NIPFP Working Paper Series

Dam Safety in India

No. 329
10-March-2021
Devendra Damle

National Institute of Public Finance and Policy
New Delhi

Abstract

India has 5334 large dams; the largest number of dams in the world after USA and China. This number is set to increase in the coming years as India constructs more dams to meet the rising demand for electricity and water. Constructing dams exposes downstream areas to the risk of catastrophic flooding — in the event the dam fails or water has to be released in an emergency. Adopting risk-based decision-making systems for making policy, implementation and management decisions regarding dams are crucial for mitigating this risk. Conducting dam break analyses is a basic requirement for creating such a system. In the existing regulatory system, clearance for constructing new dams requires the builder to conduct a dam break analysis. However, there is no standardisation in how the dam break analyses are conducted and reported. It is also unclear how many projects actually comply with this requirement. There is no statutory requirement for conducting a consequence analysis to estimate the likely loss of life and property, and economic damage in the event of dam failure. Existing design standards for dams are not based on the risk created by the dam, but rather on their heights and storage capacities. Further, there is no centralised system for documenting and reporting actual dam failures, which is another crucial component of dam risk mitigation. Putting in place systems for regularly conducting dam break analyses, regular reporting of dam failure events, and ready public availability of such data is a necessary precondition for the development of risk-based decision-making systems to mitigate risk from dams.

Acknowledgements

The author thanks Dr Ila Patnaik (Professor, National Institute of Public Finance and Policy) and Kamal Kishore (Member, National Disaster Management Authority) for their guidance in developing the paper. The author thanks , Dr Ajay Shah (Professor, NIPFP), Ms Sanhita Sapatnekar (formerly a researcher at NIPFP), and Prasanth Regy (formerly a researcher at NIPFP) for useful discussions and inputs. The author thanks Karan Gulati and Tushar Anand (researchers at NIPFP) for their thorough reviews and inputs. Last but not the least, the author thanks Dr A B Pandya (Secretary General of the International Commission on Irrigation and Drainage, and former Chairman of the Central Water Commission) for feedback on the paper and useful discussions.

Contents

Acronyms

ANCOLD Australian National Committee on Large Dams.

CAG Comptroller and Auditor General of India.

CDSO Central Dam Safety Organisation.

CTS Consequence-based Top Screen.

CWC Central Water Commission.

DRIP Dams Rehabilitation and Improvement Project.

DSAT Dam Sector Analysis Tool.

DSO Dam Safety Organisation.

EAP Emergency Action Plan.

EIA Environmental Impact Assessment.

EMP Environmental Management Plan.

FEMA Federal Emergency Management Agency.

ICOLD International Commission on Large Dams.

ISRO Indian Space Research Organisation.

MoEF Ministry of Environment and Forests.

NDSP National Dam Safety Program.

O&M operations & maintenance.

PMF Probable Maximum Flood.

SOP Standard Operating Procedure.

SPF Standard Project Flood.

WRIS Water Resources Information System.

1 Introduction

Building infrastructure is typically expected to mitigate disaster risk by (among other things) improving the delivery of essential services. However, improperly planned/built infrastructure can often aggravate existing disaster risks and in some cases introduce new hazards. Risk from infrastructure is an important consideration given the push for infrastructure building in India in the last few decades. One particularly important sector in this regard is dams.

Dams usually play a role in mitigating the impacts of regular floods. At the same time they introduce a catastrophic hazard of even greater flooding in the event of dam failure.[1] Dam failure — also known as dam break — is the physical destruction of the dam. Dam failure has multiple instigating factors, both man-made (bad design, ineffective monitoring, bad operations & maintenance (O&M) etc.) and natural (heavy rains, landslides etc.). Therefore, knowing how existing and proposed dams can fail, and the consequences of their failure is crucial for mitigating disaster risk created by their construction. Poor dam management was also reportedly a significant aggravating factor in the 2018 Kerala floods, and the Chennai flood in 2015 (Chauhan 2018). While dam failure did not take place in either of those cases, both the disasters could have been even worse had that happened. Most recently heavy floods reportedly damaged the barrages of the Rishiganga hydropower dam, which exacerbated the flood and led to significant human casualties and property damage (Upadhyay 2020). While the details of this specific tragedy were under investigation as of the writing of this paper, the *Chopra Committee Report, 2014* did point to inadequate risk management in dam construction and management as a possible cause for the floods in 2013.

India ranks 3rd in the world in the number of dams (behind China and USA) and is planning to build more in the near future, making this discussion especially pertinent.

In this paper, we review dam safety regulation in India, with an emphasis on dam failure analysis and reporting.[2] We aim to answer the following questions:

1. What are the statutory and administrative arrangements governing dam failure analysis and reporting?
2. What is the current status of the dams in India with respect to dam failure analysis?
3. How is this data utilised for decision-making?
4. How do other countries make use of dam failure analysis data? How does India compare to them?
5. What can India do better vis-a-vis mitigation of dam failure risk?

The rest of the paper is organised as follows. Section 2 gives an overview of the dams sector in India. In this section we explain the size of the sector, how much it is expected to grow, and the motivation for studying dam safety. Section 3 discusses the legislative and institutional framework for dam safety in India. Section 4 discusses dam failure analysis, and the extent to which such analyses are part of statutory requirements in India. Section 5 discusses dam safety

[1]Catastrophic hazards are those which can cause massive damage in a single event. Conversely, cumulative hazards are those which cause damage over time by degradation due to multiple low impact events.

[2]While an analysis of dam failure can be performed before or after a failure event, the term *dam failure analysis* or *dam break analysis* usually denotes an ex-ante analysis.

practices in other countries and lessons which India can draw from them. Section 6 gives the key findings of the study and policy recommendations for mitigating dam failure risk.

2 Overview of the Sector

It is estimated that there are more than 40,000 large dams in the world (International Rivers 2007).[3] The International Commission on Large Dams (ICOLD) defines large dams as those dams which are at least 15 m in height and have reservoir capacity of more than $1km^3$. While these are valuable pieces of infrastructure dam failures — due to improper management or due to insufficient risk mitigation — have led to catastrophes around the world.

2.1 Dam Failures Around the World

There have been approximately 4000 known large dam failures across 84 countries till date, not counting China (Regan 2010). However, it must be noted that this number is likely a gross underestimate since many dam failure events go unreported.

Cheng et al. (2010) find that there have been close to 4000 dam failures in China since 1954. 500 of these were in the year 1973 alone. A further 37,000 dams are classified as dangerous (*China warns of faulty dams danger, plans repairs* 2008). Apart from having had the greatest number of recorded dam failures, the most destructive dam failure event in recorded history is also from China: the Banqiao dam failure in 1975. The collapse of Banqiao Dam led to a cascade which resulted in the collapse of 60 other downstream dams. The resulting floods killed more than 80,000 people, and another 200,000 died due to ensuing epidemics and food shortages (Patrick McCully 2005). It is estimated that close to 11 million people were displaced due to this one event.

The Teton dam collapse in 1976 in Idaho, USA is another famous case study for dam failure. While the casualties in this case were low (11 deaths), it led to an estimated USD 2 billion in property damage (Teton Dam Failure Review Group (U.S.) and Eikenberry 1977).

It is estimated that at least 5000 large dams across the world are older than 50 years. They are either past or nearing the end of their design lives (P. McCully 2001), and pose a risk.

USA, China and other countries which have built large dams, have developed systems for mitigating risk from dams. India will have to develop similar systems given the large number of dams which already exist and for those which are expected to be constructed in the near future.

2.2 Demand for Dams in India

Two factors are driving the demand to construct more dams in India: the demand for water, and the demand for electricity. Of the total estimated surface storage potential of 412 bcm, currently only 214 bcm i.e. 52% has been developed (IDFC Institute 2011). With an ever-increasing

[3] Total number of large and medium dams is estimated to be in the range of 300,000.

demand for freshwater and depleting ground-water tables, the pressure to build more dams for water supply and irrigation is only going to increase over time.

In the energy sector, hydro-electric power constitutes 14% of India's total generation capacity. Trends from the last decade show a steady increase in investment in the hydro-electric power sector from USD 27.82 billion in 2007 to USD 75.38 billion in 2017 (cumulative).[4] Since 1996, 70 hydro-electric power generation projects have been completed, and another 346 have been announced and are in various stages of completion (as of July 2017).[5]

The *50,000 MW Hydro Electric Initiative* launched in 2003 aimed to build 162 new large dams for hydroelectric power generation, all of which are currently in various stages of development (Central Electric Authority, Government of India 2017). All these new dams will create new hazards, on top of the hazards already created by the existing dams.

2.3 Scope of the Hazard in India

When India gained independence in 1947, there were fewer than 300 large dams in the country. By the year 2000 the number had grown to over 4000. More than half of these were constructed between 1970 to 1990. Currently there are 5334 large dams in India, and another 411 are under construction (Central Water Commission, Government of India 2019). Of the total existing large dams, 220 are more than 100 years old (Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India 2017). Out of the 70 large dams considered *dams of national importance*, 15 are more than 50 years old, of which 3 are more than 80 years old. These dams are likely past their service lives, which is typically 50–80 years (US Army Corps of Engineers 2017; Wieland and Muller 2009).[6] A large number of dams were constructed at a time when the effects of climate change were not fully understood. Their designs have likely not taken into account large changes in precipitation patterns. In areas where the intensity of climate change results in a large increase in the intensity of floods, these older dams may not be able to withstand such floods.

Further, while the dams themselves may not have significantly changed, risk factors may have. For example, settlements typically tend to grow around dams, because of an expectation of regular water supply. Therefore, even without a change in the hazard, the disaster risk may have changed, necessitating an assessment of such dams for upgrades or decommissioning. Considering the sheer number and geographical spread of existing dams across the country, with every new dam constructed more and more people and property are being exposed to flood hazard due to dam failure.

Dam Safety Organisation, Central Water Commission, Government of India (n.d.) reports a total of 23 major dam failures in the country between 1960 and 2010.[7]. Some of them led to a significant number of deaths and damage to property. The worst known case — Machchu Dam failure in Morbi, Gujarat in 1979 — claimed more than 2000 lives. Some estimates place the number of fatalities at more 20,000 (Easwaran 2012). To prevent such damage in the future,

[4]Source: Centre for Monitoring the Indian Economy

[5]Source: Centre for Monitoring the Indian Economy

[6]At the end of the design life of a dam it is necessary to perform a thorough assessment to determine whether the dam needs to be upgraded, rehabilitated or decommissioned.

[7]This number is likely an underestimate (See Section 4.2)

India must develop robust systems for dam failure analysis, and for recording and reporting dam failures.

3 Dam Safety in India

Dam safety can be delineated into two elements based on the stage in a dam's life-cycle in which they are pertinent viz.:

1. **Pre-construction:** This includes various impact assessments, and design and engineering standards. These components inform the cost-benefit analyses which determines whether or not the infrastructure should be built in the first place. If it is to be built, then these components determine what is the optimal location and design.
2. **Post-construction:** This category includes regulations, standards and best practices in dam operations and management. It includes Standard Operating Procedures (SOPs) for day-to-day O&M, SOPs for handling exceptional events (e.g.: emergency action plans), and surveillance and monitoring.

A third category — "during-construction" elements — of safety can also be delineated, but this mainly relates only to faithful implementation of an approved design. Therefore, it will be ignored in the rest of the discussion.

3.1 Statutory and Institutional Arrangements in India

Under the 7th Schedule of the Constitution of India, water and water storage is a state subject. Therefore legislating dam safety is the responsibility of state governments. However, the Central Government can enact legislation can enact central legislation governing dams in three scenarios. First, if a project affects multiple states or international treaties. Thus, the Central Government can pass legislation regulating dams whose catchment area or downstream affected areas span multiple states or international borders. Second, if two or more states pass a resolution requiring such a law. In 2010, Andhra Pradesh and West Bengal passed resolutions requiring a law on dam safety. This is what led to the Dam Safety Bill 2019 which is pending before parliament. However, the law will only be applicable to the states that passed the resolution. Third, the Central Government can legislate on matters related to the protection of the environment under the *Environment Protection Act, 1986*. Since dams and dam failures can have a significant impact on the environment, the Central Government can regulate some aspects of dam safety. Indeed, the existing dam safety regulations are part of the Environmental Impact Assessment (EIA) notifications issued under the *Environment Protection Act, 1986*.

At the national level, the Central Water Commission (CWC) provides technical expertise and guidance on all matters related to dams. It is tasked with research into dam safety, developing standards for dam design and operations, and it is involved in the process of granting environmental clearance to dam construction projects.

The CWC has issued guidelines for:

- Dam Safety Procedures;
- Safety Inspection of Dams;

- Development and Implementation of Emergency Action Plan (EAP) for Dams;
- Standardised Data Book Format, Sample Checklist and Proforma for Periodical Inspection of Dams.

These guidelines are not legally binding on all dams. They are only applicable to projects which require environmental clearance from the Ministry of Environment and Forests (MoEF), Government of India under the *Environment Protection Act, 1986*, or dams which are part of central schemes. For example, dams under the World Bank Dams Rehabilitation and Improvement Project (DRIP) are governed by the aforementioned guidelines. Currently seven states are participating in the programme and it covers about 250 large dams (Ministry of Water Resources, Government of India 2014).

While state governments are empowered to enact dam safety legislation, only Bihar has done so, through the Bihar Dam Safety Act, 2006, which mirrors the provisions of the (now lapsed) Dam Safety Bill, 2010. Hence, only one state is currently governed by any dam safety legislation. Andhra Pradesh and West Bengal will be governed by the central Dam Safety Bill, 2019 if passed by parliament. Typically, at the state level, the respective water resources or irrigation departments are in charge of dam safety. 20 states have some institution which functions as the State Dam Safety Organisation. E.g.: In Maharashtra, the Maharashtra Engineering Research Institute in Nashik serves as the Dam Safety Organisation for the state. They are reported to usually follow CWC standards, but the CWC has no oversight powers over them.[8]

Dam failure analysis is currently only addressed by the EIA notification issued under *Environment Protection Act, 1986*. Details of these regulations are discussed in section 4.1.

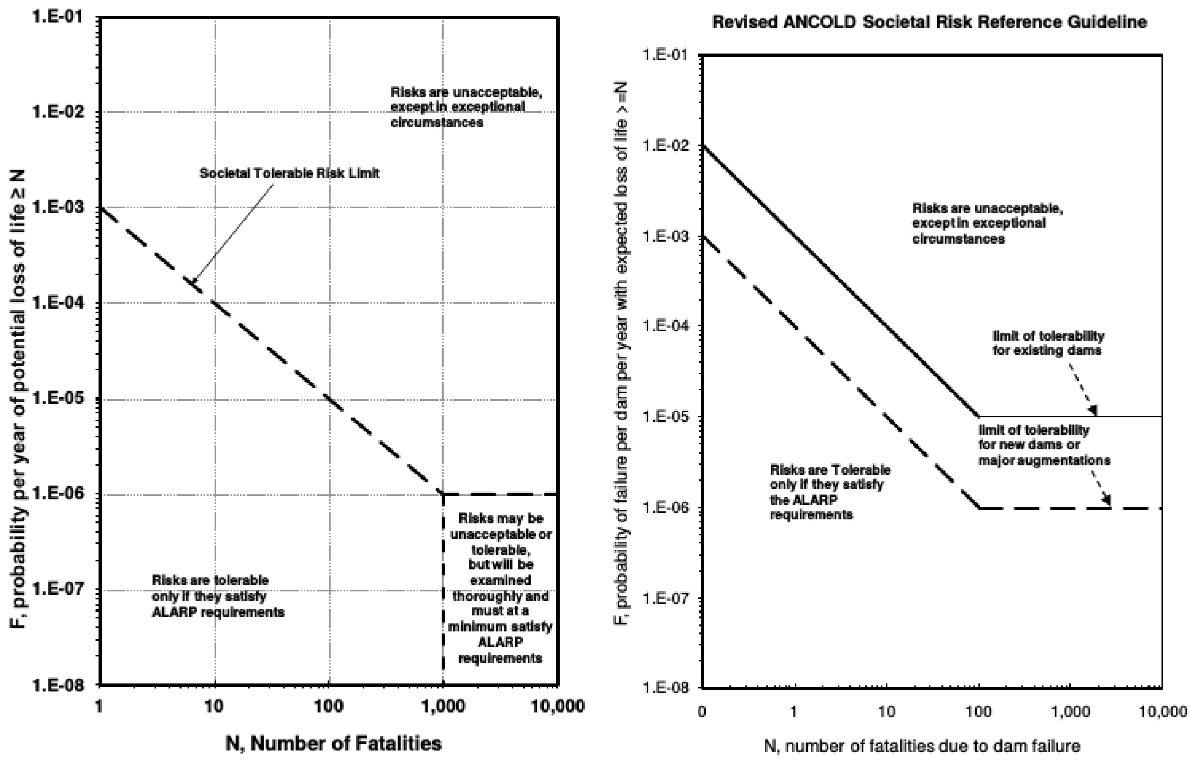
3.2 Impact Assessments

In the context of dams, impact assessment usually means an EIA. Often EIAs include socio-economic impact assessments such as displacement of human settlements and the ensuing loss of property and livelihoods. The notifications issued by MoEF for any large civil engineering projects — under the *Environment Protection Act, 1986* — require the applicant to conduct an EIA.[9] Based on the size of the dam, the project may be classified as *Category A or B*. An Environmental Appraisal Committee is set up to scrutinise the project (at central level for *Category A* and state level for *Category B*). This committee grants the environmental clearance based on the EIA submitted by the applicant.

The Environmental Management Plan (EMP) component of an EIA contains plans for mechanisms which the applicant will put in place to mitigate the impacts of the dam, both environmental and socio-economic. Dam failure analysis is a part of this EMP. While the dam failure analysis component is mandatory for receiving environmental clearance from the MoEF, it does not appear to be strictly enforced in all cases.[10] Further, the results of the dam failure analysis do not seem to inform decision-making regarding approval/disapproval or the design parameters of the dam in question.

Federal Emergency Management Agency (FEMA)'s *Federal Guidelines for Dam Safety Risk Management* and Australian National Committee on Large Dams (ANCOLD)'s *Risk based approach*

[8] Information from interviews with retired CWC officers.
[9] S.O. 1533 (E) — EIA Notification, 2006, dated 14/09/2006 (Principal Notification)
[10] See box in section 4.1



(a) FEMA, USA

(b) ANCOLD, Australia

Figure 1: Risk informed decision-making framework

to assessment of dams serve as a useful contrast. Both mandate probabilistic assessments of downstream risks of dam failure to inform decisions regarding new and existing dams.

The graphs in figure 1 show the central component of the risk-informed decision-making systems used by FEMA and ANCOLD. In the graphs, the diagonal line with a negative slope indicates the acceptable risk, from the point of view of the state. It serves as a decision-support system for almost all aspects concerning dams, be it design, location, SOPs or disaster management. It is also used to determine whether a dam should be built in the first place, or whether to pursue an alternative.[11] This kind of decision-making framework is currently absent in India. Instead, disaster risk mitigation is addressed mainly through design standards and emergency action plans.

3.3 Design Standards

Impact assessment and design standards for dam safety go hand in hand. Design elements (e.g.: height and location of the dam) determine the scale and nature of the impact on the local geography and demography (e.g.: total submerged area and resultant habitat loss). In turn the design is determined by the cost of construction plus the magnitude of negative impacts weighed against the projected benefits.

The *IS 11223-1985 : Guidelines for Fixing Spillway Capacity* mandate standards for some aspects related to mitigating dam failure hazard, specifically the design of spillways to handle floods.

[11] See figure 2 in section 5.2 for the flowchart

Since the probabilistic risk of dam failure is not estimated in India, the standards are effectively based on the deterministic risk posed by the dam in question. The design flood standards are based on the storage capacity and height of the dam.

Table 1 summarises the standards for spillway design. The 100-year standard is known as a *return period*; it is the expected number of years till the next such event. A return period of 100 years means the kind of flood which only occurs once every hundred years. Standard Project Flood (SPF), simply put, is the expected flooding as a result of the most severe storm observed in the region.[12] Probable Maximum Flood (PMF) is the flooding due to the most severe storm theoretically possible in the region.[13]

Table 1: IS 11223-1985 : Inflow Design Flood Standards for Spillway Design

Dam Gross Storage Capacity (million cu.m.)	**Hydraulic Head (m.)**	**Inflow Design Flood**
0.5 – 10	7.5 – 12	100 year flood
10 – 60	12 – 30	Standard Project Flood
above 60	above 30	Probable Maximum Flood

These standards are applied individually and not simultaneously. As an illustration, the SPF standard applies to all dams which have a storage capacity of 10–60 M.cu.m — irrespective of hydraulic head — and all dams with hydraulic heads of 12–30 m — irrespective of their storage volume. The standards are not as rigid as they may seem at first glance. Part 3.1.3 of IS 11223-1985 allows for the adoption of a different inflow design flood level based on a subjective assessment of exposure such as *"distance to and location of the human habitations on the downstream after considering the likely future developments"*. Even so, it is clear that dams of similar dimensions, with similar hazard profiles, and posing similar risks may fall in two different categories. Consider, for example, two hypothetical dams — one with a hydraulic head of 12m and another with a hydraulic head of 13 m, and both having gross storage capacity of 10 M.cu.m Under the IS 11223-1985, these dams would be designed for completely different categories of flood risk. This poses a problem because the costs involved change drastically with a change in category. Developed countries have moved towards risk-based standards (see figure 1) to overcome precisely these limitations of standards based solely on storage and height.

The problem affects not just the design of new dams, but also the retrofitting of existing dams. It has been reported that inflow design floods are being revised for approximately 80% of the dams in the DRIP programme (B. Pillai, Kumar, and Nathan 2013). These dams will be retrofitted for higher inflow design floods. The reclassification is based only on hydraulic head and gross storage, without any assessment of the actual risk posed by each of them. The large difference between the three categories is likely to lead to overspending on some dams when they are rehabilitated under projects like DRIP. This is salient given the fact that the Government of India has acknowledged that just ensuring dam safety based on current

[12]American Meteorological Society defines SPF as the discharge expected to result from the most severe combination of meteorological and hydrological conditions that are reasonably characteristic of the geographic region involved.

[13]American Meteorological Society defines PMF as the discharge expected to result from the most severe combination of critical meteorological and hydrological conditions that are reasonably possible in a region.

standards for old dams is a 'herculean task' and may not be possible for the state to accomplish (Central Water Commission 2019).

As a temporary remedy, R. K. Pillai and Gupta (2017) propose three interventions which complement each other. The first proposed intervention is to apply the gross storage standard and hydraulic head standard concurrently instead of separately. As an example, a dam with hydraulic head between 12–30 m *and* having gross storage between 10–60 M.cu.m would have to be designed for SPF, while a dam with the same height but gross storage less than 10 M.cu.m would be designed for a 100-year flood. The second proposed intervention is to increase the number of design categories from the existing three to five. This will allow for better classification of dams, and the differences between categories will not be as drastic as they currently are. The third proposed intervention is to calculate all design floods in terms of return periods. While return periods themselves are slowly being phased out in favour of SPF and PMF, the representation of SPF and PMF in terms of return periods will allow for a probabilistic representation of hazard risk.

These interventions, however, are not complete alternatives to risk-based standards, which require an assessment of hazard and exposure, which in turn require a dam failure analysis for each dam.

3.4 Operations & Maintenance

Operation of dams in India is primarily governed by the *IS 7323-1994 : Operation of Reservoirs - Guidelines*. Dam safety as such is the responsibility of states as per the National Water Policy, 2012. Safety elements in O&M involve the following:

1. Standard operating procedures;
2. Monitoring and surveillance;
3. Repairs and maintenance;
4. Inspection and audits;
5. Emergency action and preparedness.

Ideally if the first four elements are properly addressed, emergency action should not be required. However, an emergency action plan must be put in place to address the risks from exceptional events.

1. **Standard Operating Procedures**
   Each parameter of operation of a reservoir is governed by a *rule curve*. A rule curve is a graph which dictates what action to take based on given input conditions. E.g.: If rainfall is expected over the subsequent week which will raise the reservoir water level by X metres, then Y volume of water will be released from the reservoir till it reaches Y metres to account for the sudden inflow. Typically rule curves are based on the existing water levels, and rates of inflow and outflow. Rule curves are also known as *flood control diagrams*. They are usually expressed in the form of graphs and tabulations, supplemented by concise specifications and are often incorporated in computer programs. In general, they indicate limiting rates of reservoir releases required or allowed during various seasons of the year to safely meet all functional objectives of the project. These

need to be regularly updated to accommodate changes in rainfall patterns, especially after observed exceptional rainfall events.

2. **Monitoring and Surveillance**
   Monitoring and surveillance of dams can largely be automated with existing technology. Surveillance systems such as stress gauges, flow meters, rain gauges, etc. collect data on functional parameters of dams and can be directly plugged into computerised dam management systems. Some aspects of monitoring such as soil testing, and testing integrity of levees and embankments have to be performed manually. These are currently governed by the *Guidelines for Safety Inspections of Dams*. The CWC in 2012 successfully installed real-time data collection systems at the Hirakud Dam, under the Decision Support System component of the World Bank Hydrology Project.

3. **Repairs and Maintenance**
   Repair works are informed by the data from monitoring and surveillance reports, and scrutiny during inspections. Most of the dams in India are owned by the state governments, and state or central government agencies (Central Water Commission, Government of India 2019). Given the number of large dams in the country, the government needs an objective mechanism for prioritising dam-related works. This requires a periodic assessment of the risk posed by each individual dam. A related issue is the lack of a statutory mechanism for decommissioning dams which pose an unacceptable risk. Both these issues require the creation of a risk-based decision-making system, which requires dam failure analyses.

4. **Inspection and Audits**
   Inspections involve assessment of the physical health of dams as well as performance inspections i.e. checking the systems in place for all aspects of operations. In India, this is expected to be done by the Dam Safety Organisations of respective states. These reports are expected to be submitted to the Central Dam Safety Organisation (CDSO), which is part of the CWC. The inspections are performed as per the *Guidelines for Safety Inspections of Dams* in the case of dams which are part of the DRIP. State dam safety organisations may use their own guidelines or those issued by CWC. Pre-monsoon and post-monsoon inspection reports consolidated by state Dam Safety Organisations (DSOs) have to be submitted to the CWC. However, only 10 states had done so till 2011 (Ministry of Water Resources, Government of India 2011). The progress since then is uncertain. Comptroller and Auditor General of India (CAG) has performed two audits which involved assessments of dam safety, but there does not exist any statutory framework at the Central Government for regular safety auditing of dams in the country (Comptroller and Auditor General of India 2013; Comptroller and Auditor General of India 2016; Comptroller and Auditor General of India 2017). Though the 2019 Bill obligates State Dam Safety Organizations to 'keep perpetual surveillance' on dams, it will only be applicable on two states, if passed (as explained earlier).

5. **Emergency Action**
   Emergency action plans contain the procedures to be followed in the case of each category of emergency. In the case of dams these primarily have to do with flooding. Emergency action plans detail the roles of all stake-holders, communication plans and standard operating procedures for minimising the impacts of the event. Under the *The Disaster Management Act* there is a well-defined chain of communication for all kinds of disasters. In the case of dam failures, this involves informing the residents of downstream

habitations, district officials and district disaster management authorities, and the state disaster management authorities. Emergency Action Plans (EAPs) are expected to be prepared as per the *Guidelines for Preparation of Emergency Action Plans*. However, only 8 states had prepared EAPs for a total of 349 large dams, compared to the target of 4862 dams in 29 states (Comptroller and Auditor General of India 2017).

Box. 1: Components of Emergency Action Plans

According to the CWC guidelines all EAPs are supposed to contain the following components:

1. Responsibilities of every officer and stake-holder involved or affected;
2. Notification flowcharts i.e. a systematic plan for communication of the dam failure event and the emergency level to the people involved;
3. Inundation maps demarcating all the areas which are likely to get submerged, and to what depth;
4. Possible emergency conditions which will trigger the emergency action plan;
5. Location and inventory of all supplies and resources required for handling the dam failure;
6. Standard operating procedures for handling all possible types of emergencies.

The guidelines issued by CWC cover all the basic elements of responding to dam failures, but 93% of the large dams in India do not have any EAPs in place (Comptroller and Auditor General of India 2017). It is also worth noting that preparing inundation maps requires prior dam failure analysis.

4 Dam Failure: Analysis, Regulation and Reporting in India

The primary hazard presented by dam failure is flooding in the immediate downstream areas. However, since dams are often built as cascades the failure of one dam can cause a downstream dam to fail as well.[14]

[14] This is what happened in Banqiao, China. See section 2.1

Box. 2: Dam Failure Typologies

Dams can fail for any one or a combination of the following reasons (Federal Emergency Management Agency, USA 2017):

- Overtopping, usually caused by floods that exceed the capacity of the dam,
- Structural failure of materials used in dam construction,
- Inadequate maintenance and upkeep,
- Movement and/or failure of the foundation supporting the dam,
- Settlement and cracking of concrete or embankment dams,
- Piping and internal erosion of soil in embankment dams,
- Deliberate acts of sabotage.

These events are not mutually exclusive; and one may lead to another. For example, blockages can develop in piping or spillways due to improper maintenance, which may lead to overtopping due to the excess water not being drained away in time.

According to the International Commission on Large Dams (ICOLD), approximately a third of the dam failures worldwide occur due to floods exceeding the design capacity of dam spillways. ICOLD (1995) reports that, worldwide, overtopping is the leading cause of dam failure (32%) followed by internal erosion (27%). In India, on the other hand, internal erosion (breaching) accounts for the maximum number of dam failures (44%), followed by overtopping (25%) (Dam Safety Organisation, Central Water Commission, Government of India n.d.).

Mitigation of this hazard requires a comprehensive assessment of failure scenarios before constructing the dam, and an assessment of dams which have already been constructed. In addition to this, there also needs to be a system for reporting and recording every dam failure event in one consolidated database. Finally, all of this information has to be publicly available in an accessible and easily usable format.

4.1 Regulatory Requirements for Dam Failure Analysis

In 1994 it was made mandatory for dam-builders to conduct a dam failure analysis as a part of EIA for getting environmental clearance under the *Environment Protection Act, 1986* (Ministry of Environment and Forests, Government of India 1994, Notification S.O.60(E)). Inundation maps were also made mandatory. The 1994 notification was superseded by a notification issued in 2006, which does not explicitly mention the requirement of dam failure analyses for environmental clearance (Ministry of Environment and Forests, Government of India 2006, Notification S.O.1533(E)). However, in 2015 MoEF notified the *Standard Terms of Reference for EIA/EMP Report for Projects/Activities Requiring Environmental Clearance Under EIA Notification 2006*. These terms of reference made risk analysis, dam failure analysis and inundation maps compulsory, and classify them as components of the EMP, which is a part of the EIA. Apart from these, the 2019 Bill requires builders to conduct comprehensive dam safety evaluations — however, as mentioned, this will only be applicable for two states, and others have shown signs that they will not implant the Bill to their jurisdiction (Krishna 2019).

Box. 3: Typical Dam Failure Analysis Protocol

1. **Set Initial Conditions:** The first step involves identifying the starting conditions. E.g.: Type of dam (earth-fill, masonry etc.), full reservoir level, spillway capacity, dead storage, design inflow flood, and sedimentation level in the dam.
2. **Define Breach Parameters:** This step involves setting the parameters to describe the breach. E.g.: Water level and inflow flood at the time of the breach, and size, shape and location of the breach.
3. **Model Flood Routing:** This involves running simulations to model the volume, velocity, and height of the flood wave as it moves downstream. The immediate output is a depiction of the movement of the flood wave using graphs and tables (together known as a hydrograph). Retention time of flood water at each downstream zone is another important output.
4. **Consequence Analysis:** The results of the flood routing model are overlayed onto a map of downstream habitations to generate inundation maps. The inundation map is used to identify risk prone areas (corresponding to different kinds of events given as input), and the likely impact of different kinds of dam break events.

There are two main issues with the regulations under the *Environment Protection Act, 1986*. The first is with their applicability to different kinds of projects, and the second is the content of the analysis that they require. Performing dam failure analysis is compulsory for getting an environmental clearance for constructing new dams and for modifying/upgrading existing dams. There are, however, no regulations for conducting these analyses for dams which are operating but where no new engineering works are being undertaken. Furthermore, dams which have an irrigation command area less than 10,000 Ha or power generation capacity between 50 to 25 MW, only require a clearance from the state government. Such dams can be approved for construction without the Central Government's specifications being met. Dams which are smaller than that do not require an environmental clearance at all. In terms of the content of the dam failure analysis, there is no requirement to perform a *consequence analysis* i.e. a quantification of the probable loss of lives and livelihoods, and damage to property in the event the dam fails.

Conducting the dam failure analysis is one side of the issue; the other is the availability of this data. Even if it is assumed that in the case of all dams constructed or upgraded since 1994 dam failure analyses were conducted, data from these analyses is not publicly available. In 2014, the MoEF launched an online portal for submitting applications for environmental clearances.[15] The portal also allows users to access the EIA documents filed by applicants. We examined the EIA documents for *Category A* projects which have already received environmental clearances on the MoEF portal.[16] For the projects for which applications were filed before July 2014 EIA documents are not available on the website. An examination of the EIA documents for the applications for which they are available reveals that there is no standardisation in the parameters and protocols used for dam failure analysis. In some cases, the dam failure analysis is not part of the documents available on the website.

[15] Ministry of Environment and Forests, Government of India. *Website for Online Submission and Monitoring of Environmental and CRZ Clearances.* URL: http://environmentclearance.nic.in/default.aspx (visited on 06/10/2017).

[16] As of 10/06/2017

Box. 4: Dam Failure Analysis in Cleared Projects

6 dam-related projects for irrigation and hydro-electricity have received environmental clearance since July 2014.[a]

- Out of these six projects, four EIA reports contain detailed dam failure analysis with hydrograph tables.
- Two EIAs mention that dam failure analysis has been conducted, but do not give any further information.
- Of the four projects in which dam failure analysis was conducted, two have used the MIKE11 model, one has used HEC-RAS model and one has used DAMBRK model.
- The two analyses which have used MIKE11 model give flood hydrographs with a spacing of 100 m (i.e. water level and velocity at every 100 m downstream of the dam), while the other two give hydrographs with a spacing of 1 km.

None of the dam failure analyses provide inundation maps.[b]

[a] Source: Category A clearances data on http://environmentclearance.nic.in/, accessed on 10/06/2017.

[b] The Comptroller and Auditor General of India 2016 found that 6 out of the 10 sampled projects in the river and hydroelectric category did not comply with the MoEF terms of reference. However, it is unclear how many of these are dam projects.

While some data are collected by MoEF, in their current form they are of limited use.

4.2 Reporting & Recording Dam Failures

No existing statutory provisions require regular and systematic reporting of dam failures, and no single agency keeps track of all dam failures. CWC maintains a record of dam failure events but the list is collected from states, and is not regularly updated (Dam Safety Organisation, Central Water Commission, Government of India n.d.). The current list only includes dam failures till 2010, despite there having been newer incidents of dam failures since then. For example, the 2019 Tiware dam failure at Ratnagiri, Maharashtra flooded seven downstream villages and claimed 20 lives (Naveen 2016).

The (sparingly applicable) Central bill provides that every State Dam Safety Organisation has to report dam failures within its jurisdiction. However, there is no experience about how these requirements will be implemented and whether states will choose to adopt them at all.

5 Dam Safety in Other Countries

Several developed countries have faced the aforementioned dam safety issues in the past, when they first built their infrastructure. As a result, a significant body of knowledge exists on many aspects of dam safety. USA, Australia, Canada and New Zealand are anecdotally known to have developed expertise in the subject. Like India, USA and Australia are large countries with major river systems, and both went through phases of rapid infrastructure building (including dams). USA is also currently facing the issue of aging dams. Therefore, among developed countries, we studied dam safety in USA and Australia.

Among developing countries, we chose to study China. China was chosen because it went through a phase of rapid dam-building from the 1950s to 1970s, and experienced a number of dam failures. There is some anecdotal evidence to suggest that China has developed expertise in dam safety in recent years.

5.1 USA: Dam Safety Framework

At the federal level, the main governing statute for dam safety in the US is the National Dam Safety Program Act, first enacted in 1996, and then subsequently renewed in 2006. FEMA along with the Association of State Dam Safety Officials and the US Army Corps of Engineers develops safety standards, and guidelines for dam owners to follow. These agencies have also been tasked with researching dam safety. The National Meteorological Society is another key institution involved in dam safety research.

Like CWC, FEMA does not operate any dams or enforce regulations. It is responsible for coordinating dam safety efforts between various federal agencies, state governments and private entities who own dams. FEMA also chairs the National Dam Safety Review Board, which conducts reviews of safety efforts undertaken by states and federal agencies. Nearly 80% of the dams in the US are governed by state legislation; a huge majority of these are privately owned. However, the design and operational standards across states are not very different. They are all very closely aligned with the guidelines issued by FEMA. The coordination between the states and the federal government also enables better data sharing.

An important institution in mainstreaming dam safety is the National Dam Safety Program (NDSP), established in 1996. The NDSP is a partnership of the states, federal agencies, and private owners — led the FEMA — to encourage dam safety. It also conducts research, knowledge-sharing, capacity building, and public awareness.

The EAP guidelines issued by the CWC resemble the FEMA guidelines, but leave out a lot of the details. FEMA has issued detailed guidelines for every aspect of dam safety: for example, just within the ambit of risk assessment, there are separate guidelines for preparation of inundation maps and hazard profiling of dams. In contrast, inundation maps only find mention once in the CWC guidelines, and then too only in the guidelines for preparation of emergency action plans. Thus, it is not unexpected that the Comptroller and Auditor General of India could only secure information regarding inundation maps for only 2 out of the 17 states it audited (Comptroller and Auditor General of India 2017). There too, maps were only available for 2 of the 80 dams. Hazard profiling is mentioned in the Central Water Commission (1987), however, it is a purely qualitative assessment on the part of the assessor and not based on quantification of dam failure consequences. It is unclear whether quantitative ex-ante risk assessments are done in India. It has been reported that as part of Phase-II of DRIP a tool is intended to be developed to prepare inundation maps.[17] However, unlike FEMA its design is not encoded in the guidelines.

[17] Information from interviews with retired officers of CWC.

5.1.1 Dam Failure Analysis Information

FEMA has developed extensive guidelines for every component of dam failure analysis (for example, *Federal Guidelines for Inundation Mapping of Flood Risks Associated with Dam Incidents and Failures*, and *Federal Guidelines for Dam Safety Risk Management*. The guidelines specify how inundations maps are to be prepared, their use in risk assessment and decision-making systems, and dissemination protocols.

These maps and risk analyses are freely available online, along with the input data (such as hydro-meteorological data, and dam specifications) used to generate them. This allows individual researchers to use the data for building domestic knowledge on dam-engineering and risk mitigation. The inundation maps inform EAPs, zoning and land use regulations, and disaster response plans of agencies tasked with emergency rescue operations.

FEMA requires the hydrograph in a dam failure analysis to include the names and locations of downstream habitations at risk and estimates of how long these areas will remain inundated. This allows for the calculation of the exposure in terms of human lives and property (For example see: Guadalupe-Blanco River Authority 2010).

FEMA also publishes a risk assessment tool which includes inundation maps and incorporates the risk of dam failure.[18,19] The flood risk assessment tool is used to determine insurance premiums under the National Flood Insurance Programme, a social security scheme of the US federal government.[20,21] Both the maps and the risk assessment tool are freely accessible on the FEMA website, and are designed to be easy to use. Beneficiaries can easily check risk-ratings for their property through the tool, and demand better service delivery.

In contrast, dam failure analysis data for most dams in India is not available online. None of the states publish this information online. Some information is available on dams requiring clearance from MoEF. However, as explained in section 4.1, only hydrographs are available, and those too for a small fraction of dams. Inundation maps are not publicly available for any dams.

5.1.2 Integrated Dam Failure Management

The US Army Corps of Engineers along with the Department of Homeland Security has developed the Dam Sector Analysis Tool (DSAT). It is a web-based tool which combines dam failure models and decision-support systems into one software suite (Department of Homeland Security, USA 2012). The tool includes a module which utilises the Consequence-based Top Screen (CTS) methodology developed by the Department of Homeland Security to assess all manner of downstream risks in the event of a dam failure.

[18] The Risk MAP Program: Information for Homeowners, Renters and Business Owners. See: https://www.fema.gov/risk-map-program-information-homeowners-renters-and-business-owners

[19] The Risk MAP Program: Information for Real Estate, Lending and Insurance Professionals. See: https://www.fema.gov/risk-map-program-information-real-estate-lending-and-insurance-professionals

[20] National Flood Insurance Program: Flood Hazard Mapping, FEMA. See: https://www.fema.gov/national-flood-insurance-program-flood-hazard-mapping

[21] Risk Mapping, Assessment and Planning (Risk MAP). See: https://www.fema.gov/risk-mapping-assessment-and-planning-risk-map

Box. 5: Elements of Consequence-based Top Screen Methodology

The CTS module of the DSAT measures consequences along the following parameters (Department of Homeland Security, USA 2017):

- Human Impacts
  1. Total Population at Risk within Flood Scenario Inundation Zone
  2. Close Range Population at Risk
- Economic Impacts
  1. Asset Repair/Replacement Cost
  2. Remediation Cost
  3. Business Interruption Costs
- Impacts on Critical Functions
  1. Water Supply
  2. Irrigation
  3. Hydro-power Generation
  4. Flood Damage Reduction
  5. Navigation
  6. Recreation
- National Level Impacts
  1. Loss of Life
  2. Total Economic Costs
  3. Mass Evacuation
  4. National Security

It is linked to the US dam database from which it draws data regarding dam specifications. Population and habitation data are entered in their database regularly by local governments and administration. This also enables disaster response teams to prioritise relief and response activities to minimise the impact of a dam failure event. After the event, it also helps in establishing the size of liability of each stake-holder concerning damages and restitution. This kind of system is currently lacking in India.

5.2 Australia: Risk-based decision-making

The standards and practices followed by Australia are similar to those followed by the US. The risk-based decision making framework used by FEMA is similar to the framework developed by ANCOLD. The framework used in Australia is shown in figure 2 (Australian National Committee on Large Dams 2003).

This risk-based decision-making system is used to inform the feasibility, location and design parameters for new dams, and for making decisions on modifying existing dams. Thus, design standards for dams are also decided by a risk assessment rather than just dam height and storage volume. India lacks a risk-based decision-making system for determining feasibility, location and design standards of dams before construction.

An important point to note in ANCOLD's risk-based decision-making system is the mechanism for decommissioning dams. If the risk of dam failure exceeds the acceptable societal risk, then the best course of action is to decommission the dam. India does not have a policy on dam decommissioning. Given the number of old dams in India, it is necessary to develop a

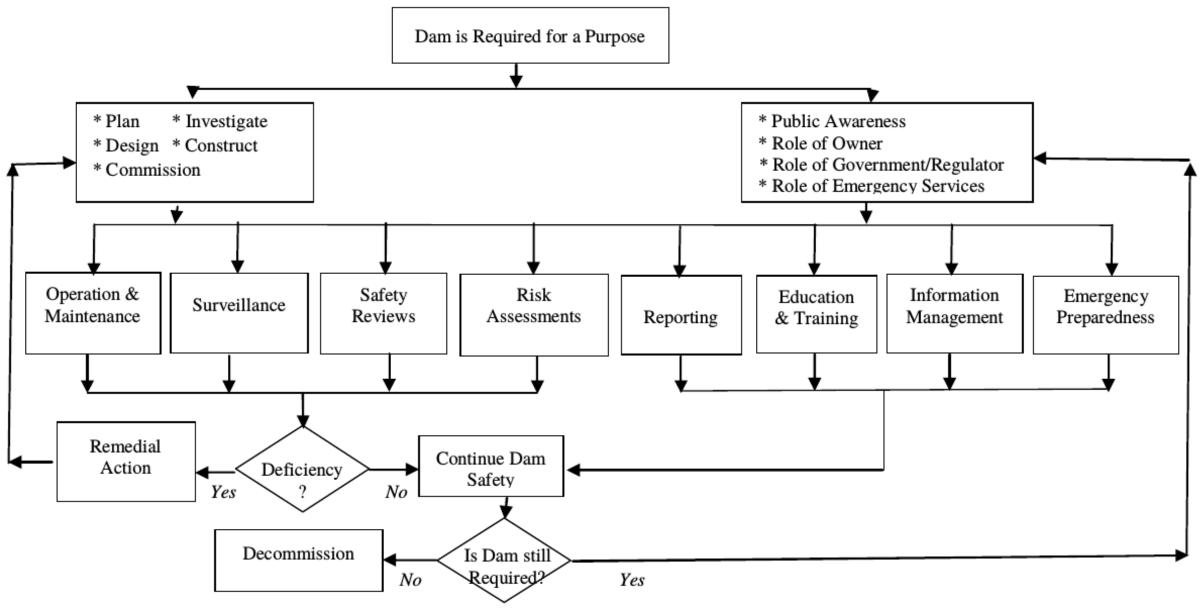


Figure 2: Risk-based Decision-Making in Australia

decommissioning policy. For example, the Mullaperiyar dam in Kerala, which is more than 100 years old has been flagged as a disaster-in-the-making (Thakkar 2011, See; Chowdhury 2013; Press Trust of India 2016). The similarly-old Jaswant Sagar dam in Rajasthan breached in 2007. However, in the case of Mullaperiyar dam, if it fails there are two downstream dams which may be at risk of failure (Rao 2014). Dams are expensive, and decommissioning them can disrupt lives, livelihoods and economic activity. Therefore, a risk-based approach is a must in any decommissioning policy.

5.3 China

Following the multiple dam failures in the 1970s China enacted several dam safety legislations in 1991. The Ministry of Water Resources created the Dam Safety Management Centre under the Nanjing Hydraulic Research Institute, and Large Dam Safety Supervision Centre to conduct dam safety assessments and research in dam safety, and for development of standards and regulation. The Nanjing Hydraulic Research Institute conducts dam failure analyses and consequence analyses for all large dams (For example, see Zhou et al. 2015; Cheng et al. 2010).

Through research China has developed sophisticated risk management systems for mitigating risks of dam failure. Consequence analyses for various dam failure scenarios are used to quantify the exposure and vulnerability of downstream habitations (Cheng et al. 2010). This vulnerability analysis is then used to regulate land use in the downstream areas, and for designing early warning systems, and emergency management plans for the region.

With the number of dams already present in India, and the expected growth in the future, it will become imperative to develop such systems in India. Dam failure analysis for all dams will serve as the foundation for these systems.

5.4 Key Takeaways for India

Since 2018 CWC has developed detailed guidelines on dam failure analysis and preparation of inundation maps. They include a component of consequence analysis. This is a welcome development.

However, since states are responsible for dam safety regulation, ultimately whether these guidelines are adopted will be up to the states. There is an urgent need to institute mechanisms for regular sharing of dam-related data between the states and the centre. This must include dam failure analysis data and inundation maps. These data also need to be made publicly available in an easy to use form for transparency, and for facilitating research in dam safety and risk mitigation.

Risk-based decision making systems need to be developed for making objectively sound decisions on all aspects of dam design, construction and operation.[22] The system should inform every step starting with whether to build a dam in the first place. The risk-based decision-making system should inform the measures to be taken for mitigating dam-failure risk. Dams which pose an unacceptable risk need to be assessed to determine whether the risk can be reduced to acceptable levels through repairs and upgrades. A decommissioning policy needs to be put in place for removing or reconstructing dams which cannot be repaired or upgraded.

6 Key Findings & Recommendations

Dam failure analysis is done in India as part of EIA for projects requiring environmental clearance from MoEF. However, there is no standardisation in how dam failure analyses are conducted and reported. While the CWC has developed some guidelines on this, they are not legally binding. MoEF therefore needs to institute legally binding standards for conducting and reporting dam failure analysis.

Data from dam failure analyses for cleared projects should be made publicly available in a usable form. This information is a public good. Its easy availability could also set the foundations for developing domestic knowledge and capacity on dam risk management.

MoEF should set up a database linking information from dam failure analyses for cleared projects with the static dam-related information from Indian Space Research Organisation (ISRO)'s Water Resources Information System (WRIS). Instituting systems for regularly sharing dam related data between centre and states will be essential for this. An integrated database is the first step towards creating an integrated risk management tool like the USA's DSAT, and for a risk-based decision-making system.

While dam failure analysis is mandatory for environmental clearance, it is unclear how many projects actually comply with this requirement. Existing dams where no new engineering activity is planned are not required to conduct dam failure analysis. Dam failure analysis needs to be a regular activity for all large dams. The methodology should be further refined to use the latest data from routine inspections and surveillance.

[22] At the time of writing this paper, CWC was reported to have been in the process of developing such a framework.

Dam failure analyses for environmental clearance are often not accompanied by inundation maps. A dam failure analysis without an inundation map, is of limited use to local officials in charge of mitigation work and emergency response, and for citizens likely to be affected by a dam failure event. Inundation maps should therefore be a compulsory feature of dam failure analyses.

There is no statutory requirement for conducting a consequence analysis of dam failure. The main purpose of a dam failure analysis is for hazard profiling of dams, and for planning disaster risk mitigation works for downstream areas. Without a consequence analysis a dam failure analysis is of limited value. The government should regularly undertake consequence analyses for large dams, to have updated estimates of exposure and vulnerability. This can then be used for disaster mitigation through regional development planning and land-use regulation, like China does.

Existing dam design standards do not take into account the actual risk profile of the dam in question. Static standards based on height and storage capacity are easy to apply, but risk-based standards can better balance safety and costs. India needs to move towards risk-based design standards like USA and Australia.

A related issue is also the lack of a risk-based decision-making system for making decisions regarding feasibility, location and design of proposed dams, like those used in Australia and USA.[23] A risk-based decision-making system will enable the government to determine the most effective risk mitigation measures, and for prioritising dam-related works. Such a framework will also be necessary for the development of a dam decommissioning policy, for dams which pose an unacceptably high risk.

Lastly, there needs to be a pan-India statutory framework for reporting and recording dam failure events, and neither is there a centralised repository for information regarding dam failure events. As a result, many dam failure events go unreported. India needs to enact legislation, and put in place systems for regular reporting of dam failure events.

7 Conclusion

A risk-based approach is necessary for making sound decisions on dam safety. Dam failure analysis is fundamental to a risk-based approach to dam safety. Some of the technological and institutional foundations for building a robust risk-based decision-making system for this sector are already in place. A few changes in policy, and leveraging already built resources (E.g.: WRIS, and MoEF environmental clearance portal) can enable India to build a better, safer dam sector.

[23] At the time of writing this paper, the CWC was reported to have been in the process of developing risk management guidelines for dams.

References

[1] Australian National Committee on Large Dams. *Risk based approach to assessment of dams*. 2003.

[2] Bureau of Indian Standards. *IS 11223-1985 : Guidelines for Fixing Spillway Capacity*. 1985.

[3] Bureau of Indian Standards. *IS 7323-1994 : Operation of Reservoirs - Guidelines*. 1994.

[4] Central Electric Authority, Government of India. *Status of 50,000 MW Hydro Electric Initiative*. 2017. URL: http://www.cea.nic.in/reports/monthly/hydro/2017/status_hydro_initiative-04.pdf.

[5] Central Water Commission. *Guidelines for Safety Inspections of Dams*. 1987.

[6] Central Water Commission. *Guidelines for Preparation of Emergency Action Plans*. 2006.

[7] Central Water Commission, Government of India. *National Register of Large Dams*. 2019.

[8] Central Water Commission, Government of India. *Training module on Dam Safety and Instrumentation for New Recruits of the Central Water Engineering Services*. 2019. URL: https://nwa.mah.nic.in/coursematerial/ITP_D&R/Module-VI.pdf.

[9] Chetan Chauhan. 2018. URL: https://www.hindustantimes.com/india-news/kerala-floods-poor-dam-management-behind-disasters-experts-say/story-WR43JJjuHQjYRms3m2VxhI.html.

[10] C. Cheng et al. *Analysis of dam safety management system in China*. 2010. DOI: 10.1109/ICEMMS.2010.5563488.

[11] *China warns of faulty dams danger, plans repairs*. 2008. URL: https://www.reuters.com/article/environment-china-dams-dc/china-warns-of-faulty-dams-danger-plans-repairs-idUSPEK33020620080115.

[12] Arnab Roy Chowdhury. "Decommissioning dams in India: a comparative assessment of Mullaperiyar and other cases". In: *Development in Practice* 23.2 (2013), pp. 292–298.

[13] Comptroller and Auditor General of India. *Performance Audit of Disaster Preparedness in India*. 2013.

[14] Comptroller and Auditor General of India. *Report of the Comptroller and Auditor General of India on Environmental Clearance and Post Clearance Monitoring*. 2016.

[15] Comptroller and Auditor General of India. *Report on Scheme for Flood Control and Flood Forecasting*. 2017. URL: https://cag.gov.in/webroot/uploads/download_audit_report/2017/Report_No.10_of_2017_-_Performance_audit_Union_Government_Schemes_for_Flood_Control_and_Flood_Forecasting_Reports_of_Ministry_of_Water_Resources,_River_Development_&_Ganga_Rejuven.pdf.

[16] Dam Safety Organisation, Central Water Commission, Government of India. *Reported Failure of Dams in India (Year-wise)*. URL: https://www.damsafety.in/ecm-includes/PDFs/List_Reported_Failure_of_Dams_in_India.pdf.

[17] Department of Homeland Security, USA. *Dams Sector Analysis Tool*. 2012. URL: https://www.dhs.gov/sites/default/files/publications/DSAT%5C%20Fact%5C%20Sheet_508.pdf.

[18] Department of Homeland Security, USA. *Dams Sector Consequence-based Top Screen*. 2017. URL: https://www.dhs.gov/sites/default/files/publications/dams-cts-fact-sheet-2017-508.pdf.

[19] S B Easwaran. "The Loudest Crash Of '79". In: *Outlook, India* (2012). URL: http://www.outlookindia.com/magazine/story/the-loudest-crash-of-79/281980.

[20] Ministry of Environment and Government of India Forests. *Environment Protection Act, 1986*. 1986. URL: http://www.moef.nic.in/sites/default/files/eprotect_act_1986.pdf.

[21] Expert Committee on Uttarakhand Flood Disaster and Role of Hydroelectric Projects, Ministry of Environment and Forests, Government of India. *Assessment of Environmental Degradation and Impact of Hydroelectric projects during the June 2013 Disaster in Uttarakhand*. 2014. URL: https://sandrp.in/2014/04/29/report-of-expert-committee-on-uttarakhand-flood-disaster-role-of-heps-welcome-recommendations/.

[22] Fedaral Emergency Management Agency, USA. *Federal Guidelines for Inundation Mapping of Flood Risks Associated with Dam Incidents and Failures*. 2013. URL: https://www.fema.gov/media-library-data/96171edb98e3f51ff9684a8d1f034d97/Dam_Guidance_508.pdf.

[23] Fedaral Emergency Management Agency, USA. *Federal Guidelines for Dam Safety Risk Management*. 2015. URL: https://www.fema.gov/media-library-data/1423661058965-58dfcecc8d8d18b7e9b2a79ce1e83c96/FEMAP-1025.pdf.

[24] Federal Emergency Management Agency, USA. "Why Dams Fail". In: (2017). URL: https://www.fema.gov/why-dams-fail.

[25] Guadalupe-Blanco River Authority. *Hazard Mitigation Plan, Section 14: Dam Failure*. 2010. URL: http://www.gbra.org/documents/hazardmitigation/update/Section14-DamFailure.pdf.

[26] IDFC Institute. *India Infrastructure Report: Water: Policy and Performance for Sustainable Development*. 2011.

[27] International Rivers. "Damming Statistics". In: (2007). URL: https://www.internationalrivers.org/damming-statistics.

[28] Navmi Krishna. *Why are States unhappy with Dam Safety Bill?* July 29, 2019. URL: https://www.thehindu.com/news/national/why-are-states-unhappy-with-dam-safety-bill/article28747531.ece.

[29] P. McCully. *Silenced rivers: the ecology and politics of large dams*. G - Reference, Information and Interdisciplinary Subjects Series. Zed Books, 2001. ISBN: 9781856499019. URL: https://books.google.co.in/books?id=6K%5C_uAAAAMAAJ.

[30] Patrick McCully. "And The Walls Came Tumbling Down". In: *World Rivers Review* (2005). URL: https://www.internationalrivers.org/and-the-walls-came-tumbling-down.

[31] Ministry of Environment and Forests, Government of India. *Website for Online Submission and Monitoring of Environmental and CRZ Clearances*. URL: http://environmentclearance.nic.in/default.aspx (visited on 06/10/2017).

[32] Ministry of Environment and Forests, Government of India. *Environment Impact Assessment Notification S.O.60E*. 1994. URL: http://envfor.nic.in/legis/eia/so-60(e).html.

[33] Ministry of Environment and Forests, Government of India. *Environment Impact Assessment Notification S.O.1533E*. 2006. URL: http://envfor.nic.in/legis/eia/so1533.pdf.

[34] Ministry of Environment and Forests, Government of India. *Standard Terms of Reference for EIA/EMP Report for Projects/Activities Requiring Environmental Clearance Under EIA Notification 2006.* 2015.

[35] Ministry of Water Resources, Government of India. "Protection of Dams". In: *Press Information Bureau* (2011). URL: http://pib.nic.in/newsite/PrintRelease.aspx?relid=77544.

[36] Ministry of Water Resources, Government of India. "DRIP Project". In: *Press Information Bureau* (2014). URL: http://pib.nic.in/newsite/PrintRelease.aspx?relid=112599.

[37] Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India. *Lok Sabha, Unstarred Question No. 4741: Safety of Dams.* 2017. URL: http://164.100.47.190/loksabhaquestions/annex/11/AU4741.pdf.

[38] P Naveen. "Dam burst wreaks mayhem in Madhya Pradesh as contractor digs for diamonds". In: *Times of India* (2016). URL: http://timesofindia.indiatimes.com/city/bhopal/Dam-burst-wreaks-mayhem-in-Madhya-Pradesh-as-contractor-digs-for-diamonds/articleshow/53868708.cms.

[39] BKR Pillai, Manoj Kumar, and LAV Nathan. *Design Flood Reviews Of Existing Dams And Related Risk Mitigation Issues Under Dam Rehabilitation and Improvement Project.* 2013.

[40] Ravi Kumar Pillai and Om Prakash Gupta. "Incorporation of 'Risk Factor' in Design Flood Review of Existing Dams". In: *American Journal of Civil Engineering* 5.5 (2017), p. 293.

[41] Press Trust of India. "Petition in SC seeks decommissioning of Mullaperiyar Dam". In: *India Today* (2016). URL: http://indiatoday.intoday.in/story/petition-in-sc-seeks-decommissioning-of-mullaperiyar-dam/1/666663.html.

[42] Sivaji.T Rao. "Dam Break Report Confirms 35 Lakh Deaths Due to Collapde of Mullaperiyar". In: (2014). URL: http://www.indiawaterportal.org/sites/indiawaterportal.org/files/dam_break_analysis_of_mullaperiyar_dam_prof._shivaji_rao_2014.pdf.

[43] Patrick J Regan. "Dams and Civil Structures: An Examination of Dam Failures vs. Age of Dams". In: *Hydro Review* (2010). URL: http://www.hydroworld.com/articles/hr/print/volume-29/issue-4/articles/dams--civil-structures.html.

[44] Teton Dam Failure Review Group (U.S.) and F.W. Eikenberry. *Failure of Teton Dam: A Report of Findings.* Department of the Interior, Bureau of Reclamation, Engineering and Research Center, 1977. URL: https://books.google.co.in/books?id=9%5C_KLVgUEq-AC.

[45] Himanshu Thakkar. "Mullaperiyar Dam needs to be decommissioned urgently". In: *Rediff News* (2011). URL: http://sandrp.in/dams/Why_Mullaperiyar_needs_to_be_decommissioned_Urgently_Dec_2011.pdf.

[46] *The Disaster Management Act.* 2005.

[47] Kavita Upadhyay. *Dams and damages.* 2020. URL: https://www.thehindu.com/opinion/op-ed/dams-and-damages/article33795426.ece.

[48] US Army Corps of Engineers. "Dam Safety Facts and Figures". In: (2017). URL: http://www.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/590578/dam-safety-facts-and-figures/.

[49] Martin Wieland and R Muller. "Dam safety, emergency action plans and water alarm systems". In: (2009). URL: https://www.researchgate.net/publication/292872467_Dam_safety_emergency_action_plans_and_water_alarm_systems.

[50] Xingbo Zhou et al. "Study on dam risk classification in China". In: *Water Science and Technology: Water Supply* 15.3 (2015), pp. 483–489. ISSN: 1606-9749. DOI: 10.2166/ws.2014.133. eprint: http://ws.iwaponline.com/content/15/3/483.full.pdf. URL: http://ws.iwaponline.com/content/15/3/483.

MORE IN THE SERIES

- Chakraborty, L., (2021). Macroeconomic Framework of Union Budget 2021–22: Reconsidering the Fiscal Rules, W.P. No. 328 (March).
- Mukherjee, S., (2020). Pandemic and GST Revenue: An Assessment for Union and States, W.P. No. 327 (December).
- Badola, S., and Mukherjee, S., (2020). Factors Influencing Access to Formal Credit of Unincorporated Enterprises in India: Analysis of NSSO's Unit-level Data, W.P. No. 326 (December).

Devendra Damle, is Research Fellow, NIPFP
Email: devendra.damle@nipfp.org.in

National Institute of Public Finance and Policy,
18/2, Satsang Vihar Marg, Special Institutional
Area (Near JNU), New Delhi 110067
Tel. No. 26569303, 26569780, 26569784
Fax: 91-11-26852548
www.nipfp.org.in