APPRAISAL OF SPILLWAY CAPACITY AND STORAGE AUGMENTATION FOR DAM SAFETY USING PIANO KEY WEIR AND FUSE PLUG FOR CLIMATE CHANGE EFFECTS

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ABSTRACT

Many of the standing dams in India are old and designed with considerations which do not match present-day scenarios of hydro-meteorological, hydraulic and structural aspects. Due to climate change effects, increased occurrences of cloudburst events have taken place causing enhanced flood intensity affecting dam safety. The resulting failures of dams due to sudden extreme precipitation events is highlighted to torch the importance of increase in spillway capacity and reservoir storage. Performance of Tehri dam in the Himalayas during Cloudburst and GLOF occurrences is appraised along with inadequate spillway capacity of Matatila dam. Augmenting deficient discharging capacity of spillways and reservoir storage of standing dams contribute to dam safety using Piano Key Weir (PKW) and Fuse Plug devices. The study appraised that besides fulfilling dam safety concerns, the required flood defense for protection of downstream areas may possibly be met by reservoir storage capacity augmentation using above technologies. Several old dams namely- Raviege dam, Gloriettes dam, and Saint Marc dam in France and the new SawraKuddu dam in India, etc. have been equipped with PKW for deriving the intrinsic hydraulic advantages. Similarly Fuse Plug devices, developed by Hydrocoop were constructed on Copeton dam in Australia, Douglas dam in The United States, etc. The potential increase of spillway capacity of Matatila dam using PKW and increase in reservoir storage using Fuse Plug have been preliminarily designed. The augmentation of Idukki and Idamalayar reservoirs using Fuse Plug has been explained keeping in view the August 2018 floods.

1. INTRODUCTION

Dams are designed to conserve and control the varying discharges of rivers by creating reservoirs and satisfy human needs. In other aspects, dams show an unpredictable hazard to life and property in the case of their failure. The safety of the dam should be given high importance during every phase i.e., during the planning, construction, maintenance, and operation of dams.

Many standing dams in India do not match or suitable for the emerging hydro-meteorological, hydraulic aspects. Safety of these dams is important to prevent the damages triggered by the emerging changes in climatic conditions. There are cases like rapid variations in temperature, increase in the occurrence of cloudburst over the decades and occurrences of glacier lake outburst flood (GLOF) due to the impacts of global warming and climate change on hydrology and water resources. There are inherent uncertainties in climate change impact studies and variations in the factors considered in the design of a dam due to associated imponderables which heightens the risk. The Intergovernmental Panel on Climate Change (IPCC, 2014) report says that there will be a decrease in cold temperature extremes, an increase in warm temperature extremes, and an increase in extreme high sea levels as well as the number of heavy precipitation events. Cloud burst is an extreme amount of precipitation over a smaller area within a shorter period of time. Cloudbursts are often reported when there is a shift of hot air from the ground up towards clouds which carry a large amount of rain drops. The temperature difference eventually causes the break, leading to the sudden discharge of water. Cloudbursts are dependent on the geography of the area. They generally occur in mountainous regions, deserts, and interior regions of continental landmasses.

The variation in climatic conditions in recent decades is adversely impacting the glacier life cycle in the Himalayan region. This results in melting of glaciers forming a large number of glacial lakes. A glacial lake according to Gupta et al. (2016), is defined as water mass existing in a sufficient amount and extending with a free surface in, under, beside, and/or in front of a glacier and originating from glacier activities and/or retreating processes of a glacier" Due to rapid rate of ice and snow melt by global warming, accumulation of water in these lakes has been increasing rapidly. Unlike storm floods, GLOFs are virtually unpredictable events since it is difficult to monitor and detect breaching of glacial lakes which are located in high altitude remote areas. The hazard of a GLOF is characterized by a rapidly rising flood wave in a very short time, causing downstream disasters without sufficient preparedness against the risks (Bhajantri, M.R., & Bhosekar, V.V., 2018). Glacial Lakes consisting of unconsolidated material are prone to failure and may cause disastrous surges of water heavily charged with debris into the hydro power projects situated in the downstream river valley.

These extreme effects of climate change are highly unpredictable by nature and happen very abruptly. The increase in inflows to dams due to cloud bursts or GLOF may cause dam safety concerns due to enhanced hydrodynamic forces.

In recent years, many dams in India have been experiencing serious debilitating dam safety concerns in which the spillway capacity as well as reservoir storage has often exceeded the safe limits due to occurrence of intense high precipitation or cloud burst incidence in their catchments areas. Evidently, such extreme hydro-meteorological event results in serious threat to safety of the dam, besides triggering severe flood havocs in the downstream areas. Many of these dams are geared for power generation only, without having any designated flood cushion in the reservoir storage space. Due to absence of flood storage space, mostly the hydel dams failed to hold back the flood waters causing devastating inundation in the riparian downstream areas. To mitigate the above stated inability of many hydel or multipurpose dams in India, it is essentially required to come out with innovative technology for overhauling these standing dams for the purpose of provisioning flood cushion within the reservoir storage space without compromising dam safety. The preliminary study has been done on Matatila dam and Idukki and Idamalayar dam in Kerala.

2. LITERATURE REVIEW

This section reviews the imperatives for considering climate change impacts in dam safety planning with regard to increase of spillway capacity and reservoir storage. recent innovative remediation technologies are appraised to prevent the catastrophic failures that might result in.

Globally many dams failed over the last several decades due to sudden increase in inflow floods due to extreme precipitation events. Macchu dam –II in Gujarat, India has failed in august 1979, the storm that resulted in the dam collapse dumped 711.2 mm of rain on the region in less than 24 hours whereas, the dam was designed to cope with an average annual rainfall of 558.8 mm (Dhar, O. N., Rakecha,P. R.,Mandal,B. N., &Sangam,R. B., 1981). the spillway capacity provided was for 6182.42 m^3/s, the actually observed flood during an intense rainfall of 1979 was estimated at nearly 13139 m^3/s (212.5%).

The failure of dams in China in 1975 explains the impact of unpredictable climate change effects in the dam safety. The Banqiao Dam on Ru River (Tributary of Hong River) in China was originally designed to pass about 1742 m^3/s. The storage capacity was 492 Mm^3 of which 375 Mm^3 are reserved for flood storage. The height of the dam was at nearly 116 m. The Shimantan Dam on Hong River in China had a capacity of 94.4 Mm^3 with 70.4 Mm^3 for flood storage. In August 1975 an unusual weather pattern resulted in a cyclone which caused torrential rains for three days giving 1 m depth of rainfall during August 5th-7th, 1975. On August 8th the flood water in Shimantan dam on Hong river rose by 40 cm above the crest of the dams and the dam collapsed and the reservoir emptied more than 113.2 Mm^3 of water within 5 hours, after half an hour the Banqiao dam also failed when it created a wall of moving water of 6 m height and 12 km width. Behind this moving wall of water was more than 566.3 Mm^3 of additional flood of water. Total 62 dams collapsed affecting 11 million people in the region (The August 1975 collapse of Banqiao and Shimantan dams, Chapter 3, 1998).

The Tehri Dam is located in Tehri Garhwal District of the state Uttarakhand on River Bhagirathi, India. It is 260.5 m high with Gross Storage of 3540 Mm^3 and Live Storage of 2615 Mm^3. The design flood is 15540 m^3/s and the spillway capacity is 13040 m^3/s.

From 16-18 June 2013 very heavy to extremely heavy rainfall was recorded at many stations in Uttarakhand. The flash floods, glacial lake outburst and landslides in different parts of Uttarakhand caused huge loss of life, properties and physical infrastructure within a few days. Tehri dam played a vital role in mitigating the floods in the downstream.

On June 17, 2013, in the morning, the peak discharge in Bhagirathi River was 7500 m^3/s. The inflow from Alaknanda was already 6940 m^3/s by then. As it was the start of monsoon season and the reservoir was relatively empty, the dam authorities released 500 m^3/s instead of 7500 m^3/s which prevented a rise in water level by at least 5 m in Devprayag (Confluence of Alaknanda and Bhagirathi Rivers) and 2.5 m to 3 m in Rishikesh and Haridwar. At Devprayag the river level rose by 11 m due to the confluence of Bhaghirathi and Alaknanda on 17th June. Alaknanda does not have storage like the Tehri dam for Bhagirathi. Bhajantri & Bhosekar (2018) said that "This single large storage helped in averting the terrible devastation, whereas the several small storage facilities collapsed in both the river valleys of Alaknanda and Mandakini". The catastrophe would have been high if the Tehri dam had already some storage instead of water level less than MDDL.

Keeping in view of the requirement of increased reservoir storage and spillway capacity, the innovative, cost-effective remediation technologies include piano key weirs, concrete fuse plugs and fuse gates.

A Piano Key Weir is a kind of labyrinth hydraulic structure, in general, placed transversely to rivers that causes flow discontinuity and affects the hydraulics of rivers. The inclined bottom of these keys alleviates the transition of sediment over the structure, reducing upstream sedimentation and minimizing the morphological change impact on the regime of the alluvial river as shown in figure 1 below. Piano Key Weir is an innovative, cost effective solution to increase the active storage capacity of the reservoirs and also for improving the safety of dam in case of erratic catastrophic flood events in the backdrop of climate change uncertainties (Leite Ribeiro et al., 2012).

Figure 1 : Piano Key Weir in operation (Laugier, 2016)

A Fuse Plug is an installation in connection to a dam that may allow a quick release of water from the reservoir in case the inflow of water exceeds the spillway capacity for an extended period. It is intended to be used as an emergency measure in order to protect the main dam from overtopping. A fuse plug can be constructed as a conventional earthfill embankment dam or in concrete blocks (developed by Hydrocoop) are designed to be washed out completely in a predictable and controlled manner at a predetermined water level. The Concrete Fuse Plugs are simple massive blocks placed side by side on a spillway sill. These are free standing and stable until the water level in the reservoir reaches a certain elevation and they start tilting when this elevation is exceeded. These may be designed to tilt before being overtopped and, in such a case, will have a significant height compared to their thickness. Elements, or blocks, placed on the same sill may have the same height but different thickness, so that they tilt at different water elevations. The arrangement of concrete fuse plugs given by Hydrocoop is as shown in Figures 2-4. The water elevations for tilting can be calculated based on horizontal water loading combined with predictable uplift pressures. To ensure that the magnitude of uplift pressure under each block develop as required, a hollow area can be provided under each block which is wide open at the upstream side and completely closed and watertight at the downstream side (Low cost technologies to improve reservoirs storage, 2013).

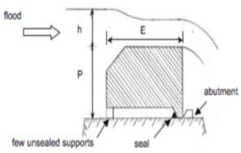

Figure 2 : Concrete Fuse Plug Overtopped

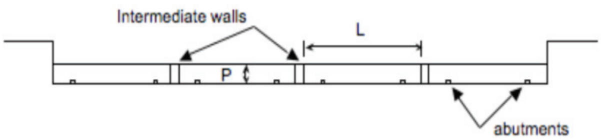

Figure 3 : Downstream view of the spillway

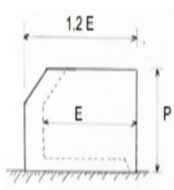

Figure 4 : Intermediate wall

Fuse Gates are the mechanical equivalent of a fuse plug. Fuse gates have been implemented successfully on more than 50 dams throughout the world illustrating undeniable evidence of its importance and effectiveness. These are permanently fixed to the crest unlike the concrete fuse plugs which get washed away in emergency situations but are relatively on the expensive side.

These techniques have been implemented in various dams for the purpose of interest i.e. enhancement of discharge capacity and reservoir storage.

In the case of Goulours dam which was constructed in the early 1940s in France is a 21m high concrete, single curvature arch gravity structure with a crest length of 71m. Laboratory tests with a 1/20 scale model showed the discharge capacity to be 92 m^3/s with a 1m nappe depth. However, the challenge facing Électricité de France (EdF) was that the updated design flood is 162m^3/s.

Options considered included changes to the operating level of the reservoir, construction of another spillway – either gated, standard or labyrinth – or installation of Fuse Gates, or a Piano Key Weir (PKW). The latter was selected for its minimum impact and cost, and reliability. And, to ensure the ongoing reliability of the existing gate, it is always to be operated to spill first and the PKW – installed on the right bank – would only be required for major floods exceeding the 25-year return period.

The Piano Key Weir was installed in a 12m long section of the dam though, due to topography, it is not strictly on the crest. It has two channels and three chutes – the five conduits were the optimum arrangement to minimize construction costs associated with achieving the same total length of walls as seven and nine conduits.

The Saint Marc dam (Leite Ribeiro et al. , 2011) is a 40 m high concrete gravity dam with an overall crest length of 170 m. The original spillways include 3 sluices with Creager type crests: one 7.5 m wide equipped with a radial gate on the right bank and two identical 10 m wide also fit out with radial gates. Before the construction of the PKW, the maximum spillway capacity was 623 m^3 /s. The update of hydrological studies showed that the existing discharge capacity is smaller than the 1,000 years return period design flood (750 m^3 /s). In order to satisfy the required dam safety, feasibility study suggested providing an additional discharge work to the existing spillways. A technical-economical comparison of several designs was carried out, among them the Piano Key Weir (PKW) turned out to be the best solution.

The PKW design was constrained by the available space on the dam crest as only a 20 m wide pass was affordable. The structure is cantilevered upstream and downstream equally. It is thus well self-balanced. The PKW has a capacity of 134 m^3/s at 283.50 m NGF (Normal altitude in France), which corresponds to an upstream hydraulic head of 1.35 m. The total spillway capacity increased up to 757m^3/s, slightly higher than the design flood. The downstream view of the dam is shown in figure.

Figure 5 : The PKW system at the EDF Saint-Marc dam in France (Laugier,2009)

The Wedbila dam (Low cost technologies to improve reservoirs storage, 2013) is located in Burkina Faso. It is situated to 30 Km south from Ouagadougou, the capital city of Burkina Faso. The dam has been constructed in 1980 by the World Federation of the Evangelical Churches (FEME). It is a small earth fill dam with a storage capacity of 2 Mm^3 intended for the irrigation of 45 Ha of land downstream of the dam. The dam has a reservoir capacity of 2.08Mm^3 with the Length of the spillway as 70 m and the length of the dam is 600m and maximal height of 4 m. The technical features of fuse plugs have been obtained by design model developed by Hydrocoop France team with the collaboration of IFEC Consulting Engineers. The fuse plugs are designed to be overtopped by water nappe before tilting. The blocks placed on the same sill may have the same height but different thickness, so that they tilt progressively for different water levels. The water elevations for tilting can be predicted quite accurately since the blocks are designed with a total uplift at their base.

The existing free overflow spillway has a length of 70 m. the project consisted of installation of seven (07) concrete fuse plugs, 0.50 m high and with Upstream/Downstream width varying between 0.78 m to 1.03m and unit length of 9.70 m. The first block tilt for the 10-year flood and all the blocks tilt in order to keep the existing MWL for the Design Flood. The tilted blocks can be easily and quickly replaced by provisional bags before replacing the block seen in the figure below.

Figure 6 : View of the spillway crest widening operation

Figure 7 : View of spillway heightened by fuse plugs

3. PRELIMINARY ANALYTICAL REVIEW

Based on the review, few dams have been identified to broadly analyze on their distress during extreme precipitation events and a very preliminary analytical study has been presented here to explore recent technological advances for potential remediation.

3.1 Matatila dam

Matatila dam is an earthen dam in Lalitpur district of Uttar Pradesh on River Betwa with a maximum height of 33.53 m from the river bed. The dam is constructed in 1964. The length of the spillway is 490 m and the reservoir capacity is 1132.68 Mm^3. The dam was designed for the maximum flood discharge of 23,390 m^3/s and with a spillway capacity of 15857 m^3/s.

Rajghat dam was constructed at 50 km upstream of Matatila dam in 1994 with a reservoir capacity of 2172 Mm^3. It is an earthen and masonry dam with a maximum height of 43.8 m. The designed maximum flood discharge of the dam is 39080 m^3/s and spillway capacity is 34000 m^3/s. The maximum flood event occurred in 1983 i.e. before the construction of Rajghat dam where the flood discharge was 19,821 m^3/s is 84 percent of the designed maximum flood inflow.

In the study by Upananda Rath et al. (2019), the design floods for both dams have been assessed using the quasi-distributed modeling by hydro-meteorological approach which involves estimation of a design storm hyetograph and derivation of the catchment response function. The design flood computations for Matatila dam have been carried out using HEC-HMS with the initial condition for reservoir routing at Rajghat reservoir being assumed as FRL (EL 371 m) i.e. considering the worst scenario which will give the maximum Design Flood. From the model, the revised design flood is estimated as 34000 m^3/s which is 46% more than the designed maximum Flood Discharge (23,390 m^3/s).

The study has been performed for different conditions i.e. with the actual spillway capacity and revised spillway capacity for assumed incoming flood discharge of 34000 m^3/s. The revised spillway capacity considered is the maximum discharge carrying capacity of the least cross section of River Betwa at downstream of Matatila dam using DEM. This has been found to be 20343 m^3/s (128% of actual spillway capacity).

Considering incoming flood discharge of 34000 m^3/s i.e. revised design discharge for 12 hours and the spillway release for 12 hours and 18 hours for the initial spillway capacity, the increase in reservoir level is found to be 21.5 m and 12.11 m respectively above FRL. The height of the fuse plug is found to be 19.5 m and 11 m for each of these scenarios by assuming overtopping before tilting mentioned by the Hydrocoop to improve storage.

When the spillway capacity has been increased to 20343 m^3/s, the increase in reservoir levels has been found to be 16.19 m and 4.13 m considering the spillage for 12 hours and 18 hours. The height of the fuse plugs is 14.7 m and 3.75 m.

Increasing the spillway capacity has been designed preliminarily by Piano Key Weir. To increase the spillway capacity to 20343 m^3/s, two considerations have been carried out. The height of the PKW is considered as 7 m and 10 m. For 7 m height of the PKW the number of bays is found to be 8 whereas for 10m high PKW it is 6 bays with h/p =1. For the economic purpose 7 m can be considered.

3.2 Multi Reservoir Augmentation - Case Study on Idukki and Idamalayar dams based on August 2018 Floods

The Idukki Hydro-Electric Project is the biggest Hydro-Electric Project in the State of Kerala which is 45 years old. The components of the project include three major dams, namely: Idukki Arch dam, 169 m high); Cheruthoni concrete gravity dam, 138 m high; and Kulamavu composite (concrete and masonry) gravity dam, 100 m high. Construction of these three dams has created an artificial lake of 60 sq. km. Cheruthoni dam has five radial gates in the dam to release the water from the reservoir. Among the three dams, the spillage is only through Cheruthoni dam with spillway capacity of 5013 m^3/s. The water from the reservoir is drawn through an intake located near Kulamavu dam and then taken to the underground power house located at Moolamattom for power generation of 780 MW. The design flood of the Idukki reservoir is 8019 m^3/s.

Idamalayar dam is constructed in 1987 on Idamalayar tributary of Periyar River. The height of the dam is 101.6 m. The gross storage capacity of Idamalayar dam is 1089 Mm^3 and the designed spillway capacity is 3013 m^3/s. The design flood of the dam is 3248 m^3/s. The main purpose of the dam is Irrigation.

Kerala state experienced an abnormally high rainfall from 1 June 2018 to 19 August 2018. As per IMD data, Kerala received 2346.6 mm of rainfall from 1 June 2018 to 19 August 2018 in contrast to an expected 1649.5 mm of rainfall. The rainfall over Kerala during June, July and 1st to 19th of August was 15%, 18% and 164%, respectively, above normal (Lal et al, 2019). The storage of Idukki reservoir is at 92.5% of FRL and Idamalayar reservoir is 97.3% during the occurrence of flood (Mishra et al. 2018). The Kerala food 2018 was unprecedented and the rare combination of the occurrence of the extreme rainfall events along with storage near FRL of different reservoirs made the management challenging.

The average inflows to Idukki reservoir during 15, 16, 17 August 2018 are 1640 m^3/s, 2000 m^3/s, 1440 m^3/s respectively against the peak release from the spillway as 1500 m^3/s. The peak inflow to the Idamalayar dam is 1164 m^3/s and the average spill was 1271 m^3/s (Lal et al, 2019). The flood peak of about 8800 m^3/s was observed at Neeleswaram G&D site which includes the discharge from Idukki, Idamalayar dams and their downstream catchment response and the other tributaries of Periyar such as Perinjankutty (near uncontrolled tributary) and Muthirapuzha is shown in the map below. The study by Sudheer et. al. stated that the role of releases from Idukki reservoir in causing the flood havoc was less, as Perinjankutty river, which is nearly uncontrolled, contributes almost twice the amount of release from Idukki reservoir.

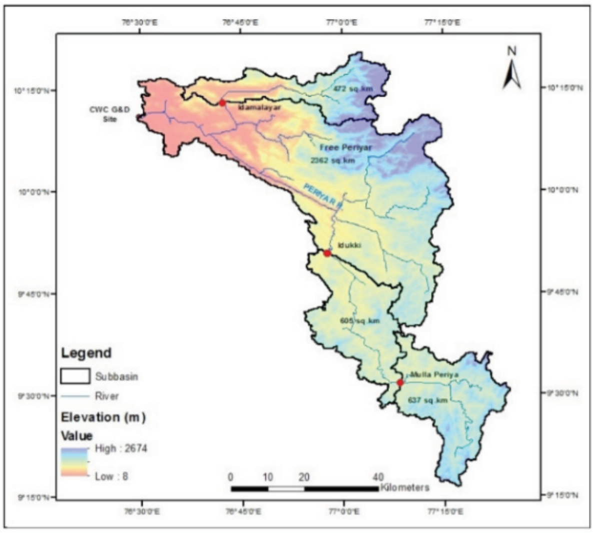

Figure 8 : Periyar river map up to Neeleswaram G&D Site (Lal,C. et al, 2019)

The study by Sudheer et al. (2018) suggested that reservoir operations could not have helped in avoiding the flood situation as only 16–21% peak attenuation was possible by emptying the reservoir in advance, as the bulk of runoff to the flooding was also contributed by the intermediate catchments without any reservoirs to control.

Contrast to the statement mentioned, the peak flow of 8800 m^3/s at Neeleswaram G&D site could have been reduced if the spillway releases from Idukki and Idamalayar are less. The peak release from Idukki dam was 1500 m^3/s and average spill from Idamalayar dam was 1271 m^3/s. The flood peak generated in the downstream free catchment was of the order of about 6030 m^3/s if there is no release from the two dams. The maximum daily discharge (6324 m^3/s) during 1971–2017 and the high-magnitude daily discharges (>2000 m^3/s) occurred either during the last week of July or during the first and second week of August (Sudheer et al, 2019).

The revised design flood of Idukki dam is 9402 m^3/s and Idamalayar dam is 6547 m^3/s given by Pillai et al. (2017). The flood cushion to cater the increased design flood can be met using concrete fuse plugs. In this respect, a very preliminary analysis on the prospect of using Fuse Plug device for Idukki dam and Idamalayar dam was performed as shared below. However, a much more comprehensive analysis is required to get a complete picture of the application.

Considering a flood of 9402 m^3/s (117% of design flood) for 12 hours to Idukki dam and the spill with the designed spillway capacity of 5013 m^3/s for 12 hours the height of the concrete fuse plug required is 2.89 m. With no spillage, the height of concrete fuse plug required would be 4.5 m.

Similarly, for Idamalayar dam, for the revised design flood of 6547 m^3/s (201.5% of design flood) for 12 hours and the spill of 3013 m^3/s for the same duration the fuse plug height is found to be 3.54m whereas without spillage it resulted to be 6.6m.

4. SUMMARY AND CONCLUSIONS

Ongoing escalation of climate change effects has intensified occurrences of cloudburst events with significantly enhanced flood intensity affecting dam safety. Many standing dams in India and elsewhere are old and designed with considerations which do not match present-day scenarios of hydro-meteorological, hydraulic and structural aspects.

Several dam failures globally due to climate change induced extreme precipitation events bring to the fore the imperative urgency to augment spillway capacity and reservoir storage. Broad appraisal of Tehri dam in the Himalayas during Cloudburst and GLOF occurrences along with inherent inadequacies of Matatila dam in the Betwa basin as well as Idukki and Idamalayar dams in Periyar basin in India revealed the underlying hazards on dam safety, which warrant urgent rehabilitation using latest R&D advances.

In recent decades, several old dams in France and some new dams in India, Vietnam, China etc. have been equipped with recent technology of Piano Key Weir for hydraulic advantages on dam safety. Similarly Fuse Plug devices, developed by Hydrocoop were constructed on Copeton dam in Australia, Douglas dam in The United States, etc.

As amply demonstrated in France, Australia and the USA in recent years, for rehabilitation of older dams Piano Key Weir and Fuse Plug devices can potentially contribute towards augmenting discharging capacity of spillways as well as deficient reservoir storage space of standing dams. Besides meeting dam safety concerns, the flood defense of downstream areas can be fulfilled by reservoir storage augmentation using these recent technological advances.

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