

## Review

# Climate-resilience of dams and levees in Canada: a review

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Received: 30 November 2023 / Accepted: 12 March 2024

Published online: 28 March 2024

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## Abstract

Increasing frequency and intensification of flooding pose significant threats to critical structures, such as dams and levees. Failure of these structures can lead to substantial economic losses and significant adverse environmental and social consequences. Improving the resilience of these structures against climate-related impacts is important to avoid future risks of failure due to the potential intensification of flooding. National-level guidance on integrating resilience-based frameworks and addressing climate risks and uncertainties in existing design flood estimation methodologies for dams and levees are lacking. To address these gaps, this study first reviews projected climate change patterns for Canada and then discusses regional vulnerabilities of dams by considering significant historical floods and their consequences. Subsequently, a review of existing design flood estimation procedures, with a focus on frequency- and probable maximum flood-based approaches, is conducted to identify areas where climate change-related aspects can be integrated. By examining the challenges associated with various stages of design flood estimation procedures, the review discusses a framework for enhancing climate resiliency of dams and levees considering four pillars of resilience. Furthermore, Canadian design flood estimation practices are compared with international practices to identify areas that require attention. The study highlights the importance of a resilience-based framework in providing design and operation guidance to ensure that dams and levees are resilient to climate impacts. Policymakers and engineers can prioritize consideration of climate-resilience in the design and operation of these structures in order to safeguard communities and infrastructure from the growing risks of future floods associated with climate change.

## Highlights

- A systematic review of frequency- and probable maximum flood-based methodologies used for estimating design floods for dams and levees.
- A basis for developing national guidelines for Canada for estimating future design floods by integrating climate change information.
- Systematic guidelines and climate-resilience framework will enable effective adaptation measures under changing climatic conditions.

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**Keywords** Climate-resilience · Climate risks · Dams and levees · Design flood estimation · Frequency-based approaches · Probable maximum precipitation · Probable maximum flood · Resilience-based framework

## 1 Introduction

Climate change is expected to impact various built infrastructure assets, including flood control infrastructure, such as dams and levees. Extreme water levels and velocities are just a few of the potential threats that could trigger failure of these structures. The inability to fulfill infrastructure performance objectives under a changing climate can have cascading effects on several sectors of society, including the economy and public health [1]. Canada has a long history of recurrent flooding, which has resulted in significant damage to property and large government disaster assistance payments [2–4]. According to the natural disaster database of Munich Re's NatCatSERVICE, seven of the ten most costly Canadian floods that occurred between 1980 and 2019 were experienced after 2010, suggesting an upward trend in flood risks [5, 6]. The most expensive flood in Canada was the 2013 Alberta flood, which resulted in total estimated losses of approximately 5,700 million CAD, according to the Canadian Disaster Database [7]. This intense flood was caused by heavy rainfall combined with melting snowpack in the steep terrain of the Rocky Mountains. In the same year, Toronto, Ontario, experienced the worst flash flooding since Hurricane Hazel in 1954 when a storm brought about 126 mm of rain. Another disastrous flood occurred in Quebec in 2017 due to rapid spring snowmelt coupled with frozen ground and several heavy rain events. Given the increasing frequency and intensity of flooding, it is crucial to evaluate the resilience of flood control structures and enhance their capacity to withstand potential future challenges of a changing climate. This study reviews vulnerability of Canadian dams and levees to flooding in light of changing regional climatic patterns and associated hydrologic design criteria to identify areas where interventions are necessary to enhance climate-resilience of these assets.

Snowmelt- and rainfall-driven floods, as well as floods originating from the combined influence of both rapid snowmelt and rain can occur in various parts of Canada [8]. Rainfall-driven floods across southern Canada tend to be associated with long-duration storms with greater area coverage, although the underlying causes may differ. In eastern Canada, such floods may be linked to extratropical cyclones or hurricane remnants [9, 10]. In coastal mountainous regions on the west, long-duration rainfalls, associated with bands of concentrated water vapor, known as atmospheric rivers, can lead to intense storms with orographically enhanced precipitation [11, 12].

As global temperatures continue to rise due to climate change, earlier snowmelt is anticipated in many regions in North America including Canada [13]. This could result in an increase in rain-on-snow events and snowmelt-driven floods and massive ice movements in Canadian rivers [14, 15]. Apart from this, Canada experiences floods caused by geomorphological features in high-relief regions of western Canada, storm surges on the Atlantic, Pacific, and Arctic coasts, and major inland water bodies such as the Great Lakes [16]. Southern urban regions are also vulnerable to flash flooding caused by intense precipitation events, while floods resulting from rising groundwater levels can occur in alluvial floodplains adjacent to large streams and rivers. Climate change may alter various characteristics of floods due to changes in driving mechanisms [17, 18]. Extreme precipitation events are projected to increase in frequency and intensity, regardless of whether the emissions are high or low [19, 20]. This increase may be explained partially by the Clausius–Clapeyron relationship, which implies that a warmer atmosphere can hold more moisture at about 7% per degree of warming, resulting in intensification of the hydrologic cycle and heavier precipitation events [6, 21–24], which may lead to intense flooding in the future in certain regions of Canada.

The changes in the frequency and intensity of floods anticipated with climate change can pose a significant threat to dams and levees, challenging conventional design flood estimation methods. In the past century, over 200 dam failures have occurred globally, resulting in significant property damage and approximately 11,000 downstream fatalities [25]. These failures are attributed to various factors including extreme flooding, internal erosion of the dam structure or foundation, earthquake loadings, or operational failures resulting in loss of flow control [26]. This review paper primarily concentrates on dam failures associated with flooding, an area of particular concern given its potential impact on dam safety and resilience. It is important to note that comprehensive data on dam failures due to extreme floods in Canada are not centrally compiled. However, scattered examples exist of historical floods that have impacted dams and levees in Canada. One such example is the overtopping of the Abitibi, Bishop's Falls Dam in Newfoundland and Labrador in 1983 during a phenomenal flood [27], resulting in one of the most significant dam failures in the province's history. In July 1996, the Saguenay flood in Quebec resulted in multiple dam failures [28], highlighting the susceptibility of dams to extreme floods. The worst flooding in the region occurred along the Rivière des Ha! Ha! where overtopping and erosion

of an earth-fill dyke caused rapid drainage of the Lac Ha! Ha! reservoir, compounding the effects of flooding from a rainstorm [29]. The 1997 Red River flood, despite the implementation of upgraded flood control systems and protection measures, caused damages amounting to around \$500 million [30, 31]. Testalinden Lake, BC, witnessed a dam failure in 2010, leading to substantial amounts of debris and mudflow due to the failure of a privately-owned earthen dam on a man-made reservoir. Similarly, heavy spring rains and snowmelt caused a small concrete dam at the outlet of Chute Lake near Naramata to overtop in April 2012 in the Okanagan region of British Columbia [32]. The 2013 Alberta flood also caused overtopping of the Elbow and Bow Rivers, resulting in severe damages despite the temporary flood barriers [33]. These incidences highlight the need for enhancing the resilience of dams in a changing climate and adopting a resilience-based strategy to safely tackle the expected increasing amount of flood flows.

Aging dams in Canada also create an increasing risk, as approximately half of the country's dams are over 50 years old [34]. The period 1950–1980 marked the peak of dam construction in the country. As Canada's climate continues to change, the increased frequency of extreme weather and climate events is likely to result in more frequent dam and levee failures. Although many of these structures have been designed and well-maintained to withstand extreme events, some have deteriorated beyond repair and are vulnerable to failure even during moderate rainstorms and associated overland flows. This vulnerability is exacerbated by the increasing occurrences of massive deluges, often following severe droughts, a trend projected to intensify over time under climate change [35, 36]. The implications of these failures can be significant, ranging from property damage to loss of life, highlighting the need for robust risk assessment and mitigation strategies for Canada's aging dams.

In the face of climate change and associated challenges, it is crucial to design and operate critical flood control infrastructure such as dams and levees, with a focus on climate-resilience. However, the current body of literature lacks comprehensive and unambiguous guidance on climate-resilience-based frameworks, leading to confusion among engineers and policymakers. This paper aims to address this gap by reviewing design flood estimation procedures, the potential impact of climatic trends and regional vulnerabilities to climate change, and the barriers and opportunities for advancing a climate-resilience framework. The main objective is to provide valuable insights that can help develop national guidance for assessing the climate-resilience of dams and levees and serve as a resource for similar studies for other infrastructure systems. This review is based on peer-reviewed articles, national guidelines, technical reports, documents pertaining to catastrophic events, and authors applied knowledge of the domain. Where necessary, references to international literature and guidelines have been made to support specific observations and conclusions. The paper is structured as follows: An overview of climate change projections for Canada is briefly discussed in Sect. 2. In order to provide context for this review, Sect. 2 includes a discussion on Canadian dams, historical floods and the associated property damages in light of future regional precipitation changes. Section 3 discusses the hazard potential classification system commonly used for dams. An examination of current hydrological design practices for dams and levees is covered in Sect. 4, where the focus is on design flood estimation methodology for all dams, ranging from low-risk small dams to high-risk large dams. Section 5 delves into climate-resilience concepts for dams and levees and discusses the technical and operational measures required to achieve resilience. Finally, Sect. 6 presents a concise overview of findings, draws main conclusions, and suggests potential avenues for future research.

## 2 Canadian dams and climate change

### 2.1 Perspectives on climate change in Canada

Here, a general understanding of climate change and its regional consequences based on published literature is discussed, followed by a discussion of the potential vulnerability of Canadian dams to flooding under regional climate change and variability. The underlying modeling issues and the role of large-scale climate drivers are also briefly mentioned. It is now well accepted nationally and internationally that accounting for potential climate change risks is essential for designing and operating critical flood control structures in a sustainable manner. However, incorporating these risks into design and operations remains challenging due to the significant uncertainty associated with climate model projections, especially at the regional and local scales. Additionally, the climate system's inherent variability, including low-frequency climate variability modes, such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), North Atlantic Oscillation (NAO), and others, play a significant role in characterizing extreme precipitation and resulting floods, with their effects varying depending on the location. Incorporating the

influence of natural climate variability and its physical mechanisms, along with anthropogenic climate change effects and the associated uncertainties is important when determining design flood magnitudes for sizing flood control structures.

Recent flood-related catastrophes in Canada have been linked to anthropogenic effects, specifically the increasing occurrence of extreme rainfall events associated with human activities [37–39]. Climate change was hypothesized as the major driver of changes behind the occurrence of these events. Canada's land surface mean annual temperature has increased by an average of 1.7 °C since 1948 and human activities are estimated to have contributed to over half of this warming [20]. Along with rising temperatures, precipitation patterns are also expected to change, with increasing rainfall intensities and decreasing snow accumulation in many parts of Canada [20, 24, 40–42]. In a recent study, based on Climate Model Intercomparison Phase 6 (CMIP6) climate model simulations, Peirce et al. [43] estimated that there would be 20–30% increases in the 5- to 500-year return values of projected daily precipitation in Canada during winter, spring, and autumn, with the projected increases being most prominent during the winter season. These changes in precipitation patterns may lead to higher risks of flooding, particularly in urban areas [44]. Rain-on-snow events, which are important contributors to floods in Canada, are also projected to undergo significant changes [20, 45, 46]. Additionally, coastal floods have resulted in significant damages, with storm surges from hurricanes like Juan and Igor leading to nearly CAD 100 million in losses [47]. Rising sea levels pose a threat to both the east and west coasts of Canada, with up to 100 cm of sea level rise projected by the end of the century, varying by region due to coastal geographies [48, 49]. These flood hazards and changing patterns of flood drivers have significant implications for safe functioning and resilience of dams and levees in Canada, particularly when considering the ongoing effects of climate change and the emergence of new weather patterns.

Understanding the potential impacts of climate change on streamflow regimes is crucial for effective water resource management. In particular, changes in high flows are important for assessing the safety and continuous reliable functioning of dams and levees. While several studies have assessed changes in streamflow at the regional level and at the level of specific watersheds in Canada (e.g., [50–53]), a comprehensive national-scale evaluation is still lacking for Canada for high flow regimes. At the global scale, Hirabayashi et al. [54] has evaluated global exposure to flooding based on CMIP6 climate model projections. Bonsal et al. [55] have documented projected changes in Canadian streamflow for the mid-to-late twenty-first century, based on local-scale studies and different emission scenarios. Their findings and those of Poitra et al. [50], Huziy et al. [52] and St. Jacques et al. [56] suggest that not all river basins will respond in the same way to climate change in the future. For example, a geographic gradient in projected annual runoff changes for Alberta and Saskatchewan indicates a possible decrease in runoff in most of the southernmost rivers and a possible increase in runoff in the northernmost rivers [56]. Based on Bonsal et al. [55], under low and medium emission scenarios, the spring peak flow for southern rivers in the middle of twenty-first century is expected to occur earlier and be smaller, with a corresponding decrease in summer runoff. Annual streamflow is projected to increase in New Brunswick and Labrador, while large watersheds such as the Mackenzie and Yukon River basins may experience higher flows due to higher amounts of projected precipitation at high latitudes. These projections were developed based on modeling experiments, by considering various physical mechanisms, including changes in temperature and precipitation patterns, and changes in other relevant fields and processes.

## 2.2 Dams, catastrophic floods, and climate change

To identify vulnerable structures, it is crucial to consider the potential interactions of climatic, topographic, and hydrologic factors that can intensify flood risks to infrastructure assets. Additionally, analyzing the recent trend of destructive floods, assessing their types, and projecting future changes to design floods are equally essential. Table 1 presents a concise overview of significant flood events, destructive flood years, and total damages from 1900 to 2017 across different provinces [57]. This information can aid researchers and policymakers in understanding historical flood patterns and their impacts on different regions and help develop more effective flood mitigation strategies. However, it is important to note that the actual damages caused by floods may be underestimated, as they may not always be fully reported or captured in the available data. Thus, continuous research efforts are needed to better understand the complex relationships among various drivers of floods and to develop climate-resilience strategies.

As mentioned before, some recent studies have attributed the severity of floods of 2013 in southern Alberta, 2014 in the Prairies region, and 2021 in British Columbia to climate change [38, 58, 59]. The increasing trend of destructive floods across different parts of Canada and the projections of rising frequencies of higher return period floods in a changing climate, reported in regional level assessments [51, 52, 60] highlight the need for new regional and national initiatives to update design flood estimates including Probable Maximum Floods (PMFs). Such efforts should incorporate novel

**Table 1** A summary of Canadian floods and associated damages (1900–2017) [57]

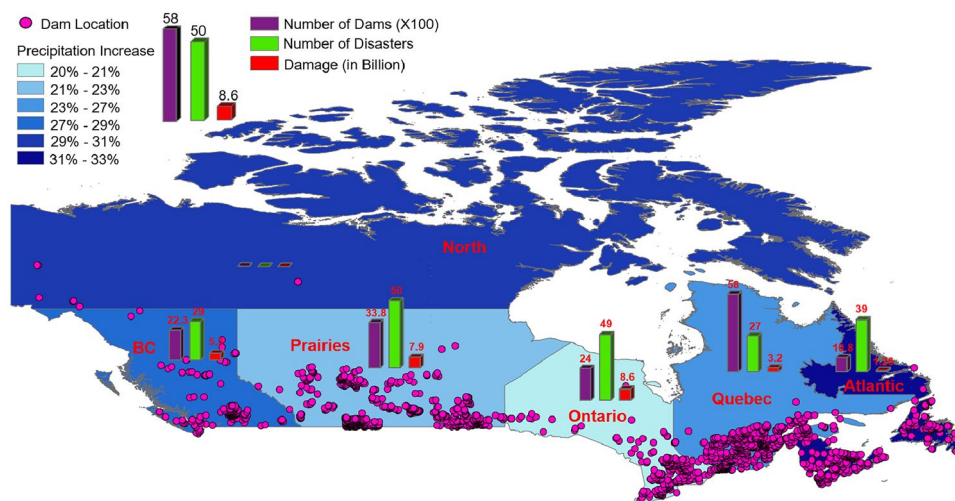
Province	Number of flood disasters	Years with the most destructive floods	Cumulative total damage in millions of Canadian dollars (adjusted to 2008 values)
Ontario	49	1916, 1920, 1937, 1948, 1954, 2004, 2005, 2013 and 2017	8577
Quebec	27	1972, 1974, 1987, 1996 and 2017	3218
New Brunswick	35	1902, 1909, 1923, 1934, 1936, 1961 and 1979	1146
Manitoba	15	1950, 1955, 1993, 1997, 1999, 2009 and 2011	<7025
Saskatchewan	4	1955, 2007 and 2010	<362
Alberta	33	1929, 1995, 2004, 2005, 2010 and 2013	588
British Columbia <sup>a</sup>	29	1894, 1920, 1948, 1972, 2011 and 2012	5303
Newfoundland and Labrador	4	1983, 1929, 2005 and 2010	115

<sup>a</sup>The most recent disastrous flood of 2021 is not included within the time window of data for this table

techniques that integrate climate change features and insights from emerging local and regional weather patterns. This will help to better understand the changing flood risks across Canada and to develop effective flood mitigation strategies for both the built infrastructure and the natural environment.

To assess the potential impacts of climate change on existing dams and levees in Canada, it is essential to consider their performance against the severity of historical floods. However, no single platform exists that maintains a complete database of all provincial dams and records of historical floods that led to dam failures. According to the Government of Newfoundland and Labrador documents [27], about 80% of total dams in Canada are located in four provinces, namely Quebec, Ontario, British Columbia, and Alberta. Quebec alone contains almost 40% of the total dams in Canada, including 651 of the total 1,157 large dams in the country, followed by Ontario and British Columbia with 118 and 95 large dams, respectively [34]. The information provided in Table 1 about historical floods and the projected changes in extreme precipitation for the RCP8.5 future scenario from Bush and Lemmen [20] are amalgamated in Fig. 1 to provide a visual representation of regional exposures to future climate change and the potential assets that could be at risk.

Although Fig. 1 provides some information about regional exposures to climate change at a larger spatial scale considering 50-year return value of 24-hour annual maximum precipitation, assessment of such exposures at the scale of individual assets considering changes to flood generating mechanisms would be more useful from climate change adaptation and flood resilience perspectives. Therefore, systematic frameworks and guidelines are required to be developed



**Fig. 1** Medium and large Canadian dams [61] and the projected changes to the 50-year return value of 24-h annual maximum precipitation based on the Climate Model Intercomparison Phase 5 (CMIP5) multi-model ensemble median for the 2081–2100 period, with respect to the 1980–2010 period, under the RCP8.5 emission scenario, sourced from Bush and Lemmen [20]. The violet, green, and red vertical bars represent the number of dams, number of flood disasters, and total damages [57], respectively, for six different large regions/provinces: British Columbia (BC), Prairies, Ontario, Quebec, Atlantic Canada, and Northern areas (North)

for assessing the impact of climate change and infrastructure vulnerability, providing guidance on integrating climate change information into design and planning methodologies. To inform design practices, the following sections review current hydrological practices and identify areas where interventions can be made to align design flood estimation procedures with climate change guidance.

### 3 Dams and hazard potential classification

In the context of dams, the Hazard Potential Classification (HPC) is widely used to categorize dams based on the population size, environmental and financial assets that could be at risk of potential dam failure due to catastrophic floods. The HPC is associated with specific thresholds for hazard and inflow design floods, represented in terms of annual exceedance probabilities (AEPs) or PMF. Table 2 provides an overview of the HPC for dams in Canada, as outlined in the Canadian Dam Association (CDA) guidelines [62] and the United States Army Corps of Engineers manual of small dam design, 1974 [63].

Regardless of the size of dam, there are two primary approaches for determining the inflow design flood or simply the design flood. The first approach is based on the target return period and that involves estimating the design flood through statistical flood frequency analysis. The second approach is based on the concept of PMF, driven by seasonal/annual Probable Maximum Precipitation (PMP), which is theoretically the maximum possible precipitation that can occur in a given watershed under physically plausible regional climate and weather patterns. Under Canadian conditions, the PMF could be categorized as spring PMF, which is driven by contributions from both snow and rain, or summer/fall PMF, which is driven mainly by rain. These approaches and the various processes and requirements involved, guided through an extensive literature review, are discussed below. The focus is on the identification of areas where interventions are possible to improve climate-resilience in the face of a changing climate.

## 4 Perspectives on design flood estimation procedures and practices

### 4.1 Flood frequency analysis

In hydrology, flood frequency analysis (FFA) is commonly used for estimating targeted design floods, corresponding to specified frequencies of occurrence, defined in terms of return periods or AEPs. This is achieved by fitting appropriate probability distribution functions to samples of high flows, which are extracted from long-term observational or simulated records based on either the annual maximum (AM) approach or the partial duration series approach. In the literature on FFA, the latter approach is also known as peaks-over-threshold (POT) approach. The probability distributions often used in FFA are estimated using several reasonable estimators, such as the method of moments (MOM), method of maximum likelihood (MML), method of L-moments (MLM), etc. In general, for a given design problem at a site of interest, it is assumed that the collected or simulated high flow values are a true representation of the associated watershed conditions and are drawn from the same probability distribution, which is the fundamental requirement for conducting FFA. It is also assumed that the high flow values are random and independent and constitute a homogeneous sample. Theoretically, the relationship between the return period  $T$ , AEP, and cumulative distribution function  $F_Q(q)$  of high flows is represented as  $AEP = 1/T = 1 - F_Q(q)$ . The inversion of this relationship for the given value of  $T$  results in the desired value of the design flood. Additional detail on these concepts along with practical examples can be found in [64–67].

According to the HPC categories (Table 2), FFA is required to satisfy design requirements for dams that fall within the first four of the five HPC categories, except the last one. There are a number of features that are important to consider

**Table 2** Classification of dams based on physical characteristics and HPC categories

Dam classification	Storage ( $10^6$ m <sup>3</sup> )	Height (m)	HPC	Inflow design flood in terms of AEP or PMF
Small	< 1.23	8–12	Low	1/100
			Significant	Between 1/100 and 1/1,000
Medium	1.23–61.7	12–30	High	1/3 between 1/1,000 and PMF
			Very high	2/3 between 1/1,000 and PMF
Large	> 61.7	> 30	Extreme	PMF

for performing credible FFA at the site of interest. These features and many other relevant requirements along with the steps involved are described below.

- Sampling Approaches

For performing FFA, the first step is to extract high flow values from continuous streamflow observations using an appropriate sampling methodology. For this purpose, the AM series approach is commonly used. One obvious limitation of this approach is information loss due to considering only the maximum flow from each year of the available record i.e., the maximum flow of a given year may not be larger than the second or even the third largest flow observed in another year [68–71]. Additionally, it is also likely that the AM sample may contain several very low discharge values compared to the rest. An alternative is the POT sampling approach, which considers all flow values that exceed a specific, reasonably selected, high threshold [69, 71]. However, the POT approach also poses certain statistical challenges such as ensuring independence of the sampled high flow values and the selection of a sufficiently high threshold to satisfy theoretical assumptions that underpin FFA [65, 67, 72, 73]. In addition to AM and POT approaches, some studies propose incorporating all observations for frequency analysis or jointly modeling low, moderate, and extreme events [74, 75]. As long as the relevant theoretical assumptions are well understood and practical implications are taken care of, the choice of a sampling approach becomes less significant from a design flood estimation viewpoint. However, it has been noticed that the AM approach is commonly used when conducting non-stationary frequency analysis, a topic discussed later in the paper, and climate change impact analysis. This could be because of the simplicity involved in applying the AM approach and developing functional relationships between flood quantiles and various covariates influencing floods, such as frequency-based temperatures, rainfall amounts, and snow accumulations; and selected physiographic attributes of watersheds, reflective of land and vegetation characteristics, waterbodies, soil moisture states, runoff potential, geologic formations, etc.

- Importance of Data Length in FFA and Surrogates

The accuracy of FFA for estimating design floods, corresponding to longer return periods, relies heavily on the availability of sufficient observational records. To ensure a meaningful analysis, the United States Geological Survey recommended a minimum of ten years of record [76], while the Intergovernmental Panel on Climate Change (IPCC) suggested 30 years of record for reliably representing climate-related aspects [77] and conducting climate sensitive analyses. However, for estimating a 100-year design flood magnitude, which is mostly recommended for several engineering applications, even a 30-year record can be insufficient due to sampling uncertainties [78]. When instrumental records are unavailable or partially available, FFA can be conducted using flows simulated by hydrologic models, forced with observed climatic data, simulated analogues, or stochastic weather-generated outputs. Alternatively, statistical relationships relating flood quantiles to catchment characteristics, developed from locations where observational records are available, can also be used. When considering the data available for FFA for both historical and future projections in the context of climate change, it is important to explicitly account for sample size uncertainties in the derived design flood magnitudes. Without doing so, it is very likely that large errors will be introduced in the analysis of targeted design values, especially when derived from shorter samples.

- Selection of an Appropriate Probability Distribution for FFA

For modeling samples of peak flows, selecting an appropriate statistical distribution function is another crucial step in FFA. The challenging question is determining the best-fitting distribution for the target data sample [79]. Although empirical guidelines have been developed in many countries to aid this process, finding an optimal universal criterion remains challenging. For example, the log-Pearson Type III distribution is recommended for FFA in the United States in Bulletin 17C [76], while the generalized logistic distribution is recommended in the United Kingdom [80]. Cunnane [65] presented an account of statistical distributions frequently used for FFA in many countries of the world. Although the generalized extreme value (GEV) is theoretically the most appropriate distribution for modeling extreme values of a sequence of independent and identically distributed random variables, a study by Salinas et al. [81] in Europe showed that the GEV distribution, while often providing a suitable fit, may not accurately represent the full range of observed hydrological diversities. Ahilan et al. [82] analyzed data from 172 gauging stations in Ireland and determined that the Gumbel distribution was most appropriate for FFA, with superior performance compared to

other extreme value distributions considered such as the Frechet and Weibull. In a similar study for Canada, Zaghloul et al. [83] argue that the Burr III distribution is preferable over the GEV distribution as the latter distribution underestimates quantiles corresponding to longer return periods and does not characterize tail heaviness features well. Other distribution functions, such as the generalized Pareto, lognormal, and Weibull distributions, have also been used to model flood flows [70, 84, 85]. Almost the same is the case for modeling POT samples. From a theoretical perspective, the generalized Pareto distribution is the most appropriate choice for modeling such samples [72], but other distribution functions have also been used e.g., Bhunya et al. [86] used the generalized logistic distribution to model POT-based samples. In their study on FFA for Australia, Rahman et al. [87] evaluated the suitability of 15 different probability distributions using multiple goodness-of-fit tests and the L-moment ratio diagram. Their analysis revealed that no single distribution can be considered ideal for Australia. To identify the best fit distribution, model selection, and goodness-of-fit tests such as the Akaike information criterion [88], Bayesian information criterion [89], Anderson–Darling test [90], Chi-squared test [91], Kolmogorov–Smirnov test [91], and probability plot correlation coefficient [92] have been used in previous studies [87, 93]. Zhang et al. [94] investigated the selection of a probability distribution for at-site FFA for Canadian basins and found that the GEV distribution is a suitable choice for most sites. For the contiguous United States, Hu et al. [78] examined the sensitivity of FFA to various sample sizes, probability distribution choices, and parameter estimation methods. Their results showed that flood frequency estimates based on the AM approach converged to the reference values for records of 35 years or longer. Recently, Zhang et al. [95] proposed an entropy-based model selection criterion for identifying an optimal distribution. This method performed relatively better for small samples, and in situations when the skewness coefficient is greater than zero and the probability distribution function exhibits a bell-shaped behavior. It is important to note that the AM and POT based samples of flood flows do not conform to bell-shaped distributions, without implementing Box-Cox type transformations [96]. The best-fitting distribution selection approach depends strongly on the characteristics of the target sample of flood flows. However, this approach cannot be used to assess the performance of the selected distribution for flows that occur outside the range of the considered sample. Thus, the performance of the selected distribution in the extrapolated range of flood quantiles, often referred to as predictive performance, is considered vital when evaluating different candidate distribution functions. Therefore, a systematic procedure for assessing the performance of different distribution functions in terms of both their descriptive and predictive abilities can be used [97]. In conclusion, selecting an appropriate distribution function for modeling flood flows relies on careful analysis of fitting procedures, performance assessment, theoretical considerations, and insights from regional empirical experience. Most importantly, a formal systematic evaluation of the predictability and descriptability of a candidate distribution is an extremely useful analysis.

In addition to the choice of a distribution discussed above, selection of an appropriate parameter estimation procedure is another critical aspect to consider. In FFA studies, methods like MOM, MLM, and the MML have often been employed. Other approaches, such as the Bayesian inference methodology are also used for parameter estimation [98]. Bayesian inference methodology incorporates prior knowledge or beliefs about the parameters of the distribution in the analysis and provides estimates of uncertainty in parameter estimates through postulating posterior distributions. However, careful consideration is essential when choosing the prior distribution, as it can significantly influence the outcomes. Additionally, the prior distribution must be appropriate for the data and context.

The topic of appropriate distribution selection has attracted a significant body of literature and has been the subject of continuous research. Although some countries have recommended specific distributions for national applications, lack of unanimity still prevails. In general, flood quantiles corresponding to longer return periods have been found sensitive to the choice of distribution. This topic becomes even more important in the case of dams as the HPC categories cover a wide range of AEPs or return periods, starting from 100 to 1000 years. Many researchers are inclined towards using the GEV distribution as it has a solid theoretical foundation for modeling extreme values [72]. Being a three-parameter distribution, it is also quite flexible in describing a wide range of empirical distributions and the parameter estimation procedures are also well-developed, in addition to the availability of automated software packages. In addition, the scale-invariance property of the GEV distribution has also been found quite useful in the regional estimation of floods for ungauged sites [99]. In spite of these known benefits of the GEV distribution, it is advisable to consider at least three established distribution functions in a given situation for estimating flood quantiles for both historical and future periods to account for distribution related uncertainties.



- Non-stationarity in FFA

The conventional approach for estimating design floods for dams and levees assumes that the selected flood frequency distribution remains stationary over time. However, in the presence of non-stationarity in various land and climatic processes, it has been shown, through plausible hypotheses, that the flood frequency distribution as well as the magnitude of the target design flood vary with time, rendering the notion of a fixed return period design flood questionable. To address this issue, Rootzén and Katz [100], among several other researchers, introduced the design life level concept to calculate the risk of a given flood magnitude occurring over a specified time interval. Following the work of Coles [72], several investigators have used a non-stationary extreme value distribution for FFA by incorporating linear trends in distribution parameters as a function of time [101], while Griffis and Stedinger [102] and Towler et al. [103] employed climate variables as covariates for describing distribution parameters. Salas and Obeysekera [104] further demonstrated the relevance of this technique using flood frequency examples. Additionally, López and Francés [105] utilized the “generalized additive models for location, scale, and shape” (GAMLSS) parameters, revealing significant non-stationarities in the flood regime. Bayesian methods have also been utilized to estimate non-stationary flood frequencies [98, 106]. Among others, Wasko et al. [107] highlighted the need to incorporate climate change and variability into FFA and the use of climate change allowances for flood risk assessments. The indices of low frequency climate variability (e.g., ENSO, PDO, AMO, and NAO) have also been suggested for conducting non-stationary FFA [108–111]. In Canada, significant trends have been detected in time series of both AM and POT based high flows, providing insights into changing patterns of floods [112]. To address non-stationarity in FFA, Cunderlik and Burn [113] introduced a second-order non-stationary approach to pooled FFA. They employed local and regional trend analyses to evaluate changes in the time-dependent components in southern British Columbia, Canada. The results revealed that even a weakly significant non-stationarity in the data cannot be ignored, as it can severely bias the predicted quantiles for time horizons as near as 0–20 years in the future. Some other studies that have addressed the issue of non-stationarity in flood frequency analyses include Strupczewski et al. [114, 115], Khaliq et al. [116], Sushama et al. [117], Mudersbach and Jensen [118], Trambly et al. [119], Tan and Gan [120], Šraj et al. [121], Gado and Nguyen [122], Salas et al. [123], and Jalili Pirani and Najafi [124].

In spite of the persuasive appeal of non-stationary frequency analysis approach, no agreed-upon solutions and guidance exist for replacing the notion of fixed return period design flood that has been used for designing engineering structures for many years. Research is still continuing to find an alternative to return period-based design methodology. Although the concept of fixed return period design philosophy is in jeopardy, it can still be utilized to evaluate the changing risks based on non-stationary frequency analyses and provide flexible adaptation measures in the face of a changing climate as we move into the future with fully operational flood control structures. By adopting flexible adaptation measures, the level of redundancies can be reduced to a minimum. Thus, a flexible adaptation strategy seems reasonable and it can be integrated with the existing design philosophies when designing new structures.

- Regional Flood Frequency Analysis

The regional flood frequency analysis (RFFA) to estimate design flood magnitudes is generally favored for locations with limited or unavailable streamflow records. Common examples of RFFA are various variants of the index-flood method and regression-on-quantiles technique [60, 125–131]. More recently, the Bayesian frameworks, particularly hierarchical Bayesian methods, have gained popularity due to their ability to pool data from multiple sites, account for spatial heterogeneity, and quantify the uncertainty through their probabilistic structure [132–135]. The RFFA generally involves two primary steps: (1) identification/delineation of hydrologically homogeneous regions, and (2) application of regional estimation methods within each of the delineated homogeneous regions for estimating desired flood quantiles at ungauged locations, in addition to estimating at-site quantiles. A region could be classified as homogeneous from a statistical, hydrological, or climatological standpoint or based on a combination of some flood-relevant features of interest. Some studies interpret the regional estimation process as a way of transferring known information from gauged locations to ungauged sites of interest. In the Canadian provinces of Quebec and Ontario, Gingras et al. [136] identified nine homogeneous regions based on statistical characteristics of flood flows. In a similar manner, the Ontario Ministry of the Environment delineated homogeneous regions within the province of Ontario based on various characteristics of high flows [137–139]. For instance, to predict high flow characteristics at ungauged locations in Ontario, 12 different regions were delineated. Similarly, Loukas and Quick [140] and Eaton et al. [141] conducted RFFA for British Columbia, Canada. In their study for Australia, Haddad and Rahman [142] employed Bayesian generalized least squares regression

within a region-of-influence (ROI) framework to develop regional estimation equations, using data from 399 catchments, for computing flood quantiles at ungauged locations.

The issue of insufficient at-site data has prompted several studies to identify an optimal method for forming homogeneous regions in different parts of Canada, such as GREHYS [126, 127], Burn et al. [143], Ouarda et al. [144], Gado and Nguyen [99], among others. The success of identifying homogeneous regions depends on various factors, including local hydrological complexities and whether the selected attributes reflect primary flooding mechanisms. Burn [143] proposed a regionalization approach that uses information related to the timing of flood events. This approach was applied within the ROI framework, and it has the advantage of reserving the use of information derived from flood magnitudes for the examination of homogeneity of flood timing-based regions, as opposed to first using flood magnitudes to form regions.

The literature on RFFA grew significantly with the publication of Hosking and Wallis [145], who formalized the index-flood method of Dalrymple [146] for RFA based on L-moments. The literature on this topic is voluminous. An earlier study by Cunnane [65] and Dalrymple's original work on the index-flood method acted as catalysts for advancing RFFA. The underlying premise of RFFA is that it not only helps in the estimation of flood quantiles at ungauged locations but also facilitates the estimation of more reliable quantiles at all locations, especially where short observational records are available, compared to at-site analysis. Thus, where possible, RFFA should be preferred over at-site analysis.

- Multivariate FFA

Multivariate frequency analysis is a rapidly emerging technique that has attracted considerable research recently [147–152]. Univariate FFA has certain limitations as it only considers flood peaks and neglects other important aspects of a flood event such as volume and duration. A multivariate frequency analysis is favored to consider these characteristics/features together. This analysis requires multivariate distributions, which exploit the inter-dependence of various features of flood events [153, 154]. Multivariate distributions are not analytically tractable for practical applications. However, due to the introduction of copula-based multi-variate frameworks, this limitation is no longer applicable [155–157]. These frameworks are also useful in dealing with compound flooding, which results from the interaction of different flood-generating sources, such as river-borne floods and storm surges [16, 124, 158–161], as well as heavy precipitation combined with snowmelt or saturated soil conditions [162, 163], all of which contribute to the magnification of the hazardous situation. The definition of conventionally used single return period becomes inadequate in the case of compound flooding since it involves the joint probability of occurrence of two or more hazardous events. Instead, some reasonable scenarios can be defined based on interactions between the involved hazards. For instance, the 'AND scenario' involves the concurrent occurrence of extreme events, while the consideration of either hazard reaching extreme levels defines an alternative "OR scenario". Research is still ongoing and a unified understanding does not yet exist to aid design philosophies and methodologies. Although some progress has been made, integration of this development with existing design flood methodologies is still being debated. In summary, while univariate FFA has certain limitations, multivariate frequency analysis can provide additional insights for assessing the ability of complex systems to deal with not only the peak flow but also the associated volume of flood waters. Such insights are useful when assessing the resilience of dam-reservoir-spillway operations. Techniques for conducting non-stationary multivariate frequency analyses will also continue to evolve in the future.

#### 4.1.1 Challenges and opportunities in FFA

The changing nature of flood events over time due to various factors such as climate change, land use change, and natural variations is a critical challenge in practice when assessing flood hazards and deriving flood magnitudes for designing infrastructure systems. The presence of such effects can complicate extrapolation of design flood magnitudes derived from limited past data into the future, which is crucial for dams and levees. In data limited situations and for some applications (e.g., dam design and dam safety evaluations), hydrological and land surface models, driven by historical, projected or stochastically generated climate data, are employed to generate continuous streamflow sequences, which in turn are subjected to FFA to derive desired design flood magnitudes along with their uncertainties [58, 161]. However, in such studies, considerations must also be given to non-stationarity of the hydroclimate system [162, 163]. Especially, in the context of climate change, it is imperative to quantify and communicate the sources of uncertainties, including emission scenarios, model structure and parameterization, and internal climate variability, among others.

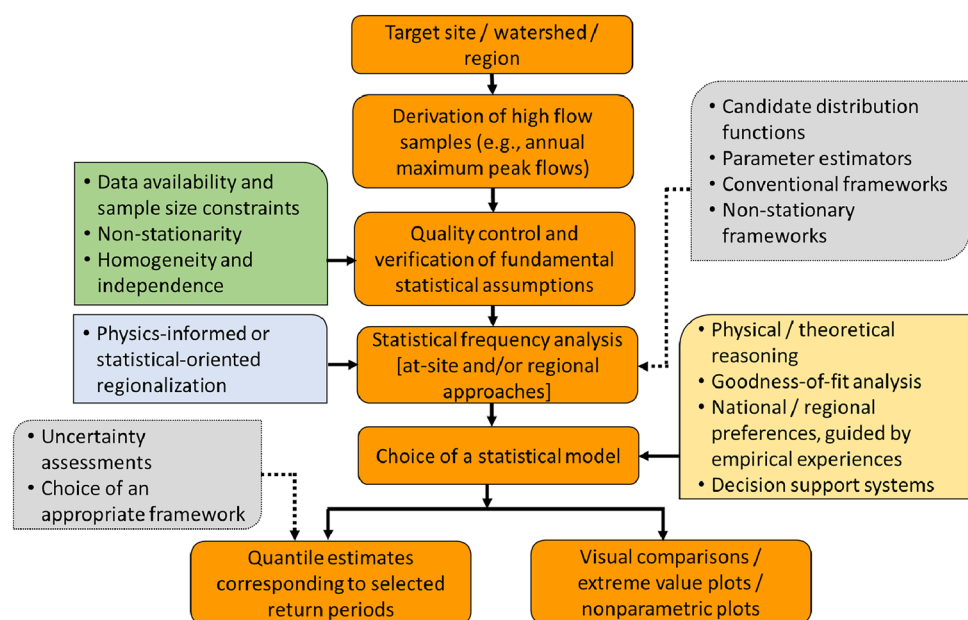
Another factor that can impact the results of conventional FFA is the assumption of independence among flood events included in the analysis. This may not hold true, particularly if floods are clustered over a shorter period when viewed at

longer time scales, which can give rise to the notion of flood-rich and flood-poor periods. Additionally, even if the floods are evenly distributed over the period of record, there could be serial dependence among the sample of flood events. These phenomena can result in a significant underestimation of the range of variability of extreme floods, leading to under-designed protection measures. The conventional FFA relies on the assumption of stationarity in the governing distributional form, which may not be valid for longer datasets. The choice of a probability distribution function and parameter estimation method can also impact the accuracy of FFA. For example, fitting a mildly skewed distribution to a skewed dataset can result in inaccurate estimates of extreme quantiles, which are often used for sizing flood control structures. Finally, proper quantification of uncertainty arising from all sources is a significant challenge in FFA. Uncertainty arises from several factors, such as incomplete data, measurement errors, instrument malfunctioning, modeling choices, and inefficient parameter estimation procedures, among others. For practical applications, it is important that FFA results should be accompanied by estimates of uncertainties in order to provide decision makers with a better understanding of the associated risks and underlying complexities. In conclusion, addressing the above discussed challenges and limitations of FFA is essential to inform design flood estimation methodology and flood risk assessment and management strategies. Certainly, further research is needed to develop more comprehensive methods for FFA that can account for these challenges and provide defensible estimates of design floods for designing flood protection and mitigation infrastructure. The procedural framework for FFA, compiled based on the literature reviewed above and empirical understanding of this area, is schematized in Fig. 2, along with interventions and improvements where possible.

## 4.2 PMP and PMF

Large dams are classified as "extreme hazard" structures due to their potential to cause catastrophic environmental and financial losses and human casualties in the event of failure. Therefore, it is essential to have an estimate of the maximum flow that the dam must be able to pass safely. This is generally accomplished based on the PMF concept. One critical component in estimating the PMF is the estimation of the PMP. According to the World Meteorological Organization (WMO) [164], the PMP is defined as the largest amount of precipitation that could accumulate within a given watershed over a specific duration at a particular time of the year. Design engineers use the PMF to establish the upper limit of what the dam must be able to withstand to ensure that the structure meets the necessary safety standards. The WMO has prescribed six methods to estimate PMP i.e., the local, transposition, combination, inferential, generalized, and statistical methods. The first five methods rely on physical meteorology, while the last one is based on statistical concepts. One of the earliest meteorological methods for PMP estimation is Paulhus and Gilman's method [165], which considers moisture maximization and transposition to define the physical state of the atmosphere. However, the upper boundaries of any meteorological factor used in storm maximization are difficult to ascertain as maximum precipitation often unexpectedly exceeds anticipated values. The estimation of PMP should be approached carefully in order to avoid underestimation

**Fig. 2** A schematic diagram showing the steps involved in univariate FFA, various aspects that should be taken into account, and indicators where interventions are possible to improve procedural frameworks by considering climate change integrations (shown with dotted lines and arrows)



and without jeopardizing the safety of communities residing near or downstream of extreme hazard structures while avoiding overestimation that may lead to unnecessary economic costs.

The meteorological approach assumes that the optimum combination of available moisture in the atmosphere and the efficiency of causative mechanisms will produce maximum precipitation. In contrast, the statistical approach relies on Hershfield's method, which provides a single value of the PMP. PMP values are typically presented in a deterministic sense, but uncertainties in the estimation process can arise from various factors, such as the amount and quality of available data, choice of the frequency distribution, and the method of analysis. Therefore, the estimation of PMP should be accompanied by a thorough analysis of the uncertainty and its quantification [166–168].

- Factors Influencing Estimation of PMP

As mentioned above, one commonly used approach for estimating PMP is the moisture maximization method, which aims to capture the physical mechanisms of extreme storms while keeping computational costs and data requirements manageable [169]. This approach involves the following equation:

$$PMP = P_{obs} \times \frac{W_{max}}{W_{storm}} \quad (1)$$

where  $P_{obs}$  is the maximum observed precipitation (mm),  $W_{max}$  (mm) is the maximum precipitable water (mm) at the same location and time of the year as  $P_{obs}$ , and  $W_{storm}$  (mm) is the actual precipitable water of the observed storm [170]. In most regions, the precipitable water is estimated from the local surface dew point temperature using the relationship defined in WMO [170]. The ratio of  $P_{obs}$  to  $W_{storm}$  is commonly known as "storm efficiency" and represents the storm's ability to convert precipitable water to precipitation [171, 172]. Therefore, the PMP is influenced by two main factors: the maximum precipitable water, which reflects the maximum moisture availability, and the storm efficiency.

Numerous studies have investigated the factors that influence extreme precipitation events in the United States. Some studies have emphasized the significance of vertical velocity [169], while others have highlighted the role of precipitable water [173, 174]. For instance, Kunkel et al. [173] found that precipitable water is the primary factor that influences extreme precipitation events in the United States, whereas Hagos et al. [174] revealed that the relationship between precipitation and precipitable water is nonlinear and is influenced by the vertical structure of moisture convergence. Some studies have also employed observations and atmospheric models to investigate extreme precipitation events. For example, Lepore et al. [175] and Loriaux et al. [176] used reanalysis data to explore the relationship between atmospheric conditions and extreme precipitation. Lenderink and Attema [177] proposed a model-informed approach to scaling precipitation extremes at the local level under future climate conditions. Furthermore, Yang and Smith [178] used an atmospheric model to simulate an extreme precipitation event in Arizona and found that different factors affected different aspects of the event. Integrating atmospheric models with traditional methods could enhance the accuracy of PMP estimates. However, uncertainties in climate models also persist, and therefore further research is necessary to reduce these uncertainties [179–182].

Recent extreme weather events in North America, such as Superstorm Sandy and Hurricane Harvey, have surpassed historical estimates of PMP, underscoring the importance of investigating the potential impact of climate change on PMP estimates [183]. Mahoney et al. [184] examined the effects of climate change on PMP estimates for dam safety in Colorado and New Mexico and found that rising atmospheric temperatures can increase the availability of water vapor to storms. The study concluded that changes in moisture content had a greater impact than changes in wind fields. Kunkel et al. [171] projected a 20–30% increase in maximum water vapor concentration, a critical input to PMP estimation, due to higher atmospheric moisture content and transport into storms. Su and Smith [185] used the non-stationary GEV distribution to analyze trends in extreme atmospheric water balance and their impact on PMP estimation. Visser et al. [186] investigated the response of conventional PMP estimation methods to potential increases in atmospheric moisture. Their study found that elevated dew point temperatures led to increased PMP estimates, with the degree of impact being dependent on whether local or transposed regional data informed the moisture maximization stage. Lee and Singh [168] quantified three main sources of uncertainty for PMP estimation in a Texas river basin i.e., the PMP estimation method, topography, and non-stationarity. Their results indicated that the uncertainty of PMP estimation was more sensitive to the choice of the method and existing observation statistics than to the differences between climate zones.

- Storm Transposition and Alternative Methods for PMP Estimation

Estimation of PMP using storm transposition is a popular method in the absence of detailed information on watershed-specific storm systems and associated atmospheric fields, with stochastic and deterministic transposition being the two recognized methods [187–190]. However, defining a transposition domain and developing an extreme storm catalog is challenging, as the method relies on storms that have occurred near the watershed of interest or in areas with similar climatology and topography [188]. To address such issues, previous studies have proposed alternative methods. For example, Ishida et al. [191] used a boundary condition shifting approach to realign several historical extreme storms from California to pass over selected watersheds, while Ødemark et al. [192] transformed extreme weather events into physically and dynamically consistent simulations by modifying lateral boundary conditions in numerical models. Toride et al. [193] utilized integrated water vapor transport to adjust the water vapor solely at the modeling boundary intersecting the trajectory of atmospheric rivers, thereby enhancing the realism of atmospheric fields and intensifying precipitation events. However, incorporating weather models to estimate PMP poses a formidable challenge for practitioners, introducing an additional layer of complexity and associated uncertainty. The statistical approach is another commonly used method for estimating PMP, particularly in regions lacking meteorological data. It was first proposed by Hershfield [194–196] and has since been widely adopted globally by the WMO [164, 170]. Hershfield's method is based on AM precipitation data collected from 2,645 stations worldwide, with approximately 95,000 station-years of data, primarily from the United States (US). However, the reliability of statistical methods depends on the availability of long-term and accurate precipitation data, which can be challenging in regions with limited precipitation recording stations. Additionally, these methods assume stationarity and independence of AM precipitation events, which may not hold true in a changing climate and can lead to potential under- or overestimation of PMP. This method utilizes the following relationship:

$$PMP = \bar{X}_n + K_m S_n \quad (2)$$

where  $\bar{X}_n$  represents the mean AM precipitation for the duration ( $n$ ) of interest,  $S_n$  is the corresponding standard deviation, and  $K_m$  denotes the frequency factor. For a given data sample,  $K_m$  is considered to be a function of precipitation duration and the mean value [164]. Hershfield's method for estimating PMP has undergone several modifications to suit different climatic regions. For example, Casas-Castillo et al. [197] used a large storm rainfall database for the Iberian Peninsula to determine PMP for sub-daily durations, while Lan et al. [198] proposed a standardized factor,  $\Phi$ , instead of  $K_m$  for PMP estimation in Hong Kong. Despite being an old method, Hershfield's approach, with or without modifications, is still widely used in many countries, particularly those lacking meteorological data on storm systems and related atmospheric fields. It must be noted that relying on a single PMP value and the resulting PMF for designing flood control structures poses various challenges due to the level of uncertainties involved in estimating PMP using statistical methods [166, 167, 182, 199]. Therefore, careful decision-making aided with empirical experiences will be useful in such situations.

- Estimation of PMP and Extreme Rainfall in Canada

Environment and Climate Change Canada provides precipitation intensity–duration–frequency curves for 549 locations across the country, offering information on extreme rainfall frequencies nationwide for 5-, 10-, 15-, 30-min, 1-, 2-, 6-, 12-, and 24-h durations ([https://climate.weather.gc.ca/prods\\_servs/engineering\\_e.html](https://climate.weather.gc.ca/prods_servs/engineering_e.html)). These curves include selected confidence limits for rainfall estimates for different return periods and durations and use the same method as was used for the earlier Rainfall Frequency Atlas of Canada, merely relying on the mean and standard deviation of the AM rainfall series [200]. The mean and standard deviation of the AM rainfall series are estimated using conventional moments. Hogg and Carr [201] provided isoline maps of the mean and standard deviation, which users can interpolate logarithmically to obtain values for their location of interest. An adjustment was made for precipitation estimates for mountainous areas, with different factors for onshore coastal and non-coastal mountains. Precipitation extremes for the cold season were dealt with separately. The values of mean and standard deviation discussed above can be used to estimate site-specific PMP, following Hershfield's method (Eq. 2). While Canada does not have national-level guidelines for estimating PMP and associated PMF, various universities, provinces, municipalities, and agencies have calculated PMP and PMF for different purposes. Previous studies on PMP and PMF estimation from different parts of Canada are discussed below. In these studies, climate change considerations were also addressed.

Rousseau et al. [202] investigated the effects of climate change on PMP and PMF in three watersheds with varying climatic conditions in Quebec, Canada. The study showed that the PMF in southern Quebec watersheds is likely to remain

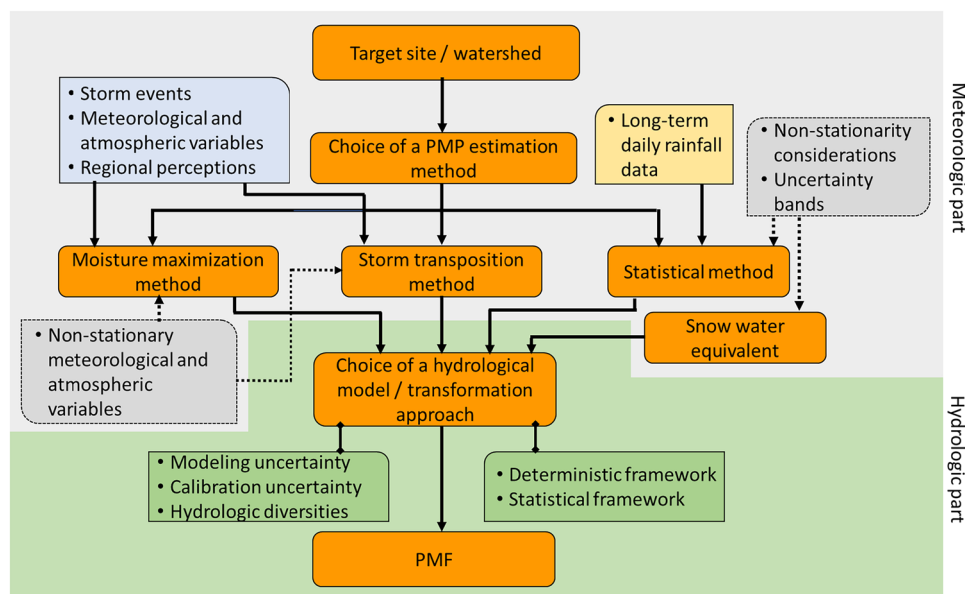
unchanged in the future. Meanwhile, the northeastern and northern regions of the province will experience an increase of up to 11% in PMF. Clavet-Gaumont et al. [203] proposed a framework for estimating PMF for five geographically dispersed Canadian basins (i.e., Nelson, Mattagami, Kénogami, Saguenay, and Manic-5) by integrating spring PMP and 100-year snowpack with operational hydrological models. The study showed an increase in spring PMF in four of these basins, except the northernmost basin, Nelson. In a separate study, Alaya et al. [204] compared PMP estimates from two versions of the Canadian Regional Climate Model (CanRCM) with those from reanalysis products and a hybrid dataset. The study revealed that both versions (CanRCM4 and CanRCM5) captured PMP components well, but CanRCM4 led to overestimation while CanRCM5 resulted in slight underestimation. In another related study, Alaya et al. [205] evaluated the uncertainty and impact of operational PMP estimates over North America using bivariate extreme value analysis. The study revealed a significant level of uncertainty in these estimates, with a weak dependence between extremes of precipitation efficiency and precipitable water. The information on the role of these components on the estimation of PMF is already discussed in the beginning of Sect. 4.2. Alaya et al. [206] further investigated the impact of climate non-stationarity and uncertainty on PMP estimates and found that PMP increases at an average rate of about 4% per 1°C warming in North America, which is lower than the nominal Clausius-Clapeyron rate of approximately 7%. Notably, regional deviations were observed due to the sensitivity of extreme values of precipitation efficiency to near-surface warming and those of precipitable water being the primary driver of PMP increase. These studies highlight the importance of incorporating climate change-related aspects in existing PMP and PMF guidance for Canada. Furthermore, these studies provide valuable insights into the impact of climate change on PMP and PMF, highlighting the need for improved estimation methods and consideration of regional variability for future dam design and management.

Figure 3 provides an overview of the estimation methods, which have been compiled based on the literature reviewed above and various data inputs considered. Additionally, it highlights the various stages where interventions and improvements can be implemented. Seasonal PMP and contributions from snowpack are important to consider for cold regions where floods can be generated by multiple driving mechanisms. The estimation of PMF involves knowledge and tools from both meteorological and hydrological fields. Therefore, an attempt has been made to demonstrate both parts separately while keeping the continuity of the procedural framework.

### 4.3 Guidelines and bulletins on design flood estimation and dam safety

Dam safety guidelines, such as those developed by the CDA and provinces, have limited coverage of the design, construction, operation, maintenance, removal, and decommissioning of low-risk small dams and levees. To address this gap, the “Small Dam Design and Construction Manual” was published jointly by Agriculture Canada, Prairie Farm Rehabilitation Administration, and Prairie Resources Service in 1992 [207]. This manual categorizes small dams based on their maximum height and storage capacity and their hazard potential rating as noted in the CDA’s HPC (Table 2), with maximum values

**Fig. 3** A schematic diagram showing the steps involved and commonly used PMP estimation methods leading to the PMF and indicators where interventions are possible to improve estimates by considering climate change integrations (shown with dotted lines and arrows-gray boxes). Main components are shown using orange background; various inputs are shown using light blue background; different possibilities are shown using dark green color



of 8 m and 400,000 cubic meters, respectively. The manual's approach to estimating flood peaks is similar to the index-flood method and relies on observed flood peaks, rainfall data, specific assumptions regarding antecedent soil moisture conditions, and significant engineering judgment. However, this approach is only applicable to small watersheds with an area of 50 km<sup>2</sup> or less that have not been significantly altered by construction. There are currently no national or provincial open-source guidelines in Canada that systematically address procedures for estimating design floods corresponding to AEP of 1/100 and upwards, as well as the PMF. Therefore, it was challenging to determine how different provinces incorporate climate change considerations into their design flood estimation techniques for flood control structures. In conclusion, there is a need for more comprehensive and up-to-date information to be synthesized for low-risk small dams and levees in order to support design, construction, operation, maintenance, removal, and decommissioning related activities. Furthermore, the development of time-evolving guidelines that address the estimation of design floods for dams and levees is crucial for future flood risk management and enhancing flood-resilience of existing structures.

The International Commission on Large Dams (ICOLD) has developed guidelines and bulletins for design flood estimation and dam safety [208]. These documents highlight the complexity of determining design floods and the importance of inputs from various specialists. They also caution against relying on a single method to interpret various phenomena and factors that affect design flood estimates. According to these guidelines, hydrologic considerations for dams are based on two design conditions: the maximum inflow flood that the dam can accommodate safely, and the optimum degree of flood mitigation that can be attained through controlled operations.

ICOLD Bulletin 170, published in 2018, provides several technical perspectives on hydrology and dam design and builds on previous bulletins [209]. Bulletin 169 focuses on the effects of climate change on dams, reservoirs, and water resource management structures. It recommends the use of an ensemble of regional climate models to estimate PMP leading to PMF [210]. For existing dams, the bulletin provides an adaptive plan for analyzing projected climate impacts in a step-wise manner, with what-if scenarios providing further structural enhancements like spillway expansion and additional tunnel construction. ICOLD Bulletins 140 and 147 offer guidance on sedimentation and its management, addressing the challenge of designing and operating reservoirs in areas with high sediment loads. Sedimentation management strategies include reservoir flushing, sediment bypass, and the construction of settling basins. Design flood estimation guidelines available from nine different countries are summarized in Table 3 based on some of the previous review articles [182, 211, 212]. For additional details, interested readers are referred to these articles and other references that are cited in this review. References cited in the table are included in the list of references and various abbreviations have already been explained in the text. In this table, Canadian guidance can be compared with those of other countries to identify areas that require additional attention and improvement.

## 5 Perspectives on climate-resilience of dams and levees

Aging dams are confronted with new climatic patterns, such as temperature shifts, changes in snowfall, and excessive flooding due to intense rainstorms, which can lead to an increased likelihood of failures [225, 226]. Infrastructure designed with the consideration of climate change impacts can offer increased service delivery and reliability, longer productive lifespan, and prolonged investment returns. Building and operating climate-resilient infrastructure require anticipating, preparing for, and adapting to changing climatic conditions [227, 228]. Additionally, the infrastructure asset should be capable of tolerating, reacting to, and recovering from the effects of severe weather conditions. Climate-resilience is a continuous process that must extend throughout the asset's lifespan. Although climate-resilient infrastructure is expected to mitigate the risks of disruptions resulting from climate change-related shocks, there is still a possibility that such a strategy may not entirely eliminate the danger. In other words, residual risk may remain even with climate-resilient infrastructure [229]. The impact of climate change on infrastructure is determined by the interplay of climate hazards, asset location (exposure), and the potential for adverse consequences (vulnerability) of the asset [230]. According to the United Nations Office of Disaster Risk Reduction (UNDRR), there is a compelling economic argument for enhancing infrastructure's climate-resilience, with a benefit–cost ratio of around 6 to 1 [231]. This high beneficial ratio means that investing in climate-resilience can save six dollars for every dollar invested, creating jobs and cost savings.

The concept of resilience was first introduced in ecology, where it referred to the ability of ecological systems to withstand disruption and maintain their functional integrity [232]. Resilience has been applied in diverse fields, but its interpretations vary across contexts [233]. This paper outlines a climate-resilience framework for dams and levees guided by another framework that was initially proposed for urban areas by de Graaf et al. [234]. The essence of resilience is encapsulated in a comprehensive framework comprising four interrelated pillars i.e., (1) threshold capacity, (2) coping

**Table 3** Design flood practices for different countries

Country	Small dams (Low HPC structure)		Medium-to-large dams (High HPC structure)		Regulatory authority/volunteer association
	Distribution type/Event definition	Return period/duration	Method	Guidelines/reference	
Canada	Gumbel/AM	2–100 years/5 min–24 h	PMP based	Hogg and Carr [201]/CDA [62]	Provincial regulatory authority, CDA (V)
United States	Log-Pearson Type III/AM	1–1000 years/5 min–60 days	PMP based	Bulletin 17C/England et al. [76]	Federal Emergency Management Authority/US Army Corp of Engineers
United Kingdom	GEV and generalized logistic distributions/AM	1–1000 years/1 h–8 days	PMP based	Flood Estimation Handbook/Robson and Reed [80]	The Environment Agency
France	GEV for long series ( $\geq 25$ years)/AM; GP fitted to short series ( $\geq 10$ –25 years)/POT	Less than 100-years/6 min–10 days	Frequency-based (up to 10,000 years)	Météo-France [215]	The Ministry of Ecology, Sustainable Development and Energy
Germany	Gumbel with AM, and exponential with POT	0.5–100 years/5 min–72 h	Frequency-based	KOSTRA/Bartels et al. [219]	States Regulatory Authority/German Water Resources Association
Sweden	Gumbel and GEV; AM	Up to a few hundred years/daily	Frequency-based (up to 10,000 years)	Lennart Wern, SMHI	Svenska Kraftnät
Australia	GEV/AM	50–2000 years/6–120 h	PMP based-generalized method (up to 10,000,000 years)	Focused rainfall growth extension (FORGEX)/Weinmann et al. [221]	Federal States Regulatory Authority
New Zealand	GEV/AM	2–150 years/10 min–72 h	–	HIRDS/Thompson (1992)	–
South Africa	GEV/AM	2–200 years/5 min–7 days	PMP based-storm maximization and transposition	Smithers and Schulze [223]	Dam Safety Office/Minister of Water and Sanitation



capacity, (3) recovery capacity, and (4) adaptive capacity (Fig. 4). To foster a robust and durable water infrastructure, it is imperative to proactively anticipate and mitigate the adverse effects of climate fluctuations, strategically minimize the impacts of extreme weather events, efficiently restore normalcy in the aftermath of disasters, and proactively adapt to the evolving and potentially disruptive trends in the environment [234, 235]. By strengthening each of these pillars, infrastructure management authorities can maximize their capacity to withstand and navigate through challenges and emerge stronger and more resilient (see Fig. 4).

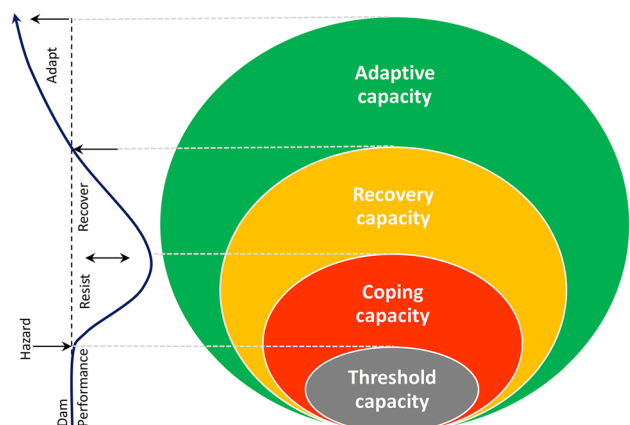
It is noteworthy that the concept of “transformative capacity” has recently emerged as a novel fifth component in the context of environmental management [235]. This refers to the capability of directing socio-ecological systems toward a trajectory that aligns with sustainable ecosystem stewardship [236]. While this aspect seems more suitable for complex and expansive systems such as urban areas, its relevance to water-related infrastructure may be indirect or limited. Therefore, the current discourse only examines in detail and critically evaluates the widely recognized and pivotal four pillars that constitute the climate-resilience framework as applied to dams and levees in the Canadian context. The objective of this section is not to quantify resilience. However, for a more detailed discussion of resilience quantification, interested readers can refer to existing literature (e.g., [237–239]) for more detailed information on how resilience can be quantified. For instance, Simonovic and Arunkumar (2016) proposed a framework that utilizes system dynamics simulation to assess the dynamic resilience of various components within a reservoir system, including the system as a whole. This approach integrates the concept of adaptive capacity, which is represented by four aggregated indicators: robustness, redundancy, resourcefulness, and rapidity. These indicators can be defined and visualized through a resilience curve, similar to the diagram on the left side of Fig. 4.

## 5.1 Threshold capacity

Dams and levees are primarily constructed to withstand hydroclimatic hazards, particularly floods, and their ability to prevent damage is commonly referred to as their threshold capacity [240]. In recent years, the US Bureau of Reclamation has focused on dam rehabilitation projects, rather than building new dams, to secure more water resources [241]. Similarly, in Australia, the majority of dam construction work involves upgrading existing infrastructure, rather than building new dams [242].

Enhancing the threshold capacity of existing dams and levees can be challenging and sometimes unfeasible and risky. However, multiple measures and strategies have been proposed to enhance their threshold capacity in response to the impacts of climate change. Recent studies on dam modifications by the US Army Corps of Engineers (USACE) have explored various options for mitigating future risks, including those related to climate change. These options include both structural measures such as additional reservoir storage, levees, tunnels, channel improvements, and spillways, and non-structural approaches like community buyouts, optimized timing of releases, flood warning systems, public outreach, and evacuation planning [243–246]. Ensuring the safety of dam infrastructure requires careful evaluation of existing standards and construction of new protection structures at identified vulnerable areas or the reinforcement of existing ones [247]. When choosing a dam and spillway upgrade, stakeholders, such as dam owners, designers, and contractors, must assess potential risks to dam safety that could be encountered during construction works [242]. After the upgrade of a dam, such as through wall-raising and spillway modification, environmental impact assessments are

**Fig. 4** Capacities required to enhance the climate-resilience of dams and levees. The figure emphasizes the importance of four interrelated pillars in fostering resilience: (1) threshold capacity, (2) coping capacity, (3) recovery capacity, and (4) adaptive capacity



legally required. These assessments may also include measures such as fishways and remediation of any negative impacts on water temperature regimes [248].

Climate change can impact the functionality of spillways in various ways, such as by altering temperature and precipitation patterns. Temperature changes can cause structural deformation of spillway gates and affect other concrete dam components, while extreme precipitation events can increase sediment concentration and abrasion processes, potentially leading to malfunctioning or failure of spillway gates. This may result in downstream flooding, which can range from small to catastrophic, as demonstrated in several cases globally. To ensure the safe and effective functioning of spillways in the face of climate change, it is crucial to revise and update the design parameters used for their construction. Climate change can also affect dam operations. In the presence of more frequent extreme events, dams' sluices will be operated more often than usually, putting additional operational demands on the infrastructure. Hydrological aspects are dealt with in the previous section of this paper, while construction related aspects are not in the scope of this paper. Several studies have suggested that climate change considerations should be integrated into the design, construction, and maintenance of spillways and other dam components and operations to ensure their long-term resilience [249, 250].

Several strategies have been proposed to address spillway performance in response to climate change. For example, in the case of a new dam or reservoir project, the spillway design can be developed by taking climate change into account and considering the maximum possible flood flow [250], along with the associated uncertainty. Even if construction has already commenced or the design phase has been completed, it may be necessary to revise the spillway design with climate change considerations. In this regard, options to enhance the spillway's physical performance include optimizing the spillway, installing an auxiliary spillway [251], constructing a bypass-diversion dam to decrease reservoir inflow [250], or installing fuse plugs to release water gradually and in a controlled manner [252]. It is likely that some of these options may not be feasible for certain sites.

According to Pandya et al. [253], internal erosion is responsible for 27% of large dam failures worldwide, making it the second leading cause of such failures. Rising temperatures and varying weather conditions, whether dry or wet, can cause additional mechanical stresses to concrete dams. Water level fluctuations and drier soils can further contribute to internal erosion and embankment problems [249]. Reinforcement measures are necessary to increase the stability and resistance of levees and dams against breaching. These may involve strengthening the inner cores, improving surface characteristics, and enhancing overall stability. To reinforce, these structures can be raised, widened, or modified by adding spatial elements where applicable [247].

## 5.2 Coping capacity

Including climate-resilience in overall design concepts involves the ability of infrastructure designers to address the impact of climate and extreme weather events and minimize the expected damages. A dam's coping capacity refers to its ability to reduce damage in the event of a disturbance that exceeds the resistance threshold. This capacity is determined by several factors such as structural integrity [254, 255], emergency preparedness [256, 257], and reservoir management [258–260]. The overall coping capacity of a dam is a result of the collective effectiveness of all the factors working together. A comprehensive approach that addresses each aspect of coping capacity is necessary to ensure the long-term resilience and functionality of dams.

Reservoir management, however, can be considered more important due to its impact on water supply, flood control, drought management, hydropower generation, ecological consideration, and sedimentation control. Boulange et al. [261] have found that, on a global scale, ignoring the flow regulation provided by dams would result in exposing an average of 9.1 and 15.3 million individuals to riverine flooding annually under RCP 2.6 and 6.0 scenarios, respectively. To mitigate the risks associated with climate change, new and innovative water release operations must be identified, researched and tested to maintain historical levels of flood protection [262, 263]. Efficient routing is necessary to reduce the loads on dams caused by incoming floods. In this regard, the outlet works and gate operation rules play a critical role, and their applicability must be assessed concerning potential climate change impacts [249].

The constraints and goals for dam operations are region- and site-specific and are strongly influenced by purposes such as flood mitigation, production of hydropower, or water supply [264]. Dam reoperation solutions involve climate-informed operations [265], re-optimization of rule curves [266–268], integration of ecosystem-based approaches [269, 270], continual risk and vulnerability assessments [271, 272], and stakeholder engagements [269, 273]. Adjusting dam operations to increase resiliency can have benefits such as the reconnection of floodplains, creating new markets for ecosystem services like groundwater banks and carbon sequestration, which have the potential to increase land value and make dam reoperation more feasible both economically and politically, benefiting both landowners and the environment

[264, 274–277]. As climate change can affect entire river basins, incorporating the concept of coping capacity within the framework of integrated water resources management enables us to comprehensively address the interconnectivity of water systems, encompassing both upstream and downstream dependencies and thus effectively coordinate dam operations.

### 5.3 Recovery capacity

Achieving climate-resilience of dams and levees depends heavily on the ability of the structure to recover from the impact of hydroclimatic hazards. This requires the capacity to return to a state that is similar, identical, or superior to the pre-impact state, commonly referred to as "building back better" [235]. The goal of enhancing recovery capacity is to promptly and efficiently address the aftermath of a disturbance caused by an extreme climate event [278]. While the initial focus is immediate, after the disaster, attention gradually shifts to the future. The recovery process can vary significantly in duration, ranging from weeks to decades [279], depending on the scale and severity of the disaster. A recovery plan is developed by identifying critical components and hazards, estimating damages, developing short- and long-term options to minimize future consequences, and documenting recommended actions. The plan also includes additional response actions coordinated with existing emergency planning documents [280]. Frequent maintenance and rehabilitation can reduce the effort required to achieve full recovery. However, assessments of dam rehabilitation (dam risk priority) have been shown to be affected by climate change [241, 281]. It should be noted that in certain cases, an aged dam may no longer be able to fulfill its intended purpose and retrofitting may not be economically feasible. Additionally, factors related to the environmental impacts of dams and their potential effects on ecosystems must be considered. In such instances, options such as decommissioning or removing the dam completely may be cheaper and preferable to rehabilitation [241, 282]. The success of a dam's recovery is significantly influenced by a country's economic capacity to fund its reconstruction [283]. For example, in the United States, dam owners in some states are likely to receive financial aid in the form of loans or grants. Several federally established systems are exclusively designed for dam rehabilitation. The National Dam Rehabilitation Program Act was enacted by Congress in 2016, and Sec. 5006 of WIIIN2016 established a grant program aimed at aiding local communities in rehabilitating, repairing, or removing high-hazard potential dams before they fail [284]. Through this program, communities can make proactive investments in aging infrastructure, ultimately enhancing the safety of assets situated downstream of a dam. In Canada, there is currently no equivalent federal funding specifically dedicated to dams. However, Public Safety Canada has been offering support for disaster recovery through the Disaster Financial Assistance Arrangements program since 1970 [285]. This program aims to aid provinces and territories in recovering from natural disasters by providing financial support for response and recovery efforts, including those involving dam-related incidents. In addition, in 2018, the Government of Canada initiated the Disaster Mitigation and Adaptation Fund [286], with an initial investment of \$2 billion and further commitments of \$1.375 billion in 2021 over a period of 12 years. This funding aims to enhance community resilience against climate-induced disasters, including flooding, through both structural and non-structural infrastructure projects.

### 5.4 Adaptive capacity

Adaptive management techniques may also play a crucial role in ensuring the long-term resilience of infrastructure assets in the face of uncertain and changing environmental conditions [227]. Given the vast range of possible future climate scenarios, it may be cost-prohibitive to prepare for all scenarios from the outset [227, 287, 288]. Instead, employing adaptive or dynamic management techniques offers a more flexible approach [289]. Developing adaptive capacity means accepting that coping with uncertain future developments may require more than just improving threshold, coping, and recovery capacities [235]. Preventing technical lock-in patterns and maintaining openness to future developments are crucial for building adaptive capacity [290, 291]. An adaptive infrastructure that can accommodate future innovations and technologies is essential for building resilience in large technical water management systems. A range of structural, operational, and regulatory adaptations are available to lower the risk of dam failure. While most operational options, such as improved flood forecasting [292] and lower operational reservoir levels are widely applicable, the feasibility and cost-effectiveness of structural adaptations can vary depending on the characteristics of each dam [25, 293]. Retrofitting an existing dam with an additional bay, for instance, may be impossible without compromising its structural integrity. Additionally, there may not be sufficient space to accommodate an auxiliary spillway. Over-reliance on structural adaptation measures can also exacerbate stresses on already highly altered aquatic ecosystems. To maximize effectiveness, enhancing existing features such as water storage units and rain gardens in the basin, in addition to rivers and dams,

can increase the basin's effective water storage capacity as a whole. Studies have shown that river improvement in Japan can handle excess floods more effectively than dam redevelopment, indicating the need to improve rivers to reduce the required storage capacity and the need to raise the dam embankment and increase the discharge pipe to increase the effective storage capacity [294].

Ecosystem-based adaptation measures, such as those that leverage natural ecosystem functions to mitigate climate change, can complement or substitute structural adaptation measures [264]. Floodplain conservation, which involves maintaining or reconnecting floodplains, is an excellent example of an ecosystem-based approach [295, 296]. Transferring flood-control responsibility from reservoirs to downstream flood management actions can be more effective in reducing flood risks [275]. If downstream flood management actions are designed in a way that allows for controlled release of water during non-flood periods, it can create opportunities for hydropower generation while simultaneously reducing flood risks during high-flow events. So, the revenue generated from hydropower can be used to fund and maintain downstream flood management actions, making them more sustainable. Moreover, enhancing institutional learning in reservoir operations and addressing civil-society critiques of "hard-path dependence", along with fostering science-policy dialogues linking infrastructure and governance, can significantly enhance adaptive capacity [297].

## 6 Concluding remarks

This review paper emphasizes the significance of evolving climatic conditions in designing and evaluating the resilience of critical flood control structures, such as dams and levees. The reviewed literature demonstrates that the conventional approaches, which utilize stationary climatic assumptions, are no longer adequate for calculating design values, and therefore new strategies must be developed not only to account for the dynamic behavior of the climate system but also to alleviate undesirable consequences of future climate change. It is imperative to continuously update estimates of various risk components, including hydrologic loads, and monitor system response in order to enhance climate-resilience and inform decision-making process. In Canada, many dams and embankments were constructed without considering the impact of climate change. The estimation of flood magnitude-frequency relationships for sizing small dams and levees was also based on the stationarity assumption. However, recent destructive floods in Canada and globally have exposed the inadequacy of this approach. In data-scarce situations, climate models can augment observed records and aid in obtaining more precise estimates of design flood magnitudes than merely depending on short instrumental records. To improve climate-resilience of dams and levees, continual climate risk assessments using improved climate predictions, updated regulations, improved design philosophies, and integration of nature-inspired solutions must be considered. Collaboration between public and private sectors is crucial to leverage sustainable financing and risk-informed investments to support climate-resilience objectives. The implementation of such recommendations is necessary to ensure the safety and resilience of dams and levees in the face of changing climatic conditions.

Although many factors are difficult to quantify and factor into design methodology, poor data quality and quantity, confounding drivers and complex interactions, non-stationarity due to changing climate and anthropogenic forcing, non-linearities, weak and imperfect domain knowledge, and lack of relevant exposure experience must be taken into account when developing guidance to innovate existing solutions for attaining climate-resilience and improving the performance and safety of critical flood control structures. Some challenges and insights for estimating climate-informed design floods for dams and levees, along with future research directions, are highlighted below:

- *Constraints of sample size and event identification difficulties:* Design flood estimation for dams relies heavily on historical records of peak discharge and extreme precipitation events. A shorter record and incomplete information about storm characteristics introduce uncertainties in both frequency-based and PMP-based flood estimation procedures and resulting quantities, in addition to other uncertainties. To overcome shorter sample size constraints, regional approaches are preferred for estimating frequency-based flood magnitudes and transposition of climatic variables and storm characteristics for estimating PMP-based floods. In the latter case, it is important to ensure that the transposition of extreme storm characteristics to the target location is both physically and geographically consistent and plausible in nature based on the prevailing atmospheric mechanisms relevant to precipitation. Defining flood events using the AM and POT approaches for frequency analysis and separating extreme storm events for estimating PMP is another challenge. Therefore, careful investigations are needed to find an appropriate method that is acceptable for practical applications, without compromising theoretical rigor and desired standards.

- **Multivariate analysis:** While this field is rapidly evolving, integrating copula-based multivariate frequency analysis with the current design flood estimation guidance is crucial to address dependency between various flood characteristics (e.g., flood peak, volume, and duration) and compound flooding (e.g., joint occurrence of fluvial, pluvial, and coastal floods) in a realistic way. Similarly, the dependency and interrelationships of different meteorological drivers (e.g., integrated vapor transport, dew point temperature, precipitable water, and convective available potential energy) is crucial for a better understanding of intense precipitation generating mechanisms and aiding storm transposition process for obtaining estimates of PMP.
- **Incorporating climate change and addressing non-stationarity:** There is strong theoretical support that global warming will likely augment the amount of water vapor in the atmosphere. Consequently, changes in precipitation characteristics and extreme weather patterns are expected. Considering such consequences, it is important to explore non-stationary techniques for estimating design floods for both small and large dams, levees, and embankments and to develop associated design guidance. To address non-stationarity within the realm of conventional frequency analyses, statistical distributions with varying parameters as a function of time, indices of large-scale atmospheric circulations, or other relevant hydro-meteorological variables/drivers, can be used. Alternatively, climate model projections for distinct non-overlapping periods characterized by different climate features can be utilized. Some countries have suggested using uplift or allowance factors for climate change adaptation, applied either directly to the peak flow magnitudes or to the flood-generating mechanisms (e.g., intense rainfall events) in their guidelines.
- **Quantifying uncertainty:** The conventional design flood estimation approaches fall short in addressing the full extent of deep uncertainty. It is imperative to take steps to identify underlying sources of uncertainties that are present at various stages of the design flood estimation process. This can be achieved by leveraging new understandings and statistical methods, such as by employing the Bayesian approaches to quantitatively capture the uncertainty or performing sensitivity experiments across a plausible range of perceptions. It is crucial to stipulate this range in the design flood estimation guidance to facilitate the development of an ensemble of plausible scenarios. By adopting such an approach, it will become possible to obtain a comprehensive understanding of flood risks. This, in turn, can also enable more informed decision-making and effective risk management strategies.
- **Climate-resilience framework:** Infrastructure designed by considering the impacts of climate change can offer increased service delivery and reliability, longer productive lifespan, and prolonged investment returns. Climate-resilience is a continuous process that must extend throughout the asset's lifespan. The degree to which climate change impacts any infrastructure asset depends on the interaction between climate hazards and exposure and vulnerability of the asset. There is documented evidence that investing in climate-resilience can result in benefits that can outpace costs by several folds. Inspired by a framework, initially proposed for urban assets, this paper introduces a climate-resilience framework tailored for dams and levees. In this framework, the essence of resilience is encapsulated in four interrelated pillars i.e., threshold capacity, coping capacity, recovery capacity, and adaptive capacity of flood control structures. Although the preliminary work has been accomplished, it is hoped that future studies will further improve and extend this framework to other infrastructure assets.

**Acknowledgements** The financial support provided by the National Research Council Canada through the Climate Resilient Built Environment (CRBE) initiative funded by Infrastructure Canada (INFC) is graciously acknowledged. The guidance and support of CRBE leadership is very much appreciated. The invaluable anonymous review comments and helpful suggestions provided by the Editors are gratefully acknowledged.

**Author contributions** MR Islam, M Fereshtehpour: Conceptualization, Formal review, Investigation, Writing - original Draft, Visualization. MR Najafi: Supervision, Conceptualization, Writing - review & editing. MR Najafi, MN Khaliq: Conceptualization, Writing - review & editing. AA Khan, L Sushama, VTV Nguyen, A Elshorbagy, R Roy, A Wilson, J Perdikaris, MB Masud, MS Khan: Writing - review & editing

**Funding** This research was financially supported by the National Research Council Canada (Contract No. 1011175).

**Data availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.

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