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Review article: Upstream reservoir operation and downstream floodplain risk: A review of hydrodynamic modelling and optimization frameworks and case perspective on the Dong Nai–Sai Gon river basin

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Abstract. Flood risk management is increasingly challenged by climate change, rapid urbanization, and the growing complexity of hydrological systems. Reservoirs play a vital role in flood mitigation, yet traditional rule-curve operations based on historical stationarity are becoming inadequate under non-stationary and compound flood conditions. This review synthesizes advances in reservoir operation, hydrodynamic flood modelling, and optimization frameworks for downstream flood risk management, drawing on literature published between 2000 and 2025. Existing studies are classified into four thematic areas: reservoir operation strategies, hydrodynamic modelling, optimization methods, and compound flooding processes. Results reveal a shift from static rule-based operations toward adaptive, forecast-informed, and data-driven approaches that improve flood control performance and reduce peak discharge. Coupled 1D–2D hydrodynamic models better capture floodplain dynamics, while evolutionary algorithms and reinforcement learning support efficient multi-objective optimization. However, a critical knowledge gap persists, as spatial flood inundation metrics and compound flood drivers remain rarely incorporated into optimization frameworks. Using the Dong Nai–Sai Gon river basin as a representative tropical, tide-influenced system, we propose an integrated framework linking reservoir operations, hydrodynamic simulation, and compound flooding processes. Future research should prioritize hybrid physics–AI approaches, real-time data integration, and climate-resilient reservoir management.

1 Introduction

Flood-related disasters have emerged as one of the defining challenges of the 21st century. Storm and flood losses have grown steadily over recent decades, costing the global economy over USD 140 billion in 2017 alone, with the following four out of five years each exceeding USD 100 billion in annual losses (Rogers et al., 2025). Looking further ahead, the global population exposed to a 1-in-100-year flood hazard is projected to rise from 1.6 to 1.9 billion people between 2020 and 2100, with

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population growth accounting for roughly 77% of that increase and climate change for about 21% (Rogers et al., 2025). Urbanization into high-risk zones is a particularly acute driver because human settlements worldwide have expanded continuously into flood zones since 1985, with growth in the most hazardous areas substantially exceeding that in flood-safe zones—especially in East Asia, where high-hazard settlements expanded 60% faster (Rentschler et al., 2023). In rapidly growing regions, these converging pressures make it urgent to rethink how water systems are managed, balancing flood protection against competing socio-economic demands (Chan et al., 2024).

Large-scale reservoirs sit at the center of this challenge. They serve as the primary defense against flooding and the backbone of broader water resource management (Argoubi and Mili, 2025). Conventionally, reservoirs are operated using “rule curves”—static guidelines derived from historical hydrological patterns (Ilich, 2024). These approaches are increasingly proving inadequate. The long-standing policy in many dams is to maintain water levels close to the full-reservoir level for most of the year to maximize power generation, leaving little flexibility in their operating rule curves—a rigid framework that is proving ineffective against the mounting unpredictability of precipitation and associated runoffs (Suresh et al., 2024). The performance gap is evident under changing conditions as studies have shown that conventional operating rules yield highly suboptimal performance under non-stationary regimes because they lack the feedback information required to enable adaptive and coordinated strategies (Giuliani et al., 2021). Furthermore, uncoordinated reservoir releases have historically exacerbated downstream flooding even when individual reservoirs were operating within their own design parameters (Argoubi and Mili, 2025).

The problem is further complicated by “compound flooding” where high river discharge coincides with intense local rainfall and tidal backwater effects. Today, near-coastal zones and low-elevation coastal zones—subject to flooding from a range of drivers—are home to approximately 2.15 billion and roughly 900 million people globally, respectively (Reimann et al., 2023). In coastal and deltaic basins, these drivers interact rather than act independently, producing water levels that can far exceed the sum of their parts (Green et al., 2025). The 2017 Hurricane Harvey event illustrated this vividly: record-breaking rainfall, river discharge, and runoff combined with long-lasting storm surge to produce catastrophic flooding in Houston, Texas—making it the second-costliest natural hazard in U.S. history at USD 152.5 billion in damages (Valle-Levinson et al., 2020). Yet traditional reservoir optimization frameworks typically treat the downstream boundary as a simple stage-discharge relationship. Most existing flood risk assessments consider the main drivers of flooding separately, oversimplifying or ignoring key interactions altogether, even though in many coastal–estuarine regions floods are naturally caused by more than one correlated driver (Green et al., 2025).

Recent technological advances offer promising paths forward. High-resolution hydrodynamic models can now simulate water movement across complex terrain with considerable precision, while sophisticated optimization algorithms are capable of navigating difficult trade-offs. Machine learning and deep learning models have shown promising results for flood inundation modelling, with deep learning approaches demonstrating better accuracy than traditional approaches—though they still face challenges in generalizability and in incorporating expert hydrological knowledge (Karim et al., 2023). On the optimization side, advanced stochastic multi-objective frameworks have demonstrated peak discharge reductions of 25–30% through

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coordinated reservoir operations, converging in as little as 42 iterations with a 6.7-fold reduction in computational time compared to full-scenario optimization. A critical knowledge gap persists because floodplain inundation metrics are rarely embedded within reservoir optimization frameworks, while studies integrating these objectives in tropical monsoon basins—where hydrological variability is dominated by pronounced seasonal extremes—remain limited (Argoubi and Mili, 2025).

This review synthesizes the current state of the art in coupling reservoir operations with downstream hydrodynamic modelling and optimization. Using the Dong Nai–Sai Gon river basin—a complex, urbanized, tide-influenced tropical system in southern Vietnam—as its focal case, the paper maps key knowledge gaps and examines how emerging tools can build more resilient water management strategies. The goal is to chart a course from reactive reservoir management toward proactive, risk-informed floodplain protection.

2 Literature review methodology

A methodological framework of five steps, as shown in Fig. 1, was used in this review paper to synthesize reservoir operations and floodplain risk. It outlines the workflow from literature search and screening to thematic classification and synthesis. The framework culminates in an integrated approach linking hydrodynamic modelling and optimization for improved floodplain risk management.

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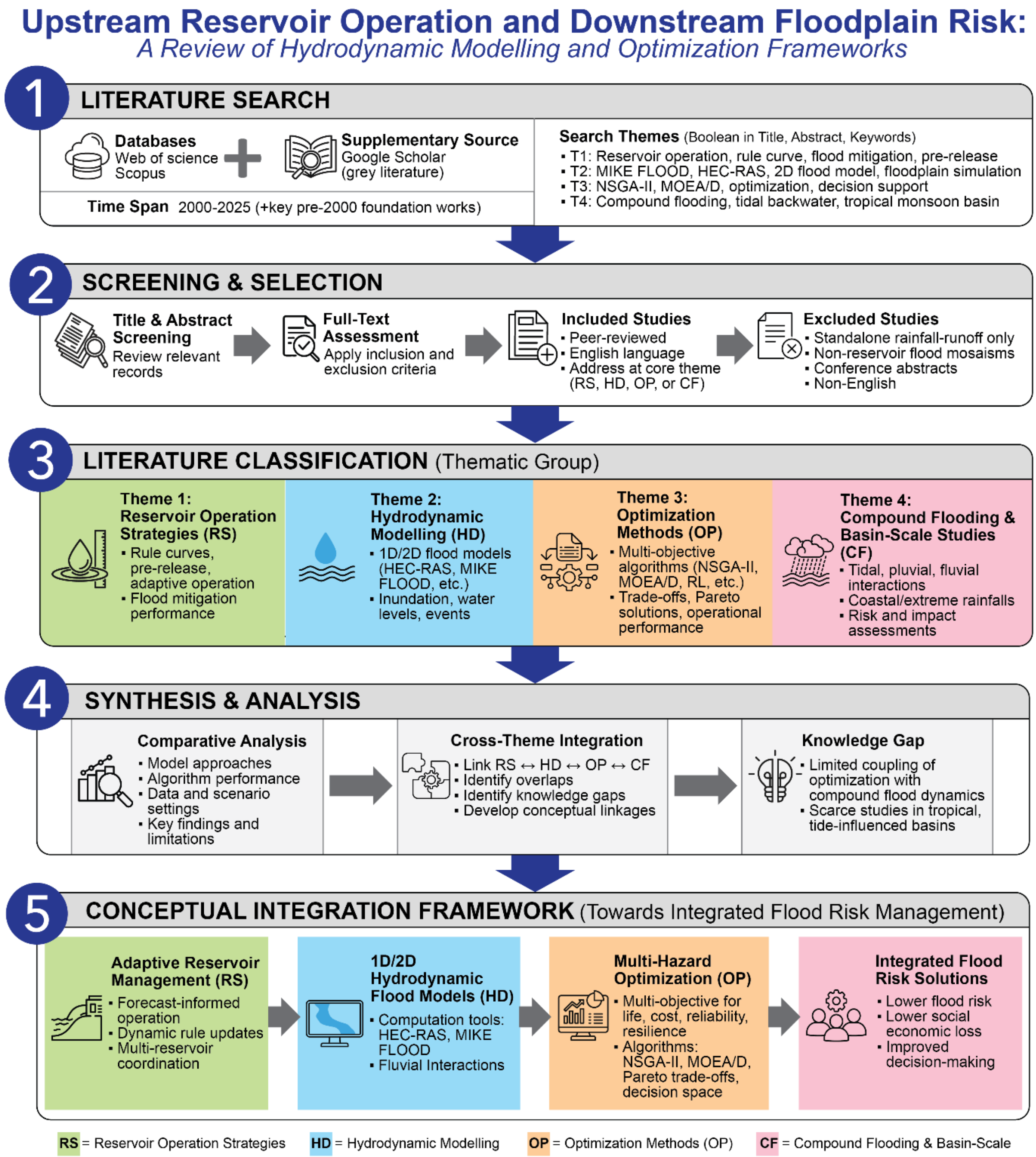

Figure 1. Methodological framework including five steps of literature search, screening and selection, literature clarification, synthesis and analysis, and developing conceptual integration framework for downstream floodplain risk management under upstream reservoir operations.

2.1 Literature search strategy

Systematic searches were conducted with a temporal scope spanning 2000–2025 (seminal pre-2000 works included where foundational context required it) across Web of Science and Scopus as primary databases (297 papers found), supplemented by Google Scholar (260 publications) for grey literature and highly cited works not captured by the major indices. Boolean operators (AND, OR) were applied across title, abstract, and keyword fields using three thematic clusters: (i) reservoir operation and flood control (e.g., reservoir operation, rule curve, flood mitigation, pre-release strategy); (ii) hydrodynamic and inundation modelling (e.g., MIKE FLOOD, HEC-RAS 2D, 2D flood model, floodplain simulation); and (iii) optimisation and compound flooding (e.g., NSGA-II, MOEA/D, compound flooding, tidal backwater, tropical monsoon basin).

2.2 Study selection criteria

Records were screened in two stages—title/abstract review followed by full-text assessment. Studies were included if they were peer-reviewed, English-language, and substantively addressed at least one of: reservoir operation strategies, numerical flood propagation modelling, optimisation methods applied to water infrastructure, or compound flood interactions. Studies limited to standalone rainfall–runoff modelling, conference abstracts, or non-reservoir flood measures were excluded. No minimum citation threshold was applied, ensuring recent high-relevance publications (2020–2025) were captured.

2.3 Literature classification

Selected studies are assigned to four thematic groups (see Fig. 1 Step 3 and Table 1) — (i) Reservoir operation strategies (RS), (ii) Hydrodynamic modelling (HD), (iii) Optimisation methods (OP), and (iv) Compound flooding and basin-scale studies (CF)— colour-coded in the reference matrix above. This classification directly maps onto the synthesis structure of Sections 3–5.

Across the four thematic clusters, a clear trajectory emerges from static, rule-based reservoir management toward adaptive, computationally sophisticated operational frameworks. Studies under Theme 1 consistently demonstrate that conventional rule curves—designed around historical hydrological patterns—produce measurably inferior outcomes under non-stationary climatic conditions, with Giuliani et al., (2021) emphasizing that these static approaches amplify operational errors because they lack the feedback information required for adaptive strategies, and the International Commission on Large Dams (ICOLD), (2025) documenting real-world cases where rigid operating frameworks either failed to prevent inundation or actively worsened downstream flooding through uncoordinated releases. The optimisation literature (Theme 3) has responded to this shortcoming with increasingly powerful algorithmic tools: evolutionary algorithms such as NSGA-II and MOEA/D have demonstrated reliable Pareto-front coverage for multi-objective flood control problems, while more recent work—particularly Wu et al., (2024) and Argoubi & Mili, (2025)—show that transformer-based reinforcement learning and stochastic progressive hedging frameworks can achieve a major reduction in peak discharges and satisfy operational constraints in over 93% of simulated scenarios, representing a step-change over the 60–70% reliability typical of rule-based approaches. Taken together, Themes 1 and 3 point toward a future in which reservoir release decisions are informed not by predetermined storage targets but by probabilistic, forecast-driven policies that respond dynamically to evolving hydrological conditions across the basin.

However, a critical disconnect separates the optimisation and hydrodynamic modelling literature from the compound flood science that characterises real floodplain risk in coastal and deltaic environments. Hydrodynamic studies (Theme 2) confirm that coupled 1D/2D models—particularly HEC-RAS and MIKE FLOOD configurations—can simulate downstream inundation with high fidelity ($R^2 = 0.92$ in Bhargav et al., 2025). These models can resolve the feedback between reservoir releases and downstream water levels in sufficient detail to support risk-informed decision-making. Yet the compound flooding literature (Theme 4) reveals that this feedback operates within a far more complex multi-driver system: Green et al., (2025) synthesise evidence across 279 studies showing that fluvial discharge, tidal backwater, and intense local rainfall interact non-linearly in coastal–estuarine settings to produce flood levels that substantially exceed single-driver estimates. This dynamic is confirmed in the Ho Chi Minh City context by Couasnon et al., (2022) and in global projections by Rogers et al., (2025), who estimate that up to 1.9 billion people will face flood exposure by 2100. To address this gap, this review systematically synthesizes reservoir operation, hydrodynamic modelling, optimization algorithms, and compound flooding processes within a unified framework for tropical, tide-influenced basins. Resolving this disconnect between what optimization algorithms can theoretically achieve and what floodplain science shows is actually occurring defines the central challenge of this work.

2.4 Literature synthesis approach

The conceptual integration framework depicted in Fig. 2 by our review synthesizes modern flood management into six interconnected components, mapping out a progression from structural strategies to advanced computational techniques. It begins by classifying physical interventions into flood control, multi-purpose, and temporary detention reservoirs (Panel 1), which are traditionally managed via historical, static rule curves but are increasingly modernized through adaptive, AI-driven forecasting methodologies (Panel 2). This operational decision-making relies heavily on flood modelling (Panel 3), which scales from simple 1D channel flow simulations to 2D floodplain mapping and fully integrated 1D-2D coupled models. To handle these complex systems, various optimization approaches (Panel 4)—such as Linear Programming (LP), Dynamic Programming (DP), and Genetic Algorithms (GA)—are paired with simulation models to determine ideal operational thresholds. Crucially, the framework accounts for the heightened risks of compound flooding (Panel 5), illustrating how the simultaneous convergence of rain, river flow, and ocean tides amplifies severe flooding outcomes. Ultimately, these elements feed into future directions (Panel 6), which advocate for machine learning integration, real-time predictive analytics, and long-term climate resilience in reservoir operations.

Out of 297 publications found, the reference matrix captures 20 key studies across all four themes, presenting each study's objective, method, key findings, and implications for integrated flood management (Table 1). Notably, the limited overlap between Theme 3 (optimisation) and Theme 4 (compound flooding) within the table reflects the core knowledge gap this

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review addresses: the scarcity of studies that couple reservoir optimisation directly with compound flood inundation metrics in tropical, tide-influenced basins.

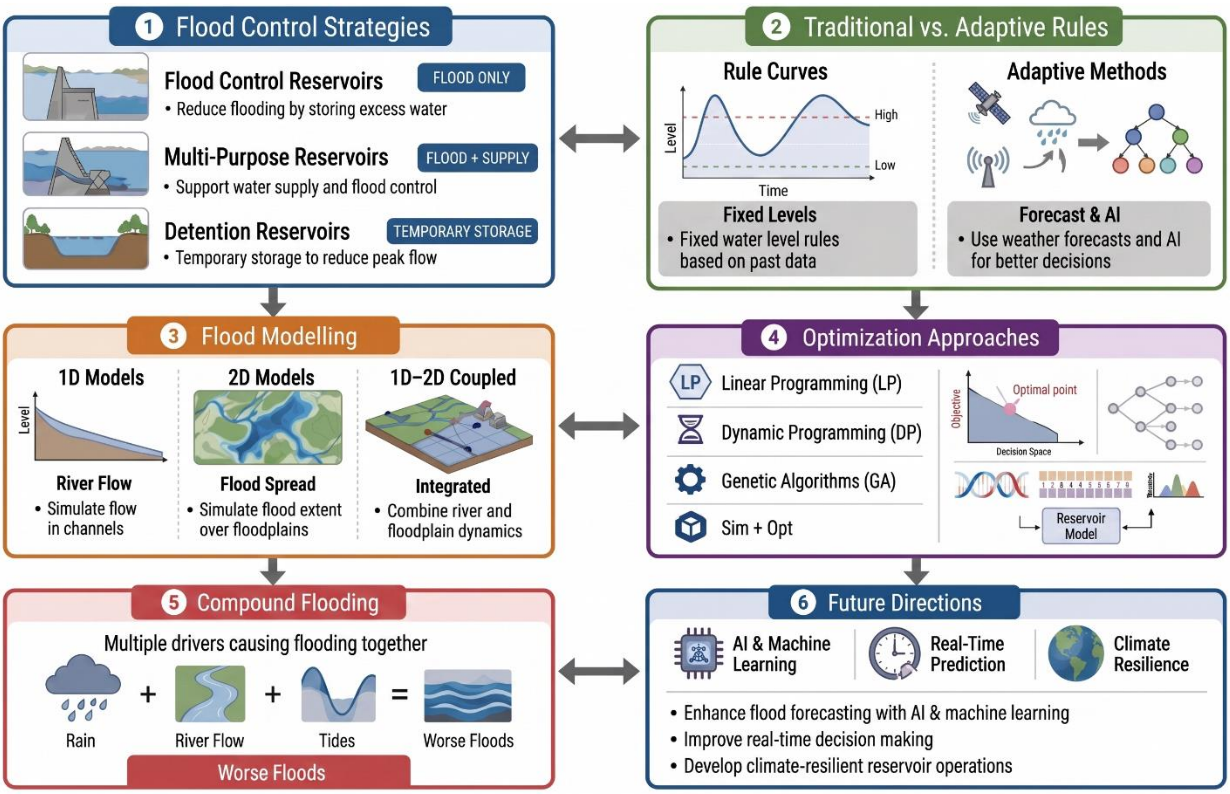

Figure 2. Integrated framework of reservoir operation for floodplain risk mitigation, illustrating the evolution from traditional rule-curve methods to adaptive, forecast-informed strategies, supported by hydrodynamic modelling (1D–2D), optimization techniques, and consideration of compound flooding processes and future AI-driven solutions.

Table 1. Literature review of primary studies.

Paper Source	Theme	Objective	Method/Tool	Key findings & implications
Regmi et al., (2025), Scientific Report	RS	Test adaptive (dynamic) rule curves vs. static operation in hydropower dams. Assess limitations of static rule-curve operation during	CMIP6 climate models, SWAT (hydrology), and HEC-ResSim for reservoir simulation	Dynamic rule curves significantly improve performance (+7–71% energy) and enable adaptive response to extreme precipitation. Trade-off between energy optimization versus flood control capacity while demonstrating need for adaptive, real-time reservoir release policies.

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Paper Source	Theme	Objective	Method/Tool	Key findings & implications
		rainfall and flow variability		
Giuliani et al., (2021), Water Resources Research	RS	Quantify performance gap between static rules and adaptive strategies under non-stationary conditions	Evolutionary multi-objective direct policy search (EMODPS); scenario analysis	Static rule curves are increasingly prone to operational errors under non-stationary conditions. The study supports a shift toward adaptive, closed-loop strategies, such as EMODPS, which allow for coordinated management of many-objective systems (4+ objectives) and leverage modern inflow forecasts to bridge the performance gaps inherent in traditional trajectory-based rules.
International Commission on Large Dams (ICOLD), (2025)	RS	Document global cases of uncoordinated reservoir releases exacerbating downstream flooding	Case study review; operational analysis	Uncoordinated releases worsened downstream impacts despite individual reservoirs operating within design limits. Highlights need for basin-wide coordination frameworks.
Wang et al., (2022), Journal of Physics: Conference Series	RS	Coordinated flood control operation for 12 major reservoirs in China's Yangtze River basin	Multi-objective optimisation; basin-scale simulation	Demonstrated potential of system-scale coordination but highlighted computational challenges for large, interconnected systems. Informs multi-reservoir management frameworks.
Rentschler et al., (2023), Nature	RS	Quantify global expansion of human settlements into	High-resolution annual settlement data; spatial flood hazard analysis	Human settlements in highest-hazard flood zones grew 122% from 1985–2015; East Asia 60% faster than safe

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Paper Source	Theme	Objective	Method/Tool	Key findings & implications
		flood-prone zones since 1985		zones. Underpins urgency of improved reservoir-based flood protection.
Kulkarni & Kale, (2024), Water Resources	HD	Develop coupled 1D–2D hydrodynamic model for flood inundation mapping in a complex river basin	HEC-RAS 1D/2D coupled model; calibration against 2019 and 2021 flood events	R^2 = 0.70–0.97 for inundation prediction. Coupled models outperform standalone 1D approaches in capturing floodplain dynamics, informing downstream boundary conditions for reservoir optimisation.
Bhargav et al., (2025), Journ al of Water and Climate Change	HD	Assess flood hazard and inundation extent for the lower Narmada basin downstream of Karjan Dam	HEC-RAS 6.0 2D; DEM, land use, stream gauge integration	R^2 = 0.92 (calibration); 326.45 km² of agricultural land severely inundated in major events; 8-hour warning window from dam release to downstream overflow. Demonstrates direct link between reservoir releases and downstream inundation.
Karim et al., (2023), Water (MDPI)	HD	Review ML and DL approaches for flood inundation modelling across basin types	Systematic literature review; comparative analysis of ML/DL model performance	DL models outperform traditional approaches in accuracy but lack physical knowledge. Benchmark data scarcity limits rigorous testing. Reinforces hybrid physics–ML frameworks as the most promising direction.
Kumar et al., (2023), Hydro logy (MDPI)	HD	Provide a comprehensive overview of flood modelling approaches including hydrodynamic, AI,	Narrative and comparative review; empirical, hydrodynamic, and AI model evaluation	No single model excels in all contexts. AI-physics hybrids emerging as leading approach. Identifies lack of integrated reservoir–inundation objective functions as a critical gap.

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Paper Source	Theme	Objective	Method/Tool	Key findings & implications
		and multi-criteria methods		
Chen et al., (2017), Water Resources Management	OP	Solve multi-objective reservoir flood control operation (RFCO) for Three Gorges Reservoir	Improved NSGA-III (ENSGA-III); orthogonal design for initial population; ε-dominance strategy	Well-distributed Pareto-optimal solutions for two objectives (upstream water level vs. maximum discharge). NSGA-III preferred for 3+ objective problems. Establishes NSGA family as benchmark for RFCO.
Zhang et al., (2019), Engin eering Optimization	OP	Apply decomposition-based MOEA to flood operations at China's Ankang reservoir	MOEA/D-DE (differential evolution-inspired recombination)	Significant reductions in peak discharge while maintaining dam safety constraints. MOEA/D-DE competitive with NSGA-II for flood-specific objective landscapes. Informs algorithm selection for reservoir RFCO.
Wu et al., (2024), cited in Journal of Hydrology	OP	Apply transformer-based deep reinforcement learning to multi-objective multi-hydropower reservoir optimisation	Transformer-based deep reinforcement learning; comparison with NSGA-III and MOEA/D	Superior generalisation over traditional evolutionary algorithms. ML integration reduces dependence on pre-specified rule structures. Opens pathway for data-driven adaptive operation in tropical monsoon basins.
Argoubi & Mili, (2025), Fronti ers in Water	OP	Stochastic multi-objective flood control optimisation for multi-reservoir systems under inflow uncertainty	Adaptive Progressive Hedging with scenario clustering; HEC-RAS as hydraulic simulator	93% of scenarios met storage and flood constraints (vs. 60–70% for rule-based). Peak discharge reduced 25–30%; 6.7 times computational speedup. Demonstrates viability of stochastic frameworks over static rule curves.

Paper Source	Theme	Objective	Method/Tool	Key findings & implications
Xiong et al., (2024), Scientific Reports	OP	Optimise water supply and ecological flow in Fenhe reservoir using enhanced NSGA-II	NSGA-II with hybrid SBAX crossover operator (SBX + arithmetic crossover)	Improved Pareto front coverage and reduced local convergence risk. Demonstrates value of crossover innovations for multi-objective reservoir problems involving competing conservation and flood objectives.
Green et al., (2025), Natural Hazards and Earth System Sciences	CF	Systematically review coastal–estuarine compound flood research (279 studies)	Systematic review (PRISMA-style); six flood drivers; thematic synthesis	~2.15 billion people in near-coastal zones exposed to compound drivers. Flood losses in major coastal cities projected at USD 1 trillion/year by 2050. Research gaps in tropical regions and integrated modelling frameworks identified.
Ruan et al., (2024), Applied Sciences (MDPI)	CF	Review compound flood risk under climate change and urbanisation across 64 studies (2014–2024)	Systematic literature review; comparative analysis of statistical, numerical, ML, and coupled models	All four model types show distinct trade-offs; coupling increasingly preferred. 100-year flood extent in Cape Fear Estuary increased by 2 times under climate projections. Emphasises need for coupled frameworks in deltaic tropical basins.
Feng et al., (2025), NHESS	CF	Disentangle atmospheric, hydrological, and coupling uncertainties in compound flood modelling using an Earth System Model	E3SM multi-component coupled framework (atmosphere–land–river–ocean); ANN sensitivity analysis	Flooded area can increase 2.4 times under extreme antecedent soil moisture. Two-way river–ocean coupling critical for accurate compound flood extent. Highlights role of soil moisture as underestimated compound flood precursor.

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Paper Source	Theme	Objective	Method/Tool	Key findings & implications
Couasnon et al., (2022), Water Research Resources	CF	Assess a flood risk framework for Ho Chi Minh City (HCMC) that accounts for the co-occurrence and seasonality of heavy rainfall and extreme sea levels	Joint probability (copula); hydrodynamic simulation (TELEMAC-2D); bivariate extreme event analysis	Compound interaction of rainfall, surge, and tide produces flood levels far exceeding individual driver estimates. Directly relevant to Dong Nai–Sai Gon basin management context; underscores need for integrated modelling.
Rogers et al., (2025), Nature Communications	CF	Project global flood exposure under combined climate change and population growth scenarios to 2100	High-resolution global flood model (coastal, fluvial, pluvial); SSP scenarios; attribution analysis	Exposed population rises from 1.6 to 1.9 billion by 2100; 77% driven by population growth, 21% by climate change. Low-GDP regions account for 63% of exposure. Frames urgency of improved flood management in rapidly urbanising tropical basins.

3. Reservoir operation for flood risk mitigation

3.1 Flood control strategies in reservoir systems

Reservoirs constitute the most widely deployed structural measure for flood risk mitigation at the basin scale (Połomski and Wiatkowski, 2023). Structural measures such as reservoir dams and retention basins help control downstream flooding by reducing peak flows and providing storage capacity for floodwaters, and multi-criteria analyses consistently rank reservoir dams as the most effective single structural measure among the full range of flood control options (Hamidifar et al., 2024). Within the broader category of reservoir-based flood control, three main reservoir types are recognised in the literature, each with distinct operational characteristics (Hamidifar et al., 2024).

Flood control reservoirs (or single-purpose detention dams) are designed exclusively to attenuate peak discharges by retaining excess inflow during flood events and releasing it gradually once the downstream channel has the capacity to receive it safely (DeNeale et al., 2019). Detention dams have smaller heights than multi-objective dams and are used solely for flood mitigation;

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in major river systems, flood-control dams have been reported to reduce flood flows by approximately half during extreme events (Yazdi and Salehi Neyshabouri, 2012).

Multi-purpose reservoirs balance flood control against competing objectives such as water supply, hydropower generation, irrigation, and ecological flow requirements (Chhuon et al., 2016; Rötz and Theobald, 2019). Reservoir managers in multipurpose systems typically aim to moderate incoming floods to the maximum feasible extent while finishing the wet season with a full reservoir—a dual imperative that creates persistent and fundamental tension between flood storage availability and conservation storage (Jain et al., 2023). This conflict is especially acute in tropical monsoon basins, where the majority of annual inflow arrives within a compressed wet season window.

Detention reservoirs operate as temporary storage infrastructure within or upstream of protected urban areas, attenuating pluvial and fluvial peak flows without permanent water storage (Terêncio et al., 2020). Traditional dams serve several flood risk reduction functions including reducing flood frequency and extent, while detention dams are specifically designed for peak flow management by restricting high-flow releases and gradually discharging retained volumes downstream (Boulange et al., 2021). However, ensuring dam safety is paramount, as aging detention infrastructure faces increasing risk under changing climatic conditions (Azhar et al., 2025).

3.2 Traditional reservoir operating rules

The dominant paradigm for reservoir flood management over the past century has been the rule curve — a set of predetermined, time-varying storage targets or water level limits that guide daily reservoir release decisions. The flood mitigation approaches in multipurpose reservoirs can be broadly classified into three operational categories: flood control rule curves, flood limited water level concepts, and hedging strategies; of these, rule curves remain the most widely implemented in practice globally (Jain et al., 2023).

Rule curves are typically static schedules derived from long-term historical hydrological records, prescribing the maximum allowable storage level at each point in the year — known as the seasonal rule curve — to maintain pre-allocated flood storage (Li et al., 2024). Rule curves, despite being the preferred tool of reservoir operators, are inherently limited when the system deviates from the typical conditions assumed during their design: they would suggest the operator spill water when storage exceeds the prescribed level, and to hope for rain when it falls below. Static flood storage allocation under rule curves is generally computed deterministically, using design floods of specified return periods (e.g., 100-year or 1000-year events) derived from historical records under a stationarity assumption — that is, the implicit assumption that future hydrology will resemble the past (Jalilian et al., 2022).

The limitations of deterministic approach have become increasingly evident. First, under non-stationary climatic conditions, the historical record no longer reliably characterises the future frequency and magnitude of extreme events, rendering historical-calibrated rule curves progressively less appropriate (Lai et al., 2022). Under increasingly variable hydrologic regimes, deviations from typical conditions are larger and more frequent, amplifying errors in the open-loop decisions determined by rule curves (Giorgio and Matteo, 2020); moreover, the lack of feedback information generates rules that largely

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ignore the potential for adaptive and coordinated strategies, especially in multi-reservoir systems managing multiple conflicting objectives. Second, rule curves treat the downstream boundary as a fixed constraint rather than a dynamic, state-dependent system. As demonstrated by the International Commission on Large Dams (ICOLD), (2025) review, uncoordinated releases from individual reservoirs operating within their own prescribed rule curves have historically exacerbated downstream flooding at the basin scale. Third, research shows that static rules yield heavily suboptimal outcomes under non-stationary conditions since Giuliani et al., (2021) note that rigid rule curves lack the adaptive capacity and feedback loops needed to manage modern hydro-climatic variability.

3.3 Forecast-informed and adaptive reservoir operation

In response to the documented limitations of static rule curves, a growing body of research has developed forecast-informed and adaptive operating frameworks. The most prominent of these is Forecast-Informed Reservoir Operations (FIRO), formally defined as a reservoir-operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operation policies with enhanced monitoring and improved weather and water forecasts (Brodeur et al., 2024). FIRO is being developed and tested across multiple U.S. basins — including Lake Mendocino, Prado Reservoir, New Bullards Bar Reservoir, and Lake Oroville — as a collaborative effort engaging civil engineers, hydrologists, meteorologists, and climate scientists (Delaney et al., 2020).

The practical benefits of FIRO pilots have been demonstrable (Brodeur et al., 2024; Timberlake et al., 2025). In water years 2019 and 2020, FIRO experimentation at Lake Mendocino increased water supply benefits while managing flood risks (Galaitsi et al., 2023); in 2020 specifically, FIRO increased water storage by nearly 20%, roughly equivalent to the water used by 22,000 households, without impairing flood protection capacity (Forbis and Ly, 2025). At the Yuba-Feather River system, a final viability assessment completed in 2025 confirmed that FIRO strategies successfully reduced downstream flood flows across a range of scale factors applied to historical extreme events, with potential to provide the equivalent of up to 260,000 acre-feet of additional flood storage capacity (Jasperse et al., 2020).

Real-time reservoir control approaches extend beyond FIRO by embedding optimization directly within the operational decision cycle (Perez Salas, 2025). Advances in data analytics and machine learning can provide valuable support for identifying the most valuable forecast information, including medium- to long-range seasonal forecasts and climate state indicators, enabling operational decisions to be conditioned on a much richer information set than traditional static rules permit (Feng et al., 2025b). The state-of-the-art in adaptive reservoir operation thus encompasses model predictive control (MPC), reinforcement learning policies, and Bayesian adaptive frameworks — each representing a progression from deterministic rule-following toward probabilistic, forecast-conditioned decision-making (Giuliani et al., 2021).

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4 Hydrodynamic modelling of flood propagation

4.1 One-dimensional hydraulic models

One-dimensional (1D) hydraulic models simulate water flow as a function of a single spatial dimension — distance along the channel — using the Saint-Venant equations (continuity and momentum). Reservoir optimisation has historically been coupled with simulation models to evaluate downstream impacts, with 1D hydrodynamic tools providing the foundational link between reservoir release decisions and downstream water level responses in river networks (Lai et al., 2022).

The most widely applied 1D tools include MIKE 11 (DHI), HEC-RAS (U.S. Army Corps of Engineers), and SOBEK (Deltares). These models excel in large-scale river network applications where computational efficiency is paramount and the primary objective is routing flood hydrographs from upstream to downstream control points. MIKE 11 has been extensively used in Southeast Asian river systems including the Sai Gon-Dong Nai basin (Markova et al., 2025), while HEC-RAS remains the global standard for regulatory floodplain mapping and reservoir tail-water analysis (Green et al., 2025; Ruan et al., 2024).

The strengths of 1D models include computational efficiency over long river reaches, well-established calibration and validation frameworks, and direct integration with rainfall-runoff models via coupled simulation environments. However, their limitations are significant for floodplain impact assessment: 1D formulations cannot represent lateral floodplain inundation, cross-flow between channels, or the two-dimensional water surface gradients that govern actual flood extent and depth. Straightforward 1D representations of floodplain flow depict flows as one-dimensional along the river channel, and while these models are well-suited to channel hydraulics, they do not provide insight into the spatial extent of inundation across the floodplain (Spor et al., 2025). This limitation is particularly consequential when assessing the downstream impact of reservoir releases in flat, deltaic, and tidally influenced basins where flow pathways are complex and non-linear.

4.2 Two-dimensional flood inundation models

Two-dimensional hydrodynamic models, such as MIKE 21, HEC-RAS 2D, LISFLOOD-FP, and TELEMAC-2D, resolve depth-averaged Saint-Venant equations across a computational mesh to explicitly map spatial variations in water depth, velocity, and inundation extent. By solving the full momentum equation to describe water motion as a function of flow depth and velocity, these 2D configurations generate highly critical flood characteristics including precise water arrival times and cell-by-cell inundation percentages across complex terrain. The operational value of this detailed physical representation is clearly evident in dam-release-dominated environments like the downstream reach of India's Narmada basin, where a 2D HEC-RAS model successfully delineated hundreds of square kilometres of severely impacted agricultural land and established a vital eight-hour warning window from initial reservoir release to downstream overflow (Bhargav et al., 2025). This practical application demonstrates how standalone 2D modelling directly quantifies the intricate physical linkage between upstream reservoir management and downstream floodplain response.

The core capability distinguishing 2D models from traditional 1D approaches is this capacity to spatially and temporally disaggregate risk indicators across the landscape. Rather than relying on averaged cross-sectional data, 2D frameworks

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leverage high-resolution digital elevation models to deliver spatially distributed depth maps essential for economic damage assessment, trace the temporal persistence of inundation at individual cells to establish flood duration, and calculate exact flow velocities to evaluate structural loading and evacuation safety. Comparative studies consistently confirm that 2D floodplain models provide vastly superior insights regarding active inundation areas and far greater accuracy in water depth values across flood-prone regions than their 1D counterparts (Bhargav et al., 2025; Kulkarni and Kale, 2024). Consequently, these multi-dimensional insights have become entirely indispensable for reservoir impact assessments that are required to directly inform emergency management, urban land-use planning, and structural damage estimation.

Despite these advanced diagnostic capabilities, a major barrier prevents the direct integration of high-fidelity 2D physics into real-time operational workflows. High-resolution 2D simulations over extensive spatial domains remain computationally expensive, which restricts their utility during active, rapid-response decision-making cycles. To bridge this gap between physical fidelity and real-time necessity, surrogate-model approaches are rapidly emerging as a practical alternative in contemporary research. Machine learning and deep learning architectures are increasingly deployed as data-driven emulators designed to substitute for the heavy computational load of the underlying hydrodynamic engines. While deep learning models often demonstrate impressive predictive accuracy, they still face notable hurdles, particularly regarding a lack of embedded expert physical knowledge and a relative scarcity of comprehensive benchmark data for rigorous testing (Karim et al., 2023).

4.3 Coupled 1D–2D modelling frameworks

Coupled 1D–2D modelling frameworks, exemplified by platforms like MIKE FLOOD and hybrid HEC-RAS configurations, represent a major advancement in basin-scale flood propagation analysis. By simulating efficient, long-distance discharge routing within a 1D river channel while simultaneously resolving lateral inundation and compound interactions on a 2D floodplain, these models successfully capture the physical mechanisms of water transfer at overflow points and lateral structures. Moving beyond standalone representations is critical because the interaction between channelized conveyance and overland flow dictates the actual footprint of disaster risk. This structural distinction is validated by comparative evaluations of standalone 2D versus coupled 1D–2D HEC-RAS configurations, which demonstrate that the two approaches yield significantly different inundation extents under identical boundary conditions, particularly within highly complex industrial and urban zones (Spor et al., 2025).

The necessity of this explicit dimensional coupling becomes even more pronounced when analysing the systemic impacts of structural flood interventions. For instance, coupled applications within the Sai Gon-Dong Nai river system reveal that while the commissioning of tidal control structures successfully mitigates flooding in central urban cores, it simultaneously exacerbates inundation in peripheral zones (Markova et al., 2025). Rather than viewing flood mitigation as a absolute reduction of volume, analytical modelling treats it as a complex spatial redistribution of risk across tidally influenced deltaic networks. Coupled 1D–2D models are uniquely equipped to trace these dynamics because they accurately simulate crucial river–floodplain interactions, including the re-entry of overland floodwater to the channel during recession phases and the compound pressures of upstream reservoir releases meeting tidal backwater.

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Ultimately, the critical insight emerging from contemporary coupled modelling literature is that realistic downstream flood assessment fundamentally relies on the explicit representation of these interactive boundary dynamics. Relying on classical reservoir optimization frameworks that reduce the downstream boundary to a simplified, static stage-discharge relationship introduces dangerous mathematical blind spots. Because simple curves cannot account for backwater effects or lateral spreading, they systematically underestimate the true spatial extent and severity of floodplain inundation under compound conditions, underscoring the need to embed high-fidelity coupled physics directly into operational decision support.

5 Optimization methods for reservoir operation

5.1 Classical optimization approaches

The foundational era of formal reservoir optimization research was deeply rooted in mathematical programming, establishing core principles that continue to shape modern operational decision support. Linear programming (LP) emerged as an early standard because it offers exceptional computational tractability and guarantees global optimality when handling linear objective functions and constraints. These characteristics made LP models highly popular for monthly or seasonal water allocation decisions where system dynamics can be reasonably linearized using standard, general-purpose solvers. However, the requirement that the objective function and all corresponding constraints must be strictly linear severely restricts the applicability of this approach. It remains poorly suited for complex problems that exhibit genuinely non-linear or non-convex behaviours, such as real-time flood control and multi-sector water resource management (Chen et al., 2018).

To address the highly non-linear, non-convex, and non-differentiable nature of water resource infrastructure, researchers shifted toward dynamic programming (DP) and stochastic dynamic programming (SDP). These frameworks decompose multi-stage decision problems into recursive sequences of simpler sub-problems, a mathematical structure that aligns perfectly with the sequential, state-dependent nature of reservoir release decisions. While SDP explicitly accounts for hydrological uncertainty and accommodates non-linear objectives, its practical application is bottlenecked by the well-known curse of dimensionality. Because computational and memory requirements grow exponentially with each added state variable, standard SDP formulations become practically intractable when applied to large multi-reservoir systems or problems featuring high-dimensional state spaces (Saadat and Asghari, 2019). Furthermore, the framework remains rigidly constrained by the underlying requirement for Markovian inflow processes, meaning it cannot easily ingest complex, long-term hydrological persistence without adding more state variables and worsening the computational burden.

Driven precisely by these compounding limitations of classical methods, the timeline of reservoir optimization research reveals a clear evolutionary trajectory away from rigid deterministic and stochastic mathematical programming. The literature has steadily transitioned toward more flexible evolutionary algorithms and contemporary meta-heuristic approaches capable of navigating complex engineering trade-offs without forcing systemic simplifications (Lai et al., 2022). This shift highlights a fundamental realization within water resources engineering that real-world operational challenges require a balance between physical accuracy and computational feasibility. While classical mathematical programming laid the groundwork for defining optimality, its structural restrictions have turned the focus of modern research toward scalable, simulation-based control strategies that can manage multi-reservoir complexity and deep hydro-climatic uncertainty without collapsing under computational constraints.

5.2 Evolutionary algorithms and multi-objective optimization

The structural constraints of classical mathematical programming directly motivated a widespread paradigm shift toward evolutionary algorithms (EAs) and multi-objective evolutionary algorithms (MOEAs). By drawing on principles of biological evolution, these frameworks navigate large, non-convex solution spaces without requiring restrictive linearity assumptions or gradient information. Contemporary research indicates that hybrid meta-heuristic configurations frequently demonstrate superior operational performance compared with standalone meta-heuristic algorithms or traditional optimization methods, proving highly effective at maintaining fast convergence rates while solving intricate water infrastructure problems (Beiranvand and Ashofteh, 2023). Genetic algorithms (GAs) established the groundwork for this transition by utilizing selection, crossover, and mutation operators to iteratively refine populations of candidate operating policies. As the field evolved to address multi-sector complexities, the Non-Dominated Sorting Genetic Algorithm III (NSGA-III) emerged as a premier benchmark for reservoir flood control operations due to its robust Pareto front identification and diversity preservation mechanisms. This algorithmic efficacy is highlighted by comparative studies against multi-objective particle swarm optimization (MOPSO), which reveal that NSGA-III provides vastly superior coverage of the true Pareto front, solidifying its role as the preferred choice for problems requiring explicit trade-off characterization between competing flood control and conservation objectives (Hojjati et al., 2018).

As the dimensionality of resource management expanded, recent research extended the capabilities of the NSGA family to overcome the limitations of early variants when handling many-objective problems. While NSGA-III introduces reference-point-based diversity preservation to better manage three or more objectives, an enhanced iteration (ENSGA-III) deployed at the Three Gorges Reservoir incorporates orthogonal design for initial population generation alongside an ε-dominance strategy to produce exceptionally well-distributed Pareto-optimal solutions that balance upstream water levels with maximum downstream discharge targets. In parallel, decomposition-based frameworks like MOEA/D-DE offer powerful alternatives for structural flood management. When applied to major infrastructure like China's Ankang reservoir, this decomposition approach achieves a substantial reduction in peak discharge while rigorously satisfying dam safety constraints by breaking down the many-objective problem into a coordinated set of scalar sub-problems solved simultaneously (Chen et al., 2017).

Finally, the core advantage of MOEAs in modern reservoir management lies in their inherent ability to resolve non-linear, multi-objective problems without gradient computation, generating complete Pareto trade-off frontiers that enable a posteriori decision-making and natural multi-reservoir coordination. However, a critical bottleneck remains because the final solution quality depends heavily on algorithm parameterization, population size, and the sheer volume of required function evaluations. This computational burden becomes particularly restrictive when each evaluation must be coupled directly with an intensive downstream hydrodynamic model simulation. To resolve these computational and generalization challenges, the absolute

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vanguard of reservoir optimization has turned to transformer-based deep reinforcement learning and stochastic progressive hedging frameworks. These next-generation architectures demonstrate superior generalization capabilities over established benchmarks like NSGA-III and MOEA/D for multi-objective hydropower systems. Furthermore, they successfully achieve operational constraint satisfaction rates of over 93% compared with the 60–70% reliability typical of traditional rule-based methods, while simultaneously delivering a substantial reduction in peak discharges under fully uncertain inflow conditions (Argoubi and Mili, 2025).

5.3 Simulation–optimization frameworks

Simulation–optimization frameworks advance riverine flood risk management by coupling a physically based hydrodynamic simulation model directly with an optimization algorithm to iteratively search for superior reservoir operating policies. Under this coupled architecture, the simulation engine—typically a 1D or a integrated 1D–2D hydrodynamic tool—acts as a computational validator that evaluates the exact downstream consequences of a candidate release policy generated by the optimizer. The resulting multi-dimensional flood metrics are then fed back into the optimization routine as objective function values to guide the next iteration of the heuristic search (Bhargav et al., 2025). The practical feasibility of integrating these heavy hydrodynamic simulations with evolutionary optimization is historically rooted in systems engineering, as demonstrated by the successful coupling of MIKE 11 with NSGA-II to derive Pareto-optimal configurations that balance the conflicting economic objectives of minimizing total structural construction investments against expected downstream flood damage costs (Yazdi and Salehi Neyshabouri, 2012).

In contemporary literature, the primary operational domains for these integrated frameworks span several critical areas of water infrastructure safety and emergency management. These domains include the systematic reduction of flood peaks at vulnerable downstream control points, the minimization of floodplain inundation areas and localized depths, and the preservation of internal reservoir safety by limiting maximum water levels and minimizing spillway activation frequencies. Furthermore, these frameworks are highly instrumental in optimizing proactive pre-release strategies ahead of forecast extreme events. By embedding explicit hedging rules directly within detailed hydrodynamic modelling architectures, water resource planners can establish a clear, mathematically defensible linkage between real-time reservoir release decisions and their immediate downstream inundation consequences across the landscape (Mohanty et al., 2025).

Despite the clear diagnostic strengths of this unified approach, a critical gap remains within the broader analytical literature regarding how flood risk is fundamentally represented inside the optimization engine. Although coupled 2D hydrodynamic models are fully capable of generating rich spatial metrics such as precise flood extents, cell-by-cell water depths, temporal inundation durations, and localized economic damage vectors, these high-fidelity outputs are rarely embedded as primary, driving objective functions within reservoir optimization algorithms. Instead, the vast majority of existing studies continue to rely on simplified discharge or water stage thresholds measured at a single downstream gauge to serve as surrogate flood objectives. This reliance on localized gauge metrics creates a severe misrepresentation of spatial floodplain risk because single-point measurements cannot capture the complex, distributed patterns of overbank flow, a structural blind spot that becomes

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dangerous in compound flood environments where tidal backwater and pluvial runoff actively amplify reservoir-release-driven inundation.

6 Compound flooding, implications for reservoir operations, and basin perspective

6.1 Mechanisms of compound flooding

Compound flooding represents a highly complex physical phenomenon where the co-occurrence or rapid succession of multiple hydro-climatic drivers generates water levels and inundation footprints that vastly exceed the impacts of any single agent. The contemporary literature formalizes these interactions by recognizing six primary hazard drivers comprising fluvial, pluvial, coastal, groundwater, tsunami, and dam failure vectors, which interact dynamically with five precursor environmental conditions consisting of soil moisture, snow, temperature, fire, and antecedent drought (Green et al., 2025). When multiple drivers converge within vulnerable coastal–estuarine zones, the resulting environmental synergy drastically intensifies the destructive consequences of the hazard. In highly regulated deltaic and estuarine networks, this phenomenon is primarily driven by the intersection of four critical components: (i) upstream river discharge dictated by both natural basin runoff and controlled reservoir releases, (ii) intense local pluvial events that trigger independent overland urban drainage failure, (iii) tidal backwater that physically restricts channel capacity, and (iv) storm-surge anomalies that force coastal waters inland through tidal pathways.

The underlying physics governing these multi-driver events are inherently non-linear and synergistic, meaning that the simultaneous or near-simultaneous convergence of fluvial, pluvial, and coastal pressures can produce disproportionately extreme disasters even when the individual components are not independently extreme. This catastrophic potential was illustrated on a global scale by Hurricane Harvey in 2017, where the simultaneous compounding of record-breaking rainfall, massive river discharge, and prolonged coastal storm surge generated 152.5 billion USD in economic losses, marking it as the second-costliest natural hazard in United States history (Green et al., 2025). The compounding nature of these events radically alters traditional engineering risk calculations. Statistical modelling confirms that treating these drivers as independent introduces massive structural blind spots; for instance, joint probability assessments demonstrate that a riverine flood traditionally classified as a 50-year event can effectively possess a much higher compound frequency equivalent to a 27-year return interval when coastal and fluvial forces are evaluated together (Maimone et al., 2025).

Overall, the analytical insight from compound flood research underscores that neglecting these joint probabilities leads to a dangerous underestimation of actual flood frequency and societal vulnerability. For reservoir managers operating near tidally influenced deltas, these findings reveal that optimization rules cannot be safely designed in isolation from coastal boundary conditions. Because tidal backwater and storm surges physically lock channelized conveyance, upstream reservoir releases that might be safe under normal conditions can inadvertently trigger severe downstream disasters when synchronized with coastal anomalies, necessitating a fundamental shift toward holistic, boundary-aware optimization framework.

6.2 Implications for reservoir operation

Compound flooding forces a fundamental re-evaluation of reservoir management because it introduces a series of fluid, interacting physical constraints that completely overwhelm conventional rule-curve frameworks. The most critical of these constraints revolves around the precise timing of reservoir releases relative to shifting downstream boundary conditions. When tidal backwater is present, a release timed to coincide with spring tides or storm surge propagation drastically amplifies downstream water levels compared to the exact same volume discharged during low-tide conditions. This high degree of temporal dependency is entirely absent from static rule curves, which are calibrated almost exclusively against upstream fluvial discharge baselines and treat the downstream terminal boundary as a passive, fixed entity.

Compounding this temporal sensitivity is the reality that downstream hydraulic capacity is dynamically compressed whenever tidal backwater elevates the localized tail-water level. Under these compound conditions, a reservoir release that would normally be safely conveyed within the river channel can inadvertently trigger severe overtopping or catastrophic levee failure when superimposed on an already elevated coastal water surface. The extreme scale of this vulnerability is verified by estuary modelling, which shows that a 100-year flood extent and its associated inundation volume in coastal zones can expand by a factor of two or more under compound rainfall–surge scenarios compared to traditional, single-driver assessments (Ruan et al., 2024). Furthermore, this structural risk is on a trajectory to worsen because the coupling of long-term sea-level rise projections is expected to amplify these spatial inundation differences even more aggressively in future decades.

The inevitable synchronization of multiple flood drivers means that effective modern reservoir governance demands continuous real-time awareness of and explicit coordination with coastal, pluvial, and meteorological conditions rather than a myopic focus on the upstream inflow hydrograph. Navigating these overlapping hazards requires the comprehensive integration of meteorological, oceanographic, and hydrodynamic forecasting streams into a single, unified operational decision framework. Because managing a reservoir under compound conditions is fundamentally an exercise in multi-system synchronization, moving beyond single-variable metrics is no longer just an academic preference but an engineering necessity, even though achieving this multi-stream predictive integration remains largely aspirational in current water management practice.

6.3 Case perspective: Dong Nai–Sai Gon river basin

6.3.1 Introduction of the study area

The Dong Nai–Sai Gon (DN-SG) river basin in southern Vietnam provides an exemplary case study for the integrated reservoir–floodplain management challenges described throughout this review. The basin drains approximately 37,400 km² and discharges through a complex deltaic network strongly influenced by semi-diurnal tides from the East Sea. Upstream flooding primarily threatens two major downstream urban areas of Binh Duong Province and Ho Chi Minh City (HCMC). Binh Duong, with about 3 million people, faces the immediate, first-line impact. HCMC, with a population exceeding 9.5

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million, occupies the lower basin — approximately 60% of its 2,095 km² area lies below 2 m above mean sea level (Giang et al., 2022).

The Dau Tieng reservoir, with a storage capacity of approximately 1.58 billion m³, is the largest reservoir in the Sai Gon sub-basin and plays a pivotal role in regulating dry-season water supply and mitigating monsoon-season flood peaks along the Sai Gon River (Figure 3A). The water level of the Sai Gon River from its upper reaches to the Thu Dau Mot gauging station is directly dependent on Dau Tieng reservoir releases, with the reservoir's outflow regime exerting the dominant hydrological control on channel water levels throughout the tidal transition zone (Markova et al., 2023). To meet water supply requirements for irrigation and flushing saltwater intrusion, Dau Tieng reservoir receives a supplemental transfer of 30–40 m³/s in average annually from the Phuoc Hoa reservoir mostly in the dry seasons. The Tri An reservoir on the Dong Nai River similarly governs the upper Dong Nai reach, while tidal influence penetrates deep into both rivers, creating a complex boundary condition for reservoir release management.

The compound flood vulnerability of HCMC arises from the simultaneous or near-simultaneous occurrence of three drivers: monsoon rainfall over the basin, reservoir releases (particularly during high-inflow periods when Dau Tieng must operate its spillway), and tidal backwater from the East Sea. A simulation study using MARINE rainfall-runoff and TELEMAC-2D inundation models found that on the event of 21 July 2009 — caused by combined heavy rainfall and high tide — the inner city flooding area (Binh Duong and HCMC) would increase by 8.2% without Dau Tieng dam crest enhancement under a climate change scenario projecting 40% increased monsoon precipitation by 2050, with maximum spillway releases reaching 1,650 m³/s (Dinh et al., 2019). This quantified analysis illustrates how reservoir release decisions interact with tidal timing and rainfall intensity to determine compound flood severity — and why integrated modelling of all three drivers is essential for effective reservoir management in this basin.

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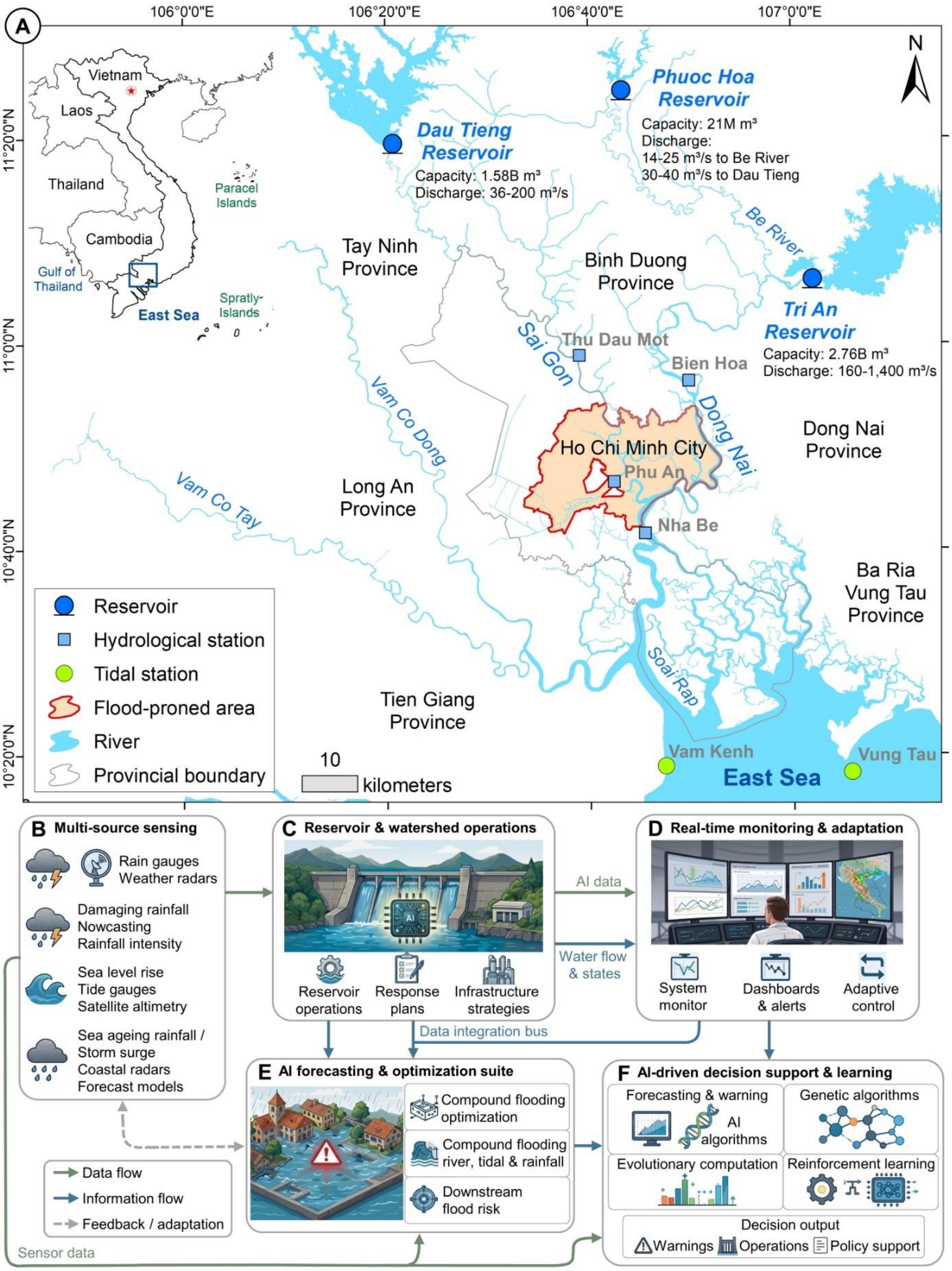

470 **Figure 3.** Dau Tieng, Phuoc Hoa and Tri An reservoirs in the Dong Nai-Sai Gon river basin with the long-term monitoring stations (A) and its proposed conceptual framework of reservoir operation for flood risk mitigation, including flood control strategies, traditional rule-curve and adaptive forecast-informed operations, and hydrodynamic modelling approaches (B—F).

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Hydraulic modelling using MIKE 11, MIKE 21, and MIKE FLOOD of the DN-SG river system has confirmed that in areas prone to flooding as a result of the operation of anti-flood sluices and reservoir releases, reconstruction of hydraulic structures — including raising foundation elevations and expanding drainage systems — is necessary, pointing toward the need for an integrated hydraulic infrastructure and reservoir operating strategy (Cao et al., 2021; Couasnon et al., 2022; Ngoc Anh et al., 2022).

6.3.2 A framework developed for flood risk mitigation under compound impacts

Based on the context and literature review, an integrated framework is proposed for the DN-SG system to enhance real-time flood forecasting, reservoir operation, and adaptive water management under compound climate hazards (Figure 3B). The system incorporates multiple hydro-meteorological drivers, including rainfall, watershed inflow, sea-level rise, storm surge, and extreme rainfall events, which collectively contribute to downstream flooding risks. Sensor networks continuously collect environmental data that are integrated into a centralized water-flow and reservoir-operation platform. Artificial intelligence techniques are then employed to analyze hydrological patterns, optimize reservoir operations (i.e., NSGA-III at Dau Tieng and Tri An reservoirs in hydrodynamic models such as MIKE or TELEMAC-2D), and support adaptive response strategies. The framework further integrates forecasting and early-warning modules using advanced computational approaches such as genetic algorithms, reinforcement learning, and evolutionary computation to improve predictive accuracy and operational decision-making. By coupling real-time monitoring with AI-based optimization, the system aims to mitigate compound flooding induced by the interaction of river discharge, tidal influence, and extreme precipitation, thereby strengthening climate resilience and supporting sustainable flood-risk management in vulnerable urban and riverine environments.

The evolution of flood mitigation strategies, based on literature review, is illustrated through three distinct operational schemes, ranging from traditional methods to advanced AI-integrated systems (Fig. 4 and Table 2). Case A represents a static, “baseline” approach prioritizing fixed flood buffers and controlled releases. Case B utilizes 72-hour forecast ensembles to create adaptive, dynamic storage space, reflecting current practices at many reservoirs worldwide, including Dau Tieng and Tri An. Finally, Case C presents a modern, high-fidelity strategy for future operations, leveraging AI and machine learning—specifically an embedded NSGA-III algorithm—to compute multi-objective, Pareto-optimal solutions. By utilizing predictive failure analysis to manage extreme risks, this reservoir optimization framework aims to minimize downstream flood impacts under strict operational constraints during compound flooding events. Ultimately, these cases highlight a fundamental shift from rigid infrastructure management toward flexible, data-driven resilience across short-, medium-, and long-term horizons.

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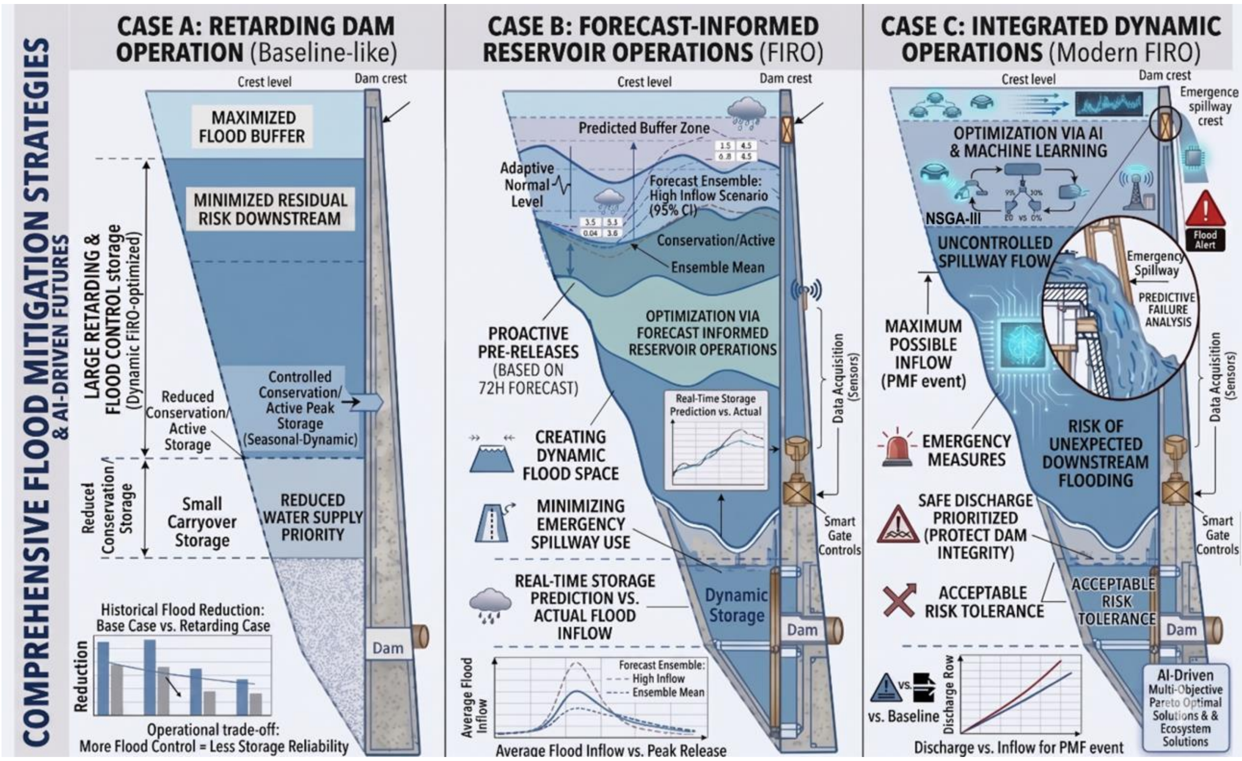

Figure 4. Conceptual illustrations of flood mitigation strategies and AI-driven futures, showing the progression from traditional retarding dam operations (Case A) to forecast-informed reservoir operations (FIRO, Case B) and advanced, AI-integrated dynamic operations for extreme inflow events (Modern FIRO, Case C). Figure conceptualized and prepared by the authors.

Table 2. The cases of dam operations from traditional to modern approach.

Case A: Retarding Dam Operation (Baseline-like) This case represents a traditional, “static” approach to dam management where operations are dictated by fixed storage zones.	**Objective:** To provide a reliable baseline for flood reduction by maintaining a permanent, large buffer for incoming water. **Mechanisms:** • *Maximized Flood Buffer*: A significant portion of the reservoir (near the crest level) is kept empty to catch sudden inflows. • *Fixed Storage Zones*: The reservoir is strictly divided into “Reduced Conservation/Active Storage” and “Small Carryover Storage”. • *Controlled Release*: Water is released via controlled conservation or active peak storage outlets to minimize residual risk downstream. • *Operational Trade-off*: This method prioritizes high flood control but results in lower storage reliability for water supply.

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Case B: Forecast-Informed Reservoir Operations (FIRO) This case introduces predictive data to make the dam's storage capacity "elastic" based on forecasting weather events.	**Objective:** To increase flexibility by using weather forecasts to create dynamic space, balancing flood safety with water supply needs. **Mechanisms:** • *Proactive Pre-Releases*: Based on a 72-hour forecast, the dam releases water early to create "Dynamic Flood Space" before a storm arrives. • *Adaptive Normal Level:* Instead of a fixed line, the water level fluctuates based on the Forecast Ensemble (Ensemble Mean vs. High Inflow Scenarios). • *Smart Infrastructure:* Uses Data Acquisition Sensors and Smart Gate Controls to monitor real-time storage predictions versus actual inflow. • *Risk Reduction:* Aims to minimize the use of the emergency spillway by optimizing storage ahead of time.
Case C: Integrated Dynamic Operations (Modern FIRO) This is the advanced strategy for future, utilizing high-tech computational tools to manage extreme "Probable Maximum Flood" (PMF) events.	**Objective:** To achieve high-fidelity, real-time optimization using AI to manage extreme risks (downstream provinces and cities) and multi-objective goals. **Mechanisms:** • *AI & Machine Learning Optimization:* Uses advanced multi-objective optimization algorithms such as NSGA-III to compute multi-objective "Pareto Optimal" solutions, balancing dam safety, flood protection (downstream provinces and cities particularly Binh Duong and Ho Chi Minh), and ecological dry flow. • *Predictive Failure Analysis:* Applies advanced modelling to assess the risk of "Uncontrolled Spillway Flow" and potential dam overtopping. • *Emergency Measures:* Incorporates a "Flood Alert" system and prioritizes safe discharge to protect the integrity of the dam structure during massive inflow events. • *Risk Tolerance:* Defines an "Acceptable Risk Tolerance" zone, acknowledging that in extreme PMF events, some downstream flooding may be unavoidable to save the dam itself. • *Advanced Connectivity:* Utilizes a dense network of sensors and AI-driven smart gate controls for precise, automated responses.

7 Conclusions

This review paper reveals four critical knowledge gaps that represent the primary frontier for future research in this domain. First, limited integration of floodplain inundation metrics in reservoir optimisation. Current RFCO frameworks predominantly use point-based discharge or water level targets at downstream gauges as flood surrogates. Spatially distributed metrics —

flood extent, depth, duration, and damage — derived from coupled 2D hydrodynamic simulations are rarely embedded directly as optimisation objectives. This gap systematically underestimates the risk reduction potential of adaptive reservoir operation, and its closure requires computationally efficient surrogate models capable of emulating 2D inundation responses within optimisation loops. Second, insufficient representation of compound flood drivers has been considered. Among the five recommendations for future compound flood research identified in a systematic review of 279 studies by Green et al., (2025), the most critical are the adoption of consistent modelling frameworks that couple dynamic Earth system components — including atmospheric, hydrological, and oceanic processes — and the design of infrastructure with compounding in mind. Reservoir optimisation frameworks currently treat downstream boundaries as simple flow-routing elements, ignoring tidal, surge, and pluvial interactions that dominate flood risk in coastal and deltaic basins (Giuliani et al., 2021). Third, limited use of coupled hydrodynamic–optimisation frameworks in tropical monsoon systems. While simulation–optimisation coupling has been demonstrated in temperate and semi-arid settings, a systematic mapping of data-driven flood forecasting publications from 2019 to 2024 found that 56% of studies are concentrated in East and Southeast Asia, yet very few address the specific combination of reservoir release dynamics, compound tidal–fluvial interactions, and seasonal monsoon extremes characteristic of tropical deltaic systems (Kuhaneswaran et al., 2025). The Dong Nai–Sai Gon basin represents an underrepresented but globally significant archetype of this challenge (Giang et al., 2022). Last but not least, real-time reservoir management is required under compound uncertainty. Operational reservoir management in compound flood environments requires simultaneous uncertainty quantification in rainfall forecasts, reservoir inflow predictions, tidal and surge forecasts, and hydrodynamic model parameters — a multi-source uncertainty challenge that no existing operational framework fully addresses.

Future research directions should prioritise three interconnected advances. First, machine learning for reservoir operation — including reinforcement learning policies, physics-informed neural networks, and surrogate emulators of 2D hydrodynamic models — offers the computational efficiency required to close the gap between optimisation and full floodplain impact assessment (Bhargav et al., 2025). Long Short-Term Memory (LSTM) networks have emerged as the dominant algorithm in data-driven flood forecasting (21% of implementations), while hybrid and ensemble approaches showed the most dramatic growth from 2% to 10% of implementations between 2019 and 2024, suggesting the field is rapidly converging on hybrid physics-ML frameworks as the operational standard. Second, digital twins for flood forecasting — virtual replicas of river basins updated in real-time from IoT sensors, satellite observations, and numerical weather prediction — provide the integrated observational–predictive infrastructure needed to support compound-aware reservoir decisions (Hlal et al., 2025). Digital twin technology applied to urban flood risk management has demonstrated reduced flood response times of up to 40% through real-time data integration and predictive modelling, with remote sensing and machine learning serving as key enabling technologies. Third, climate-resilient reservoir management must explicitly account for non-stationary hydrological conditions by embedding climate projections into optimisation frameworks, rather than assuming the stationarity of historical inflow statistics that underlies conventional rule curve design (Hlal et al., 2025).

Data availability

Data used in this study are available from the corresponding author upon reasonable request.

Author contributions

Dung Duc Tran: Conceptualization, methodology, data analysis, interpretation, writing - original draft, and manuscript preparation. Nguyen Duc Thien: Visualization; manuscript preparation. Nguyen Thi Thuy Hang: methodology, writing - original draft. Do Quang Linh: writing - original draft.

Competing interests

The author declares no competing financial or non-financial interests.

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