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Hydro-Operational Optimisation of Dam Reservoirs Based on Evaporation-Sensitive Release Scenarios under Climate-Driven Water Stress

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Abstract

Increasing climate-driven water stress has intensified evaporation losses from dam reservoirs, posing significant challenges to sustainable water resources management and long-term reservoir performance. Conventional reservoir operation policies often neglect the dynamic role of evaporation under changing climatic conditions, leading to suboptimal release strategies and reduced water supply reliability. This study develops an evaporation-sensitive hydro-operational optimisation framework that explicitly integrates climate-induced evaporation dynamics into reservoir release decision-making under water-stressed conditions. The proposed framework couples reservoir mass balance equations with evaporation-responsive release scenarios derived from observed hydro-meteorological data and climate-adjusted operational constraints. Multi-scenario optimisation is implemented to evaluate the trade-offs between water supply reliability, storage sustainability, and evaporation-induced losses under varying inflow and climatic conditions. The optimisation structure is designed to remain applicable to large multi-purpose reservoirs, where operational flexibility is constrained by competing water demands and hydrological uncertainty. Evaporation sensitivity is incorporated through dynamic adjustment of release rules based on seasonal evaporation intensity, storage–surface area relationships, and projected water stress indicators. The framework enables adaptive modification of release patterns during high-evaporation periods, thereby reducing unnecessary surface exposure and long-term storage depletion. Performance indicators including storage resilience, volumetric evaporation loss, and operational efficiency are assessed across alternative release scenarios. The methodological approach advances existing reservoir optimisation studies by explicitly linking evaporation processes with operational decision variables, rather than treating evaporation as a fixed loss term. Results demonstrate that evaporation-aware release strategies can substantially improve reservoir performance under climate-driven water stress, particularly during prolonged dry periods. The framework provides a practical decision-support tool for reservoir operators seeking to enhance water use efficiency and climate resilience without structural modifications to existing infrastructure. The findings contribute to the development of adaptive reservoir operation policies capable of addressing increasing evaporation risks under future climatic conditions.

Keywords: Reservoir operation optimization, Evaporation-sensitive release, Climate-driven water stress, Dam reservoir management, Water supply reliability.

Introduction

Dam reservoirs play a critical role in securing water supply, regulating floods, generating hydropower, and supporting agricultural and environmental demands. However, the sustainability of reservoir-based water systems is increasingly threatened by climate-driven changes in hydrological regimes, particularly under conditions of intensifying water stress. Among the various climate-related factors affecting reservoir performance, evaporation losses from reservoir surfaces have emerged as a dominant yet often underestimated component influencing long-term storage dynamics and operational efficiency [1].

Evaporation from reservoir surfaces represents a direct and irreversible loss of stored water, with its magnitude strongly dependent on climatic variables such as air temperature, solar radiation, wind speed, and humidity. Recent studies have demonstrated that rising temperatures and altered atmospheric conditions associated with climate change are significantly amplifying open-water evaporation rates, especially in arid and semi-arid regions where reservoirs are already exposed to chronic water scarcity [2]. As reservoir surface areas expand during high storage periods, evaporation losses can increase disproportionately, leading to substantial reductions in effective water availability.

Despite its importance, evaporation is commonly treated as a passive or fixed loss term in conventional reservoir operation models. Traditional operating rules primarily focus on inflow variability, downstream demand satisfaction, and flood control constraints, while assuming evaporation losses to be externally imposed and operationally uncontrollable [3]. This simplification limits the capacity of existing operational strategies to respond adaptively to climate-induced evaporation intensification. Consequently, reservoir releases that are optimal under historical climatic conditions may become inefficient or even counterproductive under future warming scenarios.

Recent hydrological assessments indicate that climate-driven evaporation can significantly alter the reliability of water supply systems and accelerate storage depletion during prolonged dry periods [4]. In multi-purpose reservoirs, this effect is further exacerbated by competing demands for irrigation, domestic water use, hydropower generation, and environmental flows. Under such conditions, rigid release policies may unintentionally increase exposed water surface area during high-evaporation seasons, amplifying losses precisely when water scarcity is most severe.

The growing recognition of these challenges has prompted a shift toward more adaptive reservoir operation frameworks that explicitly consider climate variability. However, most existing approaches still prioritize inflow uncertainty and demand-side dynamics, while the integration of evaporation as an operational decision variable remains limited. In many cases, evaporation is incorporated only as a static correction factor rather than as a dynamic process that can inform release timing and magnitude.

From an operational perspective, reservoir managers possess indirect but meaningful control over evaporation losses through release scheduling and storage level regulation. By strategically adjusting release patterns to limit unnecessary surface expansion during high-evaporation periods, it is possible to reduce cumulative water losses without compromising downstream requirements. This operational leverage underscores the need for optimisation frameworks that explicitly link evaporation dynamics with release decisions under climate-driven water stress.

In this context, developing hydro-operational optimisation strategies that are sensitive to evaporation processes represents a critical research frontier. Such strategies must account for the coupled interactions between storage, surface area, climate forcing, and release rules, while remaining practical for real-world reservoir management. Addressing this gap is essential for enhancing the resilience and efficiency of dam reservoir operations under increasingly uncertain and water-stressed climatic conditions.

Recent advances in reservoir operation research have increasingly acknowledged the necessity of incorporating climate variability into decision-making frameworks. A substantial body of literature has focused on adapting reservoir operations to altered inflow regimes, increased hydrological uncertainty, and shifting water demand patterns under climate change. Optimisation-based approaches, including dynamic programming, evolutionary algorithms, and multi-objective optimisation techniques, have been widely applied to improve operational performance under non-stationary conditions [3]. However, within this expanding research domain, evaporation has often remained a secondary consideration rather than a central operational driver.

Several recent studies have demonstrated that evaporation losses can rival or even exceed consumptive water uses in large reservoirs, particularly during extended dry seasons [1]. These findings challenge the conventional assumption that evaporation is a marginal loss relative to inflow variability. In climate-stressed basins, where inflows are declining and inter-annual variability is increasing, the proportional contribution of evaporation to total water losses becomes increasingly significant. As a result, reservoir systems that were historically resilient may experience declining performance even without substantial changes in demand.

Hydrological modelling efforts have attempted to quantify future evaporation trends using climate projections, often coupling general circulation models with hydrological or land-surface models [2]. While these approaches provide valuable insights into potential evaporation trajectories, their integration into operational optimisation frameworks remains limited. In many cases, projected evaporation rates are used solely for impact assessment rather than as actionable inputs to guide release decisions. This disconnect between evaporation assessment and operational control represents a key limitation in current reservoir management practices.

Multi-objective reservoir optimisation studies have made important progress by simultaneously addressing competing objectives such as water supply reliability, hydropower production, and environmental flow requirements [3]. Nevertheless, evaporation is frequently embedded implicitly within the system mass balance without influencing the structure of release rules. Consequently, optimisation outcomes may satisfy demand targets while inadvertently increasing cumulative evaporation losses through storage configurations that maximise surface exposure during high-evaporation periods.

Recent research has begun to explore more direct linkages between evaporation dynamics and reservoir operation. For instance, evaporation-sensitive operational strategies have been proposed to adjust release decisions based on seasonal or climate-driven evaporation intensity [5]. These studies highlight the potential benefits of explicitly accounting for evaporation in operational optimisation, including improved storage preservation and enhanced resilience under water stress. However, existing formulations often remain case-specific, lack generalisability, or rely on simplified representations of evaporation–storage relationships.

Moreover, many evaporation-aware studies focus primarily on hydrological performance metrics while paying limited attention to operational feasibility. Reservoir operators require decision-support tools that are not only theoretically robust but also compatible with existing operational constraints, rule curves, and institutional practices. The absence of such practical considerations limits the transferability of advanced optimisation methods from research to real-world application.

Taken together, the current literature reveals a clear imbalance between the growing recognition of evaporation as a critical climate-driven stressor and its limited operational integration. While the physical processes governing reservoir evaporation are increasingly well understood, their translation into actionable release strategies remains underdeveloped. This gap is particularly evident in multi-purpose reservoirs operating under chronic water stress, where even marginal reductions in evaporation losses can yield substantial system-wide benefits.

Addressing this challenge requires a hydro-operational perspective that treats evaporation not merely as an external loss, but as a dynamic process that can inform adaptive release strategies. Such an approach must bridge the gap between climate-informed evaporation assessment and operational optimisation, laying the foundation for more resilient reservoir management under future water stress conditions.

While recent studies have highlighted the importance of incorporating evaporation into reservoir operation, a fundamental limitation persists in how evaporation is conceptualised within optimisation frameworks. In many existing approaches, evaporation-sensitive strategies are implemented through predefined seasonal adjustments or static penalty terms, which fail to capture the continuous interaction between storage dynamics, surface area evolution, and climate-driven water stress [5]. As a result, operational decisions remain largely reactive rather than anticipatory, limiting their effectiveness under rapidly changing climatic conditions.

Another critical shortcoming in the current literature lies in the insufficient integration of climate-induced water stress indicators into operational decision-making. Water stress is often evaluated as an external condition affecting inflows or demands, rather than as an internal driver shaping release policies. Recent climate-reservoir coupling studies have demonstrated that water stress emerges from the combined effects of reduced inflow availability, increased evaporation losses, and constrained operational flexibility [6]. However, few operational models explicitly link these stress conditions to adaptive release scenarios that respond dynamically to evaporation intensity.

In multi-purpose reservoir systems, the implications of this limitation are particularly pronounced. Reservoirs serving irrigation, municipal supply, hydropower generation, and environmental flows must balance competing objectives under increasingly constrained water availability. Under such circumstances, conventional release rules based on historical hydrological conditions may exacerbate system vulnerability by maintaining high storage levels during peak evaporation periods. This practice can unintentionally increase surface exposure and accelerate cumulative water losses, undermining long-term storage sustainability.

Despite the recognition that release decisions influence reservoir surface area and, consequently, evaporation magnitude, operational optimisation frameworks rarely exploit this relationship in a systematic manner. Most optimisation models aim to satisfy downstream demands while minimising shortages, without explicitly considering how alternative release trajectories modify evaporation pathways over time. This oversight reflects a broader disconnect between physical evaporation processes and operational control variables, which remains largely unaddressed in the existing literature.

Furthermore, many evaporation-focused studies rely on highly specific case studies or simplified reservoir geometries, limiting their general applicability. Reservoir systems exhibit diverse morphologies, operational objectives, and climatic settings, requiring optimisation frameworks that are both flexible and transferable. The lack of generalised hydro-operational formulations that can accommodate varying degrees of climate-driven water stress represents a significant research gap.

Against this backdrop, there is a clear need for an operational optimisation framework that explicitly treats evaporation as a decision-relevant process rather than a fixed loss. Such a framework must integrate climate-informed evaporation dynamics, storage–surface area relationships, and water stress conditions into the structure of release scenarios. Importantly, it should do so without imposing unrealistic data requirements or operational assumptions, ensuring practical relevance for reservoir managers.

The present study addresses this gap by proposing a hydro-operational optimisation approach based on evaporation-sensitive release scenarios under climate-driven water stress. By embedding evaporation responsiveness directly into the release decision structure, the proposed framework advances beyond conventional optimisation methods and offers a more adaptive pathway for reservoir operation. This approach is designed to enhance water use efficiency, preserve long-term storage, and improve system resilience under increasingly water-stressed climatic conditions.

The increasing complexity of reservoir management under climate-driven water stress necessitates a shift from static operation policies toward more adaptive and process-aware optimisation frameworks. As climate change intensifies evaporation losses and alters hydrological regimes, reservoir operators require decision-support tools that can dynamically respond to evolving system conditions rather than relying on historical operating assumptions [6]. This requirement is particularly urgent in regions experiencing persistent water scarcity, where even modest operational inefficiencies can lead to significant long-term storage depletion.

A central challenge in developing such tools lies in reconciling physical process representation with operational practicality. While advanced hydrological models are capable of simulating evaporation responses to climatic forcing with increasing accuracy, their outputs are rarely translated into operationally meaningful release strategies. Conversely, many operational optimisation models prioritise computational efficiency and simplicity at the expense of adequately representing evaporation dynamics. Bridging this divide requires a hydro-operational perspective that integrates evaporation processes directly into the structure of release decision-making under water stress conditions.

In this context, the present study aims to develop and evaluate an evaporation-sensitive reservoir operation framework that explicitly links climate-driven evaporation dynamics with release optimisation. Rather than treating evaporation as an exogenous loss, the proposed approach incorporates evaporation sensitivity into release scenarios through dynamic adjustment of operational decisions based on storage levels, surface area evolution, and water stress indicators. This formulation enables reservoir operators to indirectly regulate evaporation losses by strategically modifying release patterns during critical climatic periods.

The specific objectives of this study are threefold. First, to formulate a hydro-operational optimisation model that integrates evaporation-sensitive release scenarios within a climate-informed water stress context. Second, to assess the performance of alternative release strategies in terms of storage sustainability, evaporation loss reduction, and overall operational efficiency under varying hydrological conditions. Third, to demonstrate the applicability of the proposed framework to multi-purpose reservoirs operating under competing demands and climatic uncertainty [7].

The novelty of this research lies in its explicit coupling of evaporation dynamics with operational decision variables, moving beyond conventional optimisation approaches that treat evaporation as a passive constraint. By embedding evaporation responsiveness into the release structure, the proposed framework provides a more realistic representation of reservoir behaviour under climate stress and offers actionable insights for adaptive management. This contribution is particularly relevant for large reservoirs where surface area variations significantly influence evaporation magnitude and long-term system performance.

From a practical standpoint, the proposed framework is designed to be compatible with existing reservoir operation practices. It relies on commonly available hydro-meteorological data and does not require structural modifications to reservoir infrastructure. This emphasis on operational feasibility enhances the potential for real-world implementation and supports the transition toward climate-resilient reservoir management strategies.

The remainder of this paper is structured as follows. The next section presents the problem statement, clearly defining the limitations of conventional reservoir operation under climate-driven evaporation stress. This is followed by a detailed description of the proposed methodology, including model formulation, optimisation structure, and scenario development. Subsequently, the results of the optimisation experiments are presented and analysed, highlighting the performance of evaporation-sensitive release strategies. Finally, the study concludes with a discussion of key findings, implications for reservoir management, and directions for future research.

Problem Statement

Reservoir operation policies currently applied in many water-stressed regions are largely based on historical hydrological assumptions that no longer reflect prevailing climatic realities. These policies typically prioritise demand satisfaction and flood control while treating evaporation as an unavoidable and externally imposed loss. Under conditions of climate-driven water stress, such an operational paradigm becomes increasingly inadequate, as it fails to recognise the growing influence of evaporation on storage dynamics and long-term system reliability.

A key operational limitation arises from the disconnect between release decisions and evaporation processes. Release rules are commonly designed to maintain target storage levels or meet downstream demands without accounting for how these decisions alter reservoir surface area and, consequently, evaporation magnitude. During periods of elevated temperature and prolonged dry conditions, maintaining high storage levels can significantly increase exposed surface area, leading to disproportionate evaporation losses. This operational behaviour is particularly problematic in large reservoirs, where small changes in water level may correspond to substantial variations in surface area.

Recent studies have shown that climate change not only intensifies evaporation rates but also amplifies water stress by simultaneously reducing inflow availability and increasing atmospheric demand for water [6]. Despite this compounded effect, conventional operation strategies rarely incorporate water stress indicators into release decision-making. Instead, water stress is implicitly reflected through declining inflows or increasing shortages, by which point operational responses are often reactive rather than preventive. This lag in response contributes to accelerated storage depletion and reduced system resilience during extended dry periods.

Another critical challenge lies in the absence of operational mechanisms that allow reservoir managers to proactively mitigate evaporation losses. While structural solutions such as surface covers or reservoir redesign are costly and often impractical, operational adjustments offer a potentially low-cost alternative. However, existing optimisation frameworks seldom exploit this opportunity, as evaporation is not embedded as a decision-relevant process within release scenarios. As a result, operators lack guidance on how to modify release patterns in response to evolving evaporation conditions without compromising downstream requirements.

Furthermore, the increasing competition among water uses under climate stress exacerbates the consequences of suboptimal operation. Irrigation, municipal supply, hydropower generation, and environmental flows impose conflicting demands on finite storage resources. Under such conditions, even marginal inefficiencies in operation can propagate through the system, leading to cumulative performance degradation. Studies focusing on evaporation-sensitive strategies have demonstrated their potential to alleviate some of these pressures, yet such approaches remain underrepresented in operational practice [5].

The core problem addressed in this study is therefore the absence of a hydro-operational optimisation framework that explicitly integrates evaporation sensitivity into reservoir release decisions under climate-driven water stress. Without such a framework, reservoir operations remain ill-equipped to adapt to intensifying evaporation risks, undermining both short-term performance and long-term sustainability. Addressing this gap requires re-conceptualising evaporation not as a fixed loss, but as a dynamic process that can inform adaptive release strategies within practical operational constraints.

Methodology

Conceptual Framework

The proposed methodology is built upon a hydro-operational optimisation framework that explicitly integrates evaporation sensitivity into reservoir release decision-making under climate-driven water stress. The core premise of the framework is that evaporation losses, although physically unavoidable, can be indirectly regulated through adaptive release strategies that influence reservoir storage levels and surface area dynamics. This approach positions evaporation as an operationally relevant process rather than a fixed system loss.

The methodological structure consists of three interlinked components: (i) reservoir system representation and mass balance formulation, (ii) evaporation-sensitive release scenario design, and (iii) optimisation under water stress conditions. These components are integrated within a scenario-based optimisation environment that allows systematic evaluation of alternative operational strategies under varying climatic and hydrological conditions.

Reservoir System Representation

The reservoir system is represented as a single-node storage unit characterised by time-varying inflows, releases, evaporation losses, and storage levels. The temporal resolution of the model is defined at a monthly time step, which provides an appropriate balance between capturing seasonal evaporation variability and maintaining computational tractability for long-term optimisation analysis [7].

The fundamental mass balance equation governing reservoir storage is expressed as:

$$S(t+1) = S(t) + I(t) - R(t) - E(t)$$

where:
S(t) is the reservoir storage at time t,

I(t) is the inflow volume during time step t,

R(t) is the controlled release volume,

E(t) is the evaporation loss from the reservoir surface.

This formulation ensures conservation of mass while allowing evaporation to dynamically interact with operational decisions through its dependence on storage and surface area.

Evaporation Estimation

Reservoir evaporation losses are calculated as a function of climatic conditions and reservoir surface area. Monthly evaporation depth is derived from observed meteorological variables using established open-water evaporation formulations consistent with recent hydropower and reservoir operation studies [8]. The volumetric evaporation loss is computed as:

$$E(t) = e(t) \times A(S(t))$$

where:
e(t) is the evaporation depth during time step t,

A(S(t)) is the surface area corresponding to storage level S(t).

The storage–surface area relationship is obtained from reservoir geometry curves, enabling evaporation losses to vary nonlinearly with storage. This representation captures the critical feedback between release decisions, storage levels, and evaporation magnitude.

Water Stress Characterisation

Climate-driven water stress is characterised through combined indicators reflecting reduced inflow availability and increased evaporative demand. Rather than treating water stress as an external boundary condition, it is embedded within the operational environment by constraining feasible release decisions during periods of elevated stress. This formulation allows the optimisation process to prioritise storage preservation and evaporation mitigation when system vulnerability is highest.

Operational Decision Variables

The primary decision variable in the optimisation framework is the release volume R(t), which is adjusted dynamically in response to evaporation sensitivity and water stress conditions. Release decisions are bounded by physical, operational, and demand-related constraints, ensuring that optimisation outcomes remain feasible within real-world reservoir management practices.

By structuring the model in this manner, the methodology establishes a direct link between evaporation processes and operational control variables, forming the foundation for evaporation-sensitive optimisation under climate-driven water stress.

Evaporation-Sensitive Release Scenario Design

To explicitly incorporate evaporation dynamics into operational decision-making, a set of evaporation-sensitive release scenarios is developed. These scenarios are structured to modify release behaviour in response to variations in evaporation intensity and water stress conditions, rather than relying on fixed or historically derived release rules. The underlying rationale is that release decisions influence reservoir storage levels and surface area exposure, thereby indirectly affecting cumulative evaporation losses.

Evaporation sensitivity is operationalised through a dynamic adjustment factor applied to baseline release rules. During periods of elevated evaporative demand and high water stress, release volumes are strategically adjusted to limit excessive surface expansion while maintaining essential downstream requirements. Conversely, during lower evaporation periods, release flexibility is increased to support demand satisfaction and operational objectives. This scenario-based structure allows systematic comparison between conventional and evaporation-aware operation strategies under identical hydrological conditions.

Water stress conditions are identified using combined indicators reflecting inflow scarcity and evaporative pressure, consistent with recent assessments of climate-induced water stress in reservoir systems [9]. These indicators are used to trigger transitions between release scenarios, enabling adaptive operation across seasonal and inter-annual climatic variability.

Optimisation Structure

The operational optimisation problem is formulated as a constrained, multi-period decision process over the planning horizon. The optimisation seeks to identify release trajectories that balance competing objectives while accounting for evaporation sensitivity and water stress. A scenario-based optimisation approach is adopted to evaluate alternative release strategies under varying climatic conditions, following recent advances in evaporation-aware reservoir optimisation [10].

The optimisation is implemented over a long-term simulation horizon to capture cumulative evaporation effects and storage dynamics. At each time step, release decisions are optimised subject to system constraints, ensuring continuity of storage and compliance with operational limits.

Objective Function

The primary objective function is defined to minimise the combined impact of evaporation losses and storage deviation from target levels, while implicitly supporting water supply reliability. The objective function is expressed as:

Minimise

$$J = \Sigma [w_1 \times E(t) + w_2 \times |S(t) - S\_target|]$$

where:

$E(t)$ is the evaporation loss at time t,

$S(t)$ is the reservoir storage at time t,

S_target is the desired storage level,

w_1 and w_2 are weighting coefficients reflecting the relative importance of evaporation reduction and storage stability.

This formulation allows the optimisation to penalise excessive evaporation losses while discouraging undesirable storage depletion or overfilling.

Constraints

The optimisation problem is subject to several constraints to ensure operational feasibility:

Storage constraints:

$$S\_min \le S(t) \le S\_max$$

Release constraints:

$$R\_min(t) \le R(t) \le R\_max(t)$$

Demand satisfaction constraint:

$$R(t) \ge D(t)$$

where:

S_min and S_max are minimum and maximum allowable storage levels,

$R\_min(t)$ and $R\_max(t)$ define operational release limits,

$D(t)$ represents downstream water demand.

These constraints ensure that evaporation-sensitive release strategies remain consistent with physical reservoir limits and downstream water requirements.

Scenario Evaluation

Multiple evaporation-sensitive release scenarios are evaluated within the optimisation framework to assess their performance under different water stress conditions. Performance metrics include cumulative evaporation loss, storage sustainability, and operational efficiency. By comparing scenario outcomes, the methodology enables identification of release strategies that offer improved resilience under climate-driven water stress.

Optimisation Algorithm and Solution Approach

The formulated hydro-operational optimisation problem is solved using an iterative scenario-based optimisation procedure that balances computational efficiency with solution robustness. Given the nonlinear interaction between storage, surface area, and evaporation losses, the optimisation framework adopts a simulation–optimisation approach in which reservoir dynamics are simulated forward in time while release decisions are iteratively adjusted to minimise the objective function.

At each optimisation iteration, candidate release trajectories are evaluated by simulating reservoir storage evolution and associated evaporation losses over the planning horizon. The optimisation process converges toward release strategies that reduce cumulative evaporation while maintaining storage stability and meeting downstream demands. This approach is consistent with recent developments in coupled hydrological–operational modelling, where physical process representation is embedded within operational optimisation structures [11].

The scenario-based formulation allows the optimisation to explore alternative release patterns under varying water stress conditions without relying on a single deterministic operating rule. This flexibility is particularly important under climate-driven uncertainty, where rigid optimisation solutions may perform poorly when system conditions deviate from expected trajectories.

Performance Evaluation Indicators

To assess the effectiveness of evaporation-sensitive release strategies, a set of performance indicators is defined. These indicators capture both hydrological performance and operational efficiency, enabling comprehensive comparison between alternative scenarios. The primary evaluation metrics include:

1. Cumulative evaporation loss, representing the total volume of water lost through evaporation over the simulation period.
2. Storage sustainability index, defined as the ability of the reservoir to maintain storage within acceptable operational bounds under prolonged water stress.
3. Operational efficiency, reflecting the balance between evaporation reduction and demand satisfaction without excessive release variability.

The storage sustainability index is calculated as:

$$SSI = 1 - (\Sigma |S(t) - S\_target|) / (T \times S\_target)$$

where:
SSI is the storage sustainability index,

T is the total number of time steps.

This index provides a normalised measure of how effectively the reservoir maintains target storage levels over time.

Comparative Scenario Analysis

Alternative evaporation-sensitive release scenarios are evaluated against a baseline operation strategy representing conventional reservoir management practices. Comparative analysis focuses on identifying the relative improvements achieved through evaporation-aware optimisation, particularly during periods of high evaporative demand and limited inflow availability. By examining differences in performance indicators across scenarios, the framework highlights the operational trade-offs associated with increased evaporation sensitivity.

Recent studies have emphasised the importance of evaluating reservoir operation strategies not only in terms of hydrological outcomes but also in terms of operational practicality and robustness under climate stress [12]. Accordingly, the proposed methodology prioritises solutions that offer measurable performance improvements while remaining compatible with real-world operational constraints.

Methodological Summary

In summary, the proposed methodology establishes a comprehensive hydro-operational optimisation framework that integrates evaporation sensitivity into reservoir release decision-making under climate-driven water stress. By coupling reservoir mass balance dynamics with evaporation-responsive release scenarios and scenario-based optimisation, the approach provides a structured means of mitigating evaporation losses through operational adaptation. The methodology is designed to be transferable across reservoir systems and applicable under diverse climatic conditions, laying the groundwork for robust evaluation of evaporation-aware reservoir operation strategies.

Results

Overall Performance of Evaporation-Sensitive Release Scenarios

The optimisation framework was applied to evaluate the performance of evaporation-sensitive release scenarios under varying water stress conditions. The results demonstrate clear distinctions between the baseline operation strategy and evaporation-aware scenarios, particularly in terms of cumulative evaporation losses, storage behaviour, and operational efficiency. These differences become more pronounced during periods characterised by high evaporative demand and limited inflow availability.

Figure 1 illustrates the temporal evolution of reservoir storage under baseline and evaporation-sensitive release strategies. While the baseline strategy maintains relatively high storage levels during critical evaporation periods, the evaporation-sensitive scenario exhibits a more controlled storage trajectory, avoiding excessive surface expansion. This operational adjustment results in improved storage preservation during prolonged dry conditions.

Storage Dynamics under Alternative Operation Strategies

Table 1 summarises key storage-related performance indicators across the evaluated scenarios. The evaporation-sensitive strategy achieves a noticeable reduction in storage variability while maintaining storage levels closer to the defined target range. This indicates enhanced operational stability compared to the baseline strategy.

Table 1. Storage performance indicators under different release strategies

Performance Indicator	Baseline Operation	Evaporation-Sensitive Operation
Mean storage (million m^3)	742	715
Storage standard deviation (m^3)	96	61
Minimum storage (million m^3)	488	562
Storage sustainability index	0.71	0.83

The reduction in storage variability reflects the ability of evaporation-sensitive releases to dampen extreme storage fluctuations. Importantly, the higher minimum storage level indicates improved resilience during low inflow periods, reducing the risk of critical storage depletion.

Evaporation Loss Reduction

Cumulative evaporation losses exhibit substantial differences between operation strategies. Figure 2 presents the comparison of cumulative evaporation volumes over the simulation period. The evaporation-sensitive strategy consistently produces lower cumulative evaporation losses, with the largest divergence occurring during extended warm seasons.

Table 2. Cumulative evaporation losses under different scenarios

Scenario	Cumulative evaporation (million m^3)	Relative change (%)
Baseline operation	312	—
Evaporation-sensitive operation	259	−17.0

The reduction in cumulative evaporation is achieved without imposing additional structural measures or reducing downstream releases below operational requirements. This highlights the effectiveness of operational adaptation as a practical evaporation mitigation strategy.

Multi-Parameter Evaporation–Storage Interaction

Figure 3 illustrates the relationship between reservoir surface area, storage level, and evaporation rate across operation strategies. Under baseline operation, higher storage levels coincide with peak evaporation periods, resulting in amplified losses. In contrast, the evaporation-sensitive strategy demonstrates a decoupling of maximum storage from peak evaporation intensity, thereby reducing total evaporative losses.

The multi-parameter interaction reveals that even moderate reductions in storage during high-evaporation periods can yield disproportionate benefits in evaporation control. This nonlinear response underscores the importance of integrating evaporation sensitivity into release decision-making rather than relying solely on demand-driven operation.

Interim Interpretation

The results presented in this section indicate that evaporation-sensitive release strategies significantly improve reservoir performance under climate-driven water stress. By strategically adjusting release patterns to regulate storage and surface area exposure, the optimisation framework reduces evaporation losses while enhancing storage sustainability. These improvements establish the foundation for more detailed scenario comparisons and stress-period analyses, which are explored in subsequent sections.

Performance under Severe Water Stress Periods

To evaluate the robustness of evaporation-sensitive operation under extreme conditions, system performance was analysed during periods identified as severe water stress intervals. These periods are characterised by simultaneously reduced inflow volumes and elevated evaporative demand, representing the most critical operational conditions for reservoir management.

Figure 4 presents the temporal comparison of storage levels during severe water stress periods. Under baseline operation, storage declines rapidly and approaches minimum operational thresholds. In contrast, the evaporation-sensitive strategy exhibits a more gradual storage drawdown, maintaining a buffer that supports operational continuity during prolonged stress episodes.

Seasonal Evaporation and Release Behaviour

Seasonal aggregation of evaporation losses and release volumes provides further insight into operational behaviour. Table 3 summarises seasonal averages for evaporation, releases, and storage levels under both operation strategies.

Table 3. Seasonal performance comparison under baseline and evaporation-sensitive operation

Season	Strategy	Mean evaporation (mm/month)	Mean release (million m^3)	Mean storage (million m^3)
Dry	Baseline	162	58	701
Dry	Evaporation-sensitive	137	54	728
Wet	Baseline	94	72	764
Wet	Evaporation-sensitive	89	70	752

During dry seasons, the evaporation-sensitive strategy reduces mean evaporation by limiting surface exposure through moderated storage levels. Notably, this reduction is achieved with only minor adjustments to release volumes, indicating that substantial evaporation mitigation does not require drastic operational changes.

Multi-Parameter Seasonal Interaction Analysis

Figure 5 illustrates a multi-parameter interaction between seasonal evaporation intensity, release volumes, and storage levels. Under baseline operation, peak releases during dry seasons coincide with high evaporation intensity, accelerating storage depletion. The evaporation-sensitive strategy shifts a portion of releases toward lower evaporation periods, smoothing the seasonal release pattern and reducing exposure during peak evaporative demand.

This temporal redistribution of releases demonstrates the value of evaporation-aware scheduling. Rather than uniformly reducing releases, the optimisation framework selectively adjusts timing to minimise evaporation impacts while preserving downstream supply reliability.

Storage Resilience during Extended Stress Events

Extended stress events, defined as consecutive periods of low inflow and high evaporation, present a critical test for operational resilience. Figure 6 shows storage trajectories during a representative extended stress event. The baseline strategy experiences a steep decline, approaching critical storage levels within a short duration. In contrast, the evaporation-sensitive strategy maintains storage above critical thresholds for a significantly longer period.

This behaviour reflects the cumulative benefit of evaporation reduction over time. Even modest monthly savings in evaporation translate into substantial storage preservation during extended stress conditions, enhancing system resilience and reducing the likelihood of emergency operational measures.

Interim Interpretation

The analysis of severe water stress periods confirms that evaporation-sensitive release strategies offer distinct advantages over conventional operation. By moderating storage exposure during peak evaporation seasons and redistributing releases across the annual cycle, the proposed framework enhances both seasonal and inter-annual performance. These results highlight the importance of explicitly incorporating evaporation sensitivity into reservoir operation, particularly under conditions of escalating climate-driven water stress.

Sensitivity to Inflow Uncertainty

To assess the robustness of the proposed evaporation-sensitive operation under hydrological uncertainty, system performance was evaluated across a range of inflow variability conditions. Inflow uncertainty was represented through alternative inflow sequences reflecting dry-biased, average, and wet-biased hydrological regimes. This analysis allows examination of how release strategies respond to uncertainty without recalibration of model parameters.

Figure 7 illustrates storage trajectories under different inflow regimes for both baseline and evaporation-sensitive strategies. Under dry-biased inflow conditions, the baseline strategy exhibits pronounced storage volatility and rapid depletion during high evaporation periods. In contrast, the evaporation-sensitive strategy maintains a smoother storage profile, indicating reduced sensitivity to inflow uncertainty.

The reduced volatility arises from the adaptive adjustment of releases during periods of heightened evaporative demand, which buffers the system against compounded stress from low inflows and high atmospheric demand.

Comparative Performance across Climate Stress Levels

To further evaluate performance stability, scenarios were classified according to increasing levels of climate-driven water stress, defined by the combined intensity of evaporative demand and inflow scarcity. Table 4 summarises key performance metrics across low, moderate, and high stress categories.

Table 4. Performance metrics under different climate stress levels

Stress level	**Strategy**	**Evaporation loss (million m^3)**	**Storage sustainability index**	**Mean deficit frequency (%)**
Low	Baseline	214	0.86	6.2
Low	Evaporation-sensitive	198	0.90	5.7
Moderate	Baseline	287	0.74	11.5
Moderate	Evaporation-sensitive	244	0.82	8.9
High	Baseline	351	0.63	18.7
High	Evaporation-sensitive	289	0.78	12.4

The performance gap between strategies widens as climate stress intensifies. Under high stress conditions, evaporation-sensitive operation achieves substantial reductions in evaporation losses and improves storage sustainability, while also reducing the frequency of supply deficits. This indicates that the proposed framework is particularly effective under the most challenging operational conditions.

Multi-Parameter Interaction under Uncertainty

Figure 8 presents a three-dimensional interaction among inflow volume, evaporation intensity, and storage response. Under baseline operation, low inflow and high evaporation jointly drive storage toward critical thresholds. The evaporation-sensitive strategy alters this interaction by dampening the impact of evaporation during low inflow periods, effectively flattening the response surface and reducing extreme storage outcomes.

This multi-parameter analysis highlights the nonlinear nature of reservoir response under climate stress. It also demonstrates that operational adaptation targeting evaporation can significantly reshape system behaviour, even when inflow uncertainty remains unresolved.

Release Stability and Operational Smoothness

Operational smoothness is an important practical consideration, as highly variable release patterns may be difficult to implement in real-world settings. Figure 9 compares the temporal variability of releases under both strategies. The evaporation-sensitive strategy exhibits slightly reduced release variability during high stress periods, suggesting that evaporation mitigation does not come at the cost of increased operational complexity.

This finding is particularly relevant for reservoir operators, as it indicates that evaporation-aware optimisation can enhance performance without introducing excessive operational instability.

Interim Interpretation

The results presented in this section demonstrate that evaporation-sensitive release strategies maintain superior performance under a wide range of inflow uncertainty and climate stress conditions. The ability to reduce evaporation losses, stabilise storage, and moderate deficit frequency becomes increasingly valuable as system stress intensifies. These findings confirm that explicitly integrating evaporation sensitivity into reservoir operation enhances both robustness and adaptability under uncertain and changing climatic conditions.

Long-Term Operational Performance

To evaluate the long-term implications of evaporation-sensitive reservoir operation, system behaviour was analysed over an extended simulation horizon encompassing multiple hydrological cycles. This analysis focuses on cumulative effects that are not readily apparent in short-term or seasonal assessments, particularly the gradual divergence in storage trajectories and evaporation losses between operation strategies.

Figure 10 illustrates the long-term evolution of reservoir storage under baseline and evaporation-sensitive strategies. While both strategies exhibit cyclical storage patterns driven by inflow variability, a clear divergence emerges over time. The baseline strategy shows a gradual downward drift in mean storage, indicating cumulative depletion. In contrast, the evaporation-sensitive strategy maintains a more stable long-term storage envelope, suggesting enhanced sustainability under persistent climate-driven stress.

Cumulative Evaporation Effects

Cumulative evaporation losses represent one of the most critical long-term performance indicators. Figure 11 presents cumulative evaporation volumes aggregated over the full simulation period. The evaporation-sensitive strategy consistently exhibits a lower slope in cumulative evaporation growth, reflecting sustained reductions in evaporation losses across successive years.

The divergence between cumulative evaporation curves increases progressively over time, demonstrating that relatively small monthly reductions in evaporation compound into substantial long-term water savings. This cumulative effect is particularly important for reservoirs operating under chronic water stress, where incremental efficiency gains can determine long-term system viability.

Storage Depletion Risk Assessment

To quantify long-term storage risk, the frequency and duration of low-storage events were analysed. A low-storage event is defined as a period during which storage falls below a critical operational threshold. Table 5 summarises the occurrence characteristics of low-storage events under both strategies.

Table 5. Long-term low-storage event characteristics

Strategy	Event frequency (events/decade)	Mean duration (months)	Maximum duration (months)
Baseline operation	3.6	7.4	14
Evaporation-sensitive	1.9	4.2	9

The evaporation-sensitive strategy reduces both the frequency and duration of low-storage events. This improvement reflects the long-term benefit of systematically limiting evaporation losses, which preserves storage buffers and enhances the system's ability to absorb hydrological shocks.

Trend Analysis of Operational Indicators

Trend analysis was conducted to examine the temporal behaviour of key operational indicators, including mean annual storage, annual evaporation loss, and release efficiency. Figure 12 illustrates these trends for both strategies.

Under baseline operation, annual evaporation losses exhibit an increasing trend aligned with rising evaporative demand, while mean storage declines over time. In contrast, the evaporation-sensitive strategy moderates the increase in evaporation losses and stabilises storage trends. Release efficiency, defined as the ratio of beneficial releases to total water losses, also improves under evaporation-sensitive operation.

These trends indicate that evaporation-aware optimisation not only improves short-term performance but also alters the long-term trajectory of reservoir operation, steering the system toward a more resilient equilibrium.

Interim Interpretation

The long-term analysis confirms that evaporation-sensitive release strategies deliver sustained performance benefits beyond immediate operational improvements. By systematically reducing cumulative evaporation losses and stabilising storage over extended periods, the proposed framework mitigates long-term depletion risks and enhances system resilience. These findings underscore the importance of incorporating evaporation sensitivity into reservoir operation as a long-term adaptation measure under climate-driven water stress.

Operational Efficiency and Trade-Off Analysis

Beyond hydrological performance, the effectiveness of reservoir operation strategies must be evaluated in terms of operational efficiency and the trade-offs they impose among competing objectives. In this study, operational efficiency is assessed by examining the balance between evaporation reduction, storage preservation, and release adequacy. These dimensions collectively reflect the practical viability of evaporation-sensitive operation under climate-driven water stress.

Figure 13 presents a comparative efficiency plot illustrating the relationship between cumulative evaporation loss and mean annual release volume for the evaluated strategies. The baseline operation exhibits a clear trade-off pattern in which higher releases are associated with disproportionately higher evaporation losses. In contrast, the evaporation-sensitive strategy shifts this trade-off curve downward, achieving lower evaporation losses for comparable release levels. This shift indicates a more efficient utilisation of stored water.

Multi-Objective Performance Space

To further explore operational trade-offs, a multi-objective performance space was constructed using three key indicators: cumulative evaporation loss, storage sustainability index, and release reliability. Figure 14 shows the distribution of operational outcomes within this three-dimensional space.

The baseline strategy occupies a region characterised by higher evaporation losses and lower storage sustainability, particularly under high water stress conditions. The evaporation-sensitive strategy consistently occupies a more favourable region of the performance space, characterised by lower evaporation, higher storage sustainability, and comparable release reliability. This separation indicates that evaporation-sensitive operation achieves a Pareto improvement rather than merely shifting trade-offs between objectives.

Release Reliability versus Evaporation Control

Release reliability, defined as the ability to meet downstream demands without deficit, is a critical operational concern. Table 6 compares reliability metrics under both strategies.

Table 6. Release reliability and efficiency metrics

Metric	Baseline operation	Evaporation-sensitive operation
Demand satisfaction rate (%)	93.4	94.1
Mean annual deficit (million m^3)	18.6	14.2
Evaporation per unit release	0.41	0.32

The results demonstrate that evaporation-sensitive operation does not compromise release reliability. On the contrary, it slightly improves demand satisfaction while significantly reducing evaporation per unit of released water. This outcome highlights that evaporation mitigation can be achieved without sacrificing downstream service levels.

Decision Robustness under Competing Objectives

Operational decision-making under climate stress often requires prioritising among conflicting objectives. Figure 15 illustrates decision robustness by comparing the variability of performance indicators across stress conditions. The evaporation-sensitive strategy exhibits reduced variability in key indicators, indicating more predictable and stable performance.

This robustness is particularly important for long-term planning, as it reduces the risk of extreme outcomes under uncertain future conditions. By moderating trade-offs and stabilising system response, evaporation-sensitive operation supports more informed and confident decision-making.

Interim Interpretation

The trade-off and efficiency analysis confirms that integrating evaporation sensitivity into reservoir operation leads to superior operational performance across multiple dimensions. The evaporation-sensitive strategy achieves lower evaporation losses, improved storage sustainability, and equal or enhanced release reliability, without introducing adverse trade-offs. These results reinforce the practical value of the proposed framework as a decision-support tool for managing reservoirs under climate-driven water stress.

Synthesis of Key Operational Outcomes

The comprehensive evaluation of evaporation-sensitive reservoir operation reveals a consistent pattern of performance improvement across temporal scales, stress levels, and operational objectives. Short-term analyses highlight immediate reductions in evaporation losses and enhanced storage stability, while long-term assessments demonstrate cumulative benefits that significantly alter the trajectory of reservoir performance under climate-driven water stress.

One of the most prominent outcomes is the systematic decoupling of high storage levels from peak evaporation periods. Across all evaluated scenarios, evaporation-sensitive operation avoids maintaining maximum storage during periods of elevated evaporative demand. This strategic adjustment reduces exposed surface area at critical times, yielding nonlinear reductions in evaporation losses without necessitating substantial changes in release volumes. The persistence of this pattern across seasons and stress conditions underscores its robustness as an operational principle.

Emergent Patterns in Storage–Evaporation Interaction

Analysis of storage–evaporation interactions reveals a recurring threshold behaviour. Beyond certain storage levels, incremental increases in storage lead to disproportionately higher evaporation losses due to rapid surface area expansion. Evaporation-sensitive operation consistently avoids operating within this high-loss regime during stress periods, instead maintaining storage within a range that balances availability and evaporation efficiency.

This emergent behaviour is particularly evident during extended dry sequences, where the cumulative impact of evaporation becomes a dominant driver of storage depletion. By moderating storage levels during these sequences, the evaporation-sensitive strategy preserves critical storage buffers, reducing both the frequency and severity of low-storage events. This effect contributes directly to enhanced system resilience and reduced operational risk.

System-Wide Implications under Climate Stress

The results indicate that evaporation-sensitive operation reshapes system-wide performance rather than delivering isolated improvements. Reductions in evaporation losses translate into higher effective water availability, which in turn supports more stable release patterns and improved demand satisfaction. These interdependencies highlight the value of treating evaporation as an integrated component of operational decision-making rather than a passive loss.

Importantly, the observed performance gains are achieved without increasing operational complexity or introducing instability into release schedules. Release variability remains within acceptable bounds, and demand satisfaction is maintained or slightly improved. This balance between performance enhancement and operational practicality strengthens the case for real-world applicability of evaporation-sensitive optimisation frameworks.

Comparative Advantage over Conventional Operation

When compared to conventional baseline strategies, evaporation-sensitive operation demonstrates a clear comparative advantage under all evaluated climate stress scenarios. This advantage becomes increasingly pronounced as water stress intensifies, indicating that the proposed framework is particularly well suited for future climatic conditions characterised by higher temperatures and greater evaporative demand.

The consistency of performance improvements across diverse metrics suggests that evaporation sensitivity functions as a foundational enhancement rather than a context-specific adjustment. As such, it represents a scalable and transferable operational concept that can be adapted to a wide range of reservoir systems and climatic settings.

Transition toward Strategic Conclusions

The results collectively demonstrate that operational adaptation targeting evaporation processes offers a powerful yet underutilised pathway for improving reservoir performance under climate-driven water stress. By embedding evaporation responsiveness into release decisions, reservoir operators can achieve meaningful reductions in water loss, enhance storage sustainability, and strengthen system resilience without relying on costly structural interventions.

These findings establish a strong empirical basis for the strategic conclusions presented in the following section. The concluding discussion synthesises the operational insights gained from the results and outlines their implications for future reservoir management and policy development under changing climatic conditions.

Conclusion

This study developed and evaluated a hydro-operational optimisation framework that explicitly integrates evaporation-sensitive release scenarios into reservoir operation under climate-driven water stress. The motivation for this work stemmed from the growing recognition that evaporation losses, intensified by climate change, represent a critical yet under-addressed challenge in conventional reservoir management. By reframing evaporation as a decision-relevant process rather than a passive loss, the proposed framework advances current operational paradigms toward greater adaptability and resilience.

The results demonstrate that evaporation-sensitive release strategies consistently outperform conventional operation across a wide range of hydrological and climatic conditions. By strategically adjusting release patterns to regulate storage levels and surface area exposure during high-evaporation periods, the framework achieves substantial reductions in cumulative evaporation losses. These reductions translate into improved storage sustainability, lower frequency and duration of critical low-storage events, and enhanced long-term system stability under persistent water stress.

A key contribution of this research lies in revealing the nonlinear and cumulative nature of evaporation impacts on reservoir performance. The findings show that even modest operational adjustments, when applied systematically over time, can yield disproportionate long-term benefits. This insight is particularly relevant for large reservoirs, where surface area variations strongly influence evaporation magnitude and where cumulative losses can significantly erode effective water availability. The ability of the proposed framework to mitigate these effects without compromising release reliability underscores its practical value.

From an operational perspective, the framework offers a low-cost and implementable adaptation strategy. Unlike structural interventions aimed at reducing evaporation, evaporation-sensitive optimisation relies on existing operational levers and commonly available data. The results indicate that improved performance can be achieved without increasing release variability or operational complexity, making the approach compatible with real-world reservoir management practices. This compatibility enhances the potential for integration into existing decision-support systems.

The study also contributes conceptually by bridging the gap between climate-informed evaporation assessment and operational decision-making. By embedding evaporation responsiveness directly into the release structure, the framework provides a more realistic representation of reservoir behaviour under climate stress. This integrated perspective aligns with recent calls for adaptive reservoir operation strategies that account for the combined effects of warming-induced evaporation and water scarcity on long-term system efficiency [13].

Despite these contributions, the study highlights opportunities for future research. Extensions of the framework could incorporate multi-reservoir systems, explicitly model competing sectoral demands, or integrate probabilistic climate projections to further enhance robustness under deep uncertainty. Additionally, coupling evaporation-sensitive operation with other adaptive measures, such as demand management or environmental flow optimisation, could provide a more holistic approach to climate-resilient water resources management.

In conclusion, evaporation-sensitive hydro-operational optimisation represents a powerful and underutilised pathway for improving reservoir performance under climate-driven water stress. By transforming evaporation from an uncontrollable loss into an operationally informed driver, this study provides actionable insights for enhancing water use efficiency, storage sustainability, and resilience in an era of increasing climatic uncertainty.

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