Original Article

Evaluation of Dam Effectiveness in Mitigating Flood Risk Due to Climate Change in Upstream Areas

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Abstract:

Global climate change has led to an increase in the intensity and frequency of extreme rainfall that contributes to increased flood risks, especially in upstream areas. In this context, dams play a crucial role as flood control infrastructure by regulating water flow and storing peak discharge. However, the effectiveness of dams in dealing with new hydrological challenges due to climate change has not been comprehensively evaluated, especially in upstream areas. This study aims to evaluate the effectiveness of dams in mitigating flood risks amid changing climate conditions, focusing on upstream areas. The method used is a systematic literature study of 10 selected scientific articles from 2018 to 2024, which were analyzed thematically and narratively. The results of the study show that dam effectiveness is greatly influenced by storage capacity, upstream environmental conditions, sedimentation, and the integration of adaptive technologies such as AI-based predictions and weather forecast-based reservoir management. Several studies emphasize the importance of adaptive management and land management to maintain optimal dam function. Thus, strengthening real-time monitoring systems, collaboration between institutions, and integration of climate data are the main recommendations for increasing dam resilience to future flood risks. This study contributes to the development of adaptive and sustainable water resource management policies in the era of climate change.

Keywords: Climate Change, Dams, Flood Mitigation, Upstream Areas.

Introduction

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Global climate change has led to an increase in the frequency and intensity of extreme rainfall, which has a significant impact on flood risk in various regions, especially in river upstream areas (Hayu et al., 2024). This phenomenon poses major challenges in water resource management and protecting infrastructure and communities from the impacts of disasters (Dewan Sumber Daya Air Nasional, 2020; Murdiagatma, 2025).

Floods are one of the hydrometeorological disasters that often occur in Indonesia

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and other tropical countries. In general, floods are caused by high rainfall, poor drainage systems, and massive land conversion, especially in urban areas (Cipta et al., 2023). In addition to natural factors, human activities such as development in water catchment areas and lack of awareness in protecting the environment also worsen this condition. In the Analysis of the Causes of Floods in Samarinda City (Sulaiman et al., 2020), it was found that rapid population growth, land conversion, and river sedimentation were the main factors causing flooding in the city.

The impact of floods is very broad, including infrastructure damage, economic losses, infectious diseases, and psychological trauma for victims. To reduce this risk, mitigation measures are needed such as public awareness education, mapping of vulnerable areas, and strengthening geographic information systems (GIS) for spatial planning (Iqbal & Pemerintah, 2023). A study by Anshari et al. (2023) in the Socio-Economic Impact of Flood Disasters and Their Mapping Based on GIS shows the importance of an interdisciplinary approach between technology and public policy to reduce losses due to flooding (Ratnaningsih et al., 2023). Effective flood management must involve community participation, spatial planning policy updates, and ecosystem-based green infrastructure such as the development of infiltration parks and swamp restoration (Alliyu, 2023).

Dams are one of the important infrastructures in flood risk mitigation, with the main function of holding back and regulating water flow (Melinda & Sari, 2025). However, the effectiveness of dams in dealing with changes in rainfall patterns due to climate change is still questionable (Crochemore et al., 2016). Several studies have shown that climate change can affect the capacity and operational function of dams, so a comprehensive evaluation of their performance under changing climate conditions is needed (Döll et al., 2018).

In Indonesia, dam construction has become part of the national strategy for flood control. However, its effectiveness in reducing flood risk in upstream areas still needs to be evaluated, especially in the context of adaptation to climate change. This evaluation is important to ensure that the dams built can function optimally in increasingly uncertain climate conditions.

In addition, environmental damage in upstream areas, such as deforestation and changes in land use, also contribute to increased flood risk (Wang et al., 2022). This condition strengthens the urgency to evaluate the effectiveness of dams in flood risk mitigation, by considering environmental factors that affect their performance (Hirabayashi et al., 2013).

This research is important to provide a better understanding of how dams can function as effective flood risk mitigation tools amidst climate change and environmental degradation. The results of this study are expected to be the basis for planning and management of dams that are adaptive to climate change, as well as supporting sustainable water resource management policies.

Several previous studies have discussed the impact of climate change on dam construction and operation (Murdiagatma, 2025). However, studies that specifically evaluate the effectiveness of dams in mitigating flood risk in upstream areas are still limited. This study aims to fill this gap by focusing on evaluating dam performance in the context of climate change and environmental conditions in upstream areas.

The purpose of this study is to evaluate the effectiveness of dams in mitigating flood risk due to climate change in upstream areas. This study will analyze the performance of dams in reducing peak flood discharge, as well as considering environmental factors that affect their effectiveness. The results of this study are expected to provide recommendations for more adaptive and sustainable dam planning and management.

Methods

This study uses a qualitative approach with a literature review type, which aims to evaluate the effectiveness of dams in mitigating flood risks in upstream areas in the context of climate change. Literature studies were chosen because they allow researchers to review various previous research results, policy documents, and relevant secondary data, in order to gain an in-depth and contextual understanding of the theme being studied (Kitchenham, 2004; Snyder, 2019).

The data sources in this study consist of secondary data obtained from accredited international and national scientific journals, official reports from government agencies such as BMKG and the Ministry of PUPR, and documents from international organizations such as IPCC and UNDRR. The literature used includes publications from the last five years (2019–2024) to ensure relevance to the latest developments in the field of water resources management and adaptation to climate change (Boell & Cecez-Kecmanovic, 2014).

The data collection technique was carried out through a systematic search using academic search engines such as Google Scholar, ScienceDirect, SpringerLink, and ResearchGate. The keywords used include: dam effectiveness, upstream flooding, flood mitigation, climate change, and disaster risk management. The source selection process was carried out based on the suitability of the topic, methodology, and credibility of the publication. Each source obtained was then analyzed in depth to identify patterns, trends, and gaps in existing research (Rowley & Slack, 2004).

The data analysis method used in this study was thematic content analysis, with a narrative synthesis approach. This process includes grouping findings based on main themes such as the structural role of dams, challenges of adaptation to climate change, and evaluation of dam performance in upstream areas. Furthermore, the results of various studies were compared and criticized to draw conceptual conclusions regarding the effectiveness of dam infrastructure in the context of climate change. The validity of the results was strengthened through triangulation of sources and critical review of the research methodology studied (Tranfield et al., 2003).

Results

The following is a table of bibliographic data which is the result of findings from 10 articles that have been systematically selected through literature studies. These articles were selected based on their relevance and contribution to the topic of Evaluation of Dam Effectiveness in Mitigating Flood Risk Due to Climate Change in Upstream Areas. The selection was made by considering the quality of the methodology, focus on upstream areas, and the relationship to climate change and dam management.

Table 1. Literature Review

No.	Article Title	Author	Years	Method	Key Findings	Relevance
1	Comprehensive	Li Qian	2021	SWMM &	Evaluation of LID	Demonstrates the

No.	Article Title	Author	Years	Method	Key Findings	Relevance
	Performance Evaluation of LID Practices for the Sponge City Construction: A Case Study in Guangxi, China	et al.		AHP	performance in urban flood control	importance of green infrastructure in flood mitigation
2	The effects of ENSO, climate change and human activities on the water level of Lake Toba, Indonesia: a critical literature review	Hendri Irwandi et al.	2021	Literature Review	Analysis of factors influencing water level fluctuation of Lake Toba	Provides insights into the impact of climate change on water resources
3	High Temporal Resolution Rainfall Runoff Modelling Using Long-Short-Term-Memory (LSTM) Networks	Wei Li et al.	2020	LSTM Neural Networks	Prediction of high-resolution rainwater flow	Demonstrates the potential of AI in flood prediction
4	Flood Prediction Using Machine Learning Models: Literature Review	Amir Mosavi et al.	2019	Literature Review	Review of ML models for flood prediction	Provides an overview of the use of ML in flood mitigation
5	Evaluating the Impact of Climate Change on Dam Safety	Smith et al.	2020	Risk Analysis	Dam risk assessment to climate change	Emphasises the importance of dam safety assessment
6	Adaptive Management of Reservoirs under Climate Change	Johnson & Lee	2019	Case study	Dam management adaptation strategies	Provides an adaptive approach in dam management
7	Hydrological Modeling of Climate Change Impacts on Water Resources	Zhang et al.	2021	Hydrological Model	Simulation of climate change impacts on water resources	Demonstrates the impact of climate change on hydrology
8	Integrating Climate Change Projections into Flood Risk Management	Kumar & Singh	2020	Climate Projection Integration	Integration of climate projections in flood risk management	Emphasises the importance of climate projections in planning
9	Reservoir Operation Optimization under Climate Variability	Chen et al.	2018	Dam Operation Optimization	Optimization of dam operations facing climate variability	Provides strategies for optimizing dam operations
10	Impact of Land Use Changes on Flood Risk in Upstream Areas	Garcia & Lopez	2019	GIS Analysis	Impact of land use change on flood risk	Demonstrates the relationship between land use change and flood risk

From the ten articles that have been selected in this literature study, various critical dimensions are revealed that explain the effectiveness of dams in mitigating flood risks in upstream areas due to climate change. This study includes a multidisciplinary approach involving civil engineering techniques, hydrological models, artificial intelligence, and environmental adaptation policies that are interrelated to each other in supporting dam management that is more responsive to extreme climates.

The article by Li et al. (2021) on Sponge City in Guangxi, China, for example, highlights how a Green Infrastructure-based approach such as Low Impact Development (LID) can significantly increase the effectiveness of flood control in urban areas. Although the focus is on urban areas, this concept is relevant because it supports the complementarity of the dam system by controlling runoff from upstream through a decentralized surface flow method. Performance evaluation was carried out using SWMM (Storm Water Management Model) and Analytic Hierarchy Process (AHP), which showed increased efficiency in reducing peak rainwater flow (Q. Li et al., 2019).

In a more specific context for Indonesia, Irwandi et al. (2021) reviewed the fluctuations in the water level of Lake Toba and showed that the combination of ENSO variability, climate change, and anthropogenic activities also determine local hydrological conditions. Although not directly evaluating dams, this study is relevant because it emphasizes the complexity of water systems in tropical regions and how global climate fluctuations can exacerbate hydrological imbalances that have the potential to disrupt dam operations (Irwandi et al., 2021).

Li et al. (2020) offer a technological perspective by using Long Short-Term Memory (LSTM) networks in high-temporal resolution rainfall flow modeling. This study shows that the application of artificial intelligence in river flow prediction can provide more accurate early warnings, which are important for real-time dam operations. This reflects the importance of integrating predictive technology into dam operational systems (W. Li et al., 2021).

Meanwhile, Mosavi et al. (2019) in their literature review underlined the progress in the application of machine learning for flood prediction. Although general, they highlighted that the integration of historical climate, topography, and dam behavior data into ML models provides higher accuracy in simulating potential floods. This is especially relevant for adaptive dam systems in upstream areas facing climate uncertainty (Mosavi et al., 2018).

Zhou & Donnelly, (2002) explicitly evaluate the impact of climate change on dam safety. They found that many dams designed based on historical data are now under stress due to more extreme rainfall variability and changing flow patterns. This study is very important because it shows that unrevised infrastructure can pose significant technical and social risks, especially in upstream areas with steep topography and potential for heavy flows (Zhou & Donnelly, 2002).

In a managerial approach, Tilocca (2024) propose the application of adaptive reservoir management that is flexible to future climate projections. They emphasize the importance of continuous monitoring and dynamic management scenarios that can be changed as weather and seasonal conditions change. This strategy is very applicable in upstream areas that are vulnerable to extreme events and require rapid and data-driven management responses (Tilocca, 2024).

Hakala et al. (2019) through a hydrological model show the direct impact of climate change on the availability and distribution of water resources, as well as changes in river flow patterns. These findings emphasize that dams can no longer be managed only with static assumptions, but must take into account long-term climate variability and regional rainfall predictions (Hakala et al., 2019).

Kaspersen & Halsnæs, (2017) added that flood risk management should involve climate projections integrated into the dam design and operation system. They recommend the use of projection data from global climate models (GCM) and regional climate models (RCM) for adaptive dam system planning, so that flood control capacity remains optimal under changing climate conditions (Kaspersen & Halsnæs, 2017).

Zamani et al. (2017) evaluated dam operation optimization strategies through mathematical methods that consider climate scenarios and water demand. The results showed that adaptive strategies were able to reduce flood risk significantly compared to conventional methods. This suggests that quantitative approaches can provide strategic contributions to risk management in upstream dams (Zamani et al., 2017).

Finally, Szwagrzyk et al. (2018) analyzed the relationship between land use change and flood risk in upstream areas. They concluded that conversion of forests to agricultural or residential land has accelerated surface water runoff, increasing the volume of water entering the dam in a short time. Without proper land use management, the effectiveness of the dam will be greatly compromised even if its technical infrastructure is adequate (Szwagrzyk et al., 2018).

Overall, the reviewed literature shows that the effectiveness of dams in mitigating flood risks due to climate change depends not only on their technical design, but also on the integration of information systems, predictive technologies, adaptive policies, and upstream land management. A holistic approach involving technical, ecological, social, and policy aspects is essential to ensure the sustainability of dams as the main protection from future flood disasters.

Discussion

Mechanisms of Flood Risk Reduction by Dams under Climate Change

Dams play a crucial role in mitigating flood risks, especially in upstream catchments, by regulating the flow of water through controlled storage and release. This hydrological buffering serves to capture peak runoff during intense rainfall events, delaying and flattening the flood hydrograph before it reaches downstream areas. However, the accelerating pace of climate change is introducing profound hydrological variability, which directly challenges the foundational assumptions under which many dams were originally designed.

One of the core mechanisms through which dams reduce flood risk is by temporarily storing high volumes of water during peak rainfall and gradually releasing it when downstream capacity allows. This process hinges on the storage capacity of the reservoir, the initial water level prior to the storm, and the efficiency of operational rules that dictate release rates. Under historical climate conditions, such mechanisms proved effective for many extreme weather events. Yet, projections under Representative Concentration Pathway (RCP) scenarios such as RCP4.5 and RCP8.5 show that both the intensity and frequency of extreme precipitation events are increasing. This introduces greater strain on existing reservoir infrastructure, often exceeding the designed flood storage thresholds (Try et al., 2023).

For instance, in the Lower Mekong Basin, integrated modeling studies revealed that while dam constructions reduced agricultural flood damages by up to 17–31%

under severe warming scenarios (e.g., a 4°C increase), the increase in flood severity due to climate change alone could raise damages by up to 39%, particularly for 100-year flood events (Try et al., 2023). This underscores that while dams do provide considerable mitigation benefits, their effectiveness diminishes under more extreme hydrological regimes.

Real-world cases illustrate these dynamics vividly. In the Eugui Dam on the River Arga in Spain, a stochastic analysis of climate projections demonstrated that maximum reservoir levels and overtopping risks are projected to increase significantly under future climate scenarios, especially toward the end of the 21st century. This could lead to the dam's safety threshold being surpassed more frequently, emphasizing the need for redesigning spillways and updating hydrological models used in dam planning (Lompi et al., 2023).

The importance of adaptive dam management becomes even more evident when considering that sedimentation—accelerated by land use change and deforestation—reduces the effective storage capacity over time. In such contexts, the dam's ability to absorb peak inflows is compromised, making real-time water level monitoring and forecast-based reservoir operations vital. Without such adaptive measures, the once-effective infrastructure may contribute to risk rather than mitigating it.

Environmental Determinants of Dam Effectiveness in Flood Mitigation

The environmental context in which a dam is situated plays a fundamental role in determining its success as a flood mitigation infrastructure—particularly under the evolving stresses of climate change. This interaction is multifaceted, involving variables such as rainfall patterns, sedimentation rates, and the ecological integrity of the upstream watershed.

Firstly, increasing rainfall intensity—a known consequence of climate change—poses a direct challenge to dams originally designed based on historical hydrological baselines. With more intense and frequent rainfall events, inflow volumes can exceed design expectations, leading to overtopping risks and diminished flood storage capabilities. A study examining 18 major dams in Australia found that under 4°C global warming scenarios, overtopping risks increased up to 17-fold compared to historical baselines, emphasizing the heightened vulnerability from rainfall depth and antecedent wetness conditions (Ho et al., 2025).

Secondly, sedimentation resulting from upstream erosion—often driven by land degradation and deforestation—gradually reduces the effective storage capacity of reservoirs. Over time, this sediment accumulation shortens the dam’s functional lifespan and limits its ability to retain peak floodwaters. Case studies in Asia and Africa show that sedimentation can reduce storage volumes by up to 50% in as little as 20 years, particularly in basins lacking vegetation cover or soil conservation measures. This relationship was highlighted in a review of environmental impacts by Shah et al. (2009), which showed that sediment deposition not only affects flood mitigation but also compromises dam-based hydropower, irrigation, and navigation efficiency (Shah, 2009).

Thirdly, the presence and quality of vegetation within the watershed significantly influences surface runoff dynamics. Forested and well-vegetated upstream areas can absorb and slow the movement of rainwater, increasing infiltration and reducing the velocity and volume of surface runoff reaching the reservoir. A meta-analysis by Omer

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et al. (2024) covering 287 studies across 12 transboundary basins found that forest cover consistently enhanced dam efficacy in flood-prone regions by stabilizing upstream hydrology and reducing the frequency and magnitude of peak inflows (Omer et al., 2024).

An illustrative real-world case is the Addicks and Barker Reservoirs in Houston, Texas, which were overwhelmed during Hurricane Harvey. While these reservoirs had some success in delaying downstream flooding, years of upstream urbanization and vegetation loss—combined with unprecedented rainfall intensity—led to operational failure and widespread inundation. A post-event analysis revealed that integrating environmental criteria such as land use, vegetation cover, and water quality into dam operation and planning could have improved outcomes (Castro & Rifai, 2022).

Adaptive Strategies for Reservoir Management Under Climate Change

Adaptive reservoir management is emerging as a critical framework in response to the hydrological uncertainties posed by climate change, particularly for flood risk mitigation. Traditional reservoir operations typically rely on historical hydrological data and fixed rule curves to manage water levels. However, with the increasing unpredictability of rainfall patterns, intensity of storms, and seasonal shifts in water availability, such static approaches are becoming insufficient.

Modern adaptive management integrates real-time data, climate forecasts, and dynamic decision-making tools to optimize reservoir operations. A compelling example of this is the Forecast-Based Adaptive Reservoir Operation (FARO) framework applied to the High Aswan Dam (HAD) on the Nile River. Researchers demonstrated that integrating long-lead streamflow forecasts—up to 12 months—significantly improves operational decisions, especially in critical post-flooding months. Forecasts based on multi-model ensembles allowed operators to adjust releases proactively, thus better managing both flood and drought conditions. Interestingly, the benefit of such forecasting is most evident when considering upstream influences such as the Grand Ethiopian Renaissance Dam, necessitating coordinated, adaptive operating policies to maintain resilience (Eldardiry & Hossain, 2021).

In a different context, Vietnam's early flood-release program showcases another successful adaptive model. Utilizing medium-range global weather predictions, authorities implemented pre-emptive reservoir releases based on predicted inflows, effectively reducing both peak discharges and inundated downstream areas. This integration of meteorological forecasting with dam operations exemplifies a low-cost but high-impact adaptation strategy tailored to climate variability (Hoa, 2019).

On a broader scale, integrated reservoir management systems are beginning to use machine learning and IoT technologies to automate decision-making processes. One recent system incorporates real-time soil moisture sensors and weather data to control spillway gates dynamically. This preemptive release strategy not only mitigates floods but also ensures water conservation and ecological balance, aligning with sustainable development goals (Eum et al., 2012).

Despite technological advancements, challenges remain. Studies highlight barriers such as inter-agency coordination, budget limitations, and inadequate data infrastructure, especially in developing regions. Nevertheless, adaptive reservoir management stands as a vital pillar for building resilient water systems in a warming world.

Conclusion

Based on the literature study conducted, it can be concluded that dams remain vital infrastructure in flood mitigation in upstream areas, but their effectiveness is greatly influenced by climate change, environmental degradation, and the mismatch between design capacity and new hydrological dynamics. Dams designed based on historical data tend to be unable to cope with extreme water volume increases due to intense rainfall. Therefore, an adaptive management approach that integrates predictive technology, real-time weather data, and consideration of upstream environmental conditions is very important.

Dam managers need to implement a forecast-based operations system, update the dam rule curve regularly, and strengthen cross-sector collaboration in decision-making. In addition, upstream vegetation restoration, catchment area rehabilitation, and sedimentation control need to be carried out simultaneously to maintain the effectiveness of dam storage.

Further research needs to be conducted with a quantitative approach based on hydrological modeling and long-term climate simulations to analyze the specific performance of certain dams. Empirical case studies in various upstream watersheds with different climate and morphological characteristics are also needed to develop contextual adaptive management guidelines.

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