Notably, years such as 2006, 2007, 2008, 2010, 2013, 2016, 2017, 2018, 2019, 2020, 2021, and 2022 presented positive water budgets, indicating periods of increased storage. However, years such as 2002, 2003, 2004, 2005, 2009, 2011, 2012, 2014, and 2015 experienced negative water budgets, reflecting decreased storage levels.

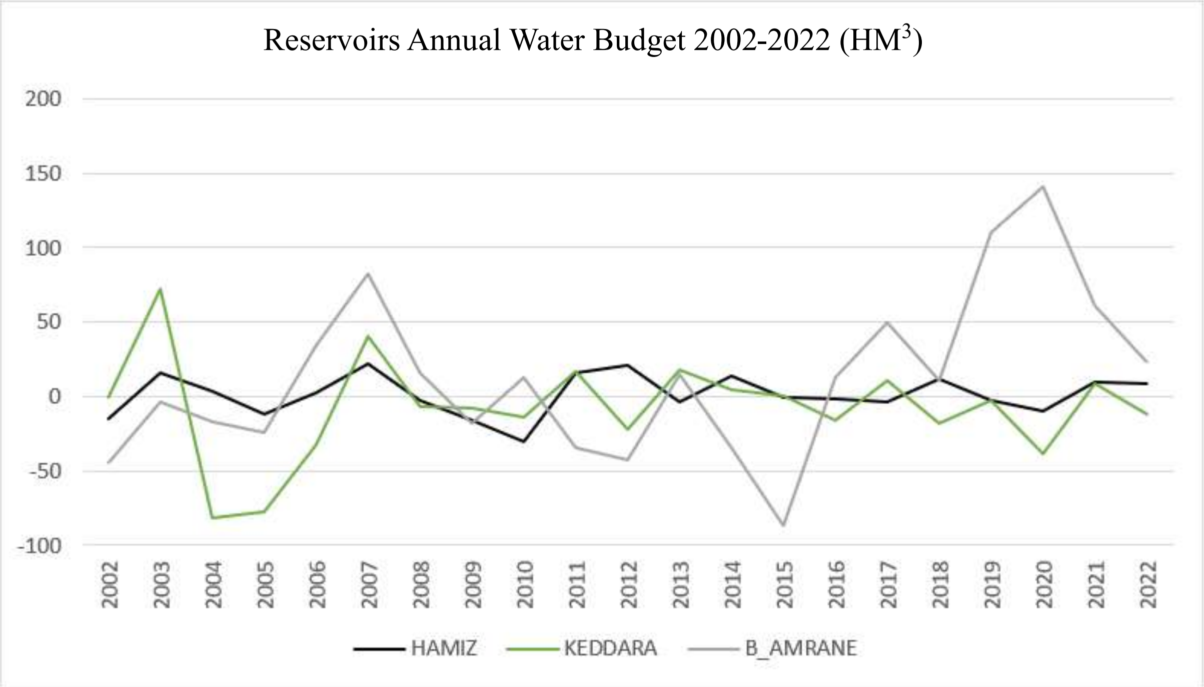

Figure 3.7: Comparison of the annual water budget of the reservoir from 2002--2022

3.5.4 Comparative Insights

Analyzing the combined water budget data for the Hamiz, Keddara, and Beni Amrane reservoirs from 2002--2022 (Figure 8) provides insights into the overall dynamics of the SPIK reservoir system. By summing the annual water budgets of the three reservoirs, we can assess the system's collective behavior and understand how these reservoirs interact to manage water resources in the region. First, from 2012--2019, the SPIK water budget closely aligned with that of Beni Amrane, suggesting that this reservoir played a crucial role in regulating the system's overall water balance. While each reservoir exhibits unique water budget patterns, some commonalities are evident. For example, 2007 had a positive water budget across all three reservoirs, suggesting favorable hydrological conditions during that period. In contrast, 2005 reflects a negative water budget for all the reservoirs, indicating a year of overall water deficit. These synchronous trends may indicate that regional climatic factors affect the entire SPIK reservoir system.

The fluctuations between positive and negative water budgets in the SPIK system highlight the variability in hydrological conditions and the interconnectedness of the reservoirs. A positive combined water budget suggests that the system, as a whole, had sufficient inflows to meet demands and potentially increase storage levels. This scenario is favorable for water supply, irrigation, and other uses, as it indicates an overall surplus. We observe periods of both positive and negative water budgets. Years such as 2003, 2007, 2013, 2017, 2019, 2020, and 2021 presented positive combined water budgets, indicating that, collectively, the reservoirs experienced a net gain in water storage during these years. In contrast, a negative combined water budget points to a system-wide deficit, where total outflows exceed inflows. Such conditions may necessitate strategic water management interventions, including adjusting release schedules, implementing water conservation measures, or coordinating transfers between reservoirs to balance the system. Conversely, 2002, 2005, 2009, 2010, 2011, 2012, 2014, 2015, 2016, and 2018 presented negative combined water budgets, reflecting a net loss in storage across the system.

The data also reveal instances where individual reservoir water budgets diverge from the system's overall trend. For example, in 2004, the Hamiz Reservoir had a positive water budget, whereas Keddara and Beni Amrane experienced negative budgets, resulting in a net negative water budget for the system. Similarly, in 2020, both SPIK and Beni Amrane had positive water budgets, whereas Hamiz and Keddara experienced deficits. Given that Keddara is the primary water supplier to Algiers, this situation may reflect constraints in transferring water downstream, leading to shortages despite an overall system surplus.

These inconsistencies suggest complex interactions within the system that are not yet fully understood. Such findings in contrasting water budgets underscore the necessity for further studies to delve deeper into the interreservoir dynamics of the SPIK system. Comprehensive studies can shed light on the hydrological, operational, and environmental variables influencing each reservoir and their collective behavior.

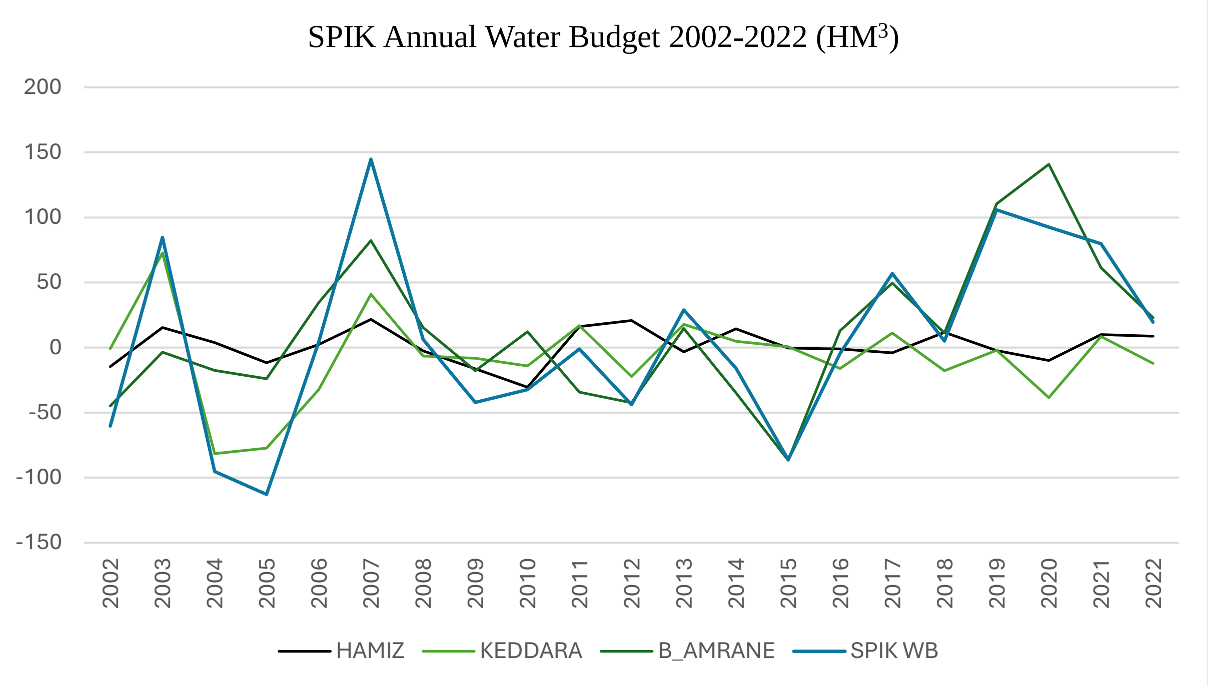

Figure 3.8: SPIK and reservoir annual water budget

4. Reservoir Operational Practices and Coordination: Insights from Questionnaires

4.1 Introduction

The survey conducted among reservoir operators within the SPIK system aimed to evaluate the coordination mechanisms, decision-making processes, and operational strategies employed by reservoir operators within the SPIK system during normal conditions, heavy rainfall or flood events, and drought periods. By assessing communication, data-sharing protocols, decision-making processes, and overall preparedness for extreme hydrological events such as floods and droughts, the questionnaire aims to identify strengths, gaps, and areas for improvement that are crucial for enhancing the operational efficiency, flood and drought risk management, and resilience of the interconnected reservoir system.

By investigating these aspects, this study seeks to understand how communication and decision-making among operators and high-level authorities are managed, particularly during extreme hydrological events. The results will be used to propose actionable recommendations for improving system performance and resilience.

The target group for this questionnaire consists of reservoir operators and officials from ANBT (National Agency for Dams and Transfers), as they are the key decision-makers and facilitators of the operational and management strategies within the SPIK. The questionnaires have the following specific objectives:

- Assessment of reservoir operation coordination: This objective focuses on evaluating the coordination mechanisms within the SPIK system, particularly examining the frequency of communication, methods used, and data-sharing processes between the reservoirs and stakeholders.
- Analysis of decision-making processes: This objective assesses how decisions related to reservoir operations are made, with a focus on the participation and engagement of various stakeholders in the decision-making process, especially during flood and drought conditions.
- The utilization of a decision support system (DSS) and prediction tools: This objective assesses the use of the DSS in managing water reservoir operations and optimizing water supply strategies, particularly under extreme events such as floods and droughts.

- Water management practices: This objective aims to evaluate water management practices under different operational conditions by analyzing water allocation methods and water transfer operations.
- Disaster resilience strategies and risk communication practices: The final objective is to evaluate disaster resilience strategies and risk communication practices during extreme events such as floods and droughts. This will include assessing the preparedness of the reservoirs and the coordination with external stakeholders during these periods.

4.2 Description of the Questionnaire Structure

The questionnaire is divided into three distinct sections, each designed to assess reservoir operations under specific conditions. They cover reservoir operation under normal conditions, during heavy precipitation events and during drought conditions. Each of these sections evaluate how coordination is maintained among the interconnected reservoirs under specific conditions. It examines communication practices, data-sharing protocols, decision-making processes, and the use of DSS tools in day-to-day reservoir management. In addition, focused questions on flood and drought resilience strategies are included in sections 2 and 3. These questions target flood control protocols, water management practices and water allocation prioritization during extreme events.

4.3 Analysis and Framework

The results from the questionnaire will be carefully examined to extract key insights regarding the coordination mechanisms, communication patterns, decision-making processes, and operational strategies employed across the system. On the basis of this analysis, the SWOT framework is used to identify the strengths, weaknesses, opportunities, and threats of SPIK operations coordination. This approach enables the categorization of the internal and external factors affecting the efficiency and resilience of the system, ultimately providing a comprehensive assessment of the current practices and potential improvements within the SPIK network. Through this SWOT analysis, areas where the system performs well and where there are significant gaps or challenges are highlighted. The outcome will offer a structured way to prioritize actions for enhancing flood and drought risk management, improving decision-making efficiency, and strengthening overall system resilience.

4.4 Overview analysis

This questionnaire analysis starts with an overview of reservoir operation under different conditions—normal, flood, and drought—to understand how operators' responses vary according to specific circumstances. By exploring these conditions, we aim to assess the adaptability and decision-making strategies employed by operators in different operational contexts. Figure 09 presents an analysis of the consensus and divergence in reservoir operators' responses across various operational conditions, including normal conditions, flood conditions, drought conditions, and a general perspective. The graph categorizes the responses into three distinct categories: same answer for all reservoirs, same answer for two reservoirs, and different answers. Overall, most of the responses across all the conditions are categorized as the same answer for all the reservoirs. This suggests that operators have strong agreement on many operational aspects, particularly when responding to flood-related questions. However, a smaller portion of the responses fall into the same answer for the two reservoirs category, whereas the fewest responses are classified as different answers, indicating areas where the operators have differing views or approaches.

Starting with operations under normal conditions, operators' responses are largely consistent, except for one different answer regarding the challenges in operating the spillway and bottom outlet gates. Another notable pattern was that, in some cases, two reservoirs provided the same answer, indicating a slightly lower level of agreement. These questions focus mostly on the type of spillway and the frequency of its maintenance. This makes sense, given the distinct characteristics of the reservoirs. For Keddara, since the spillway is ungated, no specific maintenance is needed.

In contrast, at Hamiz, the spillway is partially automatic and requires regular maintenance. For the Beni Amrane, maintenance is needed for the spillway and the bottom outlet gates, with maintenance requirements varying depending on the context. The spillway requires the cleaning of floating debris carried by the river, which was one of the main challenges cited by the operator regarding the spillway, whereas the automatic gates require regular maintenance and checks. Reservoir operators submit daily updates on their reservoirs to a dedicated platform accessible exclusively to high-level authorities, with restricted access for other operators. The methods of communication between operators are typically nonurgent, such as phone calls and emails, when necessary. This approach ensures a steady flow of information but lacks the immediacy required for rapid emergency decision-making.

Under flood conditions, operators have a strong consensus, with the highest number of responses categorized as the same answer for all reservoirs. Different and two identical answers are less common, reinforcing that operators follow similar procedures during extreme events. In terms of communication, in contrast, the situation's urgency prompts immediate notifications and escalates communication methods. Phone calls have become the dominant tool for coordination, ensuring quick responses and actions. Higher authorities take on a more significant role in decision-making, but informal agreements between operators also play a crucial part in the process. However, some reservoir operators face challenges because of the absence of established flood management protocols, which can hinder effective and coordinated flood operations.

Under drought conditions, Figure 4.1 reveals the most significant divergence. While some questions still exist where operators provide the same answer for all reservoirs, the frequency of different answers increases. This divergence highlights operators' challenges in managing water resources during droughts. Communication becomes more hierarchical, with decision-making often occurring in a top-down manner. There is little evidence of collaborative discussions, and operators appear to rely heavily on directives from higher authorities. Furthermore, the lack of real-time drought prediction tools highlights a significant gap in proactive management, making reservoirs vulnerable to the unpredictability of drought events.

Importantly, the lack of DSS tools and prediction models is a common issue across all SPIK reservoirs. The absence of such tools significantly impairs the ability to make data-driven decisions, particularly during extreme hydrological events such as floods and droughts. Reservoir operators rely on manual processes and reactive decision-making, leading to delays and a lack of real-time coordination during emergencies. Moreover, the absence of forecasting tools further exacerbates the difficulty of managing flood risks and water allocation during droughts, as it limits the ability to anticipate and prepare for changing conditions.

Overall, the analysis indicates that while flood conditions exhibit the highest level of consensus among operators, normal conditions and drought conditions highlight more variability in response. This suggests that drought management, water allocation, and operational flexibility could benefit from further standardization and coordination to ensure more consistent practices across the SPIK system.

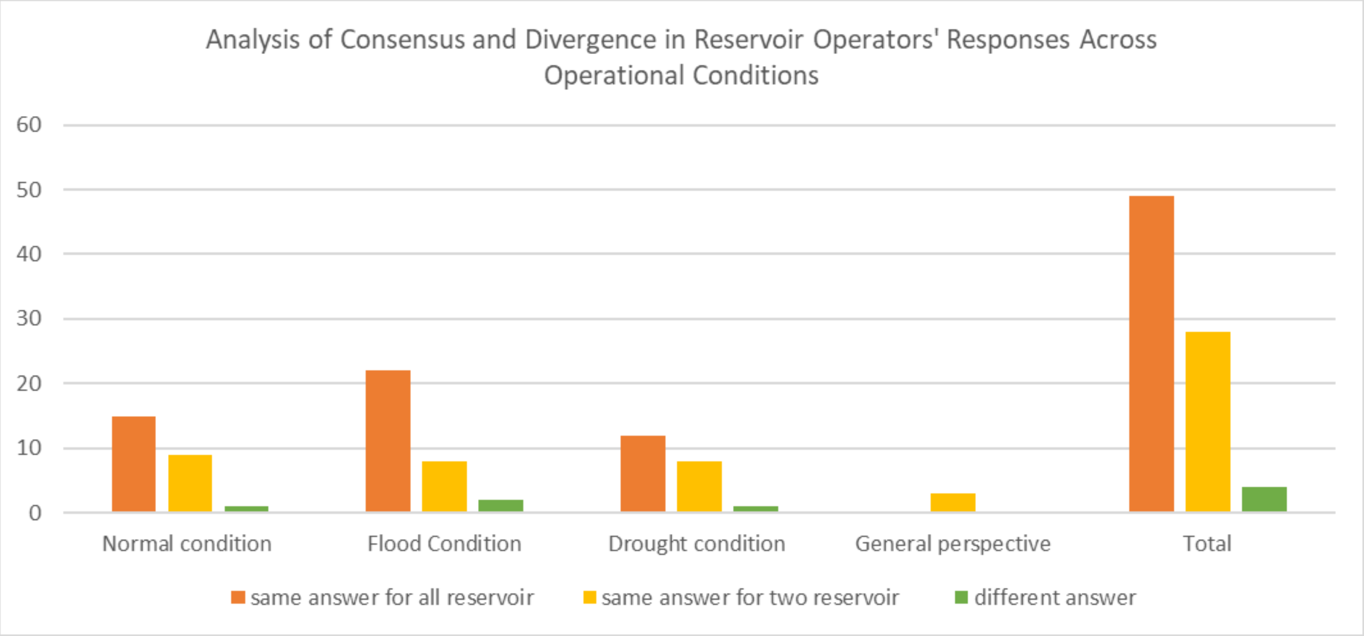

Figure 4.1: Consensus and divergence in the reservoir operator's responses across operational conditions

4.5 Parameter Analysis

This section discusses operational management factors such as communication, data sharing, decision-making, water management practices, and resilience to extreme events within different operational conditions. The objective is to evaluate how operators manage these factors and assess their effectiveness in supporting optimal reservoir operations.

4.5.1 Communication across the SPIK

Under **normal conditions**, communication primarily occurs through regular data reporting, which is typically shared in reports. Operators rely on phone calls, emails, and periodic reports instead of real-time data-sharing systems. This reliance on manual communication methods can lead to delays in decision-making and a lack of real-time responsiveness, which is crucial for addressing sudden changes in reservoir conditions.

During **flood conditions**, communication becomes more urgent and coordinated. Immediate notifications about flood operations are issued, and phone calls dominate as the method for coordination. Although higher authorities play a key role in decision-making, informal agreements between operators also contribute to coordination. While useful for quick decisions, this informal nature of communication could lead to inconsistency in responses and challenges in formalizing operational actions. Additionally, the lack of standardized flood control protocols makes coordination more reliant on ad hoc communication, which may not always be sufficient for managing critical flood situations.

Under drought conditions, communication becomes more hierarchical, with decision-making largely centralized within higher authorities. Collaborative decision-making between operators is limited, and there is little evidence of a systematic approach to information sharing, which could hinder the efficient management of water resources during droughts. The absence of real-time communication tools or predictive data-sharing systems restricts operators' flexibility in responding to emerging drought-related challenges.

4.5.2 Data Sharing Practices

The SPIK system faces several data-sharing challenges, particularly regarding real-time data access and standardized protocols. Under **normal conditions**, standardized data-sharing protocols are confined to higher-level authorities and do not extend to communication between reservoir operators. This limited data flow can cause inefficiencies, as operators lack access to critical data from other reservoirs, preventing them from making fully informed decisions.

Under flood conditions, the system's ability to share predictive or actionable data is notably absent. While flood updates are received, it is unclear what type of information is shared and whether it contains actionable insights. This lack of detailed, real-time data on inflows, outflows, and structural stability during flood events reduces the effectiveness of coordination efforts, as operators may lack the necessary details to make immediate operational adjustments.

Under **drought conditions**, data sharing further deteriorates, with decisions on water allocation relying entirely on higher authorities. Operators do not have access to rainfall or inflow projections, which are critical for making informed decisions about water management during dry periods. The use of phone calls for critical data sharing and the absence of automated, real-time monitoring systems make the system heavily dependent on manual communication, delaying responses and increasing the risk of miscommunication.

The data-sharing process across interconnected reservoirs currently lacks automation and predictive capabilities. Manual measurements are the predominant method for monitoring reservoirs, with no evidence of automated systems such as SCADA or specialized software to collect, analyze, and share real-time data. This suggests the system's data sharing is highly manual and prone to delays or inconsistencies, particularly during time-sensitive operations such as floods or droughts.

Furthermore, the data-sharing protocols in place are standardized but not comprehensive or detailed, limiting their effectiveness in ensuring the smooth and consistent flow of information between operators (Figure 4.2). Additionally, no predictive data—such as rainfall forecasts or inflow projections—are shared, leaving operators with only real-time conditions to make decisions. This reactive approach prevents effective flood preparedness and diminishes the ability to manage resources proactively.

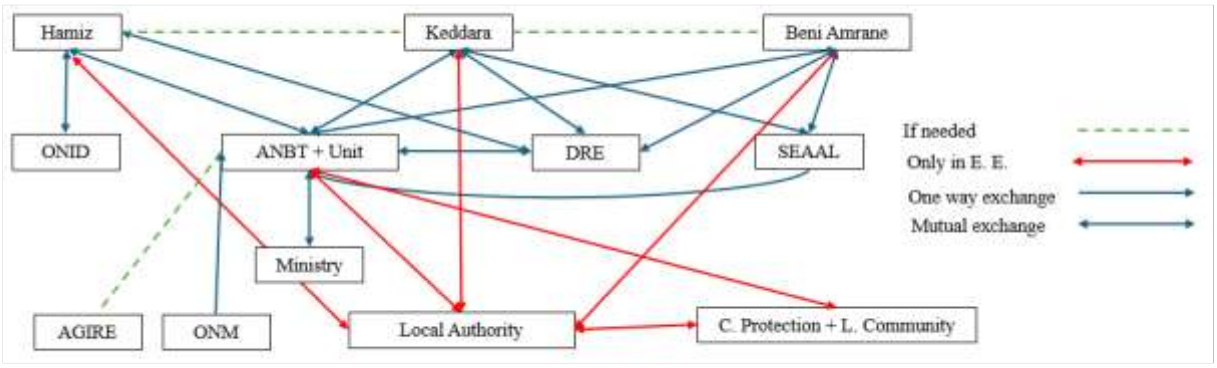

Figure 4.2: Summary survey results of the communication flow within SPIK

4.5.3 Use of decision support systems (DSSs) and predictive tools

The lack of decision support systems (DSSs) for reservoir management is a critical issue. All the reservoirs reported that they do not use DSS tools for normal operations, flood management, or drought planning. This absence of data-driven decision support means that operators must rely on manual decision-making without analytical tools to optimize their actions. Consequently, decision-making is often inefficient and reactive, particularly when individuals respond to dynamic conditions such as floods or droughts.

The lack of DSS tools is particularly impactful during flood conditions, where real-time monitoring systems are not in place to help coordinate flood responses. This results in a reactive approach to flood management, with operators unable to access predictive data that could help anticipate flood events. Similarly, under drought conditions, the lack of forecasting tools leaves water allocation decisions entirely dependent on higher authorities without the benefit of analytical insights that could optimize water use and distribution.

The absence of predictive tools for flood and drought management is a significant gap in the system. No forecasting tools are used at any reservoirs, limiting their ability to anticipate changes in water supply, potential floods, or droughts. As a result, the response to such events is entirely reactive, compromising management strategies' effectiveness. For example, flood responses are based solely on immediate observations and cannot project inflows or rainfall, leaving operators unprepared for sudden changes. Similarly, operators lack the foresight to plan water allocations effectively in drought scenarios, relying only on immediate data rather than long-term projections.

4.5.4 Decision-Making Process

The analysis of the decision-making process across the system reveals some inconsistencies in coordination methods, with a heavy reliance on higher authorities and varying levels of local operator involvement. Keddara and Hamiz adopt a more collaborative approach, combining high authority directives and mutual/informal agreements, whereas Beni Amrane relies solely on high authority directives, limiting local operator flexibility (Table 4.1). During extreme events such as floods or droughts, the decision-making process is predominantly authority-driven, with limited input from local operators. Coordination heavily depends on higher authority directives, creating a bottleneck if decisions are delayed, which could increase flood risk. Similarly, under drought conditions, decision-making remains top-down, with no use of predictive tools for proactive management. The operational decision-making structure varies among reservoirs. Keddara and Hamiz Reservoirs report that decisions are entirely based on higher authority directives, limiting local operator influence.

On the other hand, Beni Amrane allows some flexibility in decision-making guided by higher-level directives. The varying triggers for spillway operations further highlight the differences in operator autonomy across reservoirs. Keddara follows predefined protocols and higher authority directives, Hamiz incorporates operator decisions after high authority consent, and Beni Amrane considers infrastructure integrity when making operational decisions, but these decisions still require approval from higher-level authorities before being executed. These differences can lead to inconsistencies in spillway operations, particularly during emergencies.

The analysis reveals that this centralized decision-making approach leaves little room for local operators to adapt to real-time needs, potentially leading to inefficiencies in water allocation and flood management.

Table 4.1: Summary of participation levels in decision-making within SPIK

		Participation in decision-making				
Level of participation		N	Inf	C	Inv	D
Stakeholders	Keddara D. E.		▨			
	Hamiz D. E.		▨			
	Beni Amrane D. E.		▨			
	ANBT					▨
	Water utility SEAAL		▨			
	ONID		▨			
	Protection civile		🟨			
	Local Community	▨				
	Local Authorities		🟨			
	AGIRE	▨				
	DRE				▨	
	ONM	▨				
	ANRH			▨		
	Ministry					▨

N: None **Inf**: Informed **C**: Consulted **Inv**: Involved **D**: Decider

🟨 Informed only during flood events

4.5.5 Water Allocation and Decision-Making

Concerning water allocation within SPIK, despite the variations in the specific objectives of water transfer across reservoirs, these objectives align with maintaining an efficient water management system. Keddara's primary objective is to balance storage levels, coupled with an emphasis on increasing storage capacity at the Keddara dam, ensuring a steady water supply. On the other hand, Hamiz seeks to balance storage levels while also addressing downstream demand, demonstrating a dual focus on storage management and supply to downstream areas. Beni Amrane, crucial in supporting Keddara's supply, prioritizes meeting downstream demand. Its primary function is to provide water to Keddara, reinforcing the interconnected nature of the reservoirs. While these differing priorities may reflect varying strategies, they all aim to balance water storage across the system while meeting water demand.

Based on operator answers, water allocation decisions and transfer processes across reservoirs are predominantly shaped by directives from higher authorities, with all three reservoirs relying heavily on these top-down mandates, leaving minimal space for local operators to influence decisions. This hierarchical approach limits the system's adaptability, particularly in dynamic situations where more localized decision-making could improve responsiveness to changing conditions. Additionally, water allocation is governed by fixed quotas and storage levels rather than being based on real-time demand, reducing the system's ability to respond flexibly to fluctuations in water needs.

4.5.6 Assessment of flood resilience within the SPIK

During flood conditions, the prioritization of water release varies significantly among reservoirs. While Keddara and Beni Amrane attempt to balance downstream protection with storage optimization, Hamiz focuses solely on storage, increasing the risk to downstream areas. Furthermore, Keddara lacks a defined floodwater management strategy, and the differences in excess water management across reservoirs lead to uncoordinated flood mitigation efforts. The absence of standardized flood control protocols in Hamiz and Beni Amrane further exacerbates these risks, as responses to extreme events may be delayed or unclear. Keddara, despite having protocols, still relies heavily on centralized decision-making, limiting local flexibility in urgent situations.

Flood response strategies remain incomplete across all reservoirs, with no comprehensive approach. While Keddara employs early warning systems and coordination with authorities, it lacks controlled release mechanisms. Hamiz depends solely on authority coordination, whereas Beni Amrane combines controlled releases with authority coordination, presenting a more balanced approach. However, the overall lack of standardization in flood response measures creates inconsistencies in how floods are managed. Differences in spillway operation trigger further discrepancies in decision-making. Keddara follows predefined protocols, Hamiz combines authority directives with operator decisions, and Beni Amrane includes infrastructure integrity as a key trigger, offering a more comprehensive framework. These variations raise concerns about the timeliness and effectiveness of spillway operations, particularly in critical flood situations.

In the centralized decision-making structure, responses or directives from higher authorities are immediate. However, the heavy reliance on top-down control still limits flexibility at the local level, as operators must wait for official instructions rather than act proactively. While Hamiz incorporates increased communication among operators alongside authority directives, which allows for greater responsiveness, the absence of formalized protocols still leaves room for inefficiencies.

A major limitation across all reservoirs is the absence of predictive tools for flood management. None of the reservoirs employ real-time hydrological modeling or meteorological forecasts; instead, they rely on government alerts. This reactive approach results in delayed responses, especially given the short forecasting window of 1–3 days, which leaves operators with limited time to prepare for extreme flood events. The reliance on government flood alerts as the primary source of flood risk information further contributes to response delays, as these alerts may not always be timely or precise, which lowers the opportunity to improve flood preparedness. Additionally, the communication mechanisms for disseminating flood risk information remain unclear, necessitating a follow-up assessment to increase flood notification effectiveness.

The key issues identified include the lack of standardized flood control protocols, overreliance on centralized decision-making despite immediate authority responses, inadequate predictive tools, and incomplete flood response strategies.

4.5.7 Assessment of Drought Resilience across the SPIK Reservoirs

The assessment of drought resilience across the SPIK reservoir system based on operator responses reveals significant gaps in planning and decision-making, increasing the system's vulnerability during prolonged dry periods. Water allocation adjustments remain largely dependent on higher authority decisions and sector-based prioritization, leaving little flexibility for local-level management. Additionally, while alternative water sources such as desalination and groundwater exist, they are already operating at full capacity to meet their demands, leaving SPIK with no additional buffer against drought conditions.

A review of drought contingency plans across SPIK reservoirs further highlights inconsistencies and gaps in preparedness. Keddara reports the existence of a drought contingency plan but attributes it to SEAAL (Société des Eaux et de l'Assainissement d'Alger), the company responsible for water distribution in Algiers. However, no specific details regarding this plan's nature, scope, or implementation were provided, raising concerns about its actual applicability to Keddara's operational needs. Similarly, Beni Amrane refers to Koudiet Acerdoune as its backup source during droughts, yet this assumption is flawed. Koudiet Acerdoune has been nearly empty in recent years, ceasing all transfers to Beni Amrane since

2018. Moreover, it primarily serves the eastern part of the country, following its prioritization strategy, making it an unreliable source of support. In contrast, Hamiz lacks any drought contingency plan, making it particularly vulnerable during prolonged dry periods. The absence of a structured framework for managing water scarcity across these reservoirs increases the risk of inefficient resource allocation and crisis-driven responses rather than proactive management.

Reservoirs within the SPIK system also differ in their approaches to severe drought conditions. Keddara employs a relatively comprehensive strategy, including reducing water releases and prioritizing critical water uses that are always under higher instructions. In contrast, Hamiz operates under a rigid, directive-based framework dictated by higher authorities, limiting flexibility in local decision-making. Beni Amrane prioritizes essential water uses but does not integrate water release reductions or alternative supply options, making it less adaptive during severe droughts. While centralized decision-making ensures oversight from higher authorities, it delays localized responses, further impacting system efficiency. Water transfer prioritization within the SPIK remains focused on fixed quotas rather than a balanced and sustainable approach. Keddara and Hamiz primarily direct transfers to high-demand areas, whereas Beni Amrane also considers maintaining minimum storage levels. However, none of the reservoirs integrate ecological water needs into their allocation strategies. This lack of an integrated prioritization framework weakens the system’s ability to manage resources efficiently while ensuring long-term environmental sustainability.

Furthermore, a critical shortcoming in SPIK’s drought resilience is the absence of predictive tools. None of the reservoirs employ forecasting models or decision-support systems to anticipate water scarcity. Instead, decision-making relies solely on government directives, leading to a reactive rather than proactive approach to drought management.

The SPIK system faces substantial challenges in strengthening its resilience to droughts. The lack of structured contingency plans, reliance on top-down decision-making, and adaptive reservoir operation across most reservoirs hinders their ability to manage prolonged dry periods effectively and limits system flexibility to changing water availability.

4.6 SWOT Analysis

The feedback collected from reservoir operators provides valuable insights into operational practices, decision-making processes, and coordination mechanisms within the SPIK system. This survey result serves as the foundation for a SWOT analysis to assess the system’s internal strengths and weaknesses and the external opportunities and threats summarized in the table. The first part of the analysis focuses on internal factors, identifying strengths that contribute to effective coordination and water management. These may include well-established operational protocols, efficient resource management, or strong stakeholder collaboration. Moreover, the analysis highlights internal weaknesses, such as potential coordination gaps, limited decision-making flexibility, and challenges adapting to hydrological variability. The second part examines the external factors that influence the system's performance. Opportunities may arise from technological advancements, improved coordination strategies, or policy reforms that enhance drought and flood resilience. Conversely, external threats such as environmental changes, regulatory constraints, or financial limitations could present significant challenges. By structuring the analysis into these key components, the SWOT framework provides a comprehensive overview of the factors shaping the SPIK system's resilience. Table 4 presents the findings based on operators' feedback, offering a detailed assessment of these strengths, weaknesses, opportunities, and threats.

Table 4.2: SWOT analysis of SPIK system operation insights from survey responses

Strengths		Weaknesses	
Parameter	Description	Parameter	Description
Communication	All reservoirs report regular coordination through meetings and phone calls, suggesting that a structured communication system is in place. All reservoirs report receiving immediate notification for flood instruction	Decision-making process	Heavy reliance on higher authority directives and limited local operators involvement reduce flexibility especially in emergencies.
Data sharing	Daily data report to high level authority contributing to up-to-date management	Flood management and Resilience	Lack of consistent flood control protocol covering the SPIK system. Relying on higher instruction and unclear roles during emergencies
Flood Management and Resilience	Clear protocol for flood control in Beni Amrane reservoir using prerelease during high inflows occurrence.	DSS and predictive tools	No SCADA system or real-time data sharing platforms and reliance on manual measurement limiting the ability to monitor effectively No data forecasting tools weaken the ability to anticipate events.

	Predefined rule for water releases at 90% of the full capacity reservoir in Keddara.	Drought management and resilience	No clear drought contingency plan within SPIK.

Opportunities		Threats	
Parameter	Description	Parameter	Description
Data sharing	Implementing real-data-sharing platforms accessible to all operators	Climate change impacts	The consequences of climate change in terms of extreme events increase the reservoir operational complexity
DSS and Predictive tools	The implementation of forecasting tools and DSS will contribute to the ability of the operator to take proactive decisions.	Flood management	Flood risk in downstream, especially for Keddara dam due to illegal building on flood plains, and downstream Hamiz reservoir due to silted stream, and in Beni Amrane due to restricted riverbed.
Decision making process			

Flood management and resilience	Propose a decentralized decision-making policy to involve operators in shaping the reservoir operation. Propose a flood control protocol to the system across all reservoirs for a coordinated and efficient response.	Aging infrastructure Institutional bureaucracy	This is related to Beni Amrane bottom outlet releases gates which needs immediate maintenance. The system may face difficulties to shift from top down policy to more decentralized approach management.

5. Modeling Reservoir Operations via HEC-ResSim

5.1 Introduction to HEC-ResSim

HEC-ResSim (Hydrologic Engineering Center–Reservoir System Simulation) is a model developed by the US Army Corps of Engineers that allows the simulation of reservoir system behavior for integrated water management (USACE, 2021). It is particularly useful for modeling water levels, outflows, hydropower production, and other operations based on predefined management rules. In this study, we use version 3.5 of the latest publicly available model, featuring improvements in data management system compatibility and interoperability with other HEC tools.

HEC-ResSim 3.5 enables the simulation of various management strategies, the evaluation of operational alternatives, and the testing reservoir performance under extreme hydrological events (floods, droughts). It relies on a user-friendly graphical interface and a centralized data management system (HEC-DSS), facilitating the integration, visualization, and export of results in graphs and reports. The model requires input data such as natural inflows, the river network's physical and geographical characteristics, infrastructure operational rules, and management objectives (e.g., drinking water supply, flood protection, etc.).

HEC-ResSim is structured around three main modules:

- The watershed setup module which defines the spatial and structural framework of the hydrological network;
- The reservoir network module, where the physical and operational layout of the system is established (reservoirs, spillways, canals, junctions, diversions, etc.);
- The simulation module, which runs the scenarios based on the configurations and rules entered, simulates release decisions according to hydrological conditions and objectives.

Particular attention is given to the guide curve, which plays a central role in release decisions, balancing volumes to be stored and released according to the water level position. The model also allows the definition of multiple operation sets, providing the ability to compare different management regimes for the same infrastructure (USACE, 2021).

The operational analysis of the SPIK reservoir system focuses on understanding how the system functions in practice. This phase of the research examines the operational dynamics of the system, involving the analysis of both operational reservoir data and hydrological data.

Reservoir operators typically follow established guidelines or operational policies when managing water resources. However, in the case of SPIK, the decision-making process is notably centralized, with operators relying heavily on directives from higher-level authorities. Specifically, water release through the bottom outlet and water allocation decisions are exclusively made at the highest administrative levels, with minimal involvement from local stakeholders, as revealed by the survey analysis. To gain a deeper understanding of the system's behavior under varying operational and environmental conditions, HEC-ResSim is employed as a simulation tool to model the reservoir response (Figure 5.1).

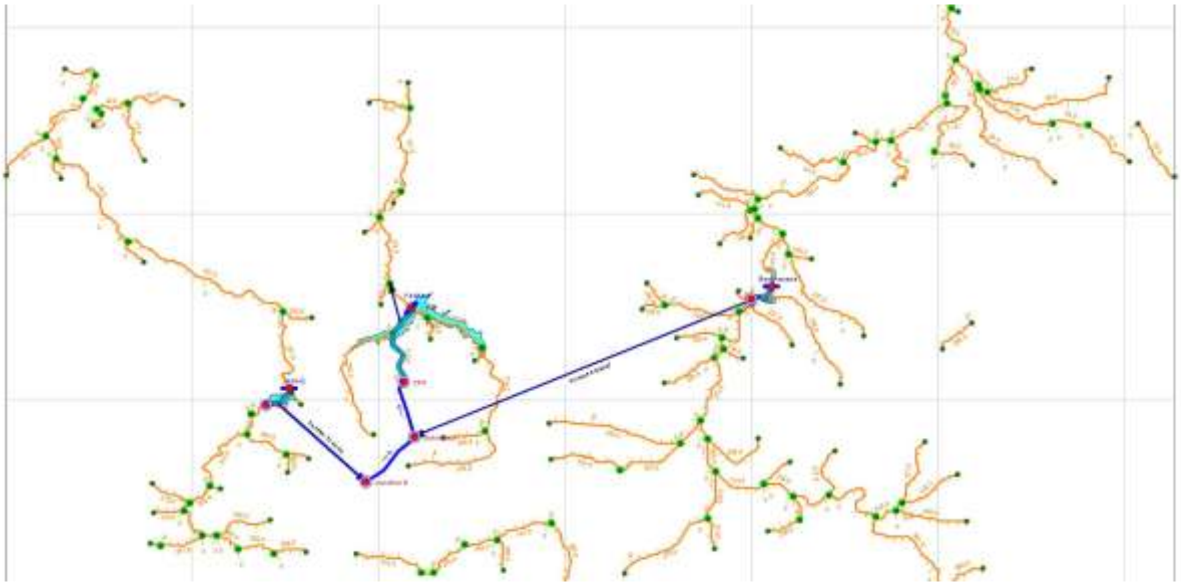

Figure 5.1: Schematic map of SPIK in the HEC-ResSim 3.5 model

5.2 SPIK baseline scenario simulation via HEC-ResSim

To simulate the SPIK system in HEC-ResSim and establish a baseline scenario reflecting the actual state of the system, a series of steps and decisions are needed. The first crucial step is defining the operational zones and rules. In the case of the SPIK system, owing to the absence of an operational rule, the reservoir elevation is utilized as the conservation zone for modeling purposes. For other zones, such as the flood control zone, the spillway elevation is used as the boundary for water management within the system. This elevation represents the point at which excess water is released to prevent overtopping and flooding of the reservoir. Similarly, the inactive zone, which represents the dead volume of the reservoir, is defined according to the elevation associated with this minimum storage level. The dead volume is critical for operational modeling, as it defines the portion of the reservoir that cannot be utilized for water supply or other purposes.

With respect to the operational rule, the system's water allocation is modeled through a time series of allocation data. Since the system lacks a specific operational rule for water release, the allocation time series serves as the primary input for guiding how water is distributed within the reservoir system. These time series data provide a dynamic view of how water is allocated across the SPIK system, reflecting real-world conditions and decision-making processes.

In the initial stage of the simulation, all relevant reservoir physical parameters are introduced into the model. These parameters include the pool elevation, spillway elevation, bottom outlet release, and diverted outlet structure. Incorporating these parameters ensures that the simulation accurately represents the physical characteristics and operational constraints of the system, accounting for key variables that influence water storage, flow, and allocation within the reservoirs.

To validate the simulation, the storage variation provided by the model is used as the key performance metric. This allows for a direct comparison between observed and simulated data, ensuring that the model is replicating real-world reservoir behavior. The accuracy of the simulation is evaluated on the basis of how well the model’s storage variation aligns with the observed storage data over time, confirming the model’s effectiveness in replicating the actual system dynamics. This systematic approach provides a robust framework for simulating the SPIK system and assessing its performance, especially in the absence of predefined operational rules. Through the careful definition of zones, rules, and relevant parameters, the simulation can closely mirror the real-world behavior of the reservoir system, providing a reliable tool for future decision-making and water management.

5.3 Calibration and validation of the model

The modeling process began with the integration of the case study map developed via ArcGIS, which included the locations of streams, reservoirs, and the elevation model. This map was then imported into the simulation environment, where the physical parameters of the reservoirs were introduced, ensuring the representation of the system’s characteristics. Transfers from the Beni Amrane and Hamiz reservoirs to the Keddara Reservoir were incorporated via the diverted outlet tool, which allowed for the simulation of controlled transfers that can be stopped via gates. This functionality is crucial, as it reflects the actual operation of the system, where water transfers are modulated on the basis of operational decisions.

For the routing in the simulation, a null routing approach was adopted because minimal water losses were observed in the system. Correlation analysis between the water transferred from Beni Amrane and the water received in Keddara revealed a high correlation of over 80%. Similarly, the correlation between water transferred from Hamiz to Keddara was exceptionally strong, at approximately 99%. These high correlations demonstrated that the transfers between the reservoirs are highly consistent, justifying the use of null routing in the model, as it indicated minimal losses during the transfer process.

To assess the accuracy of the model, both calibration and validation steps were performed. The calibration process involved the use of data from 2000--2003, with a particular focus on the drought period, to evaluate whether the operational settings in the model aligned with the actual conditions of the case study. The simulated storage data for the three reservoirs (Keddara, Beni Amrane, and Hamiz) are compared with the observed storage values, and the model is iteratively refined until an acceptable correlation coefficient is achieved.

Following successful calibration, the model is validated via data from the period from 2004--2020. The resulting correlations for all three reservoirs are high, further confirming the model’s accuracy in replicating real-world reservoir dynamics. This stepwise validation process ensures that the simulation is a reliable tool for future operational predictions and decision-making.

Figure 5.2 (a, b, and c) present the results of the simulation conducted for the reference scenario. The operation rule applied in this simulation was a function release, whereas the water allocation was modeled via time series data due to the absence of a specific operational rule for water allocation in the study area. The primary objective of this simulation is to develop a model that closely mirrors the real-world system, ensuring its accuracy and reliability. The high correlation between the observed and simulated storage data, with R^2 values of 0.9986, 0.8675, and 0.9903 for Keddara, Beni Amrane, and Hamiz, respectively, indicates that the model effectively replicates the actual reservoir behavior, thereby confirming its validity for operational decision-making.

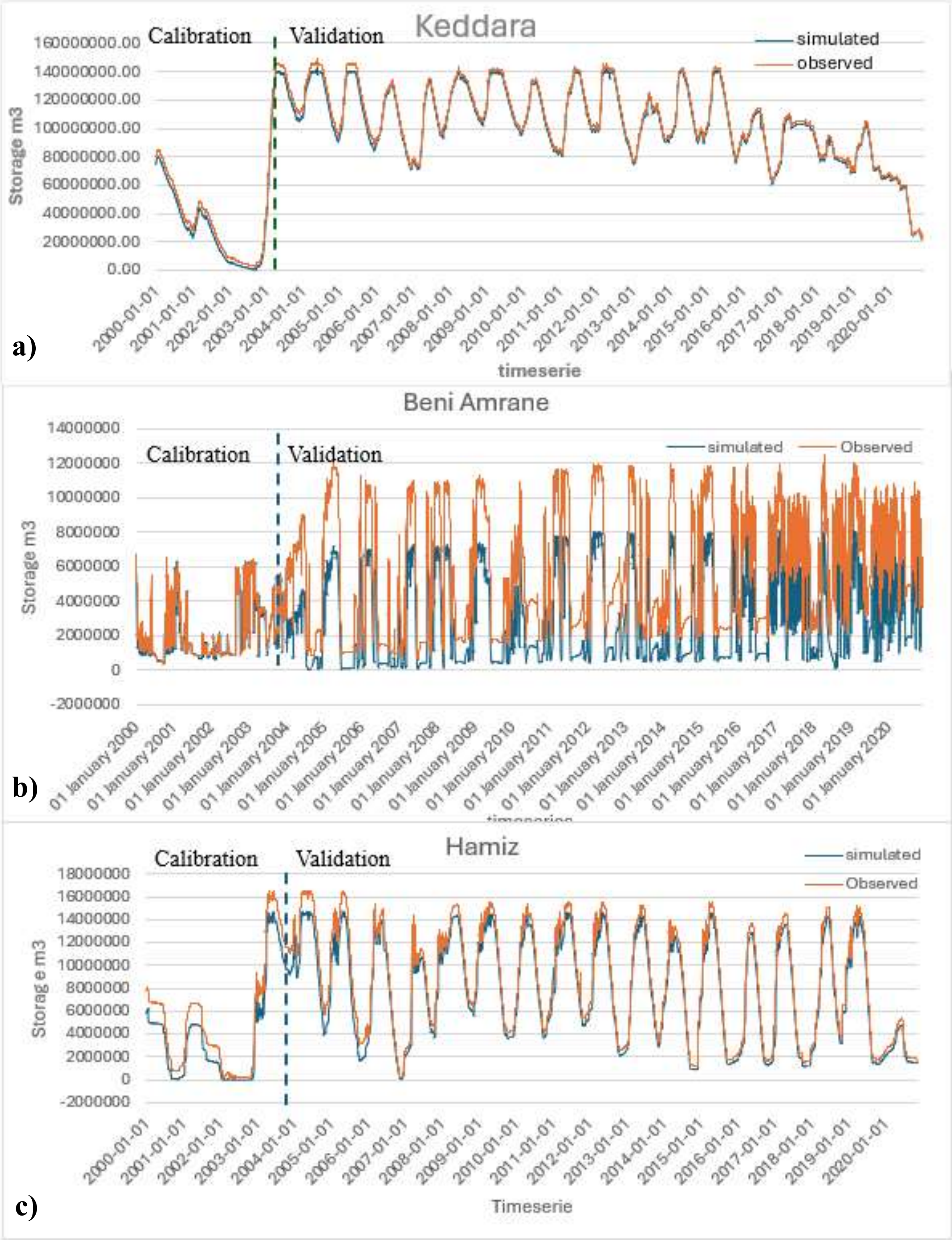

Figure 5.2: Calibration and validation results for SPIK reservoirs (a) Keddara; b) Beni Amrane; c) Hamiz)

Table 5 presents the calibration and validation results of the HEC-ResSim model for three reservoirs, namely, Keddara, Beni Amrane, and Hamiz, showing the correlation coefficients (R^2) for the calibration period (2003) and the validation period (2004--2006). For the Keddara Reservoir, the model demonstrated a strong correlation of 0.85 during calibration in 2003, which increased to 0.89 during validation, indicating that the model performs well over different time periods. Beni Amrane Reservoir, however, exhibited slightly lower correlation values, with values of 0.81 during calibration and 0.83 during validation, suggesting that while the model is still effective, there may be some limitations in accurately simulating its operational behavior. The Hamiz Reservoir showed the best performance, with very high correlations of 0.97 in 2003 and 0.89 during the validation period, reflecting an excellent fit between the simulated and observed data. Overall, the model demonstrates good reliability in simulating the operations of reservoirs, with Hamiz performing particularly well, whereas Beni Amrane may require further refinement for improved accuracy.

Table 5.1: HEC-ResSim model calibration (2000--2003) and validation (2004--2020)

Reservoir	R2 Calibration (2000-2003)	R2 Validation (2004-2020)
Keddara	0.9998	0.9983
Beni Amrane	0.8875	0.9354
Hamiz	0.9925	0.9936

5.3 Reservoir Operation Simulation During Extreme Precipitation

In this study, two distinct conditions, representing flood and drought events, are selected on the basis of the available data from survey feedback and historical reservoir data. These conditions are used to analyze the operational behavior of the SPIK reservoir system under extreme circumstances. The selected conditions serve to thoroughly examine the system's performance and propose optimization scenarios aimed at improving its resilience and operational efficiency during such events. The choice of flood event presents a challenge, as historical data are required to determine whether an extreme event is occurring. For this study, historical inflow time series data from 2000--2020 for each reservoir in the SPIK system provided valuable insights into the inflow patterns. However, no direct data on the specific flow rates that could cause downstream flooding are available. The following question arises: how can extreme events be defined and identified in the absence of explicit flood data?

One approach is to use spillway release as a potential indicator of extreme events. Each time the spillway is triggered, it could be considered an indicator that the flow has exceeded a certain threshold, potentially causing downstream flooding. While this approach could be useful, it still lacks the granularity needed to predict the exact impact of inflow on the downstream region. To address this gap, operational insights provided by the Keddara reservoir operator are utilized, with a specific historical event in 2012 being mentioned. According to the operator, the management of the reservoir during that period was unsuccessful, leading to a flood downstream, which was triggered by a combination of heavy precipitation and release from the reservoir. Upon further investigation, supporting evidence of this flood event was found from publicly available sources (Koubabi, 2012), which confirmed that the combination of extreme rainfall and water release from the reservoir contributed to downstream floods. As a consequence of the flood event, the road to neighboring agglomerations in Boudouaou, where nearly 150 families reside, was cut off for 5 days. This event provided a useful historical reference to model flood scenarios and optimize reservoir operation for similar future events. To propose a more effective approach to manage such extreme precipitation events, optimization scenarios are developed on the basis of the 2012 flood event.

5.3.1 Simulation results of the reservoir system during the 2012 flood event

The simulation of reservoir operation under heavy precipitation was conducted on the basis of historical inflow data and insights provided by the Keddara reservoir operator, with a focus on the 2012 flood event. Five scenarios were tested in addition to the reference scenario. The scenario simulation consists of two distinct approaches. The first approach focuses on bottom outlet releases to control high inflows, where prereleases are made through the bottom outlet at 90% of the total reservoir capacity (144 m elevation), in accordance with the operator's guidelines. The second approach simulates different interbasin transfer situations, where water transfers between the Hamiz and Keddara reservoirs are managed under varying conditions. The results highlight key differences in flow management and flood mitigation under these two approaches.

Reference scenario (Scenario 0): In the reference scenario (green line, Figure 5.3), no prerelease mechanism is used until the water level reaches the spillway elevation. As expected, this scenario leads to spillway activation when water storage reaches its threshold, resulting in the uncontrolled release of water. The green line in the lower section of Figure 13 illustrates the sharp increase in flow when the spillway is triggered, with water released causing a peak in flow of 74 cms. This reactive release mechanism is typical of the conventional approach to reservoir operation, where the spillway works only when the water level reaches the maximum allowable capacity.

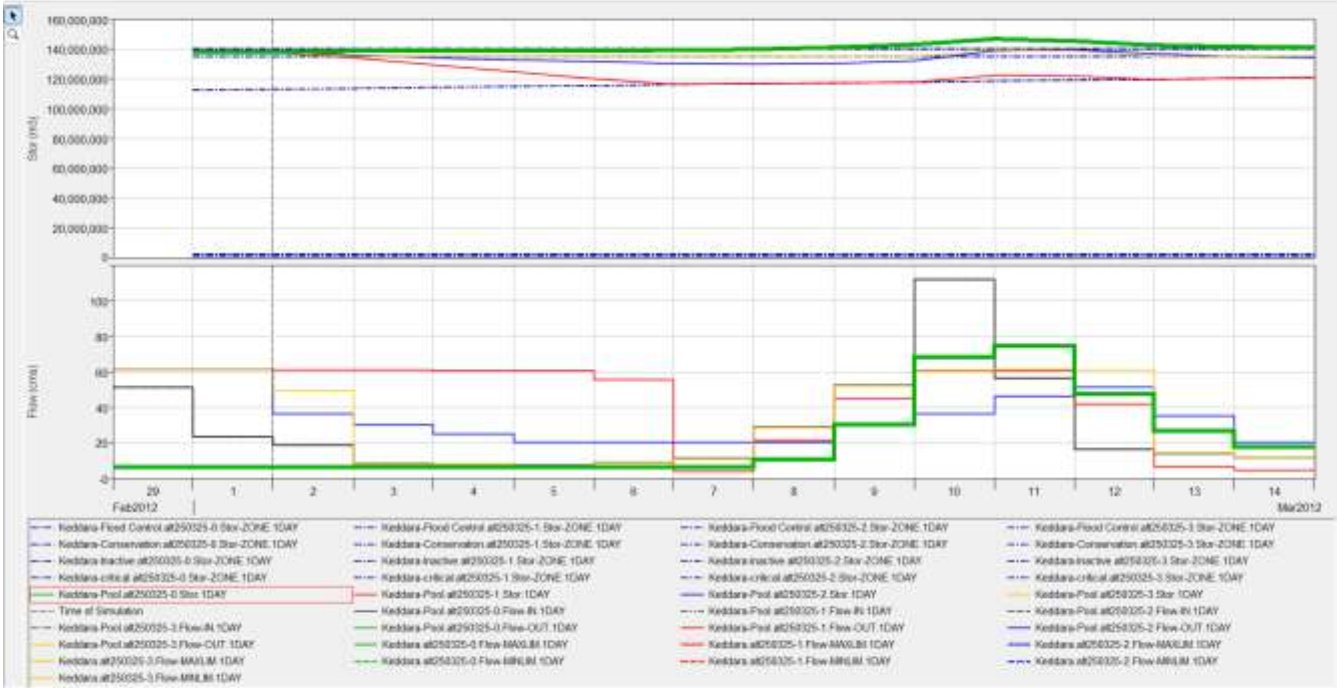

Figure 5.3: Comparison of flood control scenarios for the 2012 event via HEC-ResSim, including the reference scenario (highlighted in green)

i. Reservoir-based operation scenario

Scenario 01: Fixed bottom outlet release with guide curve priority

In Scenario 01, the system operates under the bottom outlet release strategy, with the conservation zone being defined as a guide curve that is given high priority in the decision-making rules (red plot). This approach directs the release to follow a pattern that attempts to maintain the reservoir's elevation close to the specified guide curve rather than focusing primarily on flood control objectives (Figure 13). As a result, the release rates are relatively high, reaching up to 60 cms for extended periods. This strategy aims to prioritize the conservation of water levels in the reservoir by adhering to the guide curve, which is beneficial for maintaining a steady reservoir level but may not be optimal for flood control.

Scenario 2: Adaptive Release with Prefood Control Zone

Scenario 2 introduces a new conservation zone, defined as a preflood control zone, with the reservoir elevation fixed at 144 m—1 m below the spillway elevation. This elevation serves as a critical boundary, ensuring that the reservoir is maintained at a level that minimizes the risk of spillway activation while still maintaining a sufficient water volume for operational purposes. The strategy involves setting a rule to regulate the bottom outlet releases on the basis of the reservoir's elevation at this defined threshold.

The first attempt in this scenario involved controlling the release by setting the bottom outlet at half capacity, which corresponds to 27.5 cms. The results from this test reveal a significant decrease in peak flow (approximately 70%) compared with that in the reference scenario. This attenuation suggests that the bottom outlet, even at half its maximum capacity, can effectively reduce the peak flow that enters the reservoir. However, this approach still resulted in a slight spillway exceedance of 0.06 meters. This minor overflow indicates that while the release strategy is partially successful in managing the inflow, it remains sensitive to extreme flow events, and spillway activation is still possible under higher-than-expected inflows. To address this issue, a second attempt was made by loosely mirroring the inflow trends in a stepwise manner (blue line of Figure 5.4 and Figure 5.5), incorporating delays to avoid abrupt changes in the reservoir level. This new release strategy proved to be more effective, resulting in a peak flow attenuation of over 30% compared with the reference scenario, without triggering any spillway use. The adaptive release successfully ramped up around inflow peaks, gradually decreasing once the inflow receded. The strategy demonstrated effective flood mitigation by aligning the release rate with the changing inflow patterns while also ensuring that water storage in the reservoir remained close to 95% of its full capacity.

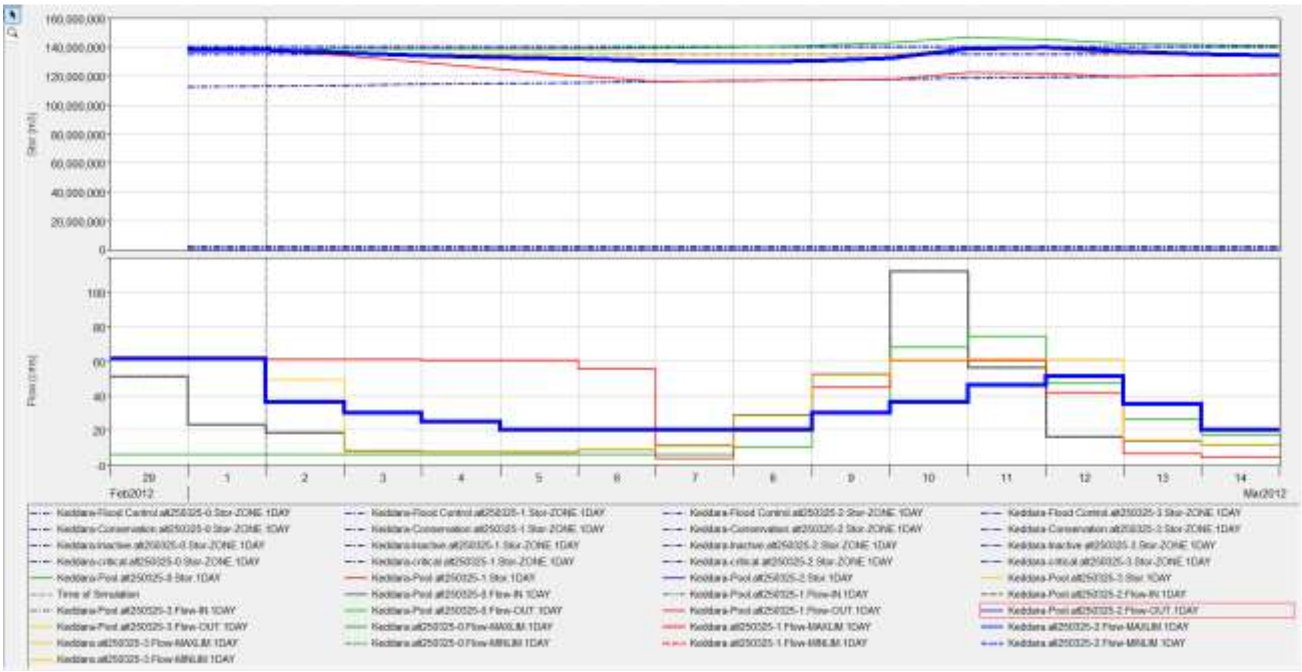

Figure 5.4: Comparison of flood control scenarios for the 2012 event, highlighting the best-performing scenario (highlighted in blue)

Scenario 03: Fixed guide curve with rule setting for flood control

In Scenario 03, the approach is similar to that in Scenario 2 in terms of defining a new flood control zone with an established rule setting. The key difference lies in the specific implementation of the release strategy. In Scenario 2, the releases were defined explicitly through the bottom outlet, with priority given to water conservation and flood mitigation. In contrast, Scenario 3 employs a guide curve rule, which prioritizes adjusting the reservoir's elevation to match the zone elevation of 144 meters. This approach aims to maintain the reservoir elevation at the target level, but it does not allow for as much flexibility in controlling the release rate on the basis of inflow conditions (yellow plot in Figure 5.5). The results reveal that, despite the use of the guide curve, the attenuation of peak flow is relatively modest, with only a 12% reduction compared with the reference scenario. This indicates that the fixed guide curve strategy is less effective in mitigating peak flows during extreme inflow events. Moreover, the release pattern in this scenario closely resembles the spillway pattern, suggesting that the system may not be responsive enough to effectively manage the variability of inflows. The primary drawback of this approach is that the guide curve rule does not incorporate the dynamic adjustments needed for real-time flood management, which limits its effectiveness during extreme events where rapid adaptation is crucial.

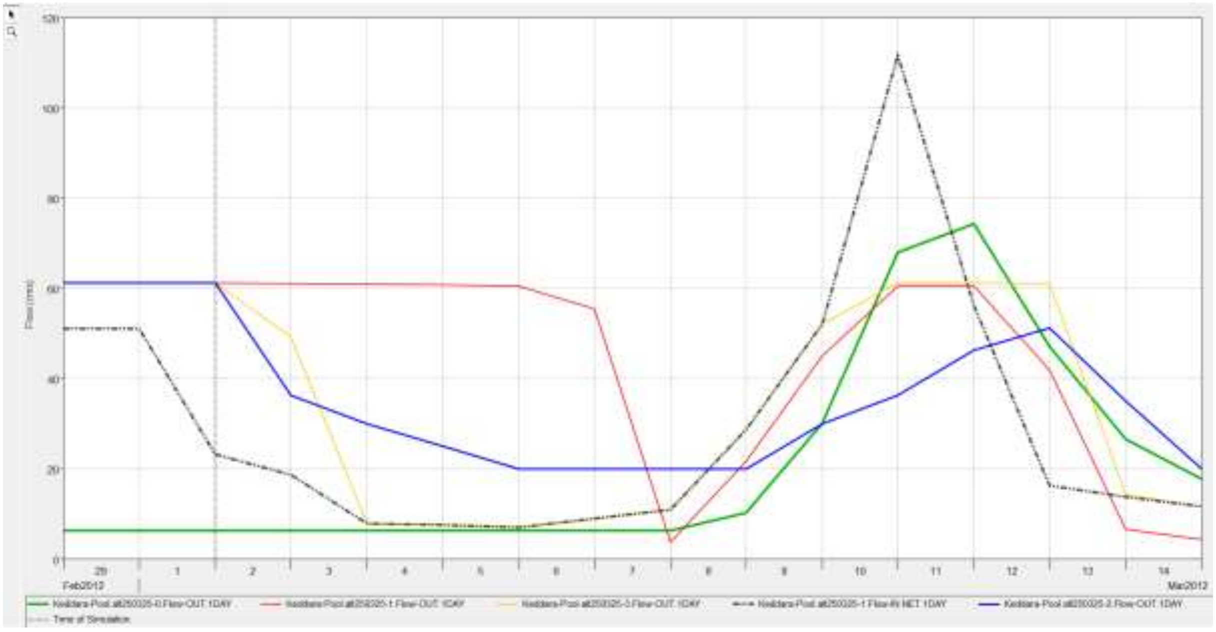

Figure 5.5: Peak flow attenuation in the Keddara reservoir during the 2012 event based on scenario simulations

ii. Transfer-based operation scenario simulation

Recognizing the significant impact that interbasin transfers can have on overall system behavior, the scenarios are expanded to study the operation of interbasin transfers and their role in flood management.

In this refined approach, the key question becomes how water transfers between reservoirs influence the overall flow dynamics and contribute to flood risk during periods of extreme inflows. An analysis of the inflow data revealed that transfer from Hamiz accounts for approximately 42% of the total inflow to Keddara during extreme events. On the basis of this finding, the scenarios are designed to explore two primary conditions: (1) the baseline scenario, where the interbasin transfer from Hamiz is applied per historical data, and (2) a scenario where no interbasin transfer occurs between Hamiz and Keddara, simulating the system's behavior with only local inflows.

By introducing the interbasin transfer operation as a key component of the reservoir management strategy, these new scenarios aim to assess the impact of interbasin operations on system performance, particularly with respect to flood mitigation, storage management, and downstream risk reduction. This adjustment allows for a comprehensive evaluation of how interreservoir water movements influence flood dynamics, providing crucial insights into how IBT management can be optimized to increase the overall resilience of the water supply system, particularly during extreme precipitation events.

Scenario 4: The operation of the Keddara reservoir is analyzed under the condition that interbasin transfer from Hamiz to Keddara is stopped when the Keddara reservoir reaches 95% of its full capacity (Figure 5.6). The reference scenario characteristics are maintained, with no bottom outlet releases being implemented. This scenario simulates a situation where spillway operation becomes the sole method of water release from reservoirs.

When the transfer from Hamiz stopped, the inflow to Keddara consisted solely of local precipitation and streamflow, without the added volume from Hamiz. As shown in the figure, the Keddara Reservoir reached its full capacity during the event, and spillway release was triggered. However, the amount of water spilled in 33 cms is notably less than that in the reference scenario (74 cms). This suggests that although Keddara reached full capacity, the absence of transfer from Hamiz helped slow the rate at which the reservoir was filled, reducing the total amount of water that needed to be spilled through the spillway. The results suggest that by stopping interbasin transfer, Keddara is able to manage its storage levels more effectively, allowing the spillway to be activated later, thus avoiding the rapid and large-scale release of water.

Like in Hamiz Reservoir, minimal spillway activation occurred, demonstrating that the decision to stop the transfer effectively reduced the potential for large-scale water release. This scenario highlights a situation where the system relies solely on spillway operation and appears to be a safer management strategy when transfers are stopped at the 95% threshold of the recipient reservoir.

Scenario 5: the simulation includes bottom outlet releases in both the Keddara Reservoir and the Hamiz Reservoir (red plot). Notably, this scenario is set under the condition that there are no interbasin transfers from Hamiz to Keddara. Instead, the bottom outlet releases are used to control the water levels, bringing each reservoir's elevation closer to the guide curves established for their operation. The bottom outlet release in the Keddara reservoir is carefully controlled to ensure that the reservoir's elevation is in line with its guide curve. This is evident in the red line in the figure, which shows the gradual increase and subsequent release of water through the bottom outlet. In this scenario, no spillway operation was triggered, as the bottom outlet releases were sufficient to manage the excess water. The flow rates observed in the red line (which corresponds to the bottom outlet operation) show that the system was able to manage the water levels without resorting to the spillway. The elevation of the Keddara reservoir (shown in the top graph) remained within the desired range, with no sharp fluctuations in water level. The gradual and controlled release through the bottom outlet helped maintain steady reservoir operations. However, the flow released through the bottom outlet gates is still relatively high compared with the flow released through the spillway, which requires more refined releases.

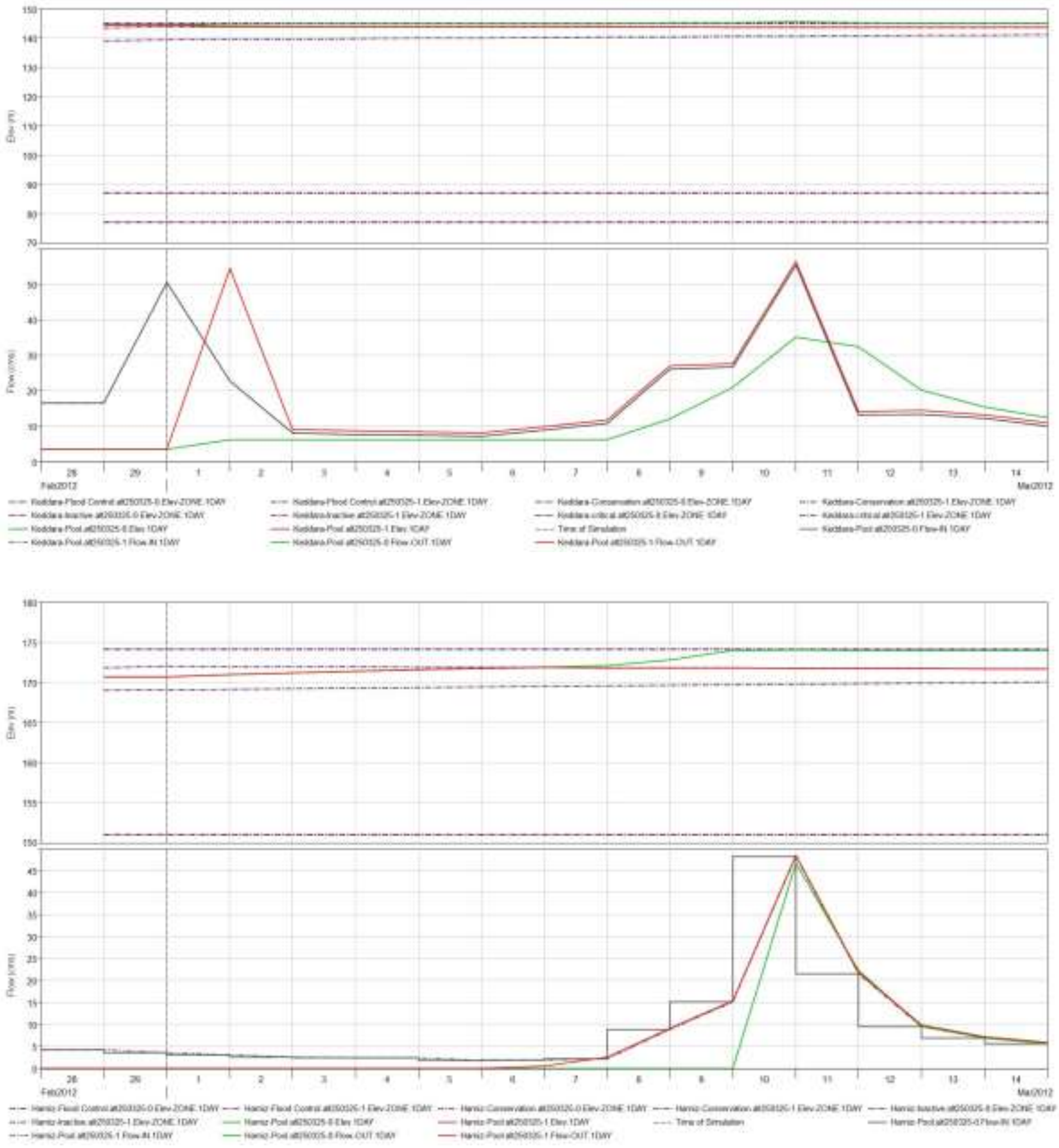

Figure 5.6: Keddara and Hamiz reservoir behavior under scenarios 04 and 05 simulations

Similarly, Hamiz Reservoir used bottom outlet releases to manage the water levels during the event, as shown by the red line in Figure 16. The water released through the bottom outlet was aimed at keeping the elevation within the guide curve set for Hamiz. As with Keddara, this controlled release avoided any spillway operation. The inflow (black line) was effectively managed by the bottom outlet, and the water level remained below the critical threshold that would have otherwise triggered spillway activation. However, the flow of the bottom outlet release in Keddara is relatively high (60 cms) compared with the spillway flow release, which suggests refinement of the bottom outlet release operation for better optimization results.

The Beni Amrane Reservoir follows specific guidelines for flood control, which prioritize the use of bottom outlet gates for prereleases, particularly during periods of high inflows or extreme precipitation. These guidelines are designed to prevent the activation of the spillway by gradually releasing water, thus mitigating the risk of downstream flooding. In Scenarios 4 and 5, the operation of the bottom outlet gates aligns with the reservoir's established flood control strategy, contributing to more controlled water management. However, a critical operational discrepancy is observed during the implementation of bottom outlet releases in both scenarios, wherein the interbasin transfer from Beni Amrane to Keddara was maintained despite explicit instructions from the operator (Figure 5.7). According to reservoir operation guidelines, transfers and bottom outlet releases should not occur simultaneously because of the relatively small difference in elevation between the elevation of the bottom outlet gates and the water intake. This operational conflict can lead to several negative consequences, particularly concerning water quality.

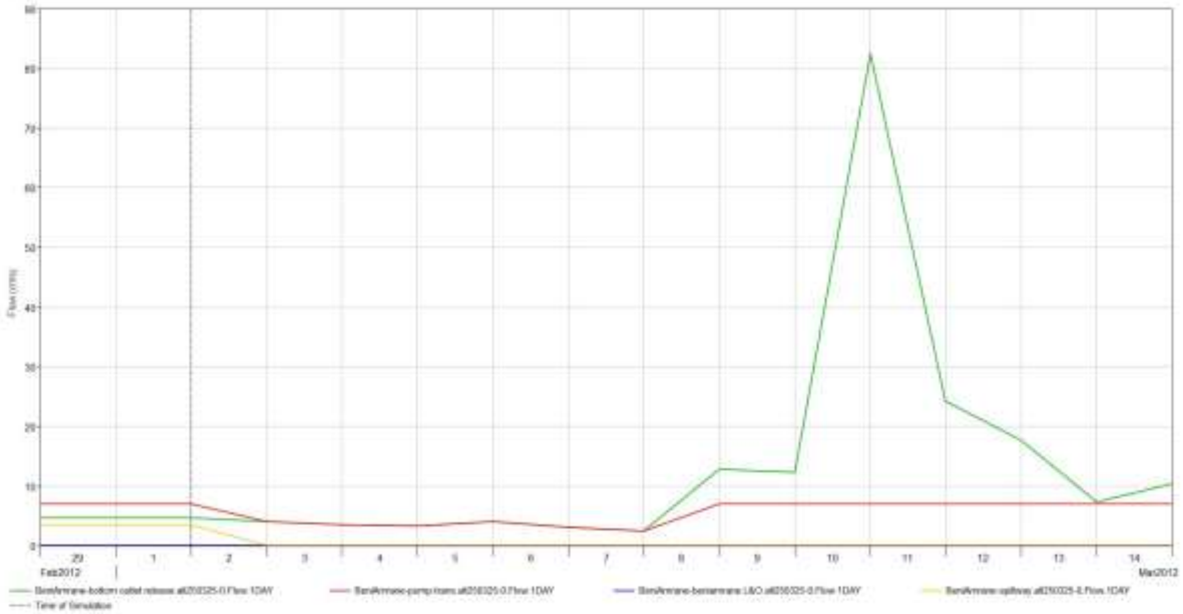

Figure 5.7: Beni membrane transfer and bottom outlet release working simultaneously

5.4 Optimizing the Drought Response: Scenario Simulation with HEC-ResSim

The approach to managing drought conditions in this section is based on the analysis of the system's storage capacity, where a significant reduction in storage is observed, ultimately leading to near-zero levels of reservoir capacity caused by periods of minimal inflows. This period is considered a drought scenario, and an optimization approach is proposed to manage water resources more effectively during such conditions. The focus will be on analyzing the storage variation in the Keddara reservoir to identify a period that reflects drought conditions. This analysis involves examining historical data on the reservoir's storage levels, with particular attention given to the periods when the storage consistently falls below the required thresholds provided by the operator (under 4 Mm3) and the reservoir's failure to reach its normal level, indicating water scarcity or drought. The aim is to assess how the reservoir responds under drought conditions. On the basis of the simulation results, optimization rules are proposed to improve water management during droughts, ensuring that the available water is used efficiently and that reservoir performance is maximized.

Figure 5.8 shows the monthly storage variation in the Keddara Reservoir from 2000-2023, alongside the drinking water supply (DWS) allocation for the same period. From the graph, two distinct drought periods can be identified on the basis of the storage levels of the reservoir. The first drought period occurred from approximately 2000-2003, when the storage levels significantly decreased, reaching extremely low values (2.8 Mm^3) and remaining below the typical thresholds (under 4 Mm^3) for several months. This decrease in storage is consistent with reduced inflows and insufficient reservoir replenishment to meet demand. The second drought period occurred more prominently from approximately 2020-2023, when the reservoir again experienced a prolonged period of low storage, reaching 1.5 Mm^3. These two periods represent critical moments in the history of the Keddara Reservoir, during which water management strategies must have been strained to meet the water demands. The selection of the second drought event, which occurred from 2020-2023, is driven primarily by the availability and comprehensiveness of the data. The time series data spanning from 2000-2023 allow for a thorough examination of the drought dynamics during this period, as they provide sufficient historical context to understand the progression of the drought. In contrast, the first drought period, from 2000-2003, lacks complete data, making tracking the system's behavior before and during the drought impossible. By analyzing this period of low storage, scenario simulation is used to propose optimized operational strategies to improve the reservoir's response to future drought events, ensuring that the water supply is sustained despite reduced inflows.

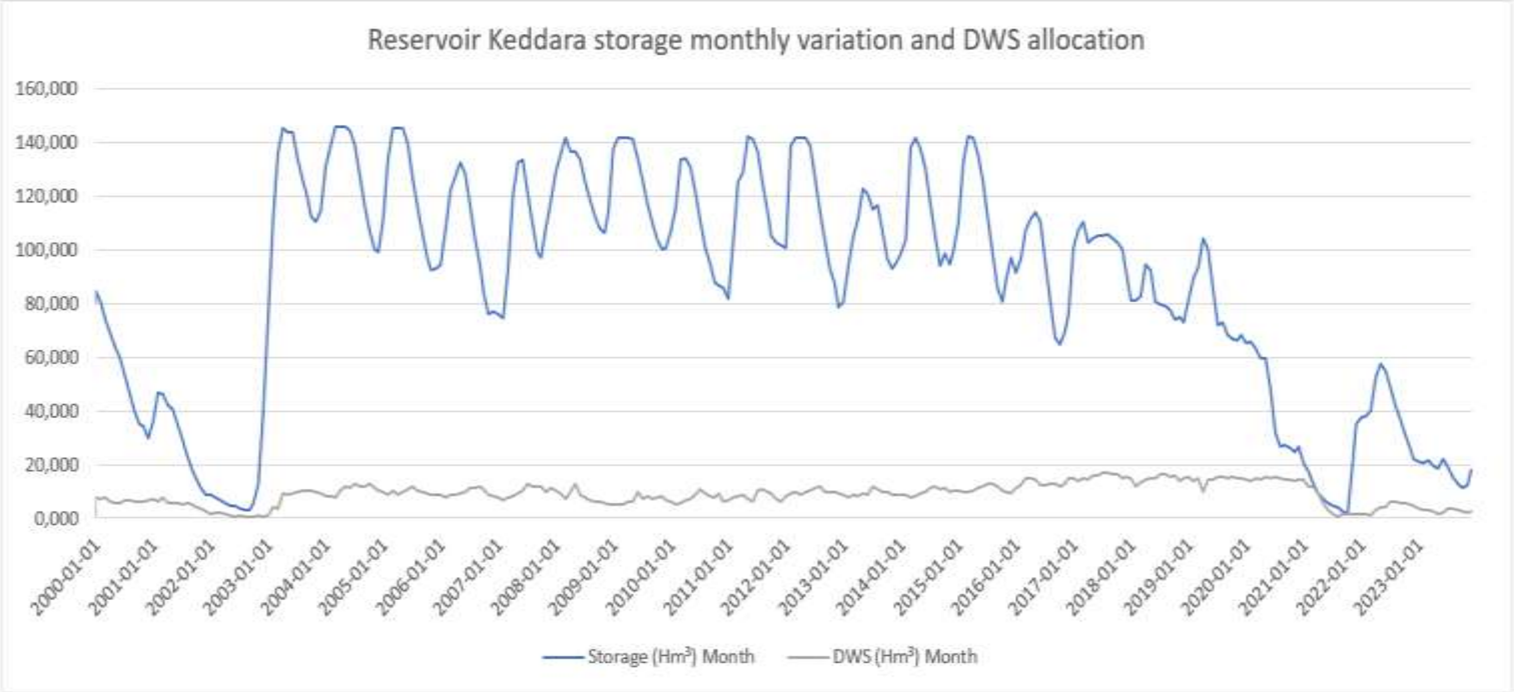

Figure 5.8: Monthly variation in reservoir Keddara storage and drinking water supply allocation

To optimize water allocation for the SPIK, a comparative analysis was conducted between the baseline and optimized scenarios (Figure 5.10), with a focus on enhancing the system's reliability during drought periods. The baseline scenario, represented by the green plot, indicates the water allocation as it was historically managed, whereas the optimized allocation, depicted by the blue plot, reflects the changes made on the basis of the optimization approach.

The optimization process was guided by the principles of the hedging rule. Hedging rule policies are implemented to ration the water supply in anticipation of potential low inflows in the near future. These policies allow for a limited deficit in current water delivery to minimize the risk of more significant water or energy shortages down the line [Bower et al., 1962 in (You & Cai, 2008)].

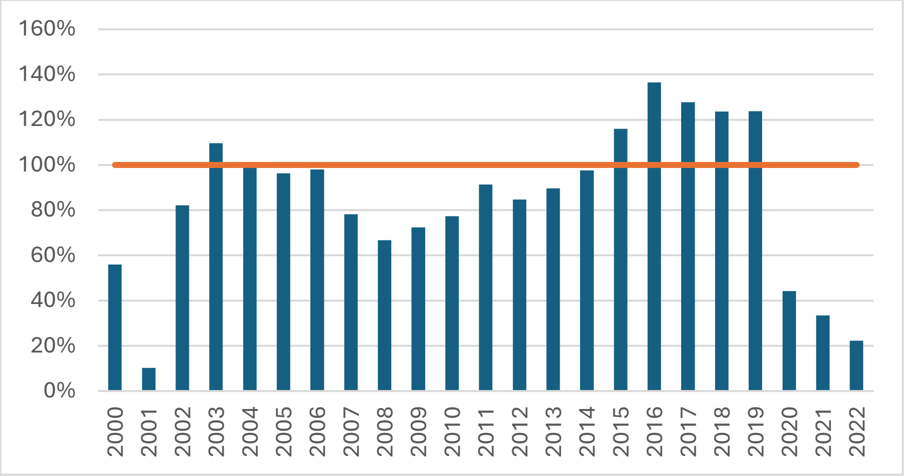

Figure 5.9: Annual demand satisfaction in SPIK 2000--2023

Before the drought period, the water supply consistently exceeded the demand within the SPIK system. This excess supply, while possibly beneficial under normal conditions, was considered unsustainable given the anticipated drought (Figure 5.9). Therefore, adjusting water allocation is applied by reducing the water supply to match demand during noncritical periods, thus conserving water for more critical times. As a result, the supply in the optimized scenario (blue plot) is brought more in line with the demand, effectively reducing the surplus water supplied before the drought. This proactive water conservation strategy increased the reliability of the system by ensuring that more water was available during drought, ultimately improving the system's overall resilience to extreme events.

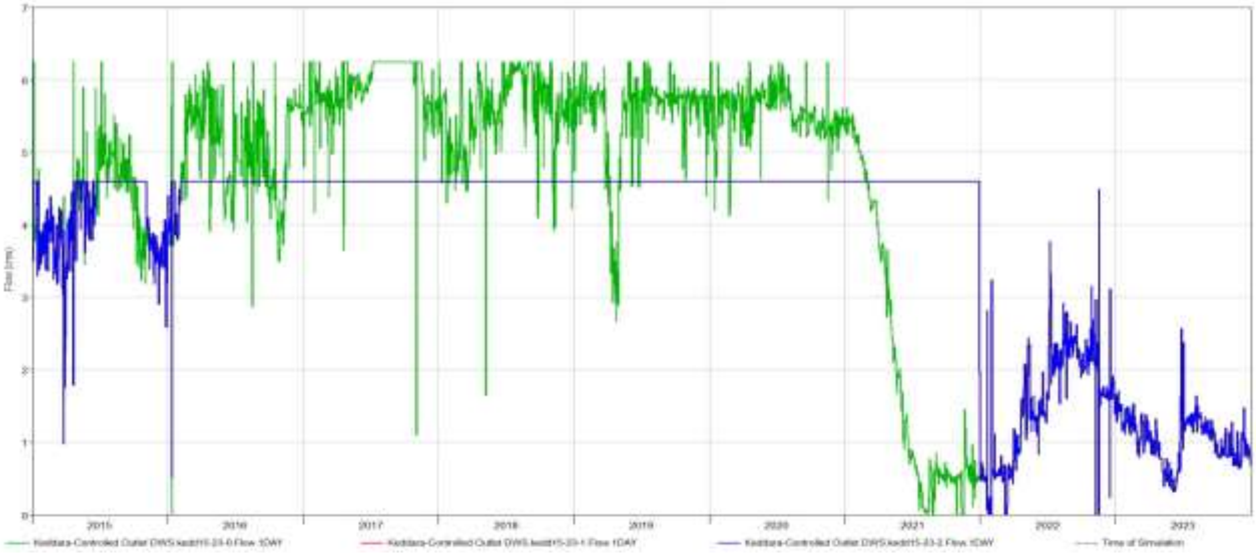

Figure 20: Water allocation based on the reference and optimized scenario simulations

5.4.1 Assessment of System Performance: Reliability, Resilience, and Vulnerability of the water supply within SPIK

The performance of water resource systems is often evaluated on the basis of simple criteria such as average benefits, variance, and operation variables. While these measures are useful, they do not provide a comprehensive understanding of system performance under varying conditions. To address this, the use of reliability, resilience, and vulnerability (RRV) indices, proposed by (Hashimoto et al., 1982), offers a more advanced approach for the classification and performance evaluation of water resource systems. These indices are particularly valuable when assessing the system's response to different operational scenarios, particularly under varying demand and supply conditions. In this context, reliability, resilience, and vulnerability are used to measure the system's ability to meet water demands. The key criterion in this analysis is the comparison between the daily water allocation and the daily water demand. If the allocated water is less than the demand, the system is considered to fail to meet the required water supply. In this approach, the performance of the drinking water supply system is assessed by comparing the daily water allocation provided by the system to the daily water demand. For each day in the simulation period, the allocated water is compared to the required demand. If the allocated water meets or exceeds the demand, the system is considered to have performed satisfactorily for that day. However, if the allocated water is less than the demand, the system fails to meet the required supply, indicating an unsatisfactory period. These unsatisfactory periods are identified and used to measure the system's overall performance.

Equations (5.1), (5.2), and (5.3) below illustrate the calculation of reliability, resiliency, and vulnerability in the context of evaluating water resource performance:

Reliability (Cr): This index measures the frequency at which the system fails to meet the expected performance criteria over the simulation period. It is defined as the proportion of time periods during which the system performs satisfactorily.

$$Cr = \frac{\sum_{i=1}^{T} Zi}{T} \qquad \text{............................ (5.1)}$$

where *Zi* = 1 if the allocated water is greater than or equal to the demand and 0 if it is lower. T is the total number of days in the analysis period.

Resiliency (Crs): Resiliency reflects the recovery rate of the system following a failure. It is calculated by the proportion of the time during which the system returns to a satisfactory state after being in an unsatisfactory state.

$$Crs = \frac{\sum_{i=1}^{T} Wi}{T - \sum_{i=1}^{T} Zi} \text{ .... } (5.2)$$

where Wi is a weighted value that represents the system's recovery from unsatisfactory states, and Zi represents the unsatisfactory periods.

Vulnerability (Cv): This index quantifies the extent of failure in the system. It is based on the maximum deviation from the satisfactory range for each water resource.

$$Cv = \max(\sum_{i=1}^{N}(c - Xi) \text{ .... } (5.3)$$

where *Xi* is the allocated water on day *i* and *C* is the unsatisfactory threshold (i.e., the minimum required water demand). *N* represents the total number of unsatisfactory periods.

The tables present the performance indices for assessing the drinking water supply under two scenarios: the reference scenario and the optimization scenario. These indices—reliability, resilience, and vulnerability—are calculated for various periods, including total periods, drought periods, and normal conditions. Below is an analysis and discussion of the results, followed by a suggestion regarding the periods used for comparison.

Table 5.2: Performance analysis of the simulation results

Reference scenario			
period	reliability	resilience	vulnerability
2000-2024	37%	8.78%	23%
2020-2023 (drought period)	31%	1%	41%
2004-2016	35%	14%	14%
Proposed optimization scenario			
2000-2024	43%	8.78%	20%
2020-2023 (drought period)	50%	0.14%	29%

2004-2016	38%	12%	14%

On the basis of Table 06, which shows the performance parameters (reliability, resilience, and vulnerability) for the drinking water supply system over different periods, the following observations can be made:

In the reference scenario, the system's performance reveals notable weaknesses, particularly during the drought period (2020--2023). The reliability index during this period is the lowest, at just 31%, indicating that the water supply is highly unreliable during times of water scarcity. In comparison, the total period (2000--2024) reliability is slightly higher at 37%, with a small increase observed during normal conditions (2004--2016) at 35%. Despite these improvements, the overall reliability of the system remains relatively low, especially under drought conditions, emphasizing insufficient water supply management during extreme events. The system's resilience is similarly weak, with a value of 1% during the drought period, indicating poor recovery capabilities when water availability is limited. This contrasts sharply with the total period resilience of 8.78% and 14% under normal conditions, further highlighting the system's inability to adapt and restore itself during periods of stress. The vulnerability index was also highest during the drought period, at 41%, suggesting that the system is extremely vulnerable to disruptions in supply under water scarcity conditions. Vulnerability decreases to 23% for the total period and 14% during normal conditions, but it remains a significant issue during droughts. These results underscore the system's poor preparedness and lack of resilience to handle long-term water scarcity, which could hinder its long-term sustainability.

In the optimization scenario, the system significantly improved across key performance metrics, especially during the drought period (2020--2023). The reliability index during this period is 50%, nearly double that of the reference scenario (31%), indicating that the optimized system performs better at meeting water demand even during drought conditions. For the total period (2000--2024), reliability increases to 43%, showing an overall improvement in the system's ability to maintain a consistent water supply across both normal and extreme conditions.

Although the resilience index decreases in the optimized scenario from 1% to 0.14% due to a reduction in the number of failures, it is important to highlight that this is indicative of a more stable and well-functioning system. The decrease in failures suggests that the optimization strategies have improved the system's overall performance, leading to fewer instances where recovery is necessary. This implies that the system, while showing a lower resilience score in the traditional sense, is actually more resilient in practice, as it now requires fewer recoveries from unsatisfactory states. This highlights the effectiveness of the optimization strategies in enhancing system stability and predictability under extreme conditions.

The vulnerability index in the optimized scenario is lower (29%) than that in the reference scenario (41%) during the drought period, indicating that the system is less vulnerable to disruptions in supply during extreme events. For the total period, the vulnerability decreases to 20%, a significant improvement from the reference scenario’s 23%, highlighting the optimized system’s greater robustness and ability to manage stress more effectively.

5.4.2 Assessment of SPIK supply performance via WEAP for pessimistic and optimistic scenarios

The water evaluation and planning (WEAP) tool is used to simulate and assess the performance of the SPIK reservoir system under extreme conditions, specifically during drought and wet periods. The WEAP model generates scenarios based on a reference scenario, utilizing historical hydrological data and predefined operational rules to simulate the behavior of the reservoir system during periods of low inflow (drought) and high inflow (heavy precipitation). While WEAP can provide insights into a variety of aspects of water management, this study focuses on using the model exclusively to assess the water supply system’s performance under extreme conditions.

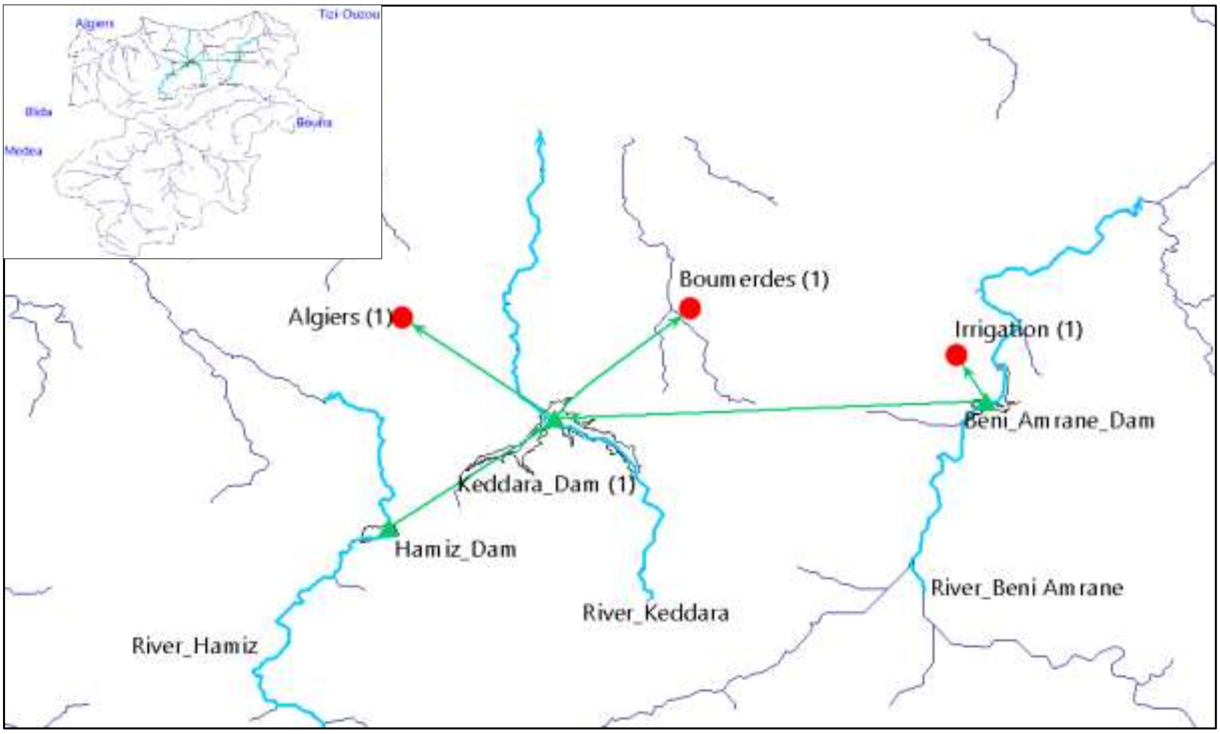

Figure 5.11: SPIK schematic on WEAP

The schematic map above (Figure 5.11) illustrates the key components of the SPIK system, including the interconnected Keddara, Hamiz, and Beni Amrane Dams, along with key demand sites such as Algiers, Boumerdes, and irrigation needs. These components are connected through rivers that facilitate the transfer of water between reservoirs. In this study, WEAP is employed to generate and analyze two specific scenarios—one during drought conditions and another during heavy precipitation events. These scenarios are designed to evaluate the SPIK system's ability to meet water demand during extreme events. The simulations serve as a critical tool to assess the system’s resilience and effectiveness in maintaining a reliable water supply under challenging hydrological conditions, thus contributing valuable insights for optimizing operational strategies for future management.

To assess the performance of the SPIK system during extreme conditions, WEAP simulations were conducted for both drought and wet periods. Unlike previous analyses that used historical data to evaluate system performance, WEAP creates distinct scenarios by generating inflow data on the basis of predefined conditions. These scenarios can be seen as optimistic and pessimistic depending on the level of inflows: the optimistic scenario simulates a scenario with higher-than-average inflows (representing more favorable wet conditions), whereas the pessimistic scenario reflects lower-than-average inflows (mimicking drought conditions). By generating these simulated inflow scenarios, WEAP provides a more dynamic and adaptive view of how the SPIK system performs under water scarcity and excessive rainfall. This simulation approach allows for an in-depth understanding of how the system reacts to varying inflow levels, offering insight into water allocation strategies, interbasin transfers, and flood risk mitigation during extreme events. These findings complement the results from HEC-ResSim, enhancing the overall understanding of the system’s performance. By simulating optimistic and pessimistic scenarios, WEAP contributes to developing optimized operational strategies, ensuring that the system is resilient and adaptable under various conditions. The detailed WEAP simulation results are provided in the the Appendix.

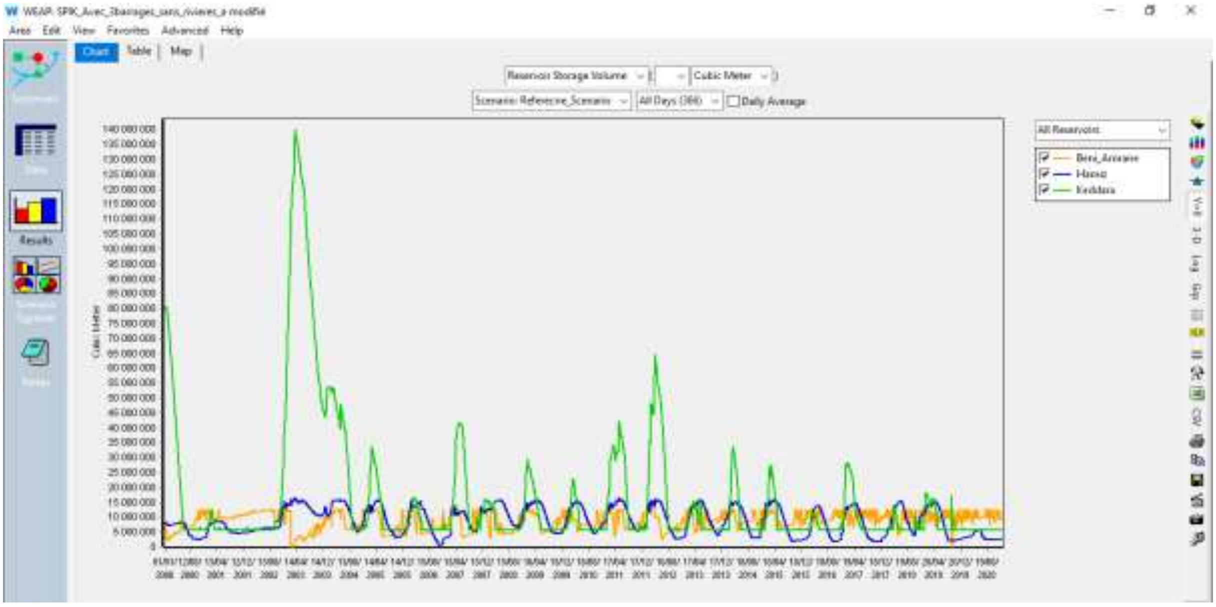

Figure 5.12: SPIK reservoir storage volume variation (reference scenario)

Table 5.3: Summary of the WEAP simulation results

Scenario	Baseline scenario	Water Demand	Dry Period	Wet period
Reliability (%)	26	38	19	51

The WEAP simulation covered the period from 2000--2020 for all the scenarios considered in this study (Table 5.3). Consequently, the results presented in the table correspond to this time frame, reflecting the system's performance during this period, which has annual inflow irregularities. Importantly, when the scenarios for both wet and dry periods are developed, the model parameters are adjusted to prioritize the filling of the Keddara reservoir. This approach is implemented because of Keddara's critical role in providing water to Algiers, ensuring that its capacity is maximized to meet the demand of the capital. The priority given to Keddara is also aligned with the primary focus of this simulation, which is to assess the performance of the water supply system.

In the baseline scenario, where water allocation follows historical data (i.e., water allocation is based on time series data), the reliability of the system is relatively low, at 26%. This suggests that the current allocation strategy is not sufficient to meet the water demand. The low reliability indicates that under the historical allocation system, the system faces difficulties in providing a consistent and adequate water supply.

The second scenario, where the water allocation is directly set according to water demand, shows unexpectedly noticeable improvement in reliability, increasing to 38%. This improvement has been explained in the previous section of the SPIK performance assessment. However, the reliability still falls short, indicating that the SPIK system struggles to meet water needs.

In the third scenario, which represents a dry period or a pessimistic scenario, the system's ability to meet real demand is assessed. In this scenario, the system faces challenges in meeting demand and falls to an alarming reliability rate of 19%.

Finally, in the optimistic scenario, the system’s performance during wet periods is evaluated. During wet periods, the system’s ability to meet demand improves because of the greater availability of water, reaching 51%. This scenario highlights how the system can better handle extreme precipitation events and effectively meet water demand when there is sufficient inflow, provided that the operation rules prioritize the storage and efficient distribution of water.

5.5 Formulation of Reservoir Management Operational Rules: The Synthesis of Historical Data, Simulation Results, and Stakeholder Insights

The development of reservoir operation rules is a critical step in ensuring effective and sustainable water management, especially during extreme events. As the final output of this study, these rules integrate historical hydrological data, simulation results, and stakeholder feedback, providing a comprehensive framework for decision-making. By developing these rules, it becomes possible to optimize reservoir performance, mitigate flood risk, and enhance water supply reliability. Furthermore, these rules serve as practical tools for operators, enabling them to manage water resources efficiently while adapting to changing environmental conditions and minimizing the risk of operational failure.

The first step is to delineate the different zones of the reservoir, which typically include flood control, conservation, and inactive zones. These zones are determined on the basis of reservoir storage levels, and each zone requires a set of operational rules that define how the reservoir should behave under specific conditions.

In the case where no operational sets or guide curves are readily available, as observed in the present study, the development of these operational rules becomes an essential task to construct a model that accurately represents the operational behavior of SPIK. For this purpose, monthly operational data are plotted, specifically focusing on the average elevation levels recorded each month from 2000-2020. The resulting plots enable the delineation of two distinct zones: a high conservation zone and a low conservation zone. The low conservation zone corresponds to a period of low inflow operation, from 2000-2002, where water conservation strategies are likely more restrictive. Conversely, from 2003-2020, a clear operational pattern emerged, suggesting a more stable management approach, which is evident in the elevation plots. The results derived from these operational patterns represent the actual operational policy in place for the SPIK system.

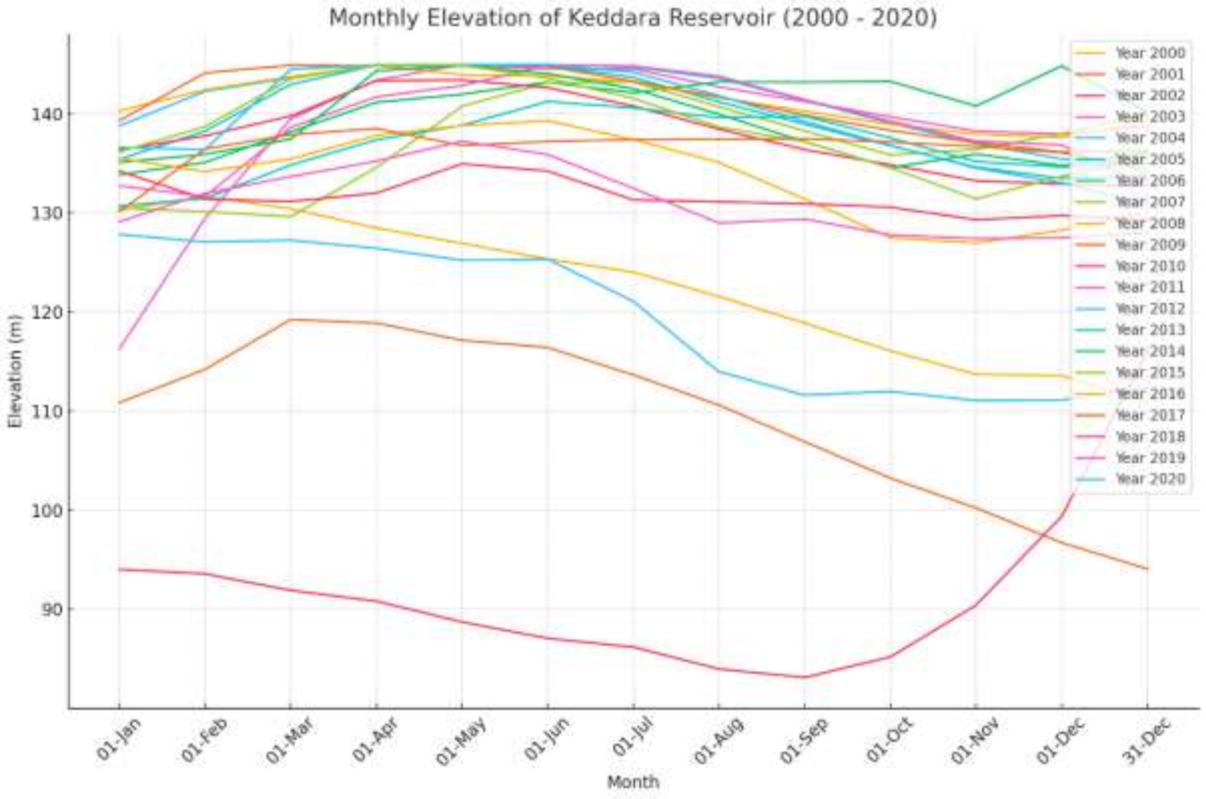

Figure 5.13: Monthly elevation of the Keddara reservoir from 2000--2020

Figure 5.13 shows the monthly elevation of the Keddara Reservoir. Each line represents the reservoir's water level for a specific year (from 2000-2020). This chart visually represents how the water levels fluctuated over time, showing both higher and lower reservoir levels during different months across multiple years. On the basis of this chart, three zones are defined: the first represents high-level conservation ranging from 144--116 m, the second represents lower conservation from 116--87 m, and the third represents the critical conservation zone below 87

m. On the basis of the simulation results, an additional zone defined as the preflood zone is added to manage the flood zone before the flood zone is set at an elevation of 144 m.

Figure 5.14 visually distinguishes these zones, providing a clear representation of the operational strategy of the Keddara Reservoir under varying hydrological conditions.

- Preflood: 144–145 m
- High conservation: 144 m - 116 m
- Low conservation: 116–92 m

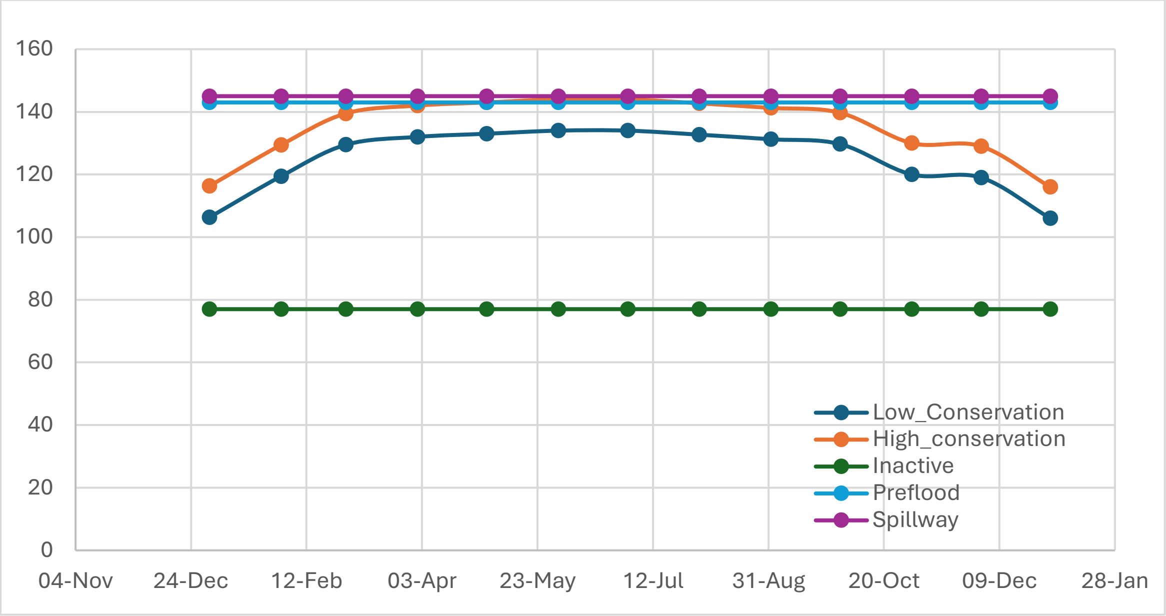

Figure 5.14: Keddara reservoir operational zones

Figure 5.15 presents the operational zones of the Beni Amrane Reservoir, which were determined from the data 5analysis, providing a visual representation of how the Beni Amrane Reservoir's operational strategy adapts to varying hydrological conditions.

- High conservation: 60–67 m
- Low conservation: 54–60 m

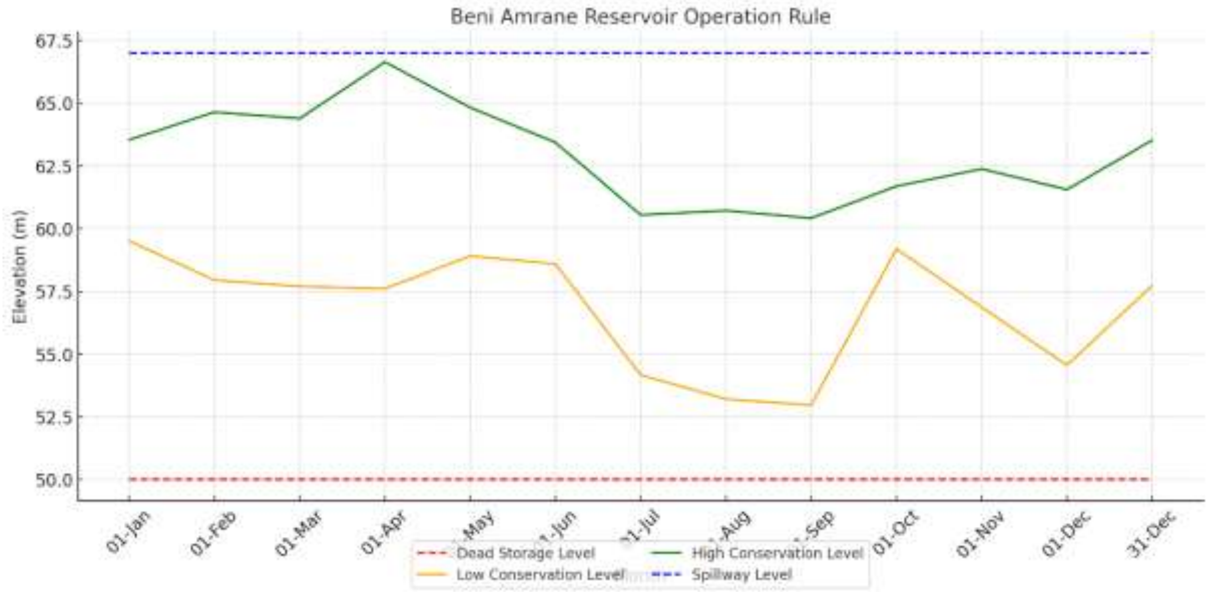

Figure 5.15: Beni Amrane reservoir operational zones

Figure 5.16 illustrates the operational zones of Hamiz, providing insights into zone conservation patterns.

- High conservation: 164.10–173 m
- Low conservation: 155–164.10 m

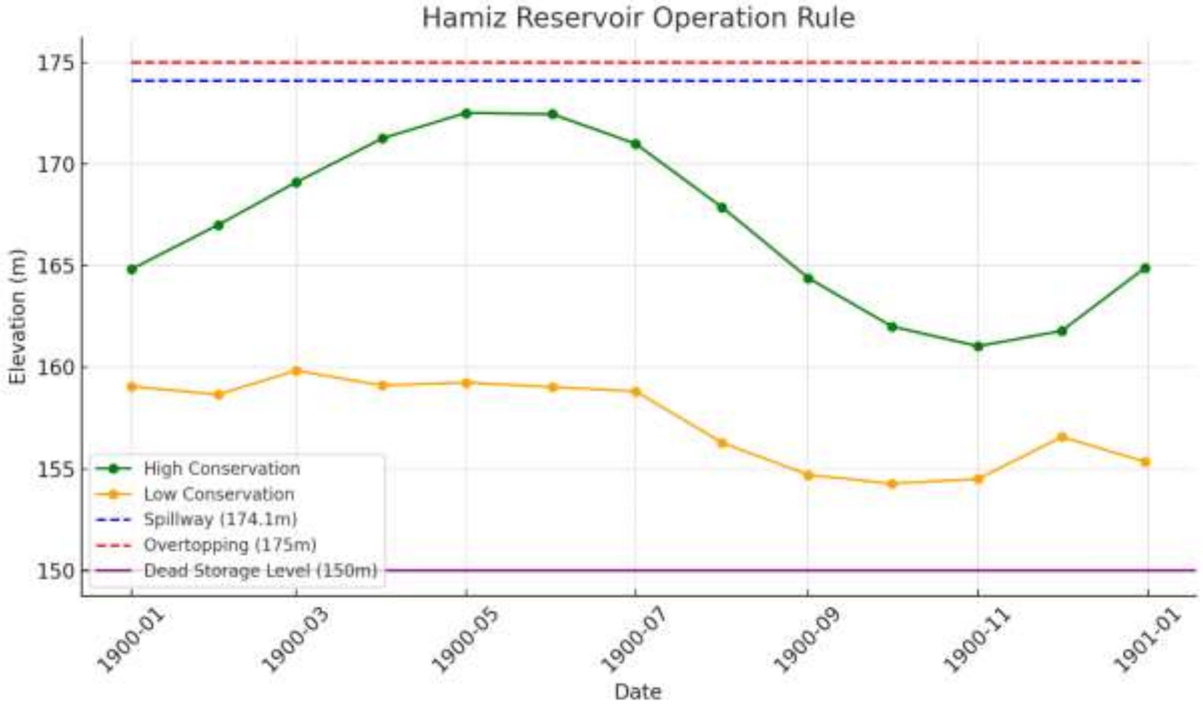

Figure 5.16: Hamiz reservoir operational rule

The table05.4 presents the proposed operational rules for each reservoir (Keddara, Beni Amrane, and Hamiz) on the basis of their respective zones and corresponding water levels. The rules have been designed to optimize the performance of the SPIK system, ensuring both flood risk management and water supply efficiency.

Table 5.4: Proposed optimization rules according to their respective zones for SPIK

Reservoir	Zone	Water Level (m)	Operation Rule
Keddara	Flood Control	Z > 145	Q_spill_max = 250 cms, Q_B_O_max = 55 cms, Q_supply = 6.25 cms
	Pre-Flood	144 > Z > 145	Q_B_O_max = 110 cms, V_supply = V_Demand
	High Conservation	134 > Z > 144	Q_supply = 6.25 cms – 4 cms
	Low Conservation	116 > Z > 134	Q_B_O_max = 0, V_supply = 0.8 V_Demand
	Critical Conservation	Z < 92	Q_B_O = 0, Q_supply = 0
Beni Amrane	Flood Control	Z > 77.5, Z < 67	Q_in > 100 cms, Q_out = Q_in, Q_spill_max = 10,000 cms, Q_Bottom_Outlet_max = 3100 cms, Q_out_max < 1000 cms Q_supply = 0
	High Conservation	67 < Z < 60	Q_in > 100 cms, Q_B_O_max = 860 cms, Q_B_O_min = 250 cms, Q_supply = 0
	High Conservation	67 > Z > 60	Q_in < 100 cms, Z(Keddara) < 144, Q_supply = 7 cms
	Low Conservation	60 > Z > 54	Q_B_O, Q_supply_max = 7 cms
	Critical Conservation	Z < 54	Q_B_O = 0, Q_supply = 0
Hamiz	Flood Control	Z > 174.10 m	Q_spill_max = 930 cms, Q_B_O_max = 70 cms
	Preflood	174.10 m > Z > 173 m	Q_B_O_max = 30 cms -70 cms
	High Conservation	173 m > Z > 164.10 m	Q_B_O = 0 Z(Keddara) < 144 m

			Q_supply = 0 – 33 cms, Q_irrigation = 4.2 cms
	Low Conservation	164.10 m > Z > 155 m	Q_supply = 0, Q_irrigation = 4.2 cms
	Critical Conservation	Z < 155 m	Q_B_O = 0, Q_supply = 0, Q_irrigation = 0

5.6 Results discussion

The simulations in this study provide important insights into reservoir operation strategies for flood control and water supply resilience under extreme conditions. For the heavy precipitation period, one critical finding is the divergence from the operator's recommended rule, which involves releasing water at 95% of the full capacity (elevation 144 m). In the reference scenario, the water is released only via the spillway once reservoir storage reaches its critical threshold, resulting in reactive and abrupt releases. This failure to implement prerelease strategies highlights a significant gap between operational protocols and real-world practices. The inability to follow the recommended rule likely contributed to the 2012 flood, underscoring the need for better enforcement of proactive measures in flood management. By adhering to the prerelease strategy, the system would have been better equipped to mitigate flood risk and control water levels more effectively.

The study results also emphasize the effectiveness of prerelease strategies and how they help attenuate peak flows and prevent downstream flooding. The optimization scenarios revealed that releasing water through the bottom outlet at 95% of the full capacity of the reservoir significantly reduced peak flow rates, highlighting the advantages of proactively managing water levels before critical spillway elevations are reached. At the same time, the simulation results highlight the need for further optimization, such as adjusting release rates based on real-time inflow data, the adaptive release strategies performed significantly better in the optimization scenarios than in the reference scenario. The adaptive approach, which adjusts water release in response to inflow trends, provides more dynamic flood control, helping to avoid spillway activation even under extreme conditions.

In Scenario 4, halting the interbasin transfer from Hamiz to Keddara substantially affected the operation of the Keddara reservoir. The reduced transfer volume resulted in a slower filling of Keddara, minimizing the risk of overflow and downstream flooding. Although spillway activation is still triggered, the amount of water spilled is significantly lower than that in the reference scenario, indicating that regulating interbasin transfers during flood-prone periods can prevent the reservoir from being overwhelmingly displaced. This highlights the importance of carefully managing transfers between reservoirs, especially during extreme events, to ensure optimal water levels and reduce flood risks.

In Scenario 5, the use of bottom outlet releases in both the Keddara Reservoir and the Hamiz Reservoir demonstrated a more controlled approach to flood management. The system managed excess water without triggering spillway activation by gradually releasing water and aligning the releases with each reservoir’s guide curve. Yet the results can be refined, especially in the case of Keddara, the release through the bottom gates in this scenario is greater than the water release through the spillway in scenario 04.

For the Beni Amrane Reservoir, a critical operational discrepancy was observed during scenario simulation, wherein the interbasin transfer from Beni Amrane to Keddara was maintained despite explicit reservoir guideline instructions. According to the operator's guidelines, transfers and bottom outlet releases should not occur simultaneously because of the relatively small difference in elevation between the bottom outlet gates and water intake. This operational conflict can have several negative consequences, particularly concerning water quality. When bottom outlet releases are triggered, water turbidity is high, exacerbating turbidity levels in the receiving reservoir. The concurrent operation of interbasin transfers with bottom outlet releases can increase the risk of turbid water transfer, potentially compromising water quality in Keddara and hindering water treatment processes downstream. Moreover, high turbidity poses a significant risk to pumps that transfer water from Beni Amrane to Keddara, as these pumps rely on relatively low turbidity water for optimal performance. The abrasive nature of the suspended particles accelerates erosion and corrosion in the pump components, resulting in increased maintenance costs, decreased pump efficiency, and a greater risk of operational failure.

During the drought period, the optimization scenario significantly improved key performance metrics, particularly reliability and vulnerability. The reliability index improved from 31% in the reference scenario to 50% in the optimization scenario, indicating that the optimized system can meet water demand even under challenging conditions. This improvement reduces the risk of water shortages during extreme events, demonstrating the effectiveness of the optimized system in managing the water supply during periods of water scarcity. In addition, vulnerability during the drought period decreased from 41% in the reference scenario to 29% in the optimization scenario. This reduction suggests that the optimization strategy helps the system handle drought-related disruptions more effectively, improving its resilience to supply interruptions during water scarcity. These findings underscore the critical importance of focusing on the drought period (2020-2023) as a key time for water supply management. The significant improvements in reliability and the reduced vulnerability observed in the optimized scenario highlight the need for targeted strategies to increase system performance during droughts.

WEAP provides an additional layer of analysis by assessing SPIK performance under pessimistic and optimistic scenarios. The results from scenarios 01 and 02 highlight the critical importance of implementing a well-defined release strategy for the drinking water supply. Despite having the same inflow and storage conditions, the shift toward aligning water allocation with actual demand significantly increased system reliability from 26% to 38%.

During the dry period, even when the filling of the Keddara reservoir is prioritized, the SPIK system struggles to meet the water demand, achieving only 19% reliability. In contrast, during the wet period, the system reaches a reliability rate of 51%, although it is important to note that this assessment did not account for higher inflows in terms of flood control, which could further influence the system’s performance under extreme precipitation events.

The WEAP simulation findings highlight a significant gap in the SPIK system's ability to respond efficiently to extreme conditions both dry and wet period. Nevertheless, it is important to note that this conclusion is based on the performance analysis of the SPIK system over a 20-year period (2000–2020), where some years (such as those with favorable inflows) show the system’s ability to meet demand. However, the overall performance still reveals that the system struggles to consistently meet water demands. Therefore, this calls for the development of alternative solutions to enhance the system’s resilience and its capacity to adapt to changing conditions.

6. Conclusion

This study emphasizes the critical importance of analyzing the coordination and operational management of the SPIK to Algiers. Given that this system is responsible for providing water to nearly half of the region's population, its effective operation is paramount for ensuring water security in the capital. Moreover, this research plays a vital role in enhancing disaster resilience, as it addresses how the SPIK system can better respond to extreme hydrological events, such as droughts and heavy floods. The integration of multi-dam operations and interbasin transfers is fundamental to the region's water supply, especially under these increasingly frequent and severe conditions.

The study has identified several operational inefficiencies within the system. A key finding is the limited coordination between the operators of the interconnected reservoirs, as well as the lack of data exchange among them. While communication with higher-level authorities is well-established, with immediate notification during extreme events such as heavy precipitation, there is no specific protocol or platform for data sharing between reservoir operators. Furthermore, decisions related to water releases and allocation are exclusively governed by higher-level authorities, with limited engagement of reservoir operators. This centralization significantly reduces operational flexibility and responsiveness, particularly in times of crisis.

Modeling using HEC-ResSim and WEAP has demonstrated that resilience in the SPIK system can be significantly enhanced through adaptive management strategies and the establishment of more robust rule-based operational frameworks. HEC-ResSim, in particular, provided valuable insights into the importance of Decision Support Systems (DSS) in reservoir operation, highlighting the potential of such systems to optimize real-world events, as exemplified by the 2012 floods. The simulation results revealed important divergences between the reservoir operation guidelines and actual real-world practices, underscoring the need for alignment between operational protocols and real-time decision.

Furthermore, the reallocation of drinking water within the SPIK system showed a significant increase in performance during drought periods, although this can be further optimized to ensure better reliability and water availability. The use of the WEAP simulation model also provided significant insights into the SPIK system’s performance over a 20-year period, simulating both pessimistic and optimistic scenarios. The system shows difficulties in meeting water demand in both scenarios for the covered period. The results were not explored in terms of flood resilience or other disaster response scenarios, as the primary focus was on evaluating water supply system performance.

The insights drawn from these models emphasize the critical role of integrated water management strategies and the necessity for improving system flexibility and operational rules. This research offers a comprehensive roadmap for institutional reforms, including the establishment of clearer emergency response protocols, enhanced data-sharing frameworks, and capacity-building for dam operators to better manage extreme events.

To conclude, strengthening technical, institutional, and operational coordination within the SPIK system is vital for ensuring sustainable water management and enhancing disaster resilience in Algiers. This research offers a valuable framework for the SPIK system and other regions facing similar challenges in managing complex water infrastructures under the pressures of climate extremes.

7. Recommendations

Based on the thorough analysis of the SPIK water supply system performance and disaster resilience, several recommendations arise for reservoir and interbasin operation, and stakeholders involved in the management of the system

First, a platform for data sharing should be established to facilitate real-time access to high-quality, accurate reservoir data among operators and stakeholders. This platform would enable seamless communication and the exchange of information regarding water levels, inflows, outflows, and operational conditions, thereby improving the overall decision-making process. Moreover, the coordination between different reservoirs should be strengthened. This can be achieved by establishing a unified communication protocol and regular coordination meetings among operators to ensure efficient water transfer and allocation across the system.

Building on the insights gained from this analysis, the development of predictive tools and the implementation of advanced forecasting systems are essential. These tools, such as decision support systems (DSSs), should be integrated with real-time reservoir data. The integration of HEC-ResSim and WEAP as decision support systems (DSSs) to optimize the performance and resilience of the water supply system in reservoir operation management is highly recommended. HEC-ResSim effectively simulates reservoir operations and flood management strategies, enabling proactive water release decisions and improving flood control. WEAP, by simulating various scenarios, helps assess system performance under different demand and inflow conditions, enhancing water allocation strategies. Together, these tools provide valuable insights for improving water supply reliability during extreme events, strengthening disaster resilience through data-driven decision-making and allowing dynamic decision-making to anticipate drought conditions and optimize reservoir operations before water shortages occur.

Furthermore, it is important to address the need for a more centralized policy. A shift toward a more decentralized approach in reservoir management is recommended. By empowering local operators with greater decision-making authority and resources, the SPIK system can become more adaptable and responsive to localized conditions, ensuring more effective management, especially in periods of crisis.

Capacity building and training for reservoir operators and decision-makers is paramount. Regular training sessions ensure that they are equipped with the necessary skills to handle the complexities of reservoir management, especially during extreme hydrological events. The training should focus on the use of DSS tools, interpretation of hydrological data, and application of adaptive water management strategies to effectively manage water resources during challenging conditions.

The optimization of water allocation strategies is also essential, particularly during drought conditions. Implementing optimization models will balance water demand for drinking, ensuring that the SPIK system can better manage resources by defining operational zones on the basis of storage levels and demand. This approach helps minimize deficits and ensures the equitable distribution of water. Additionally, establishing clear drought contingency plans, which should include specific guidelines for water allocation, storage management, and inter-reservoir transfers during periods of low water availability, is crucial. Such structured plans will help mitigate the impacts of drought on the water supply.

This study emphasizes the importance of proactive water release strategies for flood risk mitigation, particularly during periods of high inflows. The enhancement of flood control by ensuring strict adherence to the prerelease mechanisms outlined in the operational rules is recommended. These mechanisms should be activated at appropriate water levels to manage excess water before it reaches critical levels that could overwhelm reservoirs. Furthermore, improving inter-reservoir coordination and optimizing water transfer between reservoirs during peak inflow periods can help manage floodwater more effectively, reducing the risk of downstream flooding.

Implementing targeted river and wadi management strategies to address pollution in the upstream Beni Amrane River and silting issues in the downstream Hamiz River is recommended. These actions reduce flood risk, enhance water quality, and contribute to a more resilient water management system.

Finally, to address the frequent gaps in meeting water demand, alternative water resources, such as desalination, groundwater recharge, and wastewater recycling, should be developed. These solutions diversify the water supply, reducing reliance on reservoirs and enhancing system resilience, particularly during dry periods. The Incorporating these alternatives into the SPIK system will help ensure a more reliable and sustainable water supply in the future.

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9. Appendices

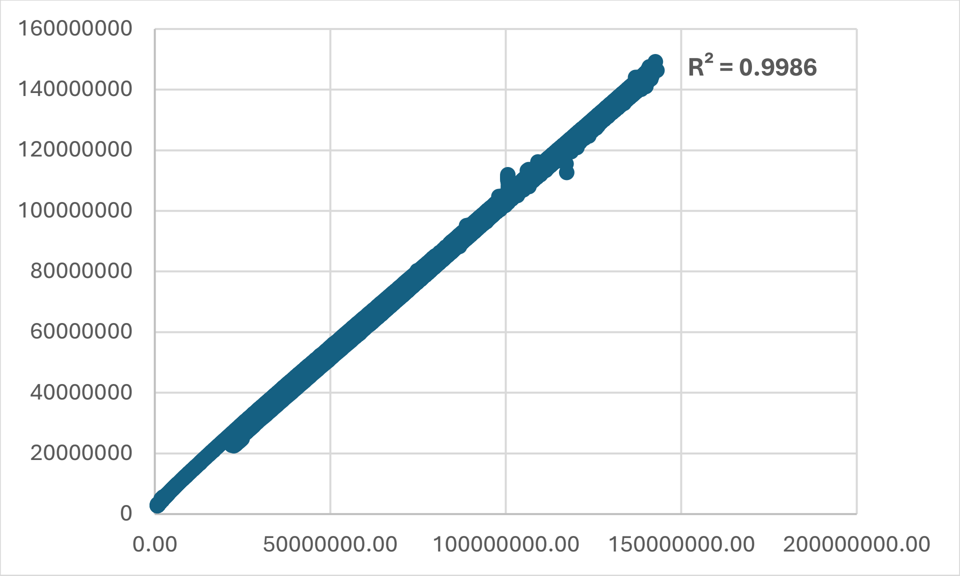


Figure 9.1: HEC-ResSim model calibration (2000-2003) and validation (2004-2020) for Keddara reservoir storage

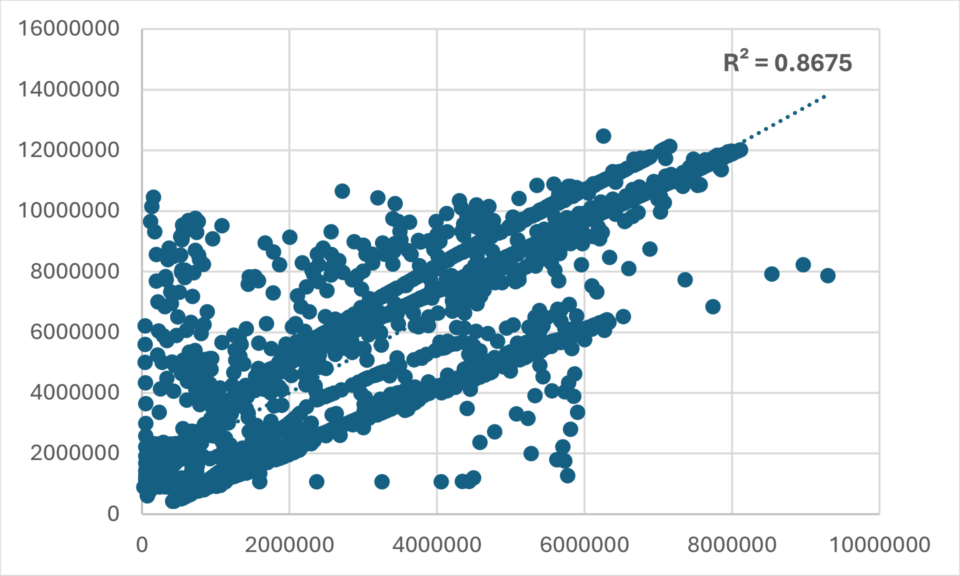


Figure 9.2: HEC-ResSim model calibration (2000-2003) and validation (2004-2020) for Beni Amrane reservoir storage

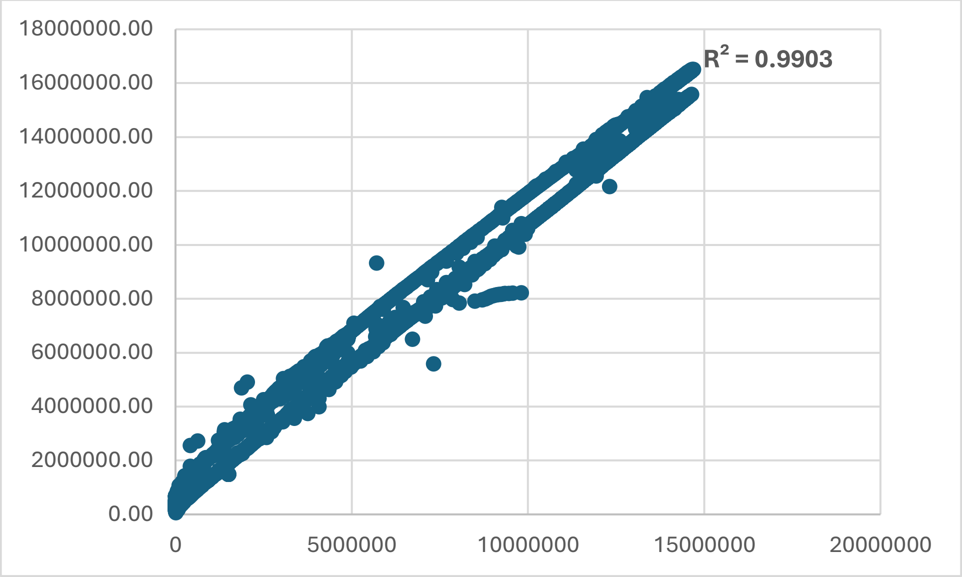
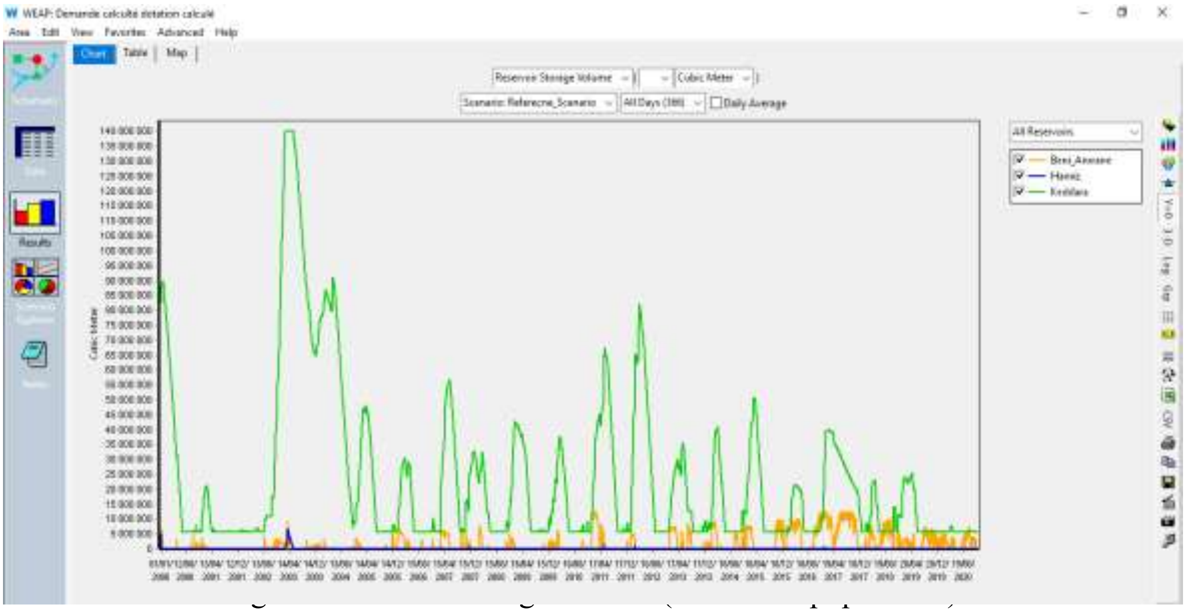


Figure 9.3: HEC-ResSim model calibration (2000-2003) and validation (2004-2020) for Hamiz reservoir storage



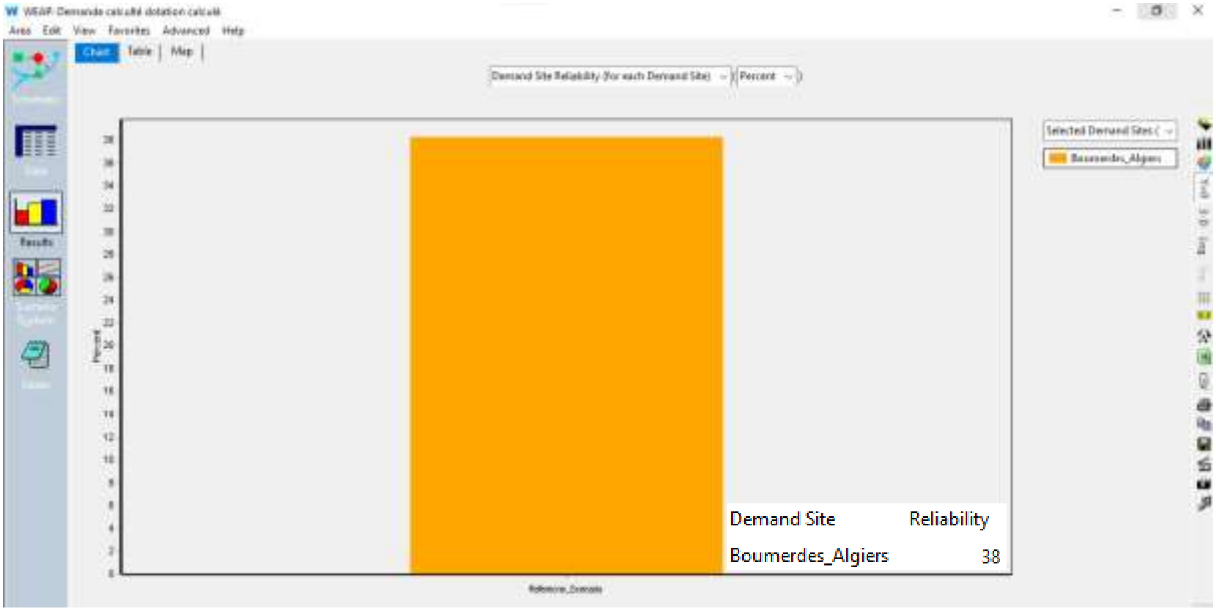
Reservoir Storage Volume | Cubic Meter

Scenario: Referecne_Scenario | All Days (366) | ☐ Daily Average

All Reservoirs

☑ Beni_Amrane
☑ Hamiz
☑ Keddara

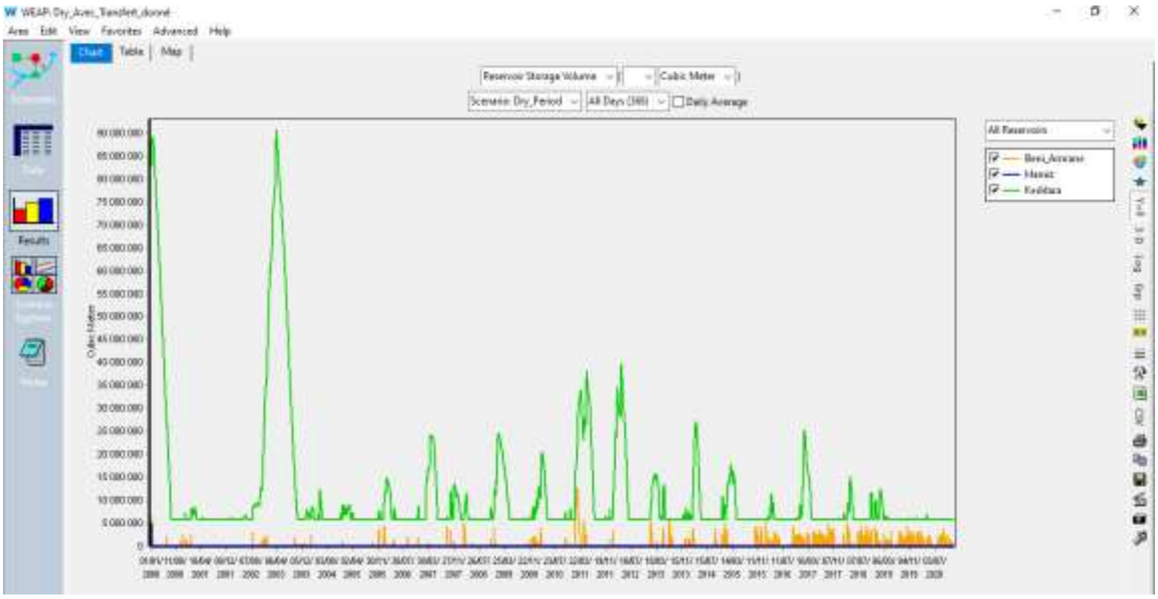
Figure 9.4: SPIK reference scenario with demand-based allocation



Demand Site Reliability (for each Demand Site) | Percent

Demand Site	Reliability
Boumerdes_Algiers	38

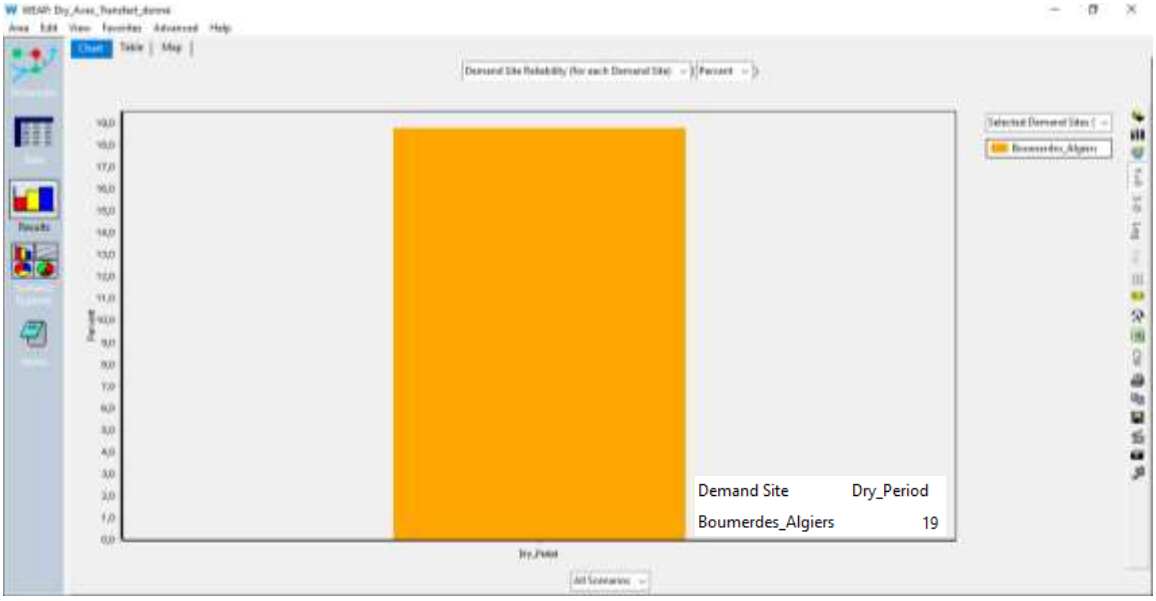
Figure 9.5: Demand-based SPIK Reliability



Reservoir Storage Volume | Cubic Meter

Scenario: Dry_Period | All Days (365) | ☐ Daily Average

Figure 9.6: Dry period simulation



Demand Site	Dry_Period
Boumerdes_Algiers	19

Figure 9.7: SPIK reliability during the dry period

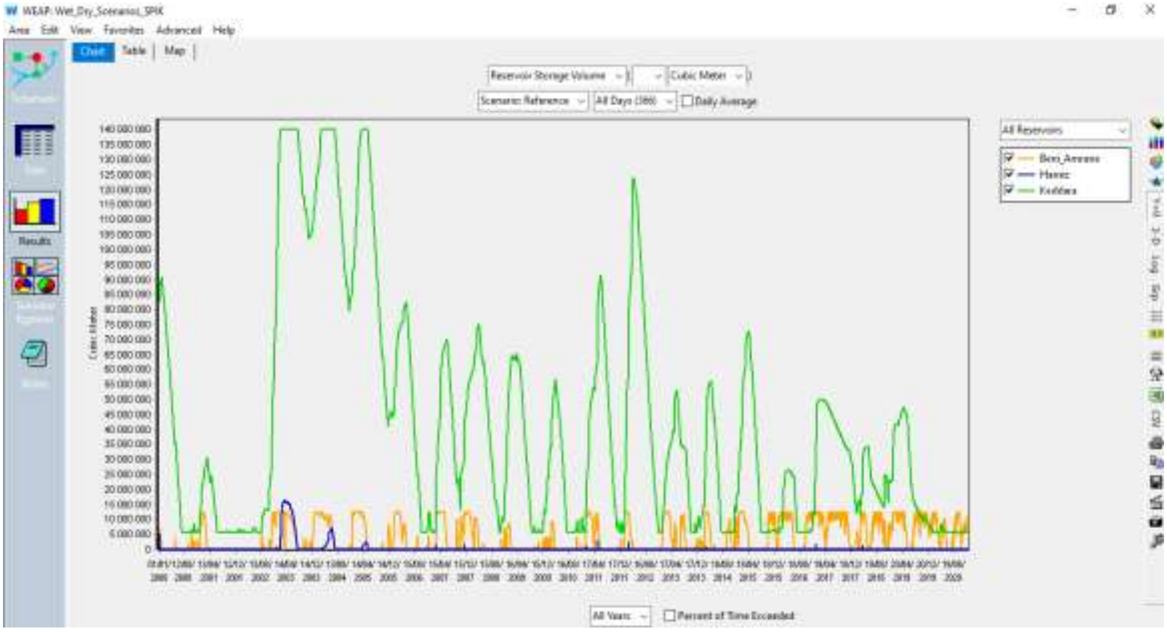
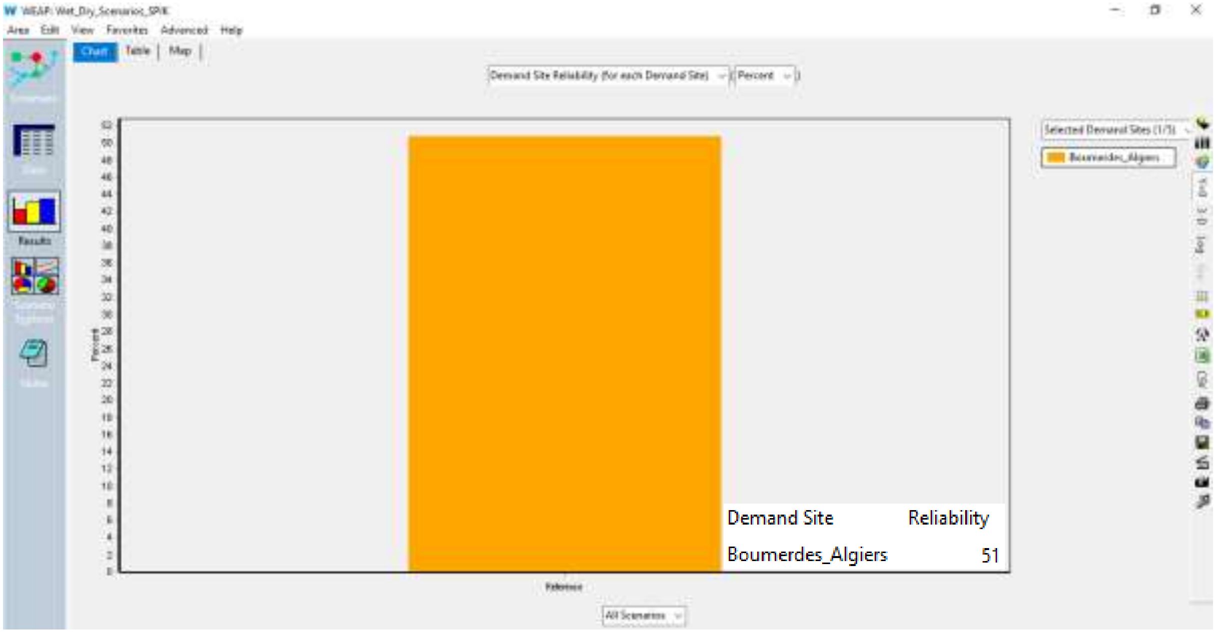


Figure 9.8: SPIK simulation during the wet period



Demand Site	Reliability
Boumerdes_Algiers	51

Figure 9.9: SPIK reliability during the wet period