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Research on Challenges and Strategies for Reservoir Flood Risk Prevention and Control Under Extreme Climate Conditions

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Abstract: In recent years, reservoir flood control and dam safety have faced severe challenges due to changing environmental conditions and intense human activities. There has been a significant increase in the proportion of dam breaks caused by floods exceeding reservoir design levels. Dam breaks have periodically occurred due to flood overtopping, threatening people's lives and properties. This highlights the importance of describing the challenges encountered in reservoir flood risk prevention and control under extreme climatic conditions and proposing strategies to safeguard reservoirs against floods and to protect downstream communities. This study conducts a statistical analysis of dam breaks resulting from floods exceeding reservoir design levels, revealing new risk indicators in these settings. The study examines recent representative engineering cases involving flood risks and reviews research findings pertaining to reservoir flood risks under extreme climatic conditions. By comparing flood prevention standards at typical reservoirs and investigating the problems and challenges associated with current standards, the study presents the challenges and strategies associated with managing flood risks in reservoirs under extreme climatic conditions. The findings show that the driving forces and their effects shaping flood risk characteristics in specific regions are influenced by atmospheric circulation and vegetative changes in underlying surfaces or land use. There is a clear increasing probability of dam breaks or accidents caused by floods exceeding design levels. Most dam breaks or accidents occur in small and medium-sized reservoirs, due to low flood control standards and poor management. Therefore, this paper recommends measures for improving the flood prevention capacity of these specific types of reservoirs. This paper proposes key measures to cope with floods exceeding reservoir design levels, to supplement the existing standard system. This includes implementing an improved flood standard based on dam risk level and the rapid reduction in the reservoir water level. To prevent breaks associated with overtopping, earth–rock dams should be designed to consider extreme rainfall events. More clarity is needed in the execution principles of flood prevention standards, and the effectiveness of flood calculations should be studied, adjusted, and validated. The research results provide better descriptions of flood risks in reservoirs under extreme climatic conditions, and the proposed strategies have both theoretical and practical implications for building resilience against flood risks and protecting people's lives and properties.

Keywords: reservoirs; extreme climatic conditions; flood risks; challenges; strategies

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1. Introduction

Reservoirs are an important type of infrastructure and play an important role in providing downstream flood control safety, production and domestic water, and water used to support the ecological environment. There are nearly 100,000 reservoirs in China and 80,000 in the United States, which significantly contribute to each country's water supply and safety. Reservoir flood risk refers to the probability of loss and injury caused by a reservoir discharge or dam-break flood; this risk is expressed using two indicators: loss value and risk rate [1]. Extreme climatic events refer to climate events that have a small probability of occurring in a specific area and time. Extreme hydrological events refer to hydrological events that have a very small probability of occurring (less than 10% of similar hydrological events) but create a significant change in net flow in a certain time frame and have a destructive power [2,3]. The frequency and intensity of extreme climatic events caused by a changing environment have increased significantly, increasing risks for reservoir safety during flood season. For example, in 2021, floods occurred in many European countries, with Germany experiencing the most serious losses [4]. On 1 October 2022, Hurricane Ian, one of the strongest hurricanes ever recorded in the United States, generated dangerous floods and caused power outages and massive damage, killing more than 100 people. In 2013, floods in Jakarta, Indonesia, caused 38 deaths and economic losses of EUR 760 million. In 2017, floods occurred in Peru, South America, killing 159 people [5].

In recent years, numerous dam failures have been caused by floods exceeding reservoir design levels, raising concerns about reservoir safety and emergency management. Examples include the 2018 Xe-Pian Xe-Namnoy dam collapse in Laos, the 2020 cascade reservoir failures in Michigan, and the Sardoba dam breach in Uzbekistan. In 2021, drought led the Hoover Dam's reservoir to its lowest historical level, while rainstorms in western Europe nearly caused the Steinbach Reservoir to overflow. Additionally, two dams in Brazil broke in December 2021, prompting emergencies in many towns, and a 2018 flood in Xinjiang's Sheyuegou Reservoir exceeded design levels, resulting in casualties. These incidents underscore the impact of atmospheric circulation and land-use changes on regional flood risks. Recent research has focused on flood risk prevention and emergency management, highlighting that while human capacity to handle natural disasters is improving, the societal impacts of extreme events like floods and droughts remain significant. Climate change and socio-economic development are increasing the frequency and intensity of these events, yet current risk management strategies are still insufficient, as demonstrated by extreme events like the Zhengzhou torrential rain on 20 July 2021.

Flood impacts are significantly shaped by hazards, exposures, and vulnerabilities exacerbated by urbanization and extreme climatic events. Zhang Jianyun et al. [6] highlighted how global changes intensify urban rainstorms in China through effects like the urban heat island and altered runoff mechanisms from urban development. Meanwhile, Xu Zeping et al. [7] emphasized ensuring flood discharge reliability in earth–rock dams, as seen in the Michigan dam failures. Zhou Xingbo et al. [8] proposed categorizing reservoirs under extreme conditions to enhance safety management, while Wuqing et al. [9] stressed the need for accurate flood calculations and improved monitoring systems. Cheng Xiaotao [10] suggested shifting the focus from loss reduction to risk reduction in flood control operations.

Research methods in flood risk analysis also play a crucial role. Guo Shenglian et al. [11] reviewed flood frequency analysis methods, while Hou Aizhong et al. [12] focused on anti-rainstorm capability development. Zhou Xianglin et al. [13] and Pan Caiying [14] provided insights into global flood control standards and defining extreme flood thresholds, respectively. Li Yuanyuan et al. [15] identified key issues in China's flood risk management, advocating for risk zones based on flood factors. Xu Bin et al. [16] pointed out the risk in real-time flood control due to forecast inaccuracies. Yanlai Zhou et al. [17] assessed flood risks considering climate and reservoir capacity changes, and Cinzia Albertini et al. [18] explored dynamic risks in flood management. Elena Ridolfi et al. [19] and Ting Zhou et al. [20] contributed to understanding reservoir operation strategies and flood frequency analysis, emphasizing the importance of reliable risk assessments.

The studies primarily focus on simulating inflow flood processes and conceptual research on reservoir flood risk prevention, but they lack comparative assessments of global dam flood control standards and a thorough analysis of the capabilities of small and medium-sized reservoirs. Few technical guidelines exist to address environmental changes in developing flood risk prevention strategies. Since 2000, climate change has intensified extreme weather patterns, making it necessary for water management authorities worldwide to identify flood risk characteristics and implement appropriate strategies. While scientists have studied climate and human impacts on flood risks, research on reservoir flood disaster prevention remains limited, with data collection and analysis methods proving inadequate. Recently, new flood risk characteristics have emerged, such as frequent dam breaks in cascades, earth–rock dam overtopping, and inadequate standards for smaller reservoirs, highlighting the need for improved flood control measures.

This paper draws on existing research and applies statistical and causative analysis and theories to explore the impact of extreme climatic conditions on reservoir flood events, compare different countries' flood control standards, describe problems and challenges, and discuss implications and recommendations. This paper examines recent typical dam-break incidents, conducts a statistical analysis of dam breaks, and reviews research findings related to reservoir flood risks under extreme climatic conditions. By comparing reservoir flood control standards and exploring current problems and challenges associated with those standards, this paper describes challenges and strategies for flood risk prevention and control in reservoirs in these conditions. This study considers both Chinese reservoirs and foreign reservoirs, using different literature sources.

2. Analysis of Reservoir Flood Risks Under Extreme Climatic Conditions

2.1. Risk of Water Conservancy Infrastructure Failures from Extreme Rainstorms and Floods

Using China as an example, dam-break accidents have decreased to less than 5‰ through reinforcement, remediation, and enhanced reservoir management. However, flood control standards for small and medium-sized reservoirs remain low; there are many such reservoirs, and they are widely distributed. Given the changing environment and intense human activities, extreme weather events are increasingly frequent, and local extreme rainstorms and floods occur more often. Reservoir safety faces significant challenges during flood seasons, and accidents and dam breaks periodically occur. Most dam accidents or failures caused by overtopping have been due to rainstorms and floods exceeding design levels; recent examples include events occurring in the Sheyuegou, Zenglongchang, and Guojiazui reservoirs. The absolute number of dam-break accidents caused by floods exceeding design levels has decreased significantly, but the proportion is increasing. This is directly related to the increased frequency of extreme climatic events. In the context of global climate changes, the frequency and intensity of extreme climatic events are significantly increasing, with increasingly prominent adverse effects on the dam safety of small and medium-sized reservoirs with relevantly low design flood levels. Adaptive strategies are needed, especially with respect to improving flood control standards, safety management standards, and the emergency management capabilities of small urban reservoirs.

2.2. Increasingly Serious Flooding Risks for Downstream Cities Caused by Insufficient Regional Flood Control and Drainage Capacity Under Extreme Climatic Conditions

Flood control and drainage standards associated with water conservancy infrastructure relate closely to the level of economic and social development. Older constructed water infrastructure tended to be built to lower flood control and drainage standards; this is particularly common in some developing countries. By 2018, the global urbanization rate reached 55%, and it is expected to reach 68% in 2050 [21,22]. China's urbanization rate increased from 10.64% in 1949 to over 60% today. Urbanization has led to great changes in water conservancy infrastructure functions, operating environment, runoff generation and confluence conditions, and dispatch and operation modes. Downstream infrastructure and wealth grow rapidly, and the flood discharge capacity of urban rivers decreases due to municipal construction and human activities. Inadequate flood control and drainage capacity associated with key water conservancy infrastructure in major cities is an increasing problem. Rainstorms and floods significantly increase the risks of urban waterlogging, infrastructure inundation, and dike breaches. For example, in 2014, a flood in Malmo, Sweden, was five times more hazardous than the previous most serious one, causing large losses.

Studies have shown that the lag in flood peak and peak discharge increase as the drainage area increases; there is an exponential relationship with the size of the drainage area [23]. Rapid urbanization is leading to a constant expansion in impermeable surfaces (such as concrete and asphalt pavements and wall surfaces), which replace the original natural underlying surfaces (such as vegetation and water surfaces). These new surfaces often have low permeability [22,24]. In addition, changes in the physical properties of urban underlying surfaces directly affect the atmosphere, runoff, and confluence process of the urban hydrological cycle. This highlights the need to study the hydrological effect of urbanization [25].

With changes in basin characteristics and the underlying surface, reservoirs have a more significant impact on risks faced by downstream cities. Xu Youpeng et al. [6,26] analyzed the hydrological impact of urbanization on the Qinhuai River in Nanjing, finding that the urbanization rate (impermeable rate) increased from 4.2% (1988) to 7.5% (2001), and then to 13.2% (2006); the annual average runoff depth and runoff coefficient of the basin increased by 5.6% and 12.3%, respectively. In addition, the initial conditions in the basin where a reservoir is located (such as initial flow, early rainfall, and early soil moisture) affect flood characteristics [27]. Different urbanization levels and different climate characteristics lead to different flood response characteristics, based on initial conditions in river basins.

When flood control and drainage characteristics change in a reservoir area, the flood discharges change under extreme climatic conditions, increasing the risks of more serious and violent flooding in downstream cities [22]. As early as 1921, Horton studied the meteorology of cities in the United States and found that urban areas are more prone to rainstorms; this highlighted an urban "rain island effect" [28]. From METROMEX in the 1960s, to meteorological radar observations in the 1990s, to numerical simulation research, many studies worldwide show that urbanization affects local rainfall characteristics [29,30]. Many reservoirs are in or near cities around the world, and many Chinese cities built reservoirs as part of their development. For example, more than 150 reservoirs in Shenzhen are urban reservoirs. Flood risk prevention and control for such reservoirs is challenging.

2.3. Flood Risks Increase Due to Ineffective Reservoir Hydrological Simulation and Flood Control Operation Technology in a Changing Environment

Climate change and human activities significantly impact the hydrological cycle and characteristic conditions in a reservoir basin [31–34]. Given increasingly significant environmental changes, it can no longer be assumed that hydrological simulations should present a "steady state". It was previously assumed that parameters representing the hydrological and physical characteristics of basins in reservoir hydrological models do not change with time; this clearly no longer applies [1]. When the parameters of a reservoir hydrological model cannot accurately reflect basin characteristics, the hydrological simulation of reservoir inflow becomes less accurate. If the model parameters are assumed not to change with time, the model may not fully reflect the hydrological cycle, or the model may not reflect the dynamic changes of basin characteristic conditions (such as land-use changes) [35,36].

Hydrological frequency analysis methods serve as a super-long-term hydrological forecasting technique. As human activities increasingly impact these processes, hydrological extreme values become more inconsistent. Reservoir hydrological simulation calculation and analysis technology do not fully consider the dual impacts of climate changes and human activities, making it difficult for them to meet actual demands. This creates risks with respect to reservoir flood control operation. In addition, traditional models of maximum expected benefits associated with optimal reservoir operation do not fully consider the uncertainty of the changing environment. Reservoir operations involve a mutual feedback and coupling system that integrates flood control, water supply, power generation, and the environment. The continuous evolution of this coupling system changes stakeholder decision preferences and social and economic conditions; this can change reservoir operation decisions [1].

Some scientists have investigated the simulation technology of flood frequency curves, considering the effects of climate changes and human activities. For example, Sivapalan et al. [37]

integrated climate changes and land use into their analysis of flood frequency and derived a formula for flood frequency curves that considers seasonal influences. Botter et al. [38] posited that precipitation follows a Poisson distribution; they developed an analytical model for flood frequency curves based on a physical mechanism. Model parameters reflected the impacts of climate changes and land use. However, the simulation technology used to develop reservoir flood frequency curves needs further development.

3. Comparative Analysis of International Flood Control Standards for Reservoirs

3.1. Analysis of the Characteristics of Flood Control Standards for Reservoirs

Flood control standards for reservoirs vary across countries with respect to values and methods. These standards are influenced by technical, economic, natural geographic, social, and political factors. Zhou Xianglin et al. [39] compared flood control standards for reservoirs across typical countries, identifying four primary categories of standards:

3.1.1. Standards Based on Surveys and Measurements of a Specific Large Flood Event, with Appropriate Incremental Levels

Used in countries such as Sweden and Norway, this approach was an early type of flood control standard. It is becoming less popular due to its dependence on accumulated hydro-meteorological data [40]. Countries like Norway are currently transitioning to risk-based approaches for determining flood control standards (see below).

3.1.2. Standards Represented by Flood Recurrence Intervals (T) or Annual Exceedance Probabilities (P%)

Design flood calculations rely on a frequency analysis. This approach is used in the former Soviet Union, Japan, Colombia, and China and is the most widely used approach [41]. However, this approach is disputed, due to the significant uncertainties associated with extrapolating theoretical frequency curves.

3.1.3. Standards Based on the Probable Maximum Flood (PMF) or Its Associated Fractions

PMF calculations use hydro-meteorological analysis methods with fractions such as three-fourths, two-thirds, or one-half. This approach continues to be practiced in the United States, India, and Canada. This approach has the disadvantage of requiring extensive hydro-meteorological data for accurate calculations. This makes it challenging to determine specific multipliers for flood control standard values, which can be arbitrary and unclear in meaning.

3.1.4. Standards Incorporating a Blend of Hydro-Meteorological Methods and Frequency Analysis

These methods may include designing for floods with a 50- to 1000-year return period and verifying with floods having a 10,000-year return period or PMF. This method is used in the United Kingdom, Australia, and Norway.

There is considerable international variation in these methods for setting flood control standards, and they generally focus on individual reservoirs rather than dam groups [42]. Consistent with Zhou Xianglin et al. [39], this study posits that there is a shifting trend towards a universal standard for determining flood control measures for reservoirs in various countries. The essential purpose of reservoirs is to ensure downstream flood safety. Therefore, an emerging standard is expected to be a graded approach that considers the extent of harm caused to downstream areas by dam breaks.

3.2. Comparative Analysis of Typical Flood Control Standards in Different Countries

There are significant differences between China and the United States with respect to their choice of flood control standards for reservoirs (see Table 1) [43]. As an overview, the United States applies flood design standards based on the potential hazard level of dams, whereas China establishes corresponding design flood standards according to the project level and building classification.

Table 1. Comparing reservoir flood control standards in China and the United States.

Engineering Scale	Region	Design Flood (China)	Check Flood (China)		United States
			Concrete and Masonry Dams	Earth-Filled and Rock-Filled Dams	Determination of High Risk Level
Medium	Mountainous and hilly regions	100~50	1000~500	2000~1000	
	Plains and coastal areas	50~20	300~100		PMF
Small-sized (type 1)	Mountainous and hilly regions	50~30	500~200	1000~300	
	Plains and coastal areas	20~10	100~50		PMF
Small-sized (type 2)	Mountainous and hilly regions	30~20	200~100	300~200	
	Plains and coastal areas	10	50~20		PMF

China's flood control standards are based on a comprehensive evaluation of engineering scale and functional indicators, with qualitative requirements on the consequences of dam breaks and the importance of downstream protected objects. China sets the highest flood control standard for small and medium-sized reservoirs in mountainous and hilly areas as the 2000-year flood and the lowest flood control standard as the 200-year flood. For reservoirs in plains and coastal areas, the highest standard is a 300-year flood, and the lowest is a 20-year flood. For Class 1 earth–rock dams, the highest flood standard can be either the PMF or a 10,000-year flood. China has noticeably different standards for small and medium-sized reservoirs compared to the United States.

Historically, the United States focused on dam safety and economic benefits during dam construction, similar to the current situation in China. This approach did not consider the consequences of dam failure as a construction criterion. Following a series of dam breaks, including the Teton Dam collapse in the 1970s [44], which caused significant casualties and property damage, the United States government systematically implemented dam safety inspection legislation, established a rigorous classification system for potential dam hazards, and set corresponding flood control standards [45,46].

In summary, the flood standards for reservoirs and dams in China and the United States have gradually evolved based on climate characteristics, topography, and socio-economic development. Both have different forms of adaptability. Without judging which standards are higher or lower, each country needs to make adjustments based on the actual situation given frequent extreme weather conditions.

The United States does not have a uniform national flood control standard, and there are multiple governing reservoir management departments. In the 1930s, frequency analysis was primarily used to determine flood control standards. Starting in 1938, hydrological and meteorological methods were gradually adopted. In 1974, the United States Army Corps of Engineers (USACE) published the "Reservoir Safety Inspection Reference Guide (Manual)". This Guide established engineering scales and flood control standards based on reservoir capacity, dam height, and the risk level of potential consequences (see Table 2). Countries like the United States and the United Kingdom consider potential disaster losses from dam failure as a primary factor. For high-risk dams, the United States consistently applies the highest hydrological design standard, the PMF.

Similar to the United States, Canada classifies dams into four categories based on the severity of potential consequences following dam breaks: extremely serious, serious, low, and extremely low. Design flood standards are determined based on the severity of these consequences (See Table 3). Canadian dam classification and safety standards specify that the flood control standards for many high-risk small and medium-sized reservoirs should meet the large reservoir standards.

Table 2. USACE's reservoir engineering scales and spillway design flood standards.

Engineering Scale			Spillway Design Flood (Recurrence Interval or Possible Maximum Flood)		
Classification	**Reservoir Capacity (in 10,000 m^3)**	**Dam Height (m)**	**High Risk**	**Medium Risk**	**Low Risk**
Large	>6170	>30	PMF	PMF	1/2 PMF~PMF
Medium	123~6170	12~30	PMF	1/2 PMF~PMF	100 years~1/2 PMF
Small	6~123	8~12	1/2 PMF~PMF	100 years~1/2 PMF	50~100 years

Table 3. Canadian design flood standards determined based on dam-break consequences.

Level of Dam-Break Consequence	Safety Review Interval	Maximum Design Earthquake Derived from Certainties	Maximum Design Earthquake Derived from Statistics	Design Inflow Flood
Extremely serious	5 years	Maximum credible earthquake	1/10,000	PMF
Serious	7 years	50~100% maximum credible earthquake	1/1000~1/10,000	1/1000~PMF
Low and extremely low	10 years	According to economic risks and other impacts	1/100~1/1000	1/100~1/1000

In Norway, dam construction began relatively early, with design flood standards and check flood standards set at a 1000-year flood and PMP flood, respectively. In 2003, new guidelines required flood control standards to be determined based on the impact of a dam break. These consequences were divided into three levels: minor, moderate, and severe, with gradually enhanced corresponding design and check flood standards. The highest design flood standard reached the 1000-year flood, while the maximum check flood standard reached the PMF level (see Table 4). Influenced by historical socio-economic development, China's reservoir flood control standards are lower than Norway's standards for both design and check flood standards.

Table 4. Norwegian design flood standards and check flood standards for reservoirs.

S/N	Level of Dam-Break Consequence	Design Flood Standard	Check Flood Standard
1	3 (severe)	1000-year flood	PMF
2	2 (moderate)	1000-year flood	PMF or 1.5 times the 1000-year flood
3	1 (minor)	500-year flood	–

More broadly, flood control standards in the United States, the Netherlands, and Norway are high. Standards in the United Kingdom, Canada, Brazil, India, and China are slightly lower, and standards in Russia are the lowest. Flood control standards for reservoirs should be further improved based on societal development levels and changes in flood series. It is vital to optimize existing flood control standards based on downstream risk levels. Also, further research is required to drive improvements in flood control standards for small-sized reservoirs that were built a long time ago.

4. Analysis of Reservoir Flooding Cases

4.1. Overtopping and Breaks of Edenville and Sanford Reservoirs in the United States

Edenville Dam, located at the confluence of the Tittabawassee and Tobacco Rivers in Michigan, 21 km upstream of Midland County, serves power generation, flood control, and recreation with a capacity of 81,700,000 m^3. Built in 1924, it is an earth-filled dam with spillways. Approximately 11.3 km downstream, Sanford Dam, operated by Boyce Hydro, was constructed in 1925 with a capacity of 17,144,000 m^3, primarily for power generation. It features a gated structure with a height of 10.97 m and a crest length of 481.3 m.

On 19 May 2020, the Tittabawassee River flooded, raising water levels to 8.60 m by 10:15 am. By 19:30, Edenville Dam breached due to seepage failure as water neared the crest (See in Figure 1). Sanford Dam subsequently overtopped and breached at 20:49 (See in Figure 2). Prompt actions by Michigan state and Midland County authorities, including communications and evacuations of about 10,000 people, ensured no casualties.

Figure 1. Aerial image of the Edenville Dam break [47].

Figure 2. Aerial image of the Sanford Gate Dam.

The main factors contributing to the dam breaks included the significant trigger of a sudden flood, insufficient flood discharge capacity of Edenville Dam as a primary cause, safety management deficiencies due to inadequate regulatory oversight, and ineffective operations exacerbating dam conditions and reducing flood capacity.

4.2. Overtopping at a German Reservoir

Starting in July 2021, heavy rainfall in central and western Europe caused significant floods. This affected Germany, Belgium, the Netherlands, Austria, and other countries, with Rheinland-Pfalz in Germany being the hardest hit. Over 200 people died in the flooding, including 165 in Germany and 31 in Belgium. Steinbach Reservoir, an essential drinking water source near Cologne, Germany, was constructed from 1934 to 1936 and was reinforced from 1988 to 1989. With a capacity of approximately 1,000,000 m^3, the reservoir has rarely been flooded since its completion. However, the sudden torrential rainfall upstream led to a flood; floating objects blocked the spillway and caused reservoir water level to continuously rise. Additionally, multiple locations on the dam showed signs of piping [48], indicating a risk of overtopping and breaking. Aerial images (Figures 3 and 4) show alarming traces of piping on the dam's upstream slope. To prevent dam collapse, a nearby highway was closed, and engineers deployed massive pumps to extract water from the reservoir, with the goal of outpacing floodwater accumulation. By the evening of 16 July, the reservoir water level began to decrease, and the Steinbach Reservoir dam did not breach.

Figure 3. Scene of Steinbach Reservoir in Germany after overtopping.

Figure 4. Downstream dam slope after overtopping of Steinbach Reservoir in Germany.

4.3. Dam Break of Xe-Pian Xe-Namnoy Hydropower Station in Laos

Xe-Pian Xe-Namnoy Hydropower (XPXN), shown in Figure 5, is on the Bolaven Plateau in southern Laos. The reservoir has a total capacity of 1,043,000,000 m^3, with a maximum water level of 72 m and a main dam crest elevation of 74.00 m. Of the five lower saddle dams, Saddle Dam D is the tallest, with a maximum height of 17 m and a dam length of 770 m. On 22 July 2018, the reservoir area experienced heavy rainfall. This was followed by the sudden break of Saddle Dam D the next evening, resulting in the discharge of more than 500,000,000 m^3 of floodwater.

Figure 5. Layout of Saddle Dam D.

The tests indicated that the foundation's permeability was low, making additional seepage control measures unnecessary. A series of investigations found that the failure in the laterite foundation's permeability was the critical factor in the dam break; the cancellation of seepage control measures had a significant negative impact. Heavy rainfall prior to the break further contributed to the incident.

4.4. Overtopping and Dam Breaks of Two Brazilian Reservoirs

From 25 to 26 December, year (local time), after nearly two months of heavy rainfall, two dams in Bahia state, Brazil (Figures 6 and 7), experienced consecutive breaks. This caused river levels to rise and floods to engulf towns throughout the region. Igua Dam on the Verruga River, located near Vitoria da Conquista in southern Bahia, breached on the evening of 25 December, prompting local governments to evacuate residents, particularly in Itambe. On the morning of 26 December, the overflowing floodwaters caused the Jussiape Dam to break, 100 km north of Igua Dam. Local authorities warned residents to relocate to safer locations.

Figure 6. Jussiape Dam before break.

Figure 7. Breaking Jussiape Dam.

4.5. Overtopping and Dam Break of Sheyuegou Reservoir

Sheyuegou Reservoir (Figures 8 and 9) is in China. The dam has a maximum height of 41 m and a total storage capacity of 6,779,000 m^3. Rapid runoff formation in the watershed can lead to flash floods, due to the exposed bedrock and sparse vegetation. From 31 July to 1 August 2018, the Sheyuegou Reservoir area experienced heavy rainfall, with upstream runoff totaling 21,970,000 m^3 on 31 July (surpassing the annual average runoff of 18,190,000 m^3). The peak inflow reached 1848 m^3 per second, which was significantly higher than the historical maximum flood peak of 170 m^3 per second. The maximum flow rate during the break was 6700 m^3 per second.

The subsequent investigation found that the reservoir experienced a flood exceeding the design level. Even with emergency measures, including adding sub-dikes on the dam crest and preemptive drainage, it was impossible to prevent the overtopping and subsequent break. The decisive factor leading to the break was an extreme short-duration rainfall event. This caused a catastrophic flood far exceeding the reservoir's flood protection capacity. This was a typical overtopping dam failure accident caused by the standard flood being exceeded.

Figure 8. Overtopping and break of Sheyuegou Reservoir.

Figure 9. Post-break scene of Sheyuegou Reservoir.

5. Problems and Challenges

Reservoir safety is crucial for public safety and socio-economic development around the world. Ensuring this safety poses tremendous challenges given the complexity and demanding nature of flood risk prevention and control technology.

5.1. Significant Challenges in the Safe Operation Management of Crucial Water Infrastructure Under Extreme Climatic Conditions

As noted in the Introduction, in recent years, climate change has led to an increase in the frequency and intensity of extreme precipitation events. The global average temperature has risen by 0.7~1 °C in the past century, while the average temperature in large cities has increased by 2~3 °C. Over the past five decades, many countries have experienced an increased average intensity and number of extreme heavy rainfall and precipitation events. The randomness, suddenness, and destructive nature of these events threatens the safety of water infrastructure. Changes in hydrological extremes, such as rainstorms, floods, and droughts, impact the size of design floods and the flood control capacity of water conservancy projects. Approximately 80% of China's reservoirs were built between the 1950s and 1970s; the average dam age is 50 years (Table 5). Therefore, many reservoirs are approaching or have reached their design lifespan. Many countries are experiencing this same challenge. As reservoir operation time increases, the aging of water project structures and performance degradation become more evident, increasing the risks and hazards from extreme precipitation [49].

Table 5. Characteristics of floods exceeding design levels leading to dam breaks in China.

Reservoir Name	Time of Dam Break	Design Standard	Check Standard	Q_{Design} m^3/s	Q_{Check} m^3/s	$W_{24\ h\ design}$ m^3 (in 10,000 m^3)	$W_{24\ h\ check}$ m^3 (in 10,000 m^3)	Maximum Peak Discharge m^3/s	Incoming Flood Volume (in 10,000 m^3)	Maximum Rainfall in a Specified Period (mm)	Verified Flood Characteristic Frequency (Return Period)
Zenglong chang	July 2018	100	1000	1580	2860	950	1638	1970	1898 (24 h)	51.9 (1 h)	1600 years (flood volume)
Sheyuegou	July 2018	30	300	219	537	/	/	1848	2197 (6 h)	84.9 (3.5 h)	>1000 years (flood peak)
Yong'an	July 2021	50	500	/	362	/	/	1060	3178 (24 h)	64.8 (1 h)	1000 years (flood peak)
Xinfa	July 2021	50	300	/	722	/	/	2710	7179 (24 h)	64.8 (1 h)	2000 years (flood peak)

5.2. Potential Safety Hazards in Reservoir Dams That Are Not Eliminated in a Timely Manner

Reservoir dam safety is complex worldwide, with problems caused by aging construction, long embankment histories, significant differences in dam material properties, and complex geological conditions. Coupled with the impacts of extreme climate, earthquakes, and other natural disasters, there are critical technical problems related to the reinforcement and remediation of defective and dangerous reservoirs. This makes it difficult to promptly and thoroughly eliminate potential safety hazards. In some cases, reservoirs may operate with defects throughout their working life. After the 1998 floods, the Chinese government invested heavily in large-scale reinforcement and remediation for reservoirs, sluices, and embankments to meet safety standards. Since 1999, the central and local governments have invested hundreds of billions of RMB to reinforce over 73,000 defective and dangerous reservoirs. However, individual reservoirs still face safety risks during or after reinforcement. Safety diagnostic technology, standards, and reinforcement decision-making technology for reservoirs and dams in China need continuous improvement.

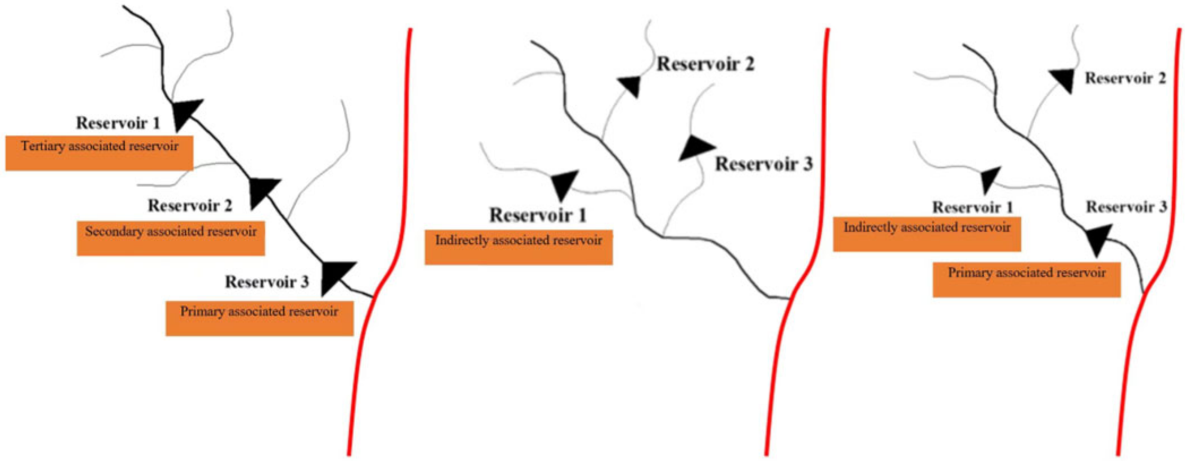
First, decision-making related to reinforcements and remediation needs improvement, and high-risk and cost-effective projects should be prioritized. Second, the dynamic nature of reinforcement may result in insufficient preliminary work and a lack of relevant historical engineering information resources, making it difficult to ensure the effectiveness of reinforcement and remediation. Third, long-term reinforcement and remediation mechanisms need further improvement. Finally, water conservancy projects have complex defects and pose significant dangers, with key technical challenges during safety diagnosis, reinforcement, and remediation. Extreme climates further complicate dam safety and management issues.

For example, in summer 2021, a masonry arch dam in China's southwest region experienced serious safety problems. Reservoir personnel lowered the water level to a near-empty level on a hot day, causing a 17 m drop in water level within four days, with an average daily drop of 5 m. Finally, the reservoir water level dropped to lower than the standing water level of 11 m. Many cracks were seen in the dam body: 20 radial cracks were found at the dam crest, and 51 cracks were found in the wave protection wall. One crack, suspected to be a penetrating crack, had formed during the initial water storage phase and affected the load-bearing mechanism of the arch. These cracks were primarily caused by high temperatures and low water levels. This is a unique scenario where extreme drought and high temperature rapidly increased dam-break risk and flood hazards. In changing environments and under extreme climatic conditions, potential safety hazards of reservoir dams are omnipresent and complex.

5.3. Need to Further Improve the Reservoir Technical Standard System

Reservoir flood standards and dam safety are interlinked, with risk-based decision-making being essential for setting these standards. China's current flood standards are based on reservoir characteristics and functional indicators, such as reservoir and installed capacity, incorporating some risk management concepts. However, rapid urbanization and socio-economic growth have altered reservoir environments significantly, increasing at-risk populations and infrastructure downstream. Existing standards fail to adequately reflect risk differences, such as dam-break consequences, downstream target importance, and dam height. They lack quantitative indicators for dam-break risk and do not sufficiently address the impacts of dam height or the effects on small and medium-sized reservoirs. Cascade reservoirs, often found in mountainous or plain areas, have historically accounted for a high proportion of dam breaks worldwide, with 131 cascade dam breaks recorded from 1954 to 2006 due to upstream breaches. Recent incidents, like the 2020 dam breaks at Edenville and Sanford Reservoirs in the U.S. and the 2021 breaks at Xinfa and Yong'an Reservoirs in China, highlight the urgent need for improved flood standards and risk prevention measures for cascade reservoirs, as current standards are inadequate.

There are differences in flood standards between mountainous and plain reservoirs, but the standards do not consider the associated differences in impact when an upstream dam breaks. The cascading development of water resources in river basins is a new trend in water conservancy and hydropower development. However, current research mostly focuses on risk analysis models or methods for individual dams. Compared to individual dams, the risk analysis for dam groups of cascade reservoirs is more complex. The overall risk depends on the combination of reservoir group locations, reservoir scales, and dam types and heights. Cascade reservoir groups are generally divided based on their positional relationships; they include series, parallel, and hybrid modes (see Figure 10).



(**a**) Series mode (**b**) Parallel mode (**c**) Hybrid mode

Figure 10. Schematic diagram of typical spatial distribution patterns of cascade reservoir groups.

6. Implications for Reservoir Flood Risk Prevention and Control

6.1. Hydrology Is a Key Aspect of Reservoir Dam Safety and Management

As countries enter a post-construction era, an increasing amount of dam safety work focuses on post-construction operation and management. A threefold approach is applied to evaluate dam safety during operation, encompassing hydrology, geology, and engineering. "Hydrology" pertains to assessing potential changes in hydrological features, "geology" involves examining changes in geological conditions or the presence of adverse factors, and "engineering" involves examining the safety status of the project. The element most prone to variation is "hydrology". Given the changes already discussed, strengthening hydrology research and application is particularly vital.

6.2. Clarification Is Needed About Interval Value Selections for Flood Control Standards

Edenville Reservoir in the United States, discussed in the case studies above, did not have sufficient capacity to discharge the PMF; its discharge capacity only reached 50% of the PMF. In 2018, the state of Michigan deemed it non-compliant, and the company's operating license was revoked by the Federal Energy Regulatory Commission (FERC). Despite this, the reservoir continued to operate, leading to the collapse of two cascade reservoirs. In China, two reservoirs—Yong'an and Xinfa—are cascade reservoirs, with one located upstream and the other located downstream. Yong'an Reservoir in Inner Mongolia follows flood control standards for small-sized (type 1) class-IV projects in mountainous and hilly regions, with the 50-year flood as the design standard and the 500-year flood as the check standard. The downstream Xinfa Reservoir follows flood control standards for medium-sized class-III projects in plains and coastal areas, with the 50-year flood as the design standard and the 300-year flood as the check standard. Determining the appropriate flood control standards for such reservoirs, especially downstream, is a significant issue affecting flood safety.

6.3. Research Is Needed on "Overtopping Without Breaking" of Earth–Rock Dams

In China, approximately 92% of reservoir dams are earth–rock dams, with over 50% of dam breaks caused by overtopping. As a case study, during the "7.20" extreme rainfall in Zhengzhou in 2021, Guojiazui Reservoir's earth–rock dam experienced continuous overflow for 7.5 h. The downstream slope was severely eroded and damaged, but the dam did not collapse, due to protection provided by the asphalt and concrete surface on the dam crest and concrete steps on the downstream slope (see Figure 11). Similarly, laying cloth strips on dam surfaces to prevent erosion and collapse has been effective in several reservoirs in Hubei and Hunan provinces. These cases demonstrate that appropriate surface protection and drainage measures help earth–rock dams withstand overtopping without breaking. Focused research on the overtopping of low earth–rock dams could lead to innovative slope protection and drainage systems that enable these dams to resist overtopping. It is important to develop emergency response equipment, materials, and techniques for protecting earth–rock dams against overtopping. Doing so would increase the ability of many widely distributed small-sized reservoirs to withstand floods exceeding design levels and reduce the probability of dam breaks.

Figure 11. Crest hardening ensures "overtopping without breaking".

6.4. Rapidly Lowering Reservoir Water Levels Addresses Floods Exceeding Design Levels

Temporary flood discharge channels have been excavated at many reservoirs. This allows for the emergency lowering of reservoir water levels, effectively slowing the progression of dam incidents. This has produced favorable results. Lessons learned from small-sized reservoir incidents show that the layouts of small-sized reservoir projects and dam structural design should include temporary flood discharge channels for floods exceeding design standards, at suitable locations. For existing high-risk small and medium-sized reservoirs, installing additional emergency spillways may increase the discharge capacity of reservoirs and meet flood control requirements. Establishing emergency spillways can provide extra protection for dams, allowing for the orderly release of floodwaters in case of a flood exceeding the design standard, or when the primary spillway is inoperable. This could prevent the overtopping of dams and a potential dam break.

6.5. Earth–Rock Dam Structural Designs Should Consider the Impact of Extreme Heavy Rainfall

In some countries, design codes for calculating the slope stability of earth–rock dams mainly focus on different upstream water levels as boundary conditions. The dam body's saturation line indicates it is dry above the reservoir water level and is saturated below that line. This does not consider the adverse impact of extreme heavy rainfall [50]. When a dam experiences such rainfall, the shear strength of the fill material above the saturation line can decrease rapidly due to soaking. This leads to insufficient anti-slide capacities and potential landslides, undermining flood control. This highlights the need for earth–rock dam design and safety assessment technical standards that account for slope stability calculations and risk assessments under extreme heavy rainfall conditions. The soil above the saturation line may need to be kept moist (or even saturated during prolonged heavy rainfall) to support flood safety under heavy rainfall conditions. Furthermore, it is key to provide proper drainage of the dam surface under heavy rainfall conditions. In 2021, a reservoir experienced drainage problems due to an improperly designed arch-shaped closed revetment structure. The structure prevented the rapid discharge of heavy rainfall through longitudinal and transverse drainage systems (Figure 12). This caused rainwater to infiltrate the dam and form "piping" points at weak downstream slope areas, affecting emergency response and handling efforts. These case studies highlight the need for countries to improve earth–rock dam design and evaluation technical standards, to respond to increased extreme heavy rainfall events.

Figure 12. Insufficient downstream dam surface drainage.

6.6. Strengthen the Construction of Upstream Hydrological Monitoring Facilities and Enhance Forecasting and Scheduling Capabilities

In recent years, dam breaks and incidents have generally been associated with floods exceeding design levels; a common problem has been a lack of upstream hydrological monitoring facilities. Hydrological monitoring, reservoir forecasting, and water flow scheduling have been shown to be inadequate prior to dam breaks or incidents. This significantly impacts the effectiveness of early flood release. Upstream hydrological monitoring facilities could help avoid this situation. This highlights the urgency of comprehensively strengthening the construction of upstream hydrological monitoring facilities, equipping reservoirs with forecasting and scheduling systems, and improving reservoir flood monitoring and forecasting capabilities.

6.7. Enhance the Flood Control Capacity of Cascade Reservoirs Within River Basins

Many reservoirs worldwide are integrated into river systems; most rivers in China have cascade reservoirs. China actively practices joint operations with water conservancy projects. Examples of these projects include reservoirs in the Yangtze River Basin to support flood control, water supply, ecology, power generation, navigation, and other socio-economic activities. By 2022, the number of water conservancy projects included in the Yangtze River Basin joint operation increased to 111; of these, 51 were control reservoirs, with a total regulation capacity of 116 billion m^3 and a total flood control capacity of 705 billion m^3. Recent years have seen frequent successive dam breaks, such as the previously discussed successive dam breaks of Edenville Reservoir and Sanford Reservoir in the United States in 2020, and the successive dam breaks of Yong'an and Xinfa reservoirs in Inner Mongolia on 18 July 2021. The scales of cascade reservoir projects on rivers vary, with different construction timelines. Control reservoirs in cascade systems often hold particularly significant importance; their destruction can have extreme adverse effects on downstream reservoirs.

6.8. The Rationality of Flood-Driven Design Calculations Needs Further Research and Resolution

There is a lack of rich and accurate water and rain information for small and medium-sized reservoirs. Design floods of most of these reservoirs are calculated using frequency analysis methods based on rainstorm data; the calculations estimate design rainstorms and subsequently calculate design floods based on calculated runoff generation and confluence.

There is considerable uncertainty in calculating design rainstorms that occur rarely beyond a certain magnitude using this method. The rainstorm measurement series is relatively short: generally over a century. It is difficult to estimate historical rainstorm events quantitatively using technical approaches. This makes it somewhat questionable to use design rainstorms, extrapolated from measured rainstorm series over less than a century, to design rainstorms with a return period of 1000 years or more [51].

United States guidelines do not recommend estimating hydrological design values beyond a 1000-year return period using frequency calculation methods based on measured hydrological series data. For small and medium-sized reservoirs with high-risk levels, the PMF is calculated using hydro-meteorological methods and is then compared with the results calculated using frequency analysis methods. This supports the selection of reasonable design values [43].

7. Recommended Strategies for Reservoir Flood Risk Prevention and Control

7.1. Determine Flood Control Standards for Small and Medium-Sized Reservoirs Based on Risk Levels

Drawing on experiences from Switzerland and France, this study comprehensively considers dam height and storage capacity to estimate China's dam risk standards (Figure 13). Reservoir dams with a level-I risk (extremely high risk) are defined as having a capacity $\geq$ 100 million m^3 or dam height $\geq$ 70 m. The associated flood control standards are determined based on current large-sized reservoir standards. Small and medium-sized (type 1) reservoirs, with dam heights of 70~100 m, follow the standards for large-sized (type 2) reservoirs. Small and medium-sized dams with dam heights $\geq$ 100 m follow the standards for large-sized (type 1) reservoirs. Dams with level-II risk (high risk) are defined as those with a capacity of 10 to 100 million m^3, or a capacity of 1 to 10 million m^3 and a dam height of 30~70 m, or a capacity < 1 million m^3 and a dam height of 50~70 m. The flood control standards for these dams are determined based on current standards for medium-sized reservoirs. Dams classified as dams with level-III risk (medium risk) are defined as those with 50 m > dam height $\geq$ 10 m and a capacity < 1 million m^3 with severe downstream impacts or a dam height < 30 m and a capacity of 1~10 million m^3. The flood control standards for these dams are determined based on current standards for small-sized (type 1) reservoirs. Dams with level-IV risk (low risk) are those with a dam height < 10 m and a capacity < 1 million m^3; the associated flood control standards are determined based on current standards for small-sized (type 2) reservoirs.

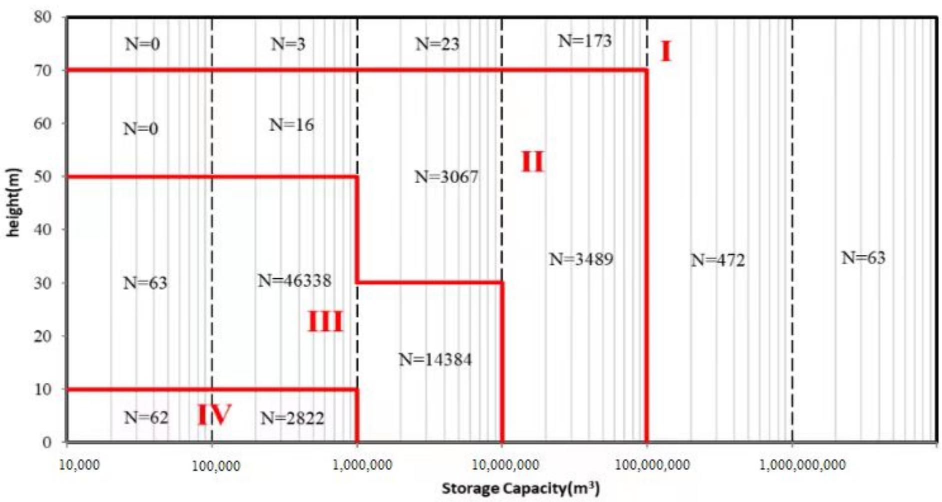


Figure 13. Schematic diagram of reservoir risk classification based on dam height and capacity.

7.2. Research Measures to Improve the Flood Control Capacity of Small and Medium-Sized Reservoir Projects

Design requirements are needed to determine dam crest elevation, upgrade spillway facilities, and arrange drainage facilities for small-sized reservoirs to address water retention, flood control, and drainage. Summarizing the experiences of earth–rock dams that have overtopped without breaking and researching resistance technologies for these dams and small-sized reservoirs could support this. It is also important to consider the arrangement of temporary flood discharge channels for floods exceeding design levels. Structural designs should include dam crest pavement hardening, slope protection and drainage, monitoring facilities, and flood control roads. Research is also needed on emergency flood prevention and rescue measures for small and medium-sized reservoirs, including temporary flood discharge channels, dam surface emergency protection, and emergency emptying of capacity. Rapid emptying techniques are needed for emergency situations, as are technologies for increasing flood discharge capacity, and for protecting small-sized reservoirs and slopes after the reservoir overtops, but before it breaches. Equipment and processes are also needed to rapidly construct emergency flood discharge channels to respond to floods exceeding design levels. Integrated technologies, materials, and compact equipment would help rapidly detect and diagnose risks in reservoir dams, detect leaks, plug dam breaks, and support the rapid emergency response and repair of structures penetrating dams [52]. These efforts would significantly improve the emergency rescue capabilities and management levels of major water conservancy projects.

7.3. Strengthen Flood Risk Prevention and Control Measures for Reservoirs

A scientific shift in flood risk management concepts is needed to transition from reducing disaster losses to alleviating disaster risks and allowing downstream areas to bear reasonable flood risks. Each country should study reservoir flood control measures tailored to their specific conditions. It is crucial to enhance emergency awareness about unexpected events, particularly at small and medium-sized reservoirs, and to improve the mindset, sense of responsibility, and technical expertise of reservoir managers and supervisors. This would help improve professional competence and implementation of regulatory standards. Comprehensive management facilities, such as meteorological and hydrological monitoring, dam safety monitoring, flood control transportation, communication, warning, and lighting systems, should be improved. Measures assessing forecasting, early warnings, drills, and contingency plans need reinforcement to effectively improve the emergency management capabilities of small and medium-sized reservoirs. Research on flood standard selection and design flood calculations is needed; topics should include improving the dependability of design rainstorms with a return period beyond a thousand years, maximizing the use of datasets spanning less than a century of recorded rainfall, and addressing the absence of recent extreme precipitation events in existing hydrological calculation guidelines.

7.4. Develop a Risk Prevention and Control Platform for Reservoir Dams

In the United States, FEMA and DHS have prioritized research and development of dam safety decision support technologies. This has resulted in a dedicated flood simulation system (DSS-Wise) for analyzing dam or levee breaches, floods, landslide-generated waves, and flood evolution. This supports the formulation of federal and state dam emergency management plans. DSS-WISE™ Lite covers 37 states, providing nearly 10,000 flood scenario simulations for over 600 users since its launch in November 2016, involving 2217 dams and averaging 32 simulations per day. The tool produces flood risk maps for emergency management planning and other tasks.

More broadly, it is critical to strengthen the construction of management and emergency facilities for hydrological and meteorological monitoring, safety monitoring, flood control transportation, communications, and managing reservoir power supplies; implement measures to assess forecasts, early warnings, drills, and contingency plans for reservoir emergencies; promote smart water conservancy construction; improve the quality of contingency plans; prepare for emergency prevention and handling; organize drills; and further enhance the risk prevention and control capabilities of crucial water conservancy infrastructure.

8. Conclusions

This paper applies statistical and causative methods to explore methods for assessing extreme climatic conditions and reservoir flood events, compare different countries' flood control standards, describe the problems and challenges, and outline implications and recommendations. By analyzing dam-break incidents worldwide, this paper describes the new flood risks confronting reservoirs. It reviews relevant research findings on reservoir flood risk management under extreme climatic conditions, compares methods that different countries use to determine reservoir flood control standards, and conducts an in-depth analysis of the problems and challenges associated with reservoir flood risk management. This paper describes implications for reservoir flood risk prevention and control and presents strategies for managing reservoir flood risks under extreme climatic conditions.

The findings indicate that the forces driving flood risks are influenced by atmospheric circulation and vegetative changes in the underlying surface or land use. There is a clear increase in the probability of dam breaks or accidents caused by floods exceeding design levels. Most dam breaks or accidents occur in small and medium-sized reservoirs, due to low flood control standards and poor management. This highlights the need for measures that improve the flood prevention capacity of medium and small-sized reservoirs. In addition to revising the existing standard system, this paper proposes key measures to cope with floods exceeding design standards. This includes implementing an improved flood standard based on dam risk and the rapid reduction in reservoir water level. To prevent breaks in the case of overtopping, earth–rock dam designs should consider extreme rainfall events. Flood prevention standards should be clearer, and the effectiveness of flood calculations should be studied and improved. This paper enriches evidence related to reservoir flood risk characteristics under extreme climatic conditions and has theoretical and practical significance for lowering reservoir flood risk and safeguarding people's lives and property under extreme climatic conditions.

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