CHAPTER 8

Adaptations for Dams and Reservoirs to Climate Change

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8.1 | Introduction

Water is a vital basic need for all living things, and managing existing water resources to meet the demand is crucial. Further, storing water is a necessity in many countries for water supply and flood management due to the spatial and temporal variability of the available water. For these purposes, dams and reservoirs were built to store and supply water in different sectors (i.e., domestic, industrial, hydropower, irrigation, and ecosystems). As climate conditions continue to shift due to climate change, the design and operation of dams and reservoirs face unprecedented challenges. These infrastructures are increasingly experiencing various operational and structural issues that lead to risks and vulnerabilities in how we handle water. Therefore, this chapter aims to guide us in the context of climate change on the retrofit of old dam designs and operations to address the current and future critical issues and challenges that many countries across the world may encounter.

This includes a summary of existing practices and projections for climate change, and the physical impact on the construction, maintenance, and functionality of dams in a changing climate. The risk associated with aging water storage infrastructure is one concern to investigate. Further, this chapter aims to develop frameworks and guidance documents for operators, owners, and policymakers to offer a general procedure to assess, plan, and design dams and reservoirs in consideration of climate change. Finally, the chapter explores recommendations for the following three components a) understanding gaps in current planning practice in a warmer climate, b) opportunities to improve planning and design concepts, and c) a research agenda for a way forward.

8.2 | Expected Climate Change

The global climate is manipulated and controlled by the dynamic interactions between oceans, land masses, and the atmosphere, and their corresponding contributions to changes in the distribution of heat flow (United Nations, 2013). Most heat changes occur in the oceans, and variations in sea surface temperatures (SSTs) are considered the direct indicator of climate change. Nonetheless, the 6th assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) declared that anthropogenic activities warmed the ocean, atmosphere, and land, due to greenhouse gases (GHG) (IPCC, 2021).

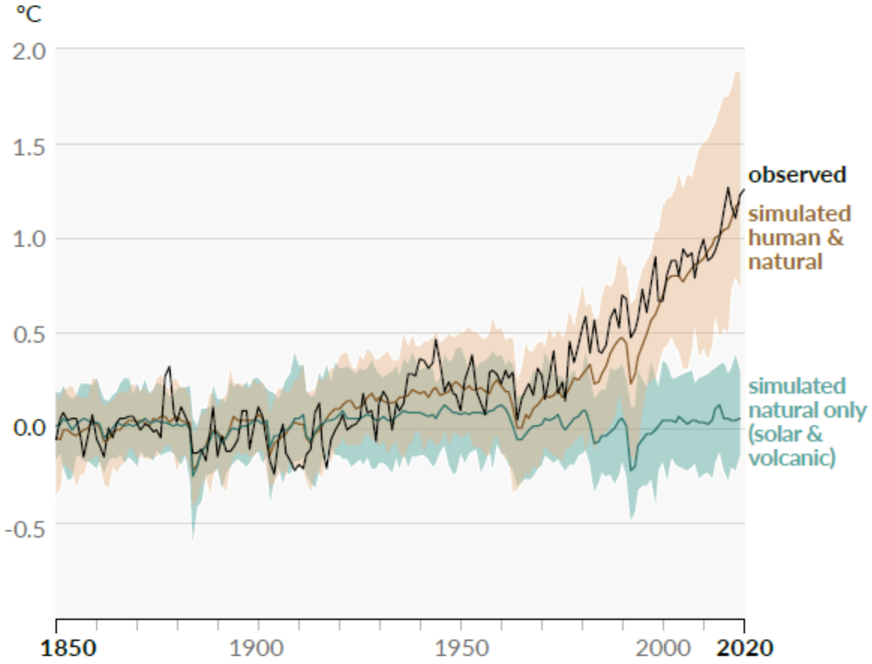

Figure 8.1 | Changes in observed and simulated (i.e., using human & natural and only natural factors) annual average global surface temperature from 1850–2020 (Source: IPCC, 2021).

The concentration of GHG in the atmosphere showed a continuous significant increase in 2019 compared to 2011:the mean annual concentrations of CO2, CH4, and N2O increased from 19 ppm to 410 ppm, 63ppb to 1866 ppb, and 8 ppb to 332 ppb during 2011–2019, respectively (IPCC, 2021). Further, land and oceans absorb annually around 56% of CO2 emitted from human activities. The global surface temperature (i.e., the sum of global mean surface temperature and global surface air temperature) has increased substantially during 1980–2020 compared to the rate in the 1850s. Global air temperatures over land surfaces have increased at about double that of the rate of the oceans' (Sivakumar and Stefanski, 2011). Moreover, the global surface temperature increased by 0.99° C and 1.09° C during the periods of 1980–2000 and 2000–2020, respectively, compared to the reference 1850–1900 period. Significantly, human intervention likely accelerates the increase in global surface temperature these days (Figure 8.1). Though the increase in surface temperature on land is more substantial than the increase in the sea surface temperatures (SSTs), anthropogenic activities caused an increase in SSTs between near-surface ocean layers (0 – 700 m) and an increase in salinity and acidity in the ocean waters (IPCC, 2021). Further, it is interesting that humans influence more strongly the melting of snow cover in the Northern Hemisphere compared to the Antarctic glacier cover. The melting of snow cover has led to global sea-level rise (SLR) and has been demonstrated to be increasing significantly at 1.3 mm/year, 1.9 mm/year, and 3.7 mm/year, with high significance during 1901 – 1971, 1971 – 2006, and 2006 – 2018, respectively (IPCC, 2021).

Precipitation has significantly increased since the 1950s, however the increasing rate of increase has declined slightly since the 1980s with moderate significance. Furthermore, the intensity and frequency of extreme rainfall has increased substantially. Interestingly, warming caused by GHG emissions has been shown to increase monsoon precipitation in South Asia, East Asia, and West Africa. Monsoon precipitation gradually decreases in response to increasing the emission of human-caused aerosols. Naveendrakumar et al. (2019) explored rainfall and temperature trends observed in South Asia and reviewed the methods used for the trend analysis. Further, compound extreme weather events such as heatwaves, floods, drought, and fire weather conditions have increased since the 1950s. Low-temperature extremes are less common in Europe because of the increase in heatwaves. The mean duration of summer heatwaves and the number of warm days in Western Europe have increased significantly (EEA, 2011). The duration of heat waves is also prolonged in South Asian regions (Sivakumar and Stefanski, 2011; Chandrasekara et al., 2021). The occurrence of tropical cyclones has been increasing since the 1980s, and the spatial occurrence of highly intensified tropical cyclones shifted from the western North Pacific to northward (IPCC, 2021).

8.3 | Climate Change Impacts on Dams and Reservoirs

8.3.1 | Hydrological Changes due to climate change

Monitoring climate change impacts over dams and reservoirs is essential where the frequent modification of water management strategies, including reservoir operation, is often required in a changing climate. The inflow from the Dez dam water basin, Iran, including sub-basins of Tire, Marbore, Sazar, and Bakhtiari sub-basins, experienced a significant decrease trend due to the reduction in summer rainfall based on the Nonparametric Mann-Kendal test, Pettit and Buishand test (Norouzi, 2020). Further, a considerable decrease in winter runoff was identified for the Yellow River in China (Hu et al., 2011) and Sanguwa rivers (Lee et al., 2014), impacting water availability. Jung and Kim (2017) identified water shortages during droughts in South Korea, and severe negative impacts were identified in the Boryeong Dam, South Korea.

Recent reviews of the South Asian monsoon system underscore the complex interplay between ocean-land temperature gradients, atmospheric circulation, and topographic influences. Climate change is projected to enhance total rainfall due to increased atmospheric moisture, yet concerns persist regarding a potential weakening of monsoon circulation. Such changes could significantly affect the hydrological cycle, especially in monsoon-dependent regions. Additionally, the role of aerosols and greenhouse gases introduces further variability in monsoon behavior, complicating water resource planning and reservoir operations. These dynamics highlight the urgency of refining climate models and observational tools to improve projections of extreme hydrological events and seasonal shifts (Fiaz et al., 2025).

Recent studies have highlighted the increasing vulnerability ofdams and reservoirs to floods due to increased extreme precipitation events. For instance, the EPA (2021) identified trends in the flow based on the indicator using the annual maximum discharge of a station, indicating a rise in peak flows associated with climate change. Yun et al. (2021) developed a model combining the hydrological variable infiltration capacity model and the reservoir module to understand the impacts of climate change on reservoir operations in the Lancang-Mekong River Basin, China. Interestingly, the study revealed that the upstream reservoirs were deficient in generating hydropower compared to the downstream reservoirs. Dam safety in the Himalayas regions is questionable because historical streamflow data on reservoir routing is not available to predict floods due to glacial melting (International Rivers, 2011).

Yasarer and Sturm (2016) stated that comprehensive studies had been undertaken from the perspective of climate change-induced water availability in reservoirs. Still, there is a limitation in studies that focus on climate change-influenced water quality degradation in reservoir waters. The sediments derived from stream bank erosion of Perry Lake, Kansas, could impact the degradation of reservoir water quality more than the sediments originating from surface soil (Juracek and Ziegler, 2009). Further, an increase in river bank and bed erosion can be associated with extreme rainfall under climate change (Seneviratne et al., 2012). More specifically, extreme rainfall events contribute more to erosion because high-intensity rainfall causes more erosion; for example, five extreme rainfall events in the Ohio watershed contributed to 66% of total erosion (Edwards and Owens, 1991). Additionally, sediment transportation increases during extreme rainfall events. For example, the seven storms observed in 2010 upstream of Kanopolis Lake, Kansas, related to 88% of total suspended sediments (Juracek, 2011).

In summary, climate change is likely to increase the severity, scale, and frequency of droughts and extreme precipitation. It is recommended to quantify hydrologic changes, including water inflows, flood and drought frequencies, and sedimentation in dams and reservoirs due to climate change using monitoring data. Parametric regression is a practical technique to track mean trends, but it ignores distributional changes at upper and lower tails, which are more effective than the mean trend in extreme climate studies. In this regard, a quantile regression has been used to provide a complete picture of long-term temporal trends (Uranchimeget al., 2018; Uranchimeget al., 2020). Moreover, parametric distribution approaches could be more efficient for normally distributed residuals, while the nonparametric approach is more robust, with residuals departing from normality (Kwon et al., 2007a; Kwon et al., 2007b; Kim et al., 2015; Lima et al., 2018).

8.3.2 | Structural Changes in dams and reservoirs due to climate change

The increased demand for water in dynamic water availability circumstances sparked the need to construct reservoirs and dams around the world. Hence, several dams were built more than 100 years ago (Figure 8.2), especially in the USA and Europe. Notably, most dams and reservoirs exceeded their active life span and have aged, causing numerous mechanical deformities and unsafety to living and non-living systems. Further, some dams and reservoirs were built for a certain life span where the impact of climate change was not considered while designing their life span. This could lead to massive economic, social and environmental risk to a country (Kraljevic, 2013).

Dams are structurally sensitive to most climate-related impacts. Notably,concrete dams, including arch-type dams, can be directly affected by changes in temperature, precipitation, and solar radiation

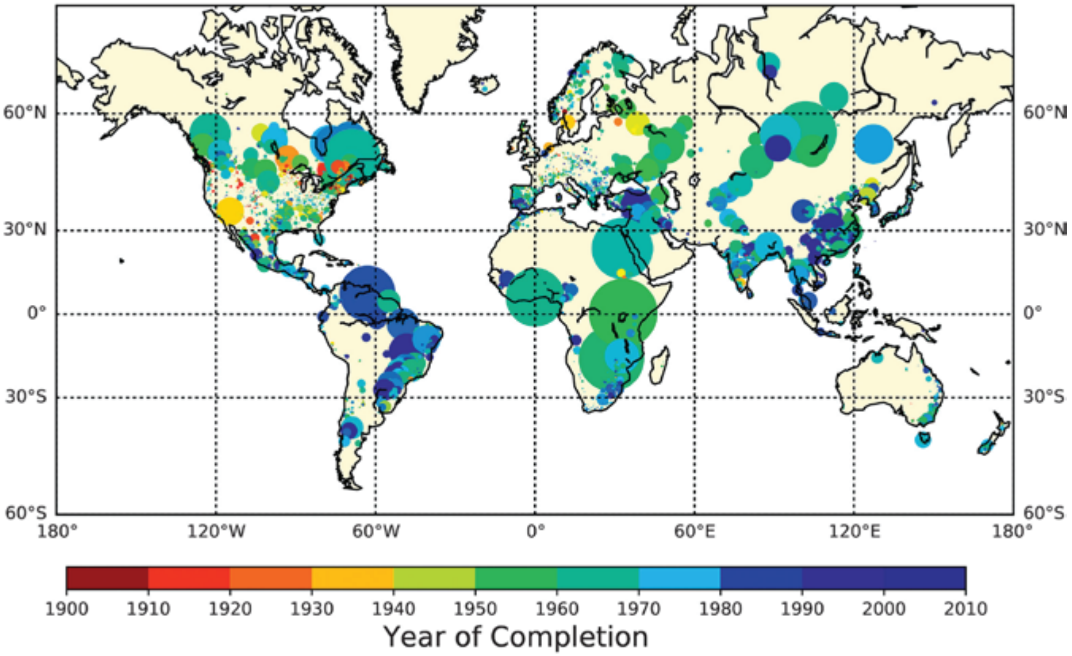

Figure 8.2 | The capacities and the year of dam completion for the dams which had been completed by 2010 in the world (The color shows the year of completion of the dams, and the size of the circle illustrates the capacity of the reservoir), Source: Lehner et al., 2011.

(FERC, 1999; Malm, 2016). Temperature is typically expected to increase under climate change and may have more significant impacts with more frequent extreme values (IPCC, 2021). Moreover, the potential variation in water storage in a reservoir can lead to increased exposure of the dam to solar radiation (both in duration and surface of exposure). In addition, an increase in temperature difference and maximum temperature is likely to affect damage to the surface of the concrete. More importantly, these issues can eventually expose the dam to mechanical stresses, thus making it more vulnerable to hydrostatic loads. In these circumstances, traditional stability analyses may be insufficient to assess whether increasing temperatures and solar radiation can influence the failure probabilities related to structural reliability, and more rigorous approaches should then be adopted. Similar concerns should be considered in other failure modes such as over topping and internal erosion) that can be influenced by climate change.

8.3.3 | Climate Change Impacts on Dams and Reservoirs

In addition to structural considerations (Section 8.3.2) and hydrological changes (Section 8.3.1), it is also crucial to synthesize the various ways in which climate change can impact dams and reservoirs. As summarized in Table 8.1, climatic factors, such as extreme temperature and precipitation events, droughts, floods, and glacial melting, can threaten the structural stability, operation, and reliability of water storage and hydropower facilities. For instance, precipitation variability can reduce inflows during dry spells, reducing water supply or hydropower generation while simultaneously causing damaging floods in wetter periods. Such variability exacerbates the challenge of determining design capacities, flood control.

Further, extreme temperature and precipitation events can threaten dam safety by intensifying erosion, sediment transport, and siltation in reservoirs, ultimately reducing their capacity and efficiency. These events can also precipitate over topping and structural damage in older earth-fill or smaller community-based dams that were never designed for higher runoff volumes. Meanwhile, glacial melting in colder regions adds additional uncertainty: melting ice accelerates sediment transfer into reservoir basins, leading to infrastructure wear and reduced storage capacity. Additionally, permafrost thaw in high-latitude regions can alter groundwater connectivity and release further sediment, posing new operational and engineering challenges.

Collectively, these climatic impacts highlight the need to adopt more adaptive and resilient strategies in designing, managing, and rehabilitating dams and reservoirs. Strategies might include integrating real-time monitoring to detect changing inflows, adopting innovative sediment management techniques, and upgrading dams and spillways for future flood extremes. Ultimately, recognizing the interconnected nature of these impacts, rather than treating each in isolation, can guide more robust approaches to reservoir safety, reliability, and ecological sustainability under a changing climate.

8.3.4 | Estimation of Climate Change Impacts on Dams and Reservoirs

The World Meteorological Organization (WMO) have recommended a) statistical method, b) generalized method, c) transposition method and d) moisture maximization method to calculate probable maximum precipitation (PMP) to investigate safety design standards at stationary climate. Chen and Hossain (2019) discuss the efficiency of PMP calculations for future dam safety. However, a stationary assumption on climate baselines is no longer suitable in a changing climate to assess dam safety (USACE, 2016). Interestingly, recently constructed dams and reservoirs have been built considering climate change, and therefore their life spans became different from historical ones (Arnell and Hulme, 2006). Therefore, frequent updating of the design flood calculation for new reservoirs is mandatory

Table 8.1 | Indicative climate change impacts on dams and reservoirs.

Climate change factors	Examples of impacts	Source
Precipitation variability	• Generation of hydropower declines due to a decrease in streamflow to the reservoir in low rainfall periods. • Loss of fish habitat and damage to the livelihood of the community	Cherry et al., 2017
Extreme temperature and precipitation events	• Difficulty in deciding construction and management criteria for reservoirs, such as design capacity, flood control, water spilling, and flood routine strategy. • Further, water wastage without using it for hydropower generation during extreme rainfall periods because of the spilling of reservoir water. • High sedimentation and siltation. Eutrophication due to sediment-bound nutrients. • Portioning of runoff into surface and groundwater • Older earth-fill dams that have erodible embankments tend to cause rainfall erosion during high rainfall events. Damages to downstream communities if dams break. • High temperatures may add additional mechanical stress to the concrete dams	Cherry et al., 2017; Vahedifard et al., 2017; Hughes and Hunt, n.d.; Sutton, 2019; Toniolo and Schultz, 2005; Rahman et al., 2025
Variabilityin air temperature	• Reduction of available water in reservoirs during following spring due to increase in autumn air temperatures in the Far North. Further, warming increases rain during winter and exceeds the capacity of the reservoirs in the northern reservoirs..	Cherry et al., 2017
Floods	• Exceeding the reservoir's existing capacity and emergency spillway may cause a devastating situation to downstream infrastructures and lives. Inundation impacts upstream infrastructures and lives. High GHG emissions such as methane from inundated vegetation. • Transporting catchment debris and vegetation may damage the outflow structures and spillways, and their performances • Deterioration of water quality in the reservoir, marginal vegetation conditions and fishery functions	Cherry et al., 2017; Hughes and Hunt, n.d.; Scherer and Pfister, 2016; Yasarer and Sturm, 2016; Kim et al., 2024
Droughts	• Generation of hydropower declines due to a decrease in streamflow to the reservoir. • Changes in micro-climate and increased evapotranspiration in reservoirs. • Heat-induced expansion of hydraulic structures	Cherry et al., 2017; Charalampos, S., et al. (2013); Kwon et al., 2016; Ho et al. (2017)
Glacial melting	• The discharge from the glaciers melt runoff is not even throughout the process and it is difficult to design and manage the hydropower reservoirs. Sometimes unexpected floods are also observable. • Discharge of large quantities of sediments leads to a reduction inthe storage capacity of a reservoir and wears off the hydrological structures. • Changes in pattern and frequency of the ice blockages and jams damage the hydrological structures. The melting of ice jams and associated flooding increase the quantity of water within the reservoir.	Cherry et al., 2017; Gurnell, 1995; Harrison et al., 1983; Gebre et al., 2013; Bergstrom et al., 2001; Prowse and Beltaos, 2002; US Department of Energy, 2017
Permafrost thaw	• An expected increase in subsurface storage and connectivity • High sediment release to the waterways due to thermal and water-driven soil erosion leads to a reduction of reservoir capacity and damage to hydrological structures	Cherry et al., 2017; Toniolo and Schultz, 2005; Gurnell, 1995
Polar amplification	• Accelerated warming in polar regions, especially the Arctic region, weakens the mid-latitude circulation and causes hot-dry extremes in mid-latitudes. These phenomena lead to heatwaves in the mentioned regions and may impact reservoirs and dams.	Coumou et al., 2018

in order to safeguard the safety of a dam. Further, simultaneous sensitivity analysis is also required to design floods for a future climate change scenario. The following section will explore in detail specific examples of such dams, and the methodologies employed to integrate climate resilience into their design and management.

8.3.4.1 | *Long-term Water Availability Evaluation*

Chung et al. (2011) identified that there would be negative changes in inflow and water storage in a group of multipurpose dams in the Han River due to climate change. Further, Gohari et al. (2014) predicted that water would be deficient for agriculture in Iran due to the reduction of available water in the Chadegan reservoir in the Zayandeh-Rud River basin, Iran. The future water capacity of the Gwanghye reservoir was evaluated based on RCP 4.5 and 8.5 climate change scenarios using the reservoir simulation process under two different conditions: a) before and b) after the heightening of the embankment (Lee and Shin, 2021). The study revealed that heightening the embankment can be an effective strategy to supply the irrigation water requirement in Korea.

The hydropower impact assessment for the USA was done using modeling of water availability by dynamically downscaling sub-daily atmospheric data under an ensemble of 10 IPCC AR5 GCM at RCP 8.5 scenario. GCM signals were downscaled using RegCM4 for both the historical (1966–2005) and future (2011–2050) periods. The Variable Infiltration Capacity hydrological model (VIC) is used to simulate future water availability for hydropower generation. The lumped Watershed Runoff–Energy Storage model was developed to analyze annual, multiannual, daily, and seasonal generation under different climate change scenarios. The study revealed an increase in winter and spring hydropower generation and a decrease in summer and fall generation (US Department of Energy, 2017).

In summary, studies on long-term water availability indicate a reduction in inflow and water storage. Some studies suggest heightening the dam as an alternative solution to the water supply shortage. Furthermore, these reductions due to climate change led to differences in seasonal hydropower generation.

8.3.5 | Flood-Risk Evaluation (or Dam Safety)

Risk assessment and water infrastructure design for extreme rainfall and flood mitigation have traditionally relied on calculating the Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF). These methods typically assume a stationary climate when designing critical dam features for worst-case scenarios. However, climate change is increasingly challenging this assumption, as static PMP and PMF values no longer reflect evolving hydrological conditions (Visser et al., 2022).A study conducted in the Upper American, Owyhee, and Holston River watersheds, encompassing the Folsom, Owyhee, and South Holston dams, emphasized the need to re-evaluate older dams originally designed with fixed PMP and PMF standards. The research found that climate change and land-use alterations have already affected current PMP values, making the previous assumptions outdated. Further, it proposed employing a dynamic PMP approach in the design of future dams to better account for changing climatic and watershed conditions (Stratz and Hossain, 2014).

The design flood can be calculated using a) flood frequency approach with observed or simulated inflow series and b) precipitation-runoff method – design rainfalls from frequency analysis and their uses for estimating design floods from hydrologic models (Killingtveit and Saelthun, 1995; NVE, 2011). Nonetheless, the precipitation-runoff approach is more desirable than the flood frequency analysis because a) uncertainty is relatively low, and b) precipitation is easily interpolated and regionalized using established regional methods (Saelthun and Anderson, 1986). However, the reliability of these techniques depends on specific regional characteristics and data availability and quality. Lawrence et al. (2012) summarized the projected changes in quantity, seasonality, and uncertainties in floods in the Netherlands, Norway, and Sweden. Notably, many studies have revealed that projected flooding patterns are not uniform for the entire country, and regional differences in climate conditions and watershed characteristics have mainly influenced these differences (Veijalainen et al. 2010). Chernet et al. (2014) and Mailhot and Duchesne (2010) described the studies carried out to investigate the impact of climate change on hydrology using different methods. Reservoir simulation under varying climate change scenarios could be an efficient way to understand the corresponding changes in future water surface elevations in reservoirs. Sutton (2019) carried out a similar study for the Central Appalachian Ecoregion, West Virginia. Niu and Shah (2018) developed an optimal control model for Jinsha Dam and Aswan High Dam in China and Egypt, respectively, to design the optimal size of a dam under future climate change scenarios. The LISFLOOD model, which is a hydrological rainfall-runoff and channel routing model, can be used for flood forecasting under climate change scenarios. Further, it can assess river regulation measures and the effects of land-use changes on floods. The detailed simulation process of LISFLOOD is available in the manual prepared by the European Union (2013).

State-of-the-art methods for evaluating climate change impacts on dam safety now emphasize risk-based, comprehensive approaches that move beyond traditional stationary assumptions. Fluixa-Sanmartin et al. (2018) provide a succinct overview of contemporary assessment methods, including climate projections, downscaling techniques, fault-tree analyses, and revised flood routing and inundation models. They also underscore the importance of considering socio-economic consequences in a changing climate. Addressing the inherent uncertainties in modeling extreme events, researchers have increasingly adopted non-stationary flood frequency analysis and stochastic weather generators to capture non-independence and non-stationarity in hydrologic data. Such risk assessments are further refined by explicitly incorporating uncertainties from diverse sources, such as climate models, downscaling methods, and hydrological model structures.

Beyond advanced modeling, climate-driven processes that affect dam infrastructure also demand close attention. Sedimentation, a natural aging phenomenon in reservoirs, is highly sensitive to extreme weather events. As storms intensify, they accelerate sediment transport, hastening reservoir capacity loss. A recent UN warning suggests that the world's large dams may lose about a quarter of their capacity by 2050 due to climate change (The Guardian, 2023). Shifts in precipitation patterns and escalating extreme weather events introduce additional sediment—particularly following wildfires, which destabilize soils and multiply sediment loads. For example, post-fire erosion in a California watershed magnified sediment transport by three to four times after combined wildfire and flood events (East et al., 2024). Diminished storage capacity under these conditions imperils water supply, flood control, and ecosystem health, underscoring the urgency of planning dam management and design strategies that can withstand increasing flood risks.

Finally, effective dam-safety planning leverages both precipitation-runoff and flood event frequency analyses, each offering distinct strengths and limitations. Numerous studies apply hydrologic simulations under various climate scenarios to identify flood-risk dynamics and compute anticipated water-surface elevations in reservoirs. LISFLOOD, for instance, can evaluate the interplay of river regulation and land-use changes on floods. Socio-economic considerations of climate change and sedimentation must also be woven into these simulations to create holistic dam-safety policies. Notably, Wild (2014) demonstrated how alternative locations, designs, and operating policies could significantly enhance sediment passage through reservoirs in the Mekong River system, although these improvements can require considerable energy investments. Altogether, an integrated approach that combines robust hydrological modeling, infrastructure design, and socio-economic analyses is essential for maintaining dam resilience in the face of evolving climatic conditions.

8.4 | Recommendations for the Adaptation of Dams and Reservoirs to Climate Change

8.4.1 | Technical and Structural Adaptations

Adaptation to climate change could be defined as a process that governs the decrease of damage and understands the benefits associated with climate variability and climate change(Smitand Pilifosova, 2003). Though there are numerous adaptation strategies available for a changing climate, the adaptive capacity of the system determines the efficiency of the proposed adaptation strategy. Further, the adaptation strategies are categorized as either a) policy, planning, and assessment, b) design and construction, and c) operation and maintenance of the dams and reservoirs.

8.4.1.1 | *Reservoir Operation and Modeling Tools*

Adaptation options related to changing the operation of a reservoir has the potential to mitigate the impact of climate change on some dams and reservoirs. The application of a comprehensive modeling framework for reservoir operation could be helpful in understanding the effectiveness of adaptation measures for a certain climatic scenario. Examples of such models are VMod regional hydrological model (Lauri et al., 2012), LPJmL global hydrological model (Biemans et al., 2013), Hydrologic Simulation Program Fortran (HSPF) (Donigian et al., 1995), Agricultural Non-Point Source Pollution Model (AGNPS) (Young et al., 1989) and Soil and Water Assessment Tool (SWAT) (Douglas-Mankin et al. 2010). Yasarer and Sturm (2016) summarize the mathematical and statistical tools used to identify the impacts of climate change on reservoirs. Feldbauer et al. (2020) used the hydro-physical General Lake Model and identified that the withdrawal rate or stored volume of a reservoir affected the spatiotemporal variation of water temperature. Further, this study identified that the effectiveness of the withdrawal method depends on the withdrawal rate and downstream water. Therefore, an adaptation of an efficient withdrawal strategy would make the best thermal stratification in a reservoir and could minimize the water quality deterioration due to climate change. Gopalan et al. (2020) discussed previous studies on the application of hydrological models to determine adaptive strategies for dams and reservoirs to climate change. However, with limited available data, the complexity of the reservoir operational plans and new adaptive plans could drawback the application of hydrological models as a means of understanding adaptive measures for climate change.

The design criteria adopted for most of the recent reservoirs cannot bear the different regimes of streamflow due to climate change. Therefore, it is essential to consider different adaptation strategies, and a combination of reservoir operation and afforestation could be an effective adaptation strategy. Further, adapting modified structures or rehabilitation would also adapt dams and reservoirs for climate change (Gopalan et al., 2020). The increase in the height of the embankment of agricultural reservoirs was implemented in 2009 by the Korean Government of Korea to safely supply the required amount of water during dry seasons (Lee and Shin, 2021). The application of a comprehensive modeling framework for reservoir operation could be helpful in understanding the effective adaptation measures for a particular climatic scenario.

8.4.1.2 | *Structural and Material Design Enhancements*

To ensure future flexibility, design standards should incorporate non-erodible structures (e.g., concrete or masonry), to prevent the increased erosion of embankments due to extreme fluctuations in water levels, as well as physical changes such as erosion during extreme wet and hot weathers. Furthermore, the selection of construction materials, including concrete joints, aggregates, and derived products, must account for the proven effects of aging and climate change, particularly those caused by UV radiation and elevated temperatures (Atkins, 2013).

With regard to the issue of sedimentation, cost-effective frameworks for sediment removal in flood-prone reservoirs should be considered. The US Bureau of Reclamation and its collaborators are actively seeking new or improved techniques for reservoir sediment removal and transport that are cost-effective and preserve the operational objectives of the reservoir (US Bureau of Reclamation, 2022). Examples of reservoir reclamation include the use of an autonomous vessel capable of removing sediment from reservoirs or a dredging technology handling sediment and larger debris (WEDA, 2021).

Furthermore, reevaluation of spillway design estimates from PMP should be considered with climate extremes in mind. This includes upgrading and optimizing spillway design (Adamo et al., 2020). For example, the HöljesDam spillway design capacity was increased to accommodate an increase in anticipated discharge (Yang et al., 2019).

Future water infrastructure design should also consider the worst-case scenario with climate projections in estimating reservoir capacity and operational models while considering ecosystem and water quality.Adaptive dam design and best management practices should be flexible and balance the control of water for water supply, disaster risk mitigation, and ecological considerations (MacTavish, 2022).

8.4.2 | Understanding Gaps in Current Planning Practice in a Warmer Climate

Revising conventional design flood estimation methods to incorporate near-term climate projections is increasingly necessary yet remains challenging due to the uncertainties inherent in these projections. Additionally, longer design life spans, often exceeding 100 years, magnify the difficulty of predicting reliable flood estimates for dams located in data-scarce regions. In response, Wasko et al. (2021) propose employing alternative approaches that do not rely solely on conventional design floods in such complex contexts.

A central issue is the lack of consensus on standard methodologies for flood estimation under climate change, with dam safety guidelines often varying considerably by country or jurisdiction. For example, raising embankments at agricultural reservoirs in Korea did not fully account for future climate scenarios (Lee and Shin, 2021). This highlights how current design guidelines, including modifications to dam structures and management practices, remain insufficiently standardized for addressing changing climate conditions.

8.4.3 | Opportunities to Improve Planning Concept

Some institutions are developing and implementing more resilient decision-making guidance that incorporates climate change scenarios and updated risk components. Although a substantial amount of research has already examined the impacts of climate change on dams and reservoirs, practical application to dam safety remains limited. Further, adaptation plans should not be restricted to a particular administrative, instead, they need to be integrated into the national-level adaptation strategies and policies to ensure broader effectiveness.

Wasko et al. (2021) summarized various methodologies designed to address uncertainties in the decision-making process of design flood estimation, such as a) standard-based, b) risk-based, c) robust, and d) adaptive. Regularly revising these methodologies throughout the design life of dams and reservoirs—and during any major structural modifications—can help to minimize significant uncertainties related to evolving climate conditions. Potential review processes might employ a) Heuristic approaches based on physical reasoning, b) projections based on historical data, and c) projections based on global climate models. Selecting the most appropriate flood estimation technique is equally important. Wasko et al. (2021) recommend approaches such as a) flood frequency analysis, b) event-based approaches that use intensity-duration-frequency curves, c) continuous simulation, and d) probable maximum precipitation.

Wasko et al. (2021) further recommend openly acknowledging uncertainties, even if they are difficult to quantify precisely. Sensitivity testing within a credible range of possible outcomes is another valuable practice, enabling researchers and practitioners to explore the effects of varying parameters or assumptions on flood estimates. Such sensitivity analyses may be performed by considering multiple plausible scenarios, including “high” and “low” projections derived from several climate models or pathways.

In terms of designing new dams and reservoirs, the application of climate allowances is critical for coping with future climatic conditions. For instance, in the United Kingdom, designers must account for central allowances when planning dams expected to serve beyond 2060, and for structures lasting beyond 2100, a flood risk assessment must incorporate upper-end allowances at the 1% annual exceedance probability event (UK Gov., 2016). This strategy reduces vulnerabilities and enhances flood resilience. Additionally, the UK Environment Agency requires a 20% increase in the design flood volume for spillway designs to safeguard against climate change impacts (Atkins, 2013).

In Australia, updated Intensity-Frequency-Duration (IFD) curves and climate-model-based uncertainty assessments are being used to inform event-based design flood estimates. An adaptive approach to dam and levee construction is gaining traction, exemplified by the inclusion of additional capacity in levee foundations and the expansion of riverbank corridors to facilitate future embankment heightening or widening. Some projects already incorporate these measures to secure protection at a 1% annual exceedance probability level of flooding (Ball et al., 2019).

8.4.4 | Research Agenda for a Way Forward

Continuous and timely research is crucial to adapt and mitigate the future climate change impact on dams and reservoirs. Research advances the knowledge of climate resilience in dams and reservoirs, and the research process must be done systematically. Most studies assessed dam safety separately by only focusing on the direct impact of climate change on dams and reservoirs. Therefore, multi-disciplinary analyses of impacts on dams and reservoirs are recommended. Research on the indirect impacts of urbanization-associated problems, such as land-use change, pollution, riverbank encroachment, etc., must be considered simultaneously because anthropogenic activities may accelerate the impact of a changing climate. The teleconnections between atmospheric and ocean circulations, coupling climate research and forecasting with distributed hydrological models using radar technologies, could enhance the new findings toward raising the resilience of dams and reservoirs to climate change. Research on dynamic flood control and AI-based operation of dams and reservoirs would be another approach to mitigating climate change impacts on dams and reservoirs.

Ho et al. (2017) proposed a comprehensive research methodology for the effective and efficient research agenda for dams and reservoirs in the USA. The agenda includes several strategies to manage climate-induced flood and drought risks for dams and reservoirs in the USA. Most importantly, the agenda discusses analyzing climate change scenarios, institutional aspects to conserve water, and reliable management of water and its relevant infrastructures.

8.5 | Concluding Remarks

Dams and reservoirs have long been constructed to store water and meet growing demand, yet climate change has introduced new and significant stresses on these infrastructures. In response, researchers and stakeholders are increasingly focused on identifying and implementing adaptation measures that enhance the climate resilience of dams and reservoirs. These adaptation strategies generally include shifting from conventional, stationary approaches to dynamic, non-stationary methods that explicitly incorporate uncertainty; conducting comprehensive risk assessments that account for worst-case scenarios, such as increased sedimentation rates, structural aging, and ecosystem impacts; and implementing adaptive management practices that can respond effectively to the growing frequency and intensity of extreme weather events.

Despite these promising solutions, the practical challenges of adjusting dams and reservoirs to changing climate conditions persist. A key step in overcoming these hurdles is the establishment of uniform, globally recognized frameworks that integrate climate change projections into all aspects of dam design, construction, and operation. Encouragingly, many regions and institutions are developing new standards and guidelines that account for both emerging research and site-specific risks. Ongoing collaboration among engineers, policymakers, and researchers will be crucial for ensuring that dams and reservoirs continue to function safely, reliably, and sustainably amid increasing climate variability.

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