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Climate Change, Unprecedented Floods, Dam Failures, Dam Hazards & Safety Aspects – An Indian Perspective

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Abstract:

Climate change is exacerbating extreme weather events globally, leading to unprecedented floods, particularly in South and Southeast Asia, including India. These events pose significant hazards to dam safety, as demonstrated by recent failures and damages to hydropower infrastructure in India, often linked to extreme hydrological events like intense rainfall, cloudbursts, and glacial lake outburst floods (GLOFs). Many Indian dams, including a significant number over 50 or even 100 years old, were designed using historical data that may not account for current climate change impacts, increasing their vulnerability. Overtopping due to inadequate spillway capacity is a primary global cause of dam failure, though piping failures are historically more frequent in India.

This paper reviews the impacts of climate change on flood frequency and intensity, examines dam failure statistics and causes (emphasizing hydrological factors), and discusses the concept of Inflow Design Flood (IDF) selection. It compares international practices for dam classification and IDF selection (including risk-based approaches used in countries like Australia, Canada, and the UK) with current Indian standards (IS 11223-1985 and recent CWC hazard potential guidelines). The review highlights a disconnect between current IDF estimation methods (including PMP/PMF concepts) and the need to incorporate non-stationary climate change effects.

Key findings emphasize the need for India to adopt a comprehensive, risk-based dam safety framework, update IDF guidelines to explicitly account for climate change projections, improve data sharing and transparency, and enhance emergency preparedness, including the implementation of Early Warning Systems (EWS). The paper concludes that ensuring long-term dam safety requires integrating climate science into engineering practices, strengthening legal frameworks like the Dam Safety Act 2021, adopting design innovations, and fostering better coordination among stakeholders. Striking a balance between risk minimization and cost management through risk-informed IDF selection is crucial for mitigating potential disasters.

Key words: Dam safety, Dam Hazard, Inflow Design Flood, Early Warning System, Unprecedented Flood, GLOF

I. INTRODUCTIONssss

WHO defines "**flood**" as "*the most frequent type of natural disaster and occur when an overflow of water submerges land that is usually dry. Floods are often caused by heavy rainfall, rapid snowmelt or a storm surge from a tropical cyclone or tsunami in coastal areas.*"[1] NWS, Morristown, TN defines **"flash flood"** as *"A flash flood caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours. Flash floods are usually characterized by raging torrents after heavy rains that rip through river beds, urban streets, or*

[1] https://www.who.int/health-topics/floods

mountain canyons sweeping everything before them. They can occur within minutes or a few hours of excessive rainfall"[2].

India like several other South Asian countries has been affected by natural disasters resulting from extreme flooding with devastating consequences, some of which are believed to be associated with the La Niña phenomenon [1]. According to IPCC, "*Generally, heavy daily precipitation events that lead to flooding have increased, not everywhere. Tropical storm and hurricane frequencies vary considerably from year to year, but evidence suggests substantial increases in intensity and duration since the 1970s……..*" [2]. While tropical storm and hurricane occurrences fluctuate annually, evidence indicates a significant rise in their intensity and duration since the 1970s [3]. Unarguably, the natural environment is impacted by climate change factors with hydrologic cycle being the directly and severely hit [4]. A recent award-winning study by a team of researchers from Japan pinpointed and earmarked regions which will be affected by weather extremes due to climate change [1], [5]. The study is highly significant, as numerous areas are already facing more frequent and intense hydrological extremes, with forecasts indicating these events to likely intensify in future. It is, however, important to acknowledge that such projections carry a considerable degree of uncertainty [6].

Across the globe in various regions, the effect of climate change on extreme weather events viz. flooding, draught, precipitation shift etc. have been a matter of extensive research. [7]. Severe unpreceded flooding has been noticed in various countries with recognizable extent in South and Southeast Asia. These extreme weather events being experienced in the recent past are an outcome of heavy precipitation, cloudbursts, high tides or a combination of all these factors [5], [8]. In recent years, climate change has contributed to a rise in severe and unprecedented flooding globally, with a notable concentration in South and Southeast Asia [9], [10]. Extreme events are seen to be frequently being activated by heavy rains, cloudbursts, high tides, or a combination of these factors [2], [11], [12], [13]. India also is confronted with similar hazards with projection indicating a rise in extreme weather events [14]. Goswami et al. (2006) emphasizes that fluctuations in sea surface temperatures across the tropical Indian Ocean significantly impact the daily variations in precipitation observed during the summer monsoon season [15]. Additionally, multiple scholars have linked the increasing trend of irregular precipitation patterns to significant anomalies in Indian summer monsoon rainfall and atmospheric circulation [16], [17]. It goes without saying that these consequences result in substantial unexpected expenses for various economic entities, ultimately reducing overall welfare. The severe toll on life and property as consequence of extreme weather events, such as floods, failure of dams due to overtopping has been extensively recognized in India [18].

Hydrological study and parameters play a critical role while fixing the spillway discharge capacity of dams during the design phase ensuring that the dam is safe under extreme hydrological event and serves the intended purpose over its designed life [19]. While historical long-term data are applied for estimation of inflow design flood (IDF) using recommended practices and sound engineering principles, the so determined flood value is also subjected to uncertainty due to climate change factors [20]. Dam safety aspects endangered by climate change has therefore become a matter of global concern.

Unprecedented floods, along with long-term shifts in precipitation patterns, have underscored the susceptibility of dams to changing climate impacts [21]. History of dam failures also highlights the fact that both natural and human related factors are responsible for dam failure, or dam break. International humanitarian law recognizes dams as "*works and installations containing dangerous forces*" due to significant hazards posed by them[3]. Dam failures can lead to devastating consequences, threatening human lives, ecosystems, and the environment.

As per report of USADSO, since 2005 till 2013, 173 dams met with failure[4]. Data indicates that extreme weather was the primary cause of most failures, with average age of failed dams being 62 years[5]. Recent disasters expose the vulnerability of hydropower dams in the Himalayas. In 2013, a severe flash flood in Uttarakhand caused significant damage to the region's hydropower infrastructure [22]. The overwhelming flow of water, along with boulders, debris, and silt, clogged dam's floodgates, resulting in overtopping and extensive destruction[6]. This was followed by further experience of drastic changes in the extreme weather events leading to damages of few more important dams[7].

[2] https://www.weather.gov/mrx/flood_and_flash
[3] https://ihl-databases.icrc.org/en/customary-ihl/v1/rule42
[4] https://damsafety.org/dam-failures
[5] ICOLD Incident database Bulletin 99 update
[6] https://www.circleofblue.org/2014/world/uttarakhand-flood-disaster-made-worse-existing-hydropower-projects-expert-commission-says/
[7] https://sandrp.in/2013/09/27/uttarakhand-floods-of-june-2013-curtain-raiser-on-the-events-at-nhpcs-280-mw-dhauliganga-hep/

Dam construction contributed to expanding irrigated cropland, providing affordable power, and supporting economic growth [23]. They do play a pivotal role in curtailing the impact arisen from frequent flooding, but do present a serious risk of catastrophic failure if it is incapable to spill the flood water in a regulated way [24] Upon completion, the investment made in dam is irreversible. Although extreme weather events, particularly precipitation fluctuations, were not a significant procedural issue in the 1980s', these dam-spillways are now confronted with risks stemming from the increased fluctuations in precipitation and extreme rainfall events [3], [23]. With rainfall intensity variations observed in last few years in India, it is essential to assess if dam-spillways are truly effective in reducing flood risks, especially in light the unforeseen hazards it brings in [3], [21], [25]. A recent evaluation of large dams in India[8] by CWC revealed higher sedimentation rates in dams along east-flowing rivers and those in the Indo-Gangetic plains and this increased sedimentation reduces the storage volume of reservoirs, which in turn raises the likelihood of flooding in upstream and the downstream area [26].

Despite its complexity, evaluating dam flood risks offers a logical foundation for effective risk management, a practice that has gained growing recognition among researchers and industry professionals. Engineers and professionals must therefore tackle this significant challenge of maintaining dam safety amid an evolving global climate [27]. As scientific advancements lead to new climate projections, dam owners must adopt a flexible approach to address this evolving challenge ([8]). It has therefore become extremely essential to look into the aspect of probable dam failures in greater details, particularly for the older dams which were designed with the then hydrological inputs, which seem to be affected drastically by climate change phenomenon.

II. CAUSES OF DAM FAILURES AND DAM FAILURE STATISTICS

ICOLD Bulletin 99 defines a dam failure as "*A failure is a catastrophic incident characterised by: an uncontrolled release of impounded water; and/or by a total loss of integrity of the dam structure, its foundation or abutments.*"

Although dam break is a physical event with tangible impacts, it occurs solely not due to a physical malfunction [28]. Dams operate according to natural physical laws, meaning failures ultimately stem from human shortcomings in design, construction, inspection, assessment, maintenance, or operation [25], [28]. A failure of dam can happen due to one the following reasons in isolation or in conjunction [29], [30], [31]: Overtopping due to flood in case the spillway capacity is exceeded; Structural failure; Poor maintenance and lack of proper upkeep; Instability or failure of the dam's foundation due to geological factors; Subsidence and cracking; Piping and internal soil erosion in fill dams; Intentional sabotage or destructive acts. These causal events are interconnected, and one can trigger another. For instance, blockages in conduits or spillways caused by poor maintenance can prevent excess water from being spilled properly, potentially leading to overtopping.

"Lessons from Dam Incidents" (1973) published by ICOLD is an important document with relevance to dam safety. Since

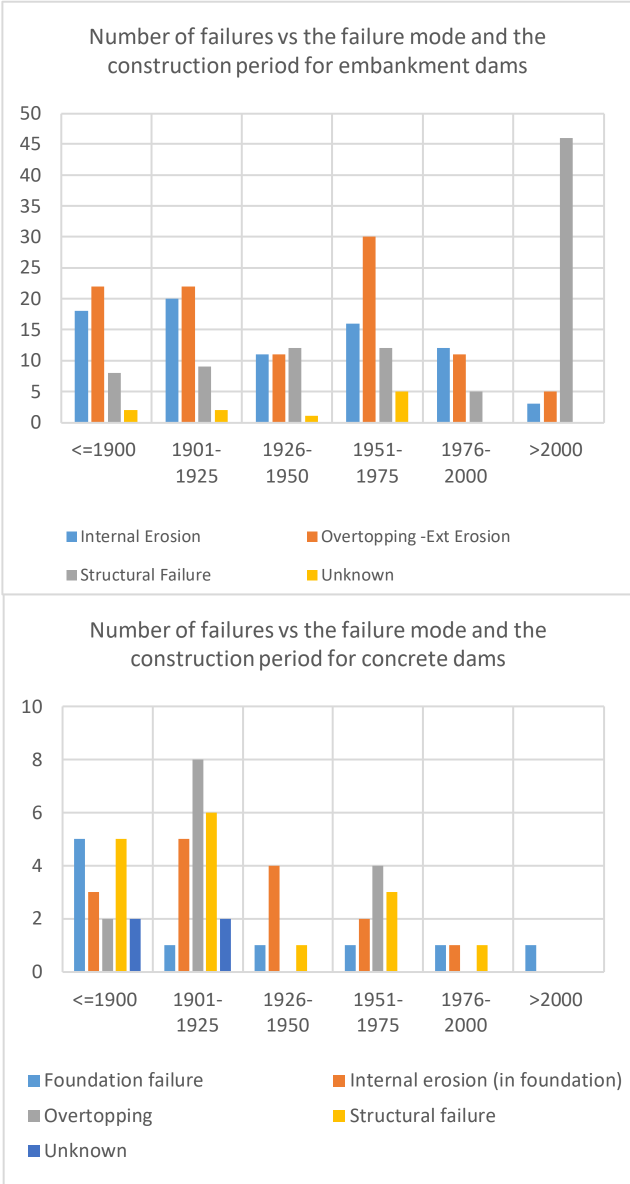

Figure 1: Dam failure statistics (Source: ICOLD Bulletin 99)

then, number of additional works expanded the collection, including ICOLD Bulletin No. 99, *"Dam Failures - Statistical Analysis"*. Three ICOLD bulletins have been specifically created to describe and statistically analyse dam incidents. The most recent of these, Bulletin 99, was published in 1995 which

[8] Central Water Commission, 2020

documented 202 large dam failures. An updated report now includes 120 more failure cases, with 65 occurring before 1993 and 55 between 1993 and 2018. About 4000 large dams have failed for various reasons across 84 countries till date, excluding failures in China[9][32]. This estimate is likely to be a gross underestimation as many such incidents remain unreported [33]. Approximately 4000 dams have failed in China alone as reported by Cheng et al. (2010) with about 500 failures in 1973 itself [34]. Moreover, 37,000 dams in China are categorised as dangerous[10]. Records indicate that China suffered most devastating dam failure; Banqiao dam break in 1975, which resulted into cascading failure of 60 downstream dams taking lives of more than 80,000 people, while further death toll due to epidemic and food shortage was close to 200,000[11]. This single failure event displaced 11 million people. A well-known instance about catastrophic dam break is the Teton-Dam collapse in Idaho, USA, in 1976. Despite the relatively low loss of life (11 deaths), the disaster led to property damages estimated at more than USD 1 billion[12,13]. It is estimated that over 5,000 large dams worldwide are over 50 years old, many of which have surpassed or are approaching the end of their design lifespans, posing potential risks[14]. Realising this aspect of dam safety for these ageing dams, countries like the USA, China, and others with extensive dam infrastructure have taken steps and developed systems to mitigate these risks.

III. HISTORICAL OVERVIEW ON DAM FAILURES DUE TO OVERTOPPING

While dams can serve as a strategy to mitigate floods caused by heavy rainfall, they may also increase risks during extreme precipitation events (Thakkar, 2018)[15]. During periods of intense rainfall, a dam can increase flood risks for both upstream and downstream areas [14]. When water flows over the crest of a dam, particularly a fill dam, erosion takes place leading to failure. Overtopping has remained most common cause of failure [35] and are typically caused by:

- *Extreme Flooding* – If a dam is not designed to handle excessive rainfall or rapid snowmelt, the reservoir may exceed capacity, leading to overtopping.
- *Insufficient Spillway Capacity* – If the spillway is too small or blocked or of inadequate capacity, spillage over the dam top will occur.
- *Structural Weaknesses* – Poor construction, aging materials, or lack of maintenance can make the dam vulnerable to erosion once overtopped.
- *Seismic Activity* – Earthquakes can destabilize the dam, making it more susceptible to overtopping if water levels rise rapidly.
- *Landslides* – A landslide into the reservoir can displace water, creating waves that overtop the dam.
- *Malfunctioning of gates* – Operation failure of gates due to total or partial jamming, or because of electrical failure

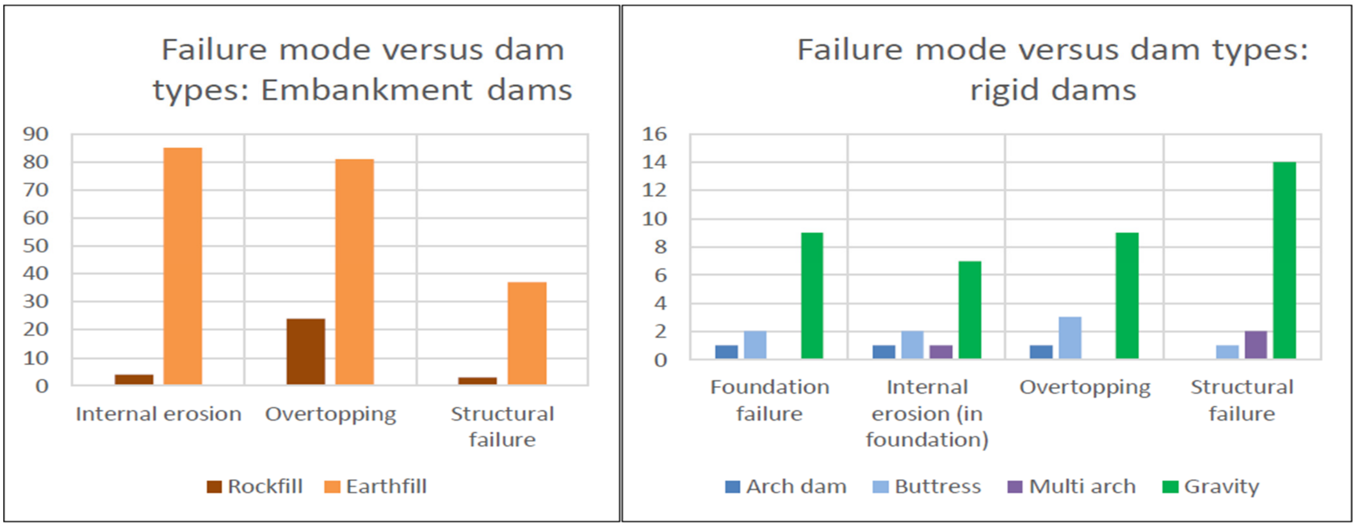

Figure 2: Number of failures according to the dam type and the failure mode (Source ICOLD Bulletin 99)

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[9] (https://www.internationalrivers.org/and-the-wallscame-tumbling-down.)
[10] https://www.reuters.com/article/environment-china-dams-dc/china-warns-of-faulty-dams-danger-plans-repairs-idUSPEK33020620080115/
[11] https://www.internationalrivers.org/and-the-wallscame-tumbling-down
[12] Failure of Teton Dam : final report / by U.S. Department of the Interior, Teton Dam Failure Review Group (https://catalog.hathitrust.org/Record/000096370)
[13] https://damsafety.org/dam-failures
[14] https://www.internationalrivers.org/damming-statistics
[15] https://www.epw.in/journal/2018/38/commentary/role-dams-keralas-flood-disaster.html (H. Thakkar 2018)

or because of excessive floating debris is susceptible to cause overtopping.

- *Human Error* – Mismanagement of reservoir levels, such as delayed water release before a major storm, can contribute to overtopping.

While some dam failures caused by flooding resulted from structural spillway issues, the majority occurred due to crest overflow followed by subsequent washing away of d/s face and base. Interval between a breach formation and its further expansion depends on the dam's material [33]: adequately compacted earth can endure a 50 cm nappe depth for several hours, with progressive breaching; insufficiently compacted sections may fail within an hour under a 30 cm nappe depth, leading to rapid breach expansion; rockfill can resist one meter flow depth for hours, though once erosion starts, it will expand fast. Therefore, overtopping interval plays critical role in determining the level of risk [33].

Factors like insufficiency of spillway capacity, blockage of spillways by floating debris, or crest settlement etc. have been responsible for about 34% of dam failures in USA [35]. It is worthwhile to mention that overtopping failures in USA for the period 2010- 2017 exceeded by far all the other failure mechanisms as per the data of ASDSO[16]. Floods are therefore a major contributing factor to dam overtopping, posing significant risks to dam safety [36]. ICOLD (1995) mentions that, the most significant reasons of failures are overtopping (40%) followed 27% failures due to piping[17]. In contrast, Indian history of dam failures shows that maximum dam failures (44%) is due to piping followed by overtopping (25%)[18].

IV. FLOOD AND HAZARD FOR DAMS IN INDIA

Over the past two decades, North, Northeast, and South India have experienced a steady rise in extreme rainfall events, likely driven by increasing sea surface temperatures, resulting in frequent flooding [37]. As flood intensity has increased, so have the damages they cause. Notable flood events in recent Indian history include the Chennai floods, the Mumbai floods, the Kedarnath flood, and the Kerala flood etc. [38]. In 2020 alone, three major flooding disasters took place: one in WB and Jharkhand because of Cyclone Amphan, another in Assam and Meghalaya caused by incessant downpour, and a third in Bihar following a sudden cloudburst in Nepal [3], [39].

Literature review focusing on the safety and sustainability of Indian dam projects in relation to climate change, including glacier melt and GLOFs, shows that extreme hydrological events triggered by climate change have become increasingly common and they carry a significant risk to the structural integrity of these dams [40]. This threat is particularly concerning due to location of most dams in inherently vulnerable regions, such as the Himalayas prone to seismic activity, young erosion-sensitive mountains, flash floods, avalanches, and landslides [41] further exacerbating the risks to dam safety.

One of the primary causes of flooding in India is the insufficient capacity of riverbanks, which struggle to contain high flows and this issue has been worsened by erosion and the silting of riverbeds and the impact of climate change [42]. Additionally, factors such as landslides altering flow paths, inadequate natural drainage, glacial outbursts, and dam failures further contribute to flooding [43].

As per the information provided in the National register of large (specified) dams, 2023, 220 Indian dams are more than a century old[19]. Amongst 70 large dams of national reputation, 15 are older than 50 years, of which 3 have surpassed 80 years or more of their lives [32]. Given this large number of dams operating in India, the country is confronted with significant risk of dam hazard due to probable structural weakness. Over the past two decades, major floods have frequently been linked to dam failures and breached embankments[20].

Another risk emanates from the absence and partial adoption of emergency plans by dam operators and administrative authorities. The CAG report submitted to Parliament in 2017 revealed that just 7% of the constructed dams have emergency plans in place (CAG, 2017)[44].

One major risk associated with dams in India arises from the risk of seismicity for their location in seismically active zones [30], [40], [45]. Additionally, cumulative sediment deposition over the years and absence of effective sediment removal mechanism has reduced storage volume of reservoirs on a continual basis [26].

It is noteworthy that while the dams themselves may not have undergone significant changes, the associated risk factors have certainly evolved due to the aforementioned factors [23]. With such large number of existing dams operating at different locations, along with the construction of new ones, it is clear that more habitat is being exposed to flood hazards from probable failures [46].

According to reports from the Dam Safety Organization, CWC, GOI, India experienced 23 major dam failures during period from 1960 and 2010, several of which resulted in significant loss of life and property [32]. The most notable case is the 1979 failure of Machchu Dam in Gujarat, which caused over 2,000 deaths, with some estimates suggesting the mortalities could have exceeded 20K [32].

In light of the risks posed by dams, the country will need to develop mitigation systems to address the significant threats

[16] https://damsafety.org/dam-failures
[17] ICOLD Incident database Bulletin 99 update
[18] Dam Safety Organisation, Central Water Commission, Government of India
[19] National register of large (specified) dams, 2023
[20] https://www.epw.in/journal/2018/38/commentary/role-dams-keralas-flood-disaster.html (H. Thakkar 2018)

associated with its large number of existing dams, following the example set by the USA and China.

V. SOME DAM FAILURES EXPERIENCED IN INDIA IN RECENT PAST DUE TO UNPRECEDENTED FLOOD

Few notable dam failures experienced in recent past due to extreme hydrological events are being cited here.

- **Dhauliganga Power station (280MW)** in Uttarakhand, an unprecedented flood of 1377 cumec was recorded on June 16th and 17th, 2013, causing significant damage to several components of the power station, including the spillway structure[21].
- **Tanakpur Power Station** in Uttarakhand was commissioned in 1992. The project experienced an unprecedented flood of 5.35 lakh cusec in June 2013, leading to a massive deposition of riverbed material in the central part of the reservoir. This resulted in a significant increase in flow concentration, causing scouring and damage to the riverbed[22].
- **Dam in Vishnuparyag hydropower project** in Uttarakhand was substantially damaged by Uttarakhand floods in 2013. The barrage of the project was covered completely with debris and the river had changed its course. The 2013 floods also damaged other hydropower projects in Uttarakhand, including the Phata-Byung Hydroelectric Project, the Singoli-Bhatwari Hydroelectric Project, and the Alaknanda Hydro Power Project[23].
- **The Bairasiul Power Station (3x60MW)** in Jammu & Kashmir surpassed its 35-year useful life in March 2017. In September 2017, an unprecedented flood damaged the d/s slope of the dam, compromising its stability.
- **Annamayya Dam, AP:** Construction of the dam comprising of a 336 m long earth dam along with 94 m long concrete Ogee spillway with 5 radial gates started in 1976-77 and completed in 2001. The spillway was designed for discharging 8069 cumec (200-year return period flood), however, model studies indicated discharging capacity of 6144 cumec only. Discharging capacity further reduced to 5097 cumec (with 5 gates operational) due to problems of right-wing wall. 5th spillway gate was damaged during cyclone NIVAR in Nov. 2020. The observed peak flood was 9200 cumec. On 19th Nov. 2021, reported inflow of about was 9061 cumec which was sustained over 2 hours, and subsequently overtopped the embankment dam causing its breach in entire length[24].
- **Dam in Rishiganga Hydro Electric Project:** The February 7 2021 Chamoli deluge has completely destroyed 13.2 MW Rishiganga Hydro Electric Project. The river bed level was elevated by a depth of 2m to 12 m following sediment deposition by the silt laden flood. The project has also become graveyard for over 50 innocent workers and villagers[25].
- **Tapovan Vishnugarh HEP** (520 MW) in Uttarakhand presently under construction was severely affected by flooding event resulting into huge silt deposition in desanding tanks, head race tunnel and adit tunnels. About 11-13 m debris deposition took place around the Tapovan plant causing extensive damage to sluices gates, and other structures[26].
- **Flooding of 2,000 MW Subansiri lower HEP -** On 25th Sept. 2022, heavy torrential rainfall resulted into a flooding situation causing severe damage to a portion of powerhouse protection wall following inundation of powerhouse. At this time, project was in advanced stage of completion and work of Dam and Erection of Electromechanical Equipment was in full swing. Ist and 2nd unit were scheduled to be commissioned by Jan.22 and Feb. 22[27].
- **Sikkim's Chungthang dam collapse on October 4, 2023-** A GLOF actuated event completed washed away the CFRD dam triggering a surge of 12-20m in the downstream Teesta River which created serious disaster across many districts. 74 mortalities were reported[28].

Dam failure by overtopping can be addressed by a proper design of spillway, the first and foremost step will be proper determination of IDF for an adequate spillway design. Accordingly, a review of the existing guidelines followed by various countries across the globe is made in this paper.

VI. SELECTION OF IDF

Estimating design floods is crucial for planning and managing flood risk [47]. The inadequacy of spillway structure to pass the impinged flood without causing any damage has remained one of the most common reason for dam failure, particularly for embankment dams [35]. Careful selection of IDF compatible with the required safety standard requirements, therefore, is of utmost importance [48]. Impact evaluation and design standards should be complimentary to each other. Design parameters typically determine magnitude and nature

[21] https://sandrp.in/2021/09/27/uttarakhand-disaster-around-nhpcs-dhauliganga-hydropower-project/
[22] https://timesofindia.indiatimes.com/city/lucknow/uttarakhand-floods-ravage-harduaganj-power-plant/articleshow/20837259.cms
[23] https://www.downtoearth.org.in/environment/vishnuprayag-hydel-project-suffers-extensive-damage-41610
[24] https://indianexpress.com/article/cities/hyderabad/andhra-pradesh-deluge-annamayya-dam-cheyyeru-river-7634151/
[25] https://www.mercomindia.com/ntpc-hydropower-project-damaged-floods
[26] https://sandrp.in/2021/02/20/tapovan-vishnugad-hpp-delays-damages-and-destructions/#:~:text=The%20feasibility%20study%20of%20the,2978.48%20Crore.
[27] https://energy.economictimes.indiatimes.com/news/power/nhpcs-2000-mw-subansiri-dam-partially-damaged-in-flooding/94444151
[28] https://www.downtoearth.org.in/natural-disasters/sikkim-s-chungthang-dam-collapse-signals-the-need-for-dam-safety-emissions-reduction-92192

of impact on local environment and in turn, design needs to be finalized after careful consideration of execution cost as well as the magnitude of harmful effects measured against estimated paybacks [20], [49].

A. *History of IDF Concept Development*

It is in 1851 when on the basis of precipitation, runoff and the watershed characteristics, Thomas Mulvaney presented a rational approach to estimate peak discharge rate from a watershed[29]. With further knowledge gained on hydrological behaviors, it was realized that only runoff coefficient is not enough to generate peak flow from a watershed area as the same depends on multitude of factors [50]. Subsequently, further researches were oriented in two distinct streams: (1) hydro-physical analysis relying on precipitation characteristics; and (2) statistical validation relying on observed peak discharges.

B. *PMF AND PMP – PHILOSOPHY AND AMBIGUITY*

Probable Maximum Precipitation (**PMP**) is defined by WMO 1986 as "*...the greatest depth of precipitation for a given duration meteorologically possible for a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends.*"

Probable Maximum Flood (**PMF**) is "*a theoretical design flood that is the largest credible flood that will be experienced from meteorological conditions at a site*". PMF is estimated from PMP, combined with conservative assumptions about the catchment's hydrological response. The determination of PMF following deterministic approach relies on estimation of PMP, and estimating PMP is not only a complex aspect of hydrologic project but a topic of ongoing debate. Researchers typically rely on two distinct approaches: deterministic and probabilistic methods. The deterministic approach focuses on understanding the physical processes behind extreme events, while the probabilistic method is based on statistical principles and probability theory [3].

More than four decades ago, renowned hydrologist Yevjevich, in his influential paper titled "*Misconceptions in Hydrology and Their Consequences*", argued that the continued reliance on the concepts of PMP, despite lacking physical proof, had hindered investigation and study about the structure and probability of extremes [5], [51], [52]. He suggested that this reliance may have fostered a false sense of security regarding flood control measures. This perspective highlighted importance of incorporating probabilistic or stochastic methods for estimating extreme events. Some researchers, such as Benson, have opined to abandon the concept of PMP altogether.

Esteemed hydrologist Klemes, in his paper "*Tall Tales about Tails of Distributions*", criticized the reliance on probability distributions and large-scale extrapolations that assume stationarity for estimating return periods [53]. He contended that, despite advancements in the mathematical complexity of hydrological frequency analysis over the past five decades, these developments have neither improved the accuracy of extreme event frequency predictions nor increased reliability of structural safety assessments. Klemes suggested that modern distribution models, despite their mathematical complexity, may be no more, if not less, reliable than traditional methods, such as visually extended duration curves used decades ago. He warned that this reliance on statistical models fosters a misleading sense of certainty, which can be more dangerous than acknowledging uncertainty.

Both perspectives on extreme event estimation have faced criticism. However, it is encouraging that some researchers advocate for a unified modeling approach that integrates seemingly divergent concepts [50]. PMP assessment remains a complex as well as debated topic with significant practical implications, particularly for dam safety. Despite the ongoing uncertainties, concept of PMP remains widely used in both research and practical applications [25], [54]. It continues to be adopted in the estimation of PMF for design of spillway capacity to reduce the risk of dam break and potential fatalities [5]; [55]; [56]; [57].

VII. APPROACH TO DAM CLASSIFICATION AND IDF ESTIMATION

A. *INTERNATIONAL PRACTICE*

Recommendations for selection of IDF differs across countries and even within regions of the same country. In USA, federal guidelines serve as a general basis that states can use to develop their own regulations, though adherence is not mandatory [25]. Various federal agencies, including FEMA, FERC, USBR, USACE, ANCOLD etc. [25], [31], [58], [59] have established their own guidelines. Similarly, some states have specific regulations, while others may have none at all. In Australia, Victoria, Norway, New South Wales, Queensland, Tasmania etc. each have their own guidelines [25], [60], [61]. On the other hand, Ireland lacks national regulations, leaving dam users to determine and follow their own criteria. Conversely, countries like China enforce federal guidelines nationwide, a system that is largely mirrored in India [25], [62].

A review comparing dam safety regulations practiced by 22 countries including India was made by the World Bank (WB) which focused on the framework vis-à-vis accountability of stakeholders instead of detailing the technicality behind the assessment [63]. A study of above indicates the absence of uniform guidelines across the globe for dam safety vis-à-vis selection of IDF. Mostly, the selection of approach is seen to be dictated by a combination of factors including a) Size and topography of catchment; b) Hydro-geological nature of catchment; c) Lenience in consideration of risks; d) Data and resource accessibility; e) Extant regulation, legislature and standards

[29] https://ocw.camins.upc.edu/materials_guia/250144/2015/MetRacio1.pdf

A key concern in estimation of IDF is that frequently extreme event is the design case which is most often beyond local information and knowledge. The problem becomes more acute with higher design standard having greater probability toward uncertainty. Ascertaining the risks and associated hazard potential is being recognized globally as an important part of design procedure. Wasko et al. report that a recent review of climate change guidelines revealed that several regions globally are already integrating climate change into their design flood recommendations and for instance, Belgium, Denmark, England, New Zealand, Scotland, Sweden, UK, and Wales are all advising the use of climate change adjustment factors for IDF rainfall intensities [25], [47], [64].

ICOLD Recommended Approach

ICOLD categorized a dam over 15m in height or with a storage volume of 3 MCM as large dam and in general the IDF for large dams corresponds to PMF. ICOLD Bulletin 125 on "*Dams and Floods: Guidelines and case histories (ICOLD 2003)*" define three generations of approaches for specifying or selecting design floods, as follows: **First generation** – *based on empirical and general considerations, and applicable to any dam and in any situation, without taking into account size or type of the dam, volume of reservoir, nor downstream consequences hazard.*[65], [66]; **Second generation** – *based principally on the classification of dams according to the incremental consequences [hazard] that a potential failure pose (loss of life, economic losses, services affected, and social and environmental impacts).* Some countries used deterministic criteria and methods to calculate the "Probable Maximum Flood" (PMF) [65], [66]; **Third generation** – *the selection of the design flood(s) is based on risk and the needs of a risk analysis [65], [66].*

Based on the literature review, guidelines followed for dam classification and IDF selection in various countries across the globe are presented in the following.

AUSTRALIA

Selection of IDF in Australia is linked with risk assessment [67]. The Acceptable Flood Capacity (**AFC**) is defined as "*the overall flood capacity, including freeboard as relevant, which provides an appropriate level of safety against a flood-initiated dam failure to protect the community and environment, to acceptable overall risk levels, within the total context of overall dam safety from all load cases*".

Based on hazard categorization, IDF is selected with consideration of PMF for extreme and Category A, Smaller between PMP design flood and a return period of 1 in 1000000 for Category B & C, Smaller between PMP design flood and a return period of 1 in 100000. [25], [32], [58], [62], [67]. Table I and Table II produced below explaining classification of dams based on PAR and PLL.

CANADA

Incremental consequences; normal and flood failure scenario; potential for dam failure; transient losses; and third-party losses are the five key approaches for classification of dams in Canada. 1/3 between 1 in 1000 and PMF is considered as IDF for Class-A dams while 2/3 between 1 in 1000-year and PMF or the 1 in 10000-year flood whichever is higher is for Class-B dams. Incremental analysis or PMF is adopted for Class-C dams.[25], [32], [62]

Table I: Dam Hazard Potential Classification based on Severity of Damage vs Population at Risk (adapted from ANCOLD,2012, [32])

Population at Risk (PAR)	**Severity of Damage and Loss** e.g. health and social, environment, infrastructure, and business cost			
<1	Very Low	Low	Significant	**High C**
≥ 1 to 10	Significant (Note 2)	Significant (Note 2)	High C	High B
≥ 10 to 100	High C	High C	High B	High B
≥ 100 to <1,000	(Note 1)	High B	High A	Extreme
≥ 1,000		(Note 1)	Extreme	Extreme
Note 1: With a PAR in excess of 100, it is unlikely damage will be minor. Similarly, with a PAR in excess of 1,000, it is unlikely damage will be classified as medium.				
Note 2: Change to "High C" where there is the potential of one or more lives being lost.				

Table II: Dam Hazard Potential Classification based on Severity of Damage vs Potential (adapted from ANCOLD,2012, [32])

Population Loss of Life (PLL)	Severity of Damage and Loss e.g., health and social, environment, infrastructure, and business cost			
<.1	Very Low	Low	Significant	High C
≥ .1 to 1	Significant (Note 2)	Significant (Note 2)	High C	High B
≥ 1 to <5	High C	High C	High B	High B
≥ 5 to <50	(Note 1)	High B	High A	Extreme
≥ 50		(Note 1)	Extreme	Extreme
Note 1: With a PLL equal to or greater than one (1), it is unlikely damage will be minor With a PLL in excess of 50, it is unlikely damage will be classified as medium				

Table III: Required range of acceptable flood capacities for different hazard categories (adapted from Source: ANCOLD, 2012 and [32])

Incremental Flood Hazard Category	Flood Annual Exceedance Probability
Extreme	PMF
High A	PMP* design flood
High B	Smaller between PMP design flood and 10⁻
High C	Smaller between PMP design flood and 10⁻
Significant	5 x 10^{-4} to
Low/Very Low	Upto 5 x 10⁻

Table IV: Parks Canada Agency (PCA) IDF Selection

Hazard Potential Classification	Range of Inflow Design Floods for Life Safety Hazards[1]			Range of Inflow Design Floods for All Other Hazards
	Expected	Transient Population at Risk	Range of Inflow Design Floods for Life Safety Hazards	
Very low	0	For major flood events, transient use would not be expected		25-yr flood to 100-yr flood
Low				100-yr flood
Significant				100-yr flood to 1,000-yr flood
High A	10 or less		1/3 between 1:1,000-yr flood and PMF	1,000-yr flood
High B	11 to 100		2/3 between 1:1,000 years and PMF or the 10,000-yr flood whichever is greater	
High C	>100		Incremental analysis or PMF	

CHINA

Based both on project characteristics, and pertinent risk to downstream in dam break event, China classifies dams into five categories considering seven different criteria. [25], [32]

Table V: China Dam Classification Table (Adopted from ICOLD, Bulletin 170, [32])

Rank c Projec	Storage Capacity (hm^3)	Flood Prevention		Water Logging	Irrigation	Water Suppl	ater Pow
		Cities and Industrial Areas	Flood Preventio Farmlanc (10^3 ha)	ogged Area (10^3 ha)	Area (10^3 ha)	ities and Min	IC (MW)
I	> 1000	Very Important	> 333	>133.3	> 100	Very Important	>750
II	100 – 1000	Important	67 - 333	40 – 133.3	33.3 - 100	Important	250 - 750
III	10 - 100	Moderately Important	20 - 67	10 - 40	3.3 – 33.3	Moderately Important	25 - 250
IV	1 - 10	Less Important	3.3 - 20	2.0 - 10	0.3 – 3.3	Less Important	0.5 - 25
V	< 1		< 3.3	< 2	< 0.3		< 0.5

Table VI: Table 6: Classification of Hydraulic Structures in China (ICOLD, Bulletin 170)

Rank of Project	Grade of Permanent Structures		Grade of Temporary Structures
	Main Structures	Grade of Permanent Structures - Less Important Ones	
I	1	3	4
II	2	3	4
III	3	4	5
IV	4	5	5
V	5	5	-

Table VII: Inflow Design Flow in China (ICOLD Bulletin 170)

Return Period of Flood		Grade of Hydraulic Structures				
		1	2	3	4	5
Design Flood		500	100	50	30	20
Check Flood	Embankment	10000 or PMF	2000	1000	500	200
	Concrete	5000	1000	500	200	100

France

Risk approach is not explicitly used for dam categorization in France. France adopts four level classification system, on the basis of dam height, and an empirical factor related to height and storage volume.[25], [32], [62]

Class	A	B	C	D
H (m) V (hm^3)	H ≥ 20	H ≥ 10 $H^2\sqrt{V} \geq 200$	H ≥ 5 $H^2\sqrt{V} \geq 20$	H ≥ 2

The French adopts a double approach for IDF selection for all dams above 50,000 m^3: Exceptional flood and Extreme flood.

	Exceptional floods		Extreme Floods
Class	Rigid Dams	Fill Dams	Exceedance probability
A	1000 to 3000	10000	10^{-5}
B	1000	3000	3 x 10^{-5}
C	300	1000	10^{-4}
D	100	300	10^{-3}

For exceptional floods, sufficient freeboard safeguarding the dam from waves is available, but the freeboard is smaller than the one computed to cater normal conditions without adoption of exceptional floods. The dam must satisfy all safety aspects with respect to stability, piping, etc. For an extreme flood situation, rise in water level may compromise the structural stability. For extreme floods, therefore, existing dams are reassessed to explore the need to augment spillway capacity or incorporate any other innovations.

GERMANY

DIN 19700 part 10 and part 11 relate to the recommendations. Explicit consideration of downstream hazard is not followed, but one of the classified IDF takes the risks into account indirectly. Bulletin 170 (ICOLD, 2018)[25], [32], [62]

The DIN classifies dams under two types, class 1 with dams > 15m high and volume of 1 hm^3 and rest of the dams falling under Class 2. IDF corresponding to these dam classes are

A. IDF 1, for normal spillway design and safety with a flood frequency 1 in 1000 for Class 1 type and 1 in 500 for Class 2 type.
B. IDF 2, ensures structural safety while allowing some damages to ancillary components.
C. IDF 3 is applicable to normal flood storing capacity.

IRELAND

No national recommendations exist in Ireland. Rather, selection criteria is left to the dam operators, top priority however safety aspects of the dam. Two types are defined: Category A, where a break is a threat to loss of life, and Category B where a dam break not causing fatality. The design flood for Cat-A dams is 10000-year flood without overtopping, with all the gates operating, and 1000-year flood with one gate inoperative. Category B dams should have capacity to safely pass 1000-year flood with 1 gate inoperative and with freeboard adequacy for wave run-up. [25], [32], [62]

JAPAN

Japan classifies dams in two classes with dam height criteria greater than or less than 15 m. The IDF for fill dams is 20% higher than those of concrete dams. T_{200} flood, Maximum observed flood or the flood value computed following Creager's formula, whichever is greater is adopted as IDF.[25], [32], [62]

ITALY

As per the guidelines, spillways are designed for 1000-yr flood in case of rigid dams, and the T_{3000} flood is considered for fill dams. Reservoir routing is accepted. Additionally, freeboard is considered on the basis of dam type and height. The flood value is determined by standard probabilistic hydrologic procedures with consideration of rainfall and runoff. Estimation of frequency-based flood with no freeboard consideration is also a requirement. Additionally, the verification has to consider flood with frequency of 50, 100, 200 and 500 years.[25], [32], [62]

NEW ZEALAND

The dam classification considers potential incremental consequence of a dam break, i.e. on loss of lives and the socio-economic, financial and environmental impact. The dam height and reservoir storage are adopted for initial preliminary determination of IDF does not impact classification when significances of a dam break are uneven with the preliminary determination.[25], [32], [62]

Table VIII: New Zealand Dam Classification ([25], [32], [62])

Potential Impact Category	Potential Incremental Consequences of Failure		IDF
	Life	Socio-Economic, Financial & Environmental	
High	Fatalities	Catastrophic damages	Between 10^{-4} Annual Exceedance Probability and PMF
Medium	A few Fatalities are possible	Major damages	Between 10^{-3} and 10^{-4}
Low	No fatalities are expected	Moderate damages	Between 10^{-2} and 10^{-3}
Very Low	No fatalities	Minimal damages beyond the dam owner's property	No requirement

NORWAY

Risk-based approach is adopted for dam categorization, very low dam with insignificant storage being exception. The following table provides the details of IDF selection.[25], [62]

Table IX: Norway Dam Classification and IDF

Dam Class	Classification Criteria	Inflow Design Flood	Safety Check
0	H < 2m; V < 10 000 m3 minimal consequence	200-year flood	Not Applicable
1	Low consequence (No permanent dwelling)	500-year flood	PMF or 1.5 x 500-yr flood
2	Medium consequence (1 to 20 dwellings)	1000-year flood	PMF or 1.5 x 1000-yr flood
3	High consequence	1000-yr flood	PMF
4	Very High Consequence (More than 150 dwellings)	1000-yr flood	PMF

***PORTUGAL (Adapted from** [32], [65]*

Portuguese Guidelines are specified in two Decree-Laws1 2. Dam classification divides dams into Large Dams (Classes I, II and III), based on both physical characteristics of the dam and reservoir, and the potential impact downstream. It defines two variables, X and Y, where X = H2√V with H being the height of the dam in meters, and V the volume of the reservoir in hm3. The IDF for small dams corresponds to a return period of 500 years, unless the volume of the reservoir is less than 100,000 m^3. In that case, the IDF would be 100 years. [25] [32], [62]

Table X: Large Dam Classification in Portugal

Class	Dam risk and potential damages
I	$Y \geq 10$ and $X \geq 1000$
II	$Y \geq 10$ and $X < 1000$ Or $0 < Y < 10$ independently of the value of X Or Impact to infrastructure, facilities, and important environmental assets
III	$Y = 0$, independently of the value of X

UK

On the basis of potential impacts of a dam break. UK classifies dams under four classes, each class having both a normal design flood, and a minimum design flood when overtopping is admissible [32]. The guidelines also make provision of 2 gates mandatory. And with one gate inoperative, the system should be able to safely pass flood corresponding to T_{150}. [25], [32], [62]

Table XI: United Kingdom Dam Classification and IDF (adopted from [25], [32], [62])

Category	Consequence of dam breach	Normal design standard	Minimum standard if overtopping tolerated	Initial reservoir condition	Minimum wave speed and minimum a wave surcharge
A	Endangers lives in a community (more than 10 persons)	PMF	10000-yr flood	Spilling long-term average inflow	Mean annual maximum wind speed Minimum 0.6 m wave surcharge
B	Endangers lives of individuals or causes extensive damage	10000-yr flood	1000-yr flood	Full to spillway crest (no spill)	As Category A
C	Negligible risk to life and limited damage	1000-yr flood	150-yr flood	Full to spillway crest (no spill)	Mean annual maximum wind speed Minimum 0.4 m wave surcharge
D	Mean annual maximum wind speed Minimum 0.4 m wave surcharge	150 yr flood	150 yr flood	Spilling long-term average inflow	Average annual maximum wind speed Minimum 0.3 m wave surcharge

Table XII: Comparison of the Characteristics Considered to Evaluate The Design Flood (Adapted from ICOLD, 2018, [32])

Country	System Characteristics				Consequences of dam failure						Design flood		Check flood	Free board
	Height	Volume	Type of dam	Permanent /temporary	LOL	PAR	Economic	Social	Environment	Flooded area	Min	Max		
Australia						X	X				100-yr	PMF		
Austria	X	X										5000-yr		
Brazil	X	X			X						1000-yr	PMF		
Bulgaria			X	X							33-yr	10000-yr		
Canada					X		X		X		100-yr	PMF		
Canada-Quebec						X	X				100-yr	PMF		X
China	X	X	X	X			X				100-yr	10000-yr	X	
Czech Republic					X	X	X		X		20-yr	10000-yr		
Finland					X	X			X		100-yr	10000-yr		
France	X	X	X								1000-yr	10000-yr		
Germany	X	X									1000-yr	10000-yr		X
India	X	X									100-yr	PMF		
Ireland					X						1000-yr	10000-yr		
Itly			X								1000-yr	3000-yr		X
Japan			X								200-yr	1000-yr		X
New Zealand					X		X				100-yr	10000-yr		
Norway						X					500-yr	1000-yr	X	X
Panama					X		X				100-yr	5000-yr		
Poland	X	X				X				X	200-yr	1000-yr		
Portugal	X	X			X		X					1000-yr		
Romania	X	X					X				100-yr	10000-yr		
Russia	X	X	X				X				20-yr	1000-yr	X	
South Africa	X				X		X				1200-yr	6000-yr	X	
Spain						X	X	X			100-yr	1000-yr	X	
Sweden						X	X		X		100-yr	SDF		
Switzerland	X	X	X								1000-yr	1.5x1000-yr	X	X
Turkey	X	X	X								500-yr	PMF	X	X
UK					X	X	X				150-yr	PMF		
USA/FEMA					X		X		X		100-yr	PMF		
USA/USBR					X						100-yr	PMF		

INDIAN PRACTICE

IS 11223-1985: Guidelines for Fixing Spillway Capacity are typically followed for determining the spillway capacity. Reservoir storage and dam height are considered factors for classification of dams which in turn dictates the IDF. However, probabilistic risk approach for dam failure is not in vogue in India since the codes primarily focus on deterministic risks

Gross Storage Capacity (Mm^3)	Hydraulic Head (m)	IDF
0.50 to 10	7.5 - 12	100 year flood
10 to 60	12 -30	SPF
> 60	>30	PMF

associated with the dam. IDF revision for approximately 80% of the existing dams are under active consideration in the DRIP programme[30] [25], [32], [62].

Recently, CWC issued long awaited guidelines for classifying dams based on hazard classifications (Table XIII).

Table XIII: Recommended Dam Classification System Based on Hazard Potential (adopted from [32])

Hazard Potential Class		Consequences Categories			
		Capital Value of Project	Potential for Loss of Life	Potential for Property Damage	Potential for Environmental and Cultural Impact
Class I	Low	Low	None. Occasional or no incremental population at risk, no potential loss of life is expected. No inhabited structures.	Minimal. Limited economic and agricultural development.	None
Class II	Intermediate	Average	Minimal or low population at risk. No potential loss of life is expected even during the worst- case scenario of emergency management	Notable agriculture or economic activities. States highways and/or rail lines.	Minimal incremental damage. Short-Term or reversible impact (less than 2 years)
Class III	High	Significant	Considerable. several inhabited developments. Potential for loss of life highly dependent of the adequacy of warning and rescue operations.	Significant industry, commercial and economic developments . National and state highways and rail lines.	Limited. Impact has a mid- term duration (less than 10 years) with high probability of total recovery after mitigation measures
Class IV	Extreme	Critical	Extreme. High density populated areas. Potential for loss of life is too high even during the best scenario of emergency management	Highly developed area in terms of industry, property, transportation , and lifeline features	Severe. long-term impact /effects in the protected areas or cultural heritage sites with low probability of recovery.

[30] B. Pillai, Kumar, and Nathan 2013

VIII. INDIAN DEMAND FOR DAMS

The construction of modern dams in India originated from the Keynesian fiscal stimulus approach, which was part of macroeconomic planning in the U.S. aimed at preventing economic depressions [68]. Institutions such as WB believed that controlling the powerful rivers of developing countries was key to alleviating poverty, which led them to invest heavily, emerging as the leading investor of mega dam projects in the early 1970s' [69].

The country already has over **6,318 large dams**[31], making it the **third-largest dam-owning nation** after China and USA. However, there is still a demand for building new dams and upgrading existing ones. So far, India could exploit only 214 BCM out of total estimate surface water potential of 412 BCM. India has a significant demand for dam construction due to its growing population, agricultural needs, water management challenges, and increasing energy requirements [44]. Key factors influencing dam construction in India are:

Irrigation and Agriculture: A significant portion of India's dams are primarily used for irrigation purposes, supporting the country's agriculture sector.

[31] National Register of Large (Specified) Dams, Central water Commission & National Dam safety Authority, September 2023

Hydropower Development: India is investing in hydropower projects to meet its renewable energy targets.

Urbanization and Industrialization: Rapid urban growth and industrialisation have enhanced demand for water, necessitating construction of more dams to ensure adequate water supply.

Flood Moderation: Dams are crucial in flood moderation, especially in flood prone zones experiencing heavy monsoon. Projects like the Polavaram Project on the Godavari River, a $6 billion engineering endeavour, aim to provide irrigation, water supply, and flood control benefits.

Aging Infrastructure and Rehabilitation Efforts: As per the Economic times news article dated 16th December 2024, India's dam infrastructure is aging, with 1,065 large dams between 50 and 100 years old and 224 over a century old[32]. To address safety and operational challenges, India has initiated one of the world's largest dam rehabilitation programs, upgrading 198 large dams since 2012 with support from WB [70].

IX. CHALLENGES FCAED BY INDIA

India is the most flood-prone country globally, as reported by the Ministry of Home Affairs in Disaster Management in India (2011) [71]. Between 1970 and 2009, floods were among the costliest disasters in the country, according to WB. During this time, India faced 192 flood events, resulting in 48,000 fatalities and affecting 783 million people. Additionally, flood-related economic losses accounted for 63% of the total disaster-related losses, making them the most significant in terms of financial impact [18], [72].

On an aggregate, India is positioned at the fourteenth on the international Climate Risk Index (CRI)[33] and holds second position in terms of annual average disaster fatalities and third in terms of average damage due to disasters [18], [73]. Combined with snowfall, the country's annual precipitation is estimated at 3,880 BCM[34][42]. Due to the uneven seasonal pattern, spatial variations, and geographical patterns of rainfall, the flood-prone areas have significantly expanded, impacting an average of 7.563 million hectares annually [42]. An average of approximately 33 million people were affected by floods between 1953 and 2000 [42], and this number is expected to rise due to population growth.

Over the past six decades, India has incurred an estimated loss of ₹4.7 trillion (at current prices) and an average of 1,695 lives annually due to floods. (CWC, 2019). The Jal Shakti Ministry of India reported that the country faced a financial loss of ₹95,736 crores due to floods in 2018, marking a threefold increase compared to the losses incurred in 2017[35]. An analysis of long-term data from 1978 to 2006by by Omvir Singh et al. shows that 2,443 flood events have resulted in approximately 44,991 fatalities, averaging 1,551 deaths per year [74].

Fortunately, advancements in technology now enable early warning systems that can help mitigate losses [75]. India is, however, yet to implement Automated Flood Early Warning Systems (FLEWS) in a full-fledged manner. The initial program has been developed through a collaboration between "The Energy and Resources Institute (TERI)" and "National Disaster Management Authority (NDMA)" [32].

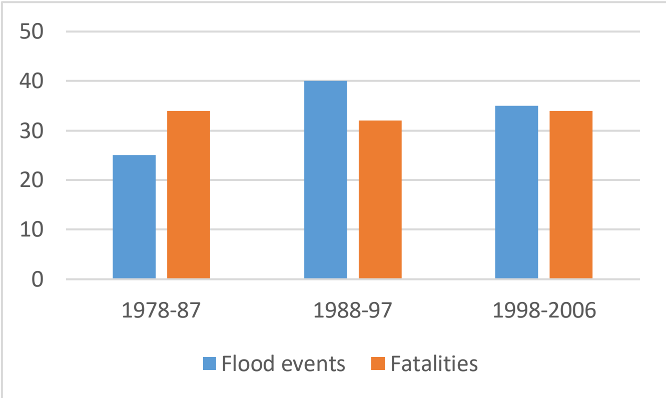

Figure 3: Decadal distribution of flood events and fatalities in India during the period 1978–2006 [74]

To ensure that the dams are safe against impending failure risks due to overtopping by flood water, the prerequisites are to introduce higher safety margins, creation of additional spillage structures, safe operation and maintenance and making emergency arrangements to address devastation caused by flooding situations [76].

A combination of technical innovation coupled with warning information management is warranted for maintaining an enhanced safety. To effectively manage the consequences of a dam break or an emergency arising from extreme or extra ordinary flooding, it is crucial to regulate several other parameters in addition to having a strong dam safety law. Enactment of Dam safety Law 2021 is a welcome step in this direction[36].

Key factors such as land use in floodplain zones downstream, catchment area management, disaster management readiness, and coordination among dam operators and other stakeholders

[32] https://economictimes.indiatimes.com/news/india/1065-large-dams-50-100-years-old-224-are-over-a-century-old-govt/articleshow/116369588.cms

[33] Global Climate Risk Index, 2017 has constructed the overall Climate Risk Index as well as estimated the annual average disaster fatality and average economic losses in million US$ (Purchasing Power Parity) in 181 countries over the period 1996–2015.

[34] Source:https://www.pib.gov.in/PressReleasePage.aspx?PRID=1783527#:~:text=by%20PIB%20Delhi-,As%20per%20the%20assessment%20made%20by%20the%20department%2C%20India%20receives,been%20assessed%20as%201999.20%20BCM.

[35] https://www.downtoearth.org.in/governance/as-told-to-parliament-november-18-2019-floods-caused-damage-worth-rs-95-736-crore-in-2018-67812#:~:text=India%20suffered%20a%20loss%20of,presented%20by%20the%20minister%20showed.

[36] https://jalshakti-dowr.gov.in/acts/dam-safety-act-2021/

are all highly relevant and significant in mitigating the impacts of such events.

Dam operation within its ambit also necessitates a thorough knowledge of likely effect on communities, their livelihoods and also on infrastructure and property susceptible to damage or in any emergency situation or in the event of dam break vis-a-vis management of the situation. In fact, countries like Sweden, Switzerland and many states of the US, introduced a dam safety classification viz. A, B or C based on the importance of likely damage because of dam break with class A being assigned to dams whose failure will cause significant fatalities and loss of property [40].

As per the Environmental Protection Act, 1986 and EIA notification 2006, dam failure analysis is a crucial requirement for obtaining environmental clearance and recommendations thereof in the EIA study should be implemented in letter and spirit. Existing dams that do not undergo new engineering modifications are exempt from this requirement. Safety aspects of all large dams shall be ensured through regular periodic dam failure analysis. Additionally, the procedure should be updated to incorporate most recent information gathered from routine inspections.

Dam failure analysis is done in India as part of EIA for projects requiring environmental clearance from MoEF for projects larger than 25 MW. At present, no standard procedures have been outlined regarding how the dam failure analyses are to be performed and documented. Although, CWC has framed some guidelines in this regard, but they are not legally enforceable, which requires GOI institutes a legally binding standards in above direction.

Taking examples of developed countries, CWC published guidelines, in November 2020, classifying the hazard potential of dams to identify projects whose failure or disruption could potentially lead to most severe consequences[37]. Four major factors viz. capital value, potential fatality, potential property loss and potential impact on environment and culture are considered for ‘Hazard classification’ as per these guidelines, and Class IV is deemed to be the most hazardous dam category [77].

X. KEY FINDINGS AND WAY FORWARD

A dam can never be regarded as entirely risk-free. However, recognizing the presence of risk factors allows for targeted efforts to reduce or eliminate specific hazards, ensuring that the overall risk remains within acceptable limits [61]. Flooding has been the culprit for more than 50% dam failures and majority of resulting fatalities, a hazard exacerbated by climate change impacts on flood events. While concrete dams have a low failure risk, the primary concern lies with the numerous embankment dams storing over 0.1 Mm³, particularly the ones equipped with single gate [33].

A properly designed, built, and managed dam can help lower flood risks in downstream developed areas by temporarily storing floodwaters and reducing flood intensity in vulnerable low reaches, even if flood mitigation not deemed as its primary purpose [31], [32]. However, storing water in a reservoir created by dam also introduces risks to d/s areas, as a dam failure could lead to an uncontrolled release of the reservoir water, resulting in peak flow discharges far exceeding natural flood event. Dam failures can occur due to various factors, including hydrologic, hydraulic, geologic, seismic, structural, mechanical, and operational issues [31], [32], [66]. One of the leading causes of dam failures is the inability to safely manage flood flows [32], [35]. Hydrologic-related failures can occur suddenly, resulting in a complete breach or collapse, or develop gradually through progressive erosion and partial breaching [32]. Common dam failure mechanisms linked to hydrologic conditions include erosion due to overtopping, spillway erosion, internal erosion at high reservoir levels, and excessive stress on the dam's structural components [31], [35], [65]. The issue has been further complicated due to climate change impacts on the hydrological cycles resulting to extreme flooding events. Hence is the requirement of selecting and accommodating IDF for Dams.

Literature review on the guidelines adopted by various countries across the globe on selection of IDF and dam safety measures vary extensively [25]. A review of international practice as well as Indian practice has been made in the foregoing.

[37] CWC Guidelines of Dam safety, 2020

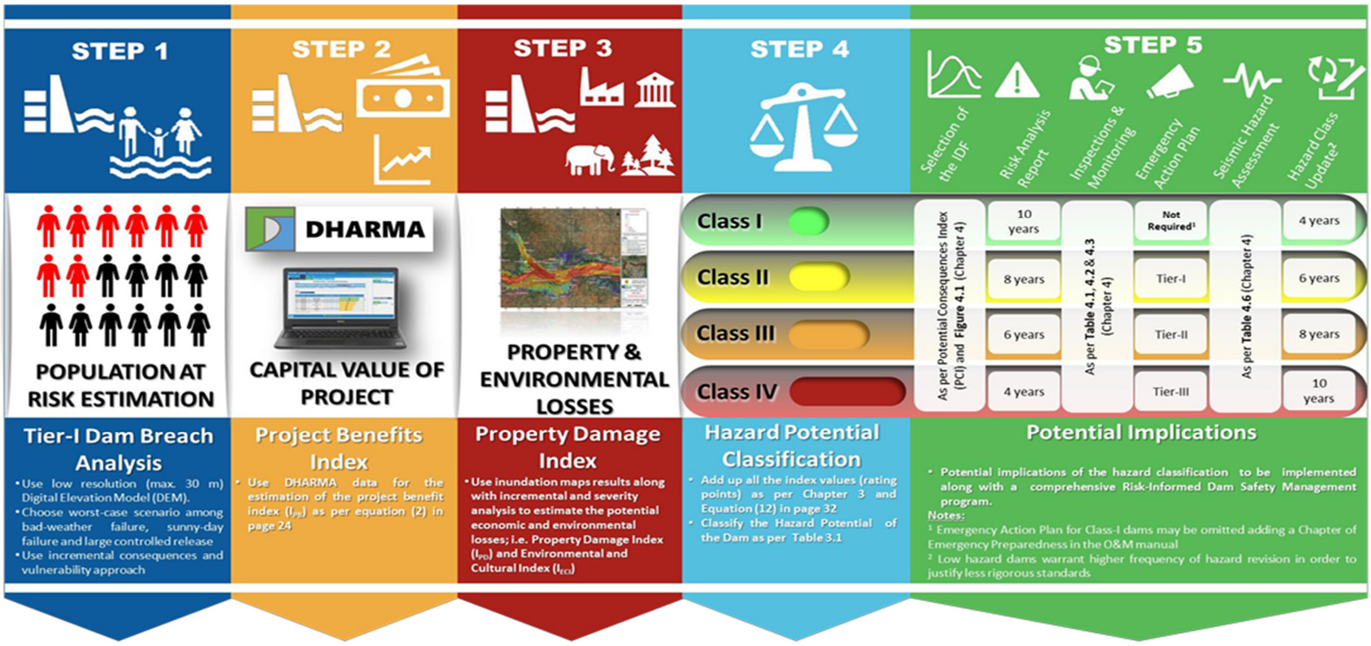

Figure 4: CWC Guidelines for Stepwise Hazard Potential Classification of dams in India

A. *Disconnect between IDF estimation and Climate Change Factors*

A shifting climate will inevitably alter the foundation for assessing the safety of dams and other hydraulic structures, potentially requiring updates to design flood calculations. There are two primary approaches for calculating design floods: the flood frequency method and the precipitation-runoff method. IDF, whether determined through deterministic or probabilistic methods, is essential for design of spillway. Within a risk-based decision-making approach for dam safety, IDF holds limited significance, regardless of how precisely it is defined [49], [52].

Most modern dams are constructed without considering the potential effects of future extreme events resulting from climate change [8] and are therefore subject to risk due to climate change resulting to frequent extreme weather events, cloud bursts and glacial lake outbursts (GLOFs). Despite progress in incorporating climate change into design flood estimation, gaps remain between climate science and current guidelines. For instance, no guidance recommends adjusting rainfall sequences for continuous simulation, and PMP estimation still assumes a stationary climate [78], contrary to evidence [47], [79]. Furthermore, non-stationary flood frequency analysis, though well-developed [78] has not been adopted in guidelines like Bulletin 17C, which assumes time invariance [80]. Several factors contribute to the gap between science and flood estimation practice. The widely accepted "chain-of-models" approach, which involves bias-correcting and downscaling general circulation model (GCM) outputs for hazard modeling, carries significant uncertainties [47], often hindering its adoption. Most dams were built at a time when the climatological effects were not researched adequately or fully appreciated and therefore it is quite likely that the designs did not take into account the unprecedented flooding scenario [32]. Both existing and newly constructed dams are expected to face climatic conditions during their lifespan [21], [23]. More research and revision in IDF estimation based on climate change factors are therefore called for.

B. *Ensuring dam safety through legislation*

One key concern in Indian context is the non-consideration of a risk-based decision-making framework for assessing the proposed dam's feasibility, location and design While static criteria based on hydraulic head and storage volume are simple for implementation, standards on the basis of evaluated risks offer a more effective balance between safety and cost. India should adopt a risk-based approach to dam design, similar to practices in the USA and Australia. The common global approach has been to correlate IDF for dam safety evaluations to the possible d/s impacts in case of failure. Additionally, the classification may consider dam's hydraulic head and storage capacity it holds.

CWC has issued guidelines for a) Dam Safety Procedures; b) Safety Inspection of Dams; c) Development and Implementation of Emergency Action Plan (EAP) for Dams; d) Standardised Data Book Format, Sample Checklist and Proforma for Periodical Inspection of Dams. However, these guidelines are not legally binding on all dams and India lacks a comprehensive legal mandate for conducting a impact study of all dam breaches [32]. Primary objective of dam break study in India aims at assessing dam-related hazards and to plan disaster risk mitigation measures for downstream areas. The government might consider regular conduction of consequence analyses, similar to practices followed in China since a dam failure analysis has limited usefulness without evaluating consequences.

Since dam safety regulation falls under the jurisdiction of individual states, the implementation of these guidelines ultimately depends on their willingness to adopt them. It is essential to implement systems for the consistent sharing of dam-related data between states and the central government. This should include data related to dam break analysis and submergence etc. Additionally, to promote transparency and support research on dam safety and risk mitigation, this information must be made publicly accessible in a user-friendly format.

C. Ensuring safety through Design improvements

Since 1980, insights gained from numerous dam failures have led to significant advancements in design, particularly in free-flow spillways and fuse devices. Traditional free-flow spillways, such as those with a Creager profile, have a limited discharge capacity, approximately 2 m^3/s for a 1-meter nappe depth and 10 m^3/s for a 3-meter depth. However, over the past decade, the development of new labyrinth weir designs, such as Piano Key (PK) Weirs, has increased discharge capacity by up to three times. PK Weirs have been implemented for managing flood flows ranging from hundreds to thousands of cubic meters per second. This design has even been considered for extreme flood events, such as the 70,000 m^3/s flood projected for the Inga dam in Congo. Additionally, PK Weirs have been integrated into existing free-flow spillways to enhance storage capacity and improve overall safety [33].

An alternative free-flow discharge method for low dams and floods under 100 m^3/s involves releasing water with a reduced nappe depth over extended embankment sections. Linings vary from grass in the UK (up to 0.5 m depth) to roller-compacted concrete (RCC) in the US, allowing greater depths. Well-compacted clay embankments can endure 0.3 m depths for up to two hours. This approach significantly boosts storage capacity while lowering costs, with affordable downstream toe protection options [33].

Fuse devices, a cost-effective alternative to gated spillways, open and are sacrificed during extreme floods, then replaced afterward, making them ideal for managing rare but severe events.

D. Mitigation through Early Warning System (EWS)

Given that existing and ongoing dams may exacerbate flooding events, there is a compelling case for fast-tracking the deployment of EWS and other technical answers to lessen losses from flooding disaster [75]. For the success of EWS, individuals in flood-prone areas need to swiftly respond to early warnings, and a coordinated efforts among all stakeholders at every level are essential. Dams are typically overseen by multiple authorities, which can lead to communication gaps and a lack of coordination in their management. Water surges from extreme rainfall extend beyond state and national borders. Lack of coordination, worsened by bureaucratic hurdles, amplifies the domino effect of dam failures. To derive benefits of EWS and ensuring a proactive approach to flood risk reduction demands collaboration between governments, organizations, and local communities to enhance preparedness and resilience.

E. Ensuring dam safety through revision in applicable standards

In Indian context, gross storage volume of dam and the hydraulic height cited in Indian Standard IS:11223 are applied separately rather than simultaneously. For instance, the SPF standard is enforced for all dams with a storage capacity of 10 million cubic meters to 60 million cubic meters, regardless of head, and for all dams with heads of 12 meters to 30 meters, irrespective of storage capacity. However, these codal recommendations are more flexible than they initially appear. Section 3.1.3 of IS 11223-1985 permits adjustments to IDF on the basis of a subjective evaluation of factors viz. the proximity, location of downstream settlements, considering potential future developments. Due to this flexibility, dams with similar dimensions and hazard profiles may still face inconsistencies in classification and safety assessments.

Lastly, to safeguard the dam from overtopping, the spillway structure shall be so designed for spillage of flood effectively ignoring the routing effect in the reservoir. Additionally, while checking the adequacy of spillway arrangement, discharge from other outlet facilities may be ignored and the current BIS recommendation of 10% of the total gates inoperative (with minimum one gate) shall be followed diligently. A reduction of the spillway design discharge may be permitted if:

1) Adopting higher criteria of safety than required by current design practice and technology or prevalent design standards to ensure no failure against overtopping.

2) A reserve storage capacity between the normal and the maximum reservoir level may be maintained as a measure of additional safety. The reserve storage capacity in a reservoir must be combined with dependable reservoir rule curve.

XI. CONCLUSION

This research paper provides a global perspective on IDF for hydro-infrastructure planning. The climate change effects have become rampant and dam failures are being experienced due to unprecedented floods which is a likely outcome of global climate change, warranting adoption of safety measures including a relook into the selection procedure of IDF for design of spillways to save human lives and property downstream of dam. While absolute flood protection is unattainable, a balance must be struck between minimizing failure risks and managing costs coupled with judicious selection of IDF based on risk-intensity approach instead of solely relying on deterministic or stochastic approach. Given the long lifespan of dams, the conditions in the protected areas are likely to change over time. Therefore, design flood criteria should account for these changes, and guidelines should adapt accordingly to ensure continued effectiveness. Also, the proper coordination and sharing of data amongst all dam operators in the country is a requirement for holistic management of risks pertinent to dam operations. Installation of EWS and its monitoring and keeping the emergency measures in place will go a long way in early mitigation of risks of flood disaster. Lastly, periodic conduction of dam break consequence analyses in line with practices followed in developed countries and implementing the appropriate planned mechanism shall be mandatory through legislation, which is the need of the hour.

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