DRAWDOWN CAPACITY FOR RESERVOIR SAFETY AND EMERGENCY PLANNING – UK GUIDANCE

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ABSTRACT

The ability to lower a reservoir's water level quickly in an emergency is a key factor in ensuring reservoir safety. In the past there had been no universally accepted approach in the UK for assessing what is an adequate drawdown capacity. Jacobs UK delivered a government funded project to develop guidance on what constitutes a reasonable minimum rate of reservoir drawdown for UK reservoirs (Environment Agency, 2017), as part of an ongoing programme of improving the safety of UK dams.

A literature review was initially carried out to consider existing approaches in the UK and internationally. Scoping studies identified that a key parameter is the time it would take for a dam to fail by internal erosion and methods for predicting this were reviewed. Theoretical drawdown rates required to avert internal erosion formed the basis of the guidance.

The guide covers:

- *Types of drawdown facility and considerations for designing, maintaining and operating them*
- *Determining existing drawdown capacity, taking into account concurrent inflows and reliability of outlet works*
- *Assessing what is an appropriate drawdown capacity, based on consequences of failure and expressed as a percentage of reservoir depth (H)/day, with a basic standard of 5%H/day for high consequence dams*
- *Mitigation options where existing facilities are deemed inadequate, including methods to quantify risks of inadequate drawdown capacity*

This paper presents an overview of the guide and summarises the research carried out in its development. It also summarises feedback from two years of applying the guide by the UK industry.

1. INTRODUCTION

1.1 Overview

In England, 1.1 million properties are at risk of flooding from the structural failure of large raised reservoirs and their associated dams. The average age of these structures is 120 years and the possibility of a catastrophic failure may be expected to increase with age. There are continuing dam safety incidents at UK dams with published annual summaries (Environment Agency, 2004 to 2017).

A key factor in controlling an incident and thus avoiding a catastrophic failure is the ability to draw a reservoir down in the event of an emergency. This will reduce the load on the dam structure, reduce the likelihood of failure and, in the very worst outcome, minimise the impacts downstream in the event of failure.

1.2 The need for guidance

Under UK reservoir safety legislation, inspecting engineers are required to review whether a reservoir has adequate facilities to lower the water level efficiently. For example the Statutory Instrument applicable to English reservoirs states that inspection reports under Section 10 of the Act should include "*findings as to the efficiency of the scour pipe or discharge culvert or other means of lowering the water in…the reservoir*", with the inspections being carried out at least every 10 years. Similar requirements are included in Welsh legislation and it is good practice in Scotland.

In the past there has been no universally accepted approach to assess what constitutes an adequate rate of drawdown, which resulted in inconsistency. This was confirmed during the scoping phase of the project which reviewed a sample of 197 inspection reports, of which less than a third of them described a documented assessment of the adequacy of emergency drawdown facilities. Even fewer of the reports referenced a specific criterion for establishing adequate drawdown capacity (only 26 of the 197 reports sampled). The need to develop guidance was therefore identified as a priority in the 2009 UK research and development strategy (Environment Agency, 2009).

1.3 Function of drawdown facilities

Drawdown facilities can provide a means to lower a reservoir's level quickly in an emergency where a structural problem occurs which threatens, or potentially threatens, the safety of the dam. This may be a precautionary measure while the problem is investigated, or an emergency measure. In either case, the primary objective would be to reduce the load on the dam, and thereby arrest a failure mode which has already initiated, or is at high risk of initiating, and prevent it from developing. If this objective cannot be achieved then partial drawdown may at least buy time to make repairs, or evacuate downstream, or employ other techniques to avert failure. In the very worst outcome the intervention of drawdown may at least reduce the consequences of failure by reducing the volume of water released in a breach. In the period after an emergency drawdown, the drawdown facilities may allow the reservoir level to be controlled while repairs are carried out.

It should be noted that the purpose of drawdown facilities is not to mitigate against failure from flood discharges; this is the function of the spillway.

The common failure modes for concrete and masonry dams differ from embankment dams and are considered separately in the guidance.

2. LITERATURE REVIEW

2.1 Existing International Drawdown Standards

No references to a specific drawdown rate were found in any of the ICOLD bulletins, however, the literature review identified six international drawdown standards as summarised in Table 1. Each expresses drawdown rate as a percentage of reservoir volume, with values ranging between 0.46 and 2.9% dam height/day.

Table 1 : Summary of international standards.

Organisation	Origin	Drawdown criteria	Assumed inflow	% dam height/ day*
State of California (Babbit & Mraz 1999)	USA	**For reservoirs <6.2Mm³: 50% of reservoir capacity <7 days.** **For larger reservoirs: 10% of reservoir depth in 7 to 10 days.** (Logic appears to be that larger dams are more thoroughly designed and constructed). Excludes releases through power plants.	Nil (it is stated that in California this is true 9 months of the year)	Reservoirs < 6Mm³ 2.9 Larger reservoirs : 0.3–0.5
French practice (Combelles 1985)	France	Bottom outlets should be capable of reducing load on dam by 50% in 8 days. This approximates to a dam with a storage capacity of N x $10^6 m^3$ requiring a bottom outlet capacity of N m^3/s.	Nil	2.6
US Bureau of Reclamation (USBR 1990)	USA	Varies with class of hazard and risk (9 Classes). High risk dams lower by 25% in 10-20days and 50% in 30-40days. Low risk lower by 25% in 60-90days and 50% in 90-120 days	Highest mean monthly inflows for the duration of the evacuation period	High risk: 0.2-2.5 Low risk 0.3-0.4%
Bureau of Indian Standards (Bureau of Indian Standards, 2004)	India	Varies with class of hazard and risk: 20–50 days for 25% lowering, 40–70 days for 50% lowering and 80–100 days for 75% lowering. Overall requirement to drawdown the reservoir within a period of 1 to 4 months.	Highest consecutive mean monthly inflows for the duration of the evacuation period	0.4–0.5
Norwegian Dam Safety Regulations (FAO 2009)	Norway	Highest class: 1m/day Second highest class: 0.5–1m/day	Average inflow	
* Conversion to percent water depth from reservoir volume assumes a cubic relationship with 50% volume equating to 79% reservoir depth and 75% volume equating to 91% reservoir depth. This is an approximation of the rule of thumb that 50% storage is in the upper third.				

Papers from Australia confirmed that there were no Australian (ANCOLD) guidelines for sizing emergency low-level outlet works and USBR (1990) remained the primary reference for Australian dam owners undertaking these assessments (stated in Johnson et al. 2010).

2.2 Existing UK Drawdown Standards

The literature review identified ten systems which had previously been applied to UK reservoirs. The standards were expressed in different ways which makes direct comparison difficult. Some criteria are based on an initial drawdown rate to give time to implement other measures while others are expressed as a minimum period to achieve a global reduction in capacity or height (to stabilise the situation). To provide some comparison the criteria have been normalized and expressed as a percentage of dam height per day in Table 2.

Table 2 : Summary of previous UK standards.

Organization	Drawdown criteria		Assumed inflow	% dam height/ day*
	Initial rate	Global rate		
Thames Water	1m/day		Nil	13
United Utilities	1m/day		Nil	7.7
UK individual (Jonathan Hinks)	300mm/day + 5H + $8{,}640Q_{10}/a$		Q_{10}	3.4
Canal & River Trust		Drawdown to 50% volume in 5 to 9 days depending on consequence class	Winter daily mean inflow	2.3–4.1
Wessex Water		Drawdown to 75% height in 3 days	$0.5m^3/s$	3.0
Anglian Water		Drawdown to 50% capacity in 10 days (20 days for non-impounding/ small relative catchment)	Nil	2.1 (1.0)
Northumbrian Water		Drawdown to 25% capacity in 28 days	Winter 28-day peak	1.3
Northern Ireland Water	Minimum 0.5m/ day		Nil	2.7%
Severn Trent Water	(i) Hinks' formula	Drawdown to 75% height in: (ii) 14 days for Category A/B (iii) 30 days for Category C/D	Q_{10} for Hinks	(i) 2.7 (ii) A/B: 1.8 (iii) C/D: 0.8
Scottish Water	Hinks' formula for first 24 hours	CRT rule but with relaxations for specific aspects	Q_{10}	Category A: 5.4–9.0 C/D: 1.35
* Conversion to percent water depth from reservoir volume as Table 1 and by taking the median dam height for each company's stock of dams from BRE (1994).				

Table 2 highlights that there was previously no common approach to designing reservoir drawdown capacity in the UK and reservoir owners adopted a wide range of different standards. Indeed, the research found that in many cases drawdown adequacy was not being evaluated at all.

2.3 Incidents where failure has been averted by reservoir drawdown

The research also reviewed failures and incidents which have occurred at British and overseas dams between 1800 and 2012, as summarised in CIRIA Report SP167 (CIRIA 2014). The report describes 11 incidents in particular, including 3 overseas, where the ability to draw the reservoir down averted disaster. The drawdown rate in these cases varied between 0.8 and 1.7m per day which equates to 1.4 to 11.3% reservoir height per day. The depth of drawdown was only stated in three cases and ranged from 3m to 9.3m; hence it is not possible to be certain whether these rates are initial drawdown rates or global rates but they are likely to be the latter. This highlights the importance of adequate drawdown facilities and provides a useful benchmark for required drawdown capacity.

2.4 Questionnaire to UK industry

Between December 2014 and January 2015, a questionnaire was sent out to registered dam owners and all members of the British Dam Society. In total 84 responses were received, the majority (70%) from reservoir owners who between them operate 570 reservoirs. The questionnaire covered existing practices, past incidents and preferences for the guide. A similar questionnaire was sent to international reservoirs owners and regulators with 12 responses from USA, Canada, Sweden, France, New Zealand and Austria. The results are discussed in Volume 2 of the guide and confirmed the inconsistency in existing approaches.

3. FACTORS GOVERNING DESIRABLE DRAWDOWN CAPACITY

3.1 General

The threats which could ultimately lead to structural problems with a dam were reviewed and for each threat, the factors controlling the time to failure were assessed, and quantifiable parameters were identified. These parameters were then scored and screened to identify which were most relevant and most easily ascertained.

For embankment dams, it was concluded that there are four main threats where emergency drawdown is an effective means of mitigation; floods, wind (waves), earthquake and deterioration (internal erosion). Internal erosion, was concluded to be the most critical as it is the most common cause of reservoir failure in the UK, accounting for 43% of the UK dam incidents reported in CIRIA, 2014. There are two key factors that affect the potential for internal erosion to initiate and the speed at which it progresses, namely (i) the hydraulic gradient through the dam, I, and (ii) the erodibility of the dam fill (i.e. the erosion rate index, IHET).

While another major failure mechanism is external erosion caused by overtopping flows, this was not taken into account for the basis of determining drawdown capacity because overtopping failure is generally the result of flood flows and it would be unrealistic for drawdown facilities to be sized to pass such high flows. Similarly, other threats to UK dams (e.g. waves, ice, earthquakes) are either of rare occurrence, or are better managed by other means.

3.2 Review of the time to failure for embankment dams

A key parameter in determining an appropriate drawdown rate is the time it would take for the dam to fail, from the point when a defect becomes detectable, to the point when catastrophic failure and uncontrolled release of water is unavoidable.

Based on the conclusion above that internal erosion was the most critical failure mechanism for embankment dams, a review was carried out of the various methods available to predict the time it would take an embankment dam to fail by internal erosion. This included processes defined in guidance and papers, published data from expert opinion, software models and physical tests. The method given in ICOLD Bulletin 164 (ICOLD, 2013) was ultimately adopted because it is simple and rapid to carry out, has a strong link to hydraulic gradient (and thus drawdown) and the results broadly agree with actual observed failure incidents. The method was used to develop Figure 1.

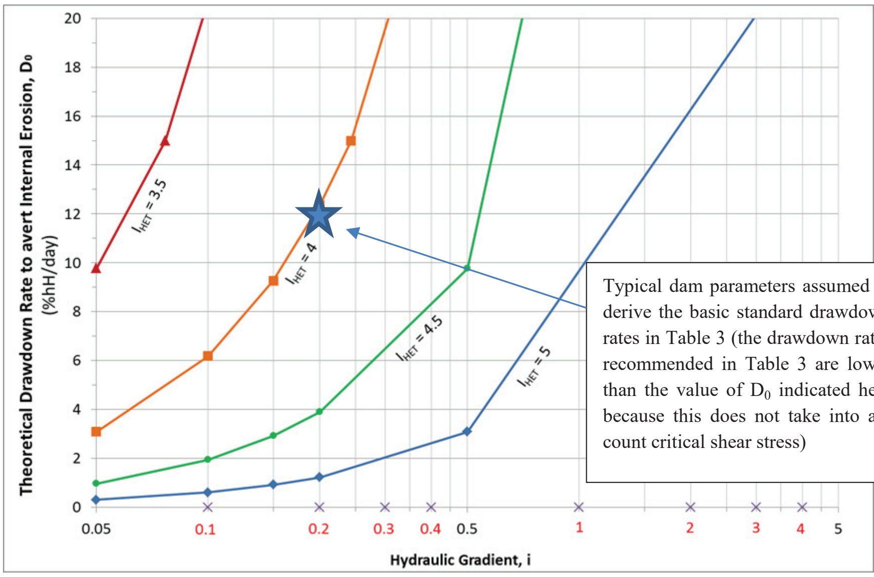

Figure 1 : Theoretical drawdown rate to avert internal erosion

The original relationship published by ICOLD defined the 'time to failure' as the time it would take for a 25mm diameter hole to widen to 1m diameter. However, it is assumed a leak would be detected before the hole reached this size such that drawdown to avert failure could be commenced earlier. Therefore Figure 1 is instead based on the 'time to failure' starting from an initial hole size of 5mm which represents the point at which a concentrated leak may first be detectable.

Several simplifications and approximations were made in order to produce the graph, including:

- In keeping with the relationship published in ICOLD Bulletin 164, Figure 1 conservatively takes no account of critical shear stress (i.e. the principle that erosion will only initiate once the shear stress generated by the flowing water exceeds a certain threshold). This means that the theoretical drawdown rates in Figure 1 may be **overestimated**. Guidance on critical shear stress is provided separately in the guide.

- Due to the complexity of modelling the actual hole size at each time step, the current time to failure at each step, has been taken as the time for a hole to develop from 5mm to 1,000mm. This approximation means that the theoretical drawdown rates are **underestimated.**
- Flow out of the leak was conservatively neglected when calculating the falling head, because it would be illogical for the guide to allow uncontrolled leakage to be considered a benefit. This means that the theoretical drawdown rates may be **overestimated**.

It is considered that the above three approximations will broadly cancel each other out and thus the rates in Figure 1 are deemed appropriate for gaining a rough indication of the theoretical rate required but, as with any theoretical models of this type, the results should be considered within an overall framework of engineering judgement.

3.3 Application to individual embankment dam

To apply Figure 1 to a specific embankment dam it is necessary to know the erodibility of the fill forming the dam, as measured in the hole erosion test (I_{HET}). In practice this information is often not available and there are limited published correlations with other geotechnical parameters. Appendix C of the guide presents a correlation between I_{HET} and soil particle size and plasticity which allows appropriate index values to be estimated for the purposes of drawdown assessment. The lack of published correlations is one factor that has led to scoping a European research programme into breach, with a scoping report commissioned under the UK Defra/ EA research programme currently in press.

4. THE UK GUIDE TO DRAWDOWN CAPACITY

4.1 General

The 'Guide to drawdown capacity for reservoir safety and emergency planning' was published in 2017 (Environment Agency, 2017) and provides guidance on:

- types of drawdown facility and considerations for designing, maintaining and operating them
- characterizing a reservoir site in order to evaluate the drawdown capacity
- determining existing drawdown capacity, taking into account concurrent inflows and reliability
- determining an appropriate drawdown capacity for reservoirs in the UK
- mitigation measures where existing facilities do not meet this capacity

The guidance is published on the GOV.UK website; Volume 1 is the main guidance and Volume 2 contains background and supplementary information. The guide was produced by Jacobs UK under the oversight of a steering group, with early drafts providing significant concern from some reservoir owners because of the perceived potential cost of upgrades to meet the draft standards. The final guidance was therefore developed in a workshop session, with increased emphasis on engineering judgement, and description of the different factors that need to be considered.

This section presents a brief overview of the guide. The guide is free to download, and reference should be made to the guide and supporting volume for detail. The guide includes descriptions and photographs of different types of drawdown facilities and discusses merits and hazards of each.

4.2 Allowance for inflows

- There are two components which make up the total drawdown capacity for a reservoir:
- reservoir lowering capacity
- inflow pass-through allowance

Where a by-wash channel exists, or there are other means of storing or diverting some or all of the normal inflows around the reservoir, then the inflow pass-through allowance may be reduced accordingly. This concept is illustrated in Figure 2.

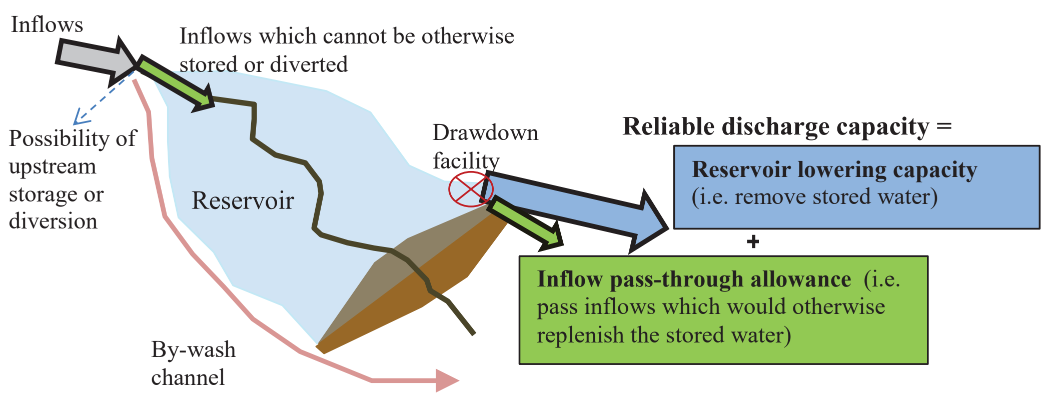

Figure 2 : Concept of reservoir lowering capacity and inflow pass-through capacity

In most situations, the Q_{50} flow (i.e. the flow which is exceeded on 50% of days in a typical year) is considered to be an appropriate pass-through allowance. Sensitivity checks are however recommended to understand how higher inflows might hamper the ability to draw a reservoir down.

Section 3 of the guide includes guidance on estimating reservoir inflows using flow statistics from the UK's network of 1,581 river gauging stations, publicly available from http://www.ceh.ac.uk/data/nrfa/data/search.html. Alternatively, a rule of thumb (Hinks, 2009) suggests that for most areas of the UK, excluding Wales, the west of Scotland and possibly the Lake District, the Q_{10} flow can be approximately estimated based on the catchment area as $Q_{10} = 0.035 m^3/s/km^2$.

4.3 Determining installed capacity

Guidance is provided in Section 4 on calculating the hydraulic capacity of low level outlets and siphons. It is normally sufficient to consider the head at top water level to determine the initial drawdown rate over the first 24 hours. Although the discharge rate will reduce with falling reservoir levels, normally so too does the incremental storage volume of the reservoir and these two effects partially counteract each other when calculating the rate of drawdown as a depth per day.

Temporary and emergency drawdown capability should only be taken into account if an emergency plan exists to demonstrate it can be feasibly achieved within the necessary timeframe. Allowance should be made for the delay in identifying a leak, raising the alarm and then installing any temporary facilities. Consideration should be given to whether drawdown facilities are likely to be reliable both in terms of their structural condition and operational considerations (i.e. access to the site and specific valves, and the availability of trained staff in emergency conditions).

4.4 Determining drawdown rate

The discharge capacity for reservoir lowering is defined as the reliable discharge capacity minus the inflow pass through allowance (see section 4.2). The installed drawdown rate is expressed as the percentage of maximum reservoir depth, H, which can be lowered in 24 hours abbreviated to %H/day.

Although the installed drawdown rate, expressed as %H/day is considered the most critical parameter for assessing drawdown capacity, the time to empty a significant portion of the reservoir depth should also be considered as part of a comprehensive evaluation, and is particularly relevant where significant reliance is placed on mobile pumps. The choice of depth should be based on any specific level(s) associated with critical failure modes but in the absence of such considerations it is recommended that the time it would take to empty the upper third of the reservoir depth should be evaluated.

4.5 Assessing the adequacy of installed drawdown rate – embankment dams

Section 6 of the guide provides a method for judging whether the installed drawdown rate at a reservoir is adequate. The format of the guidance evolved through industry consultation, and a quantitative method linked directly to time to failure was rejected in favour of a more flexible approach allowing engineering judgement, but taking into account four 'considerations' which need to be assessed in relation to a specific reservoir by an experienced engineer, as illustrated in Figure 3.

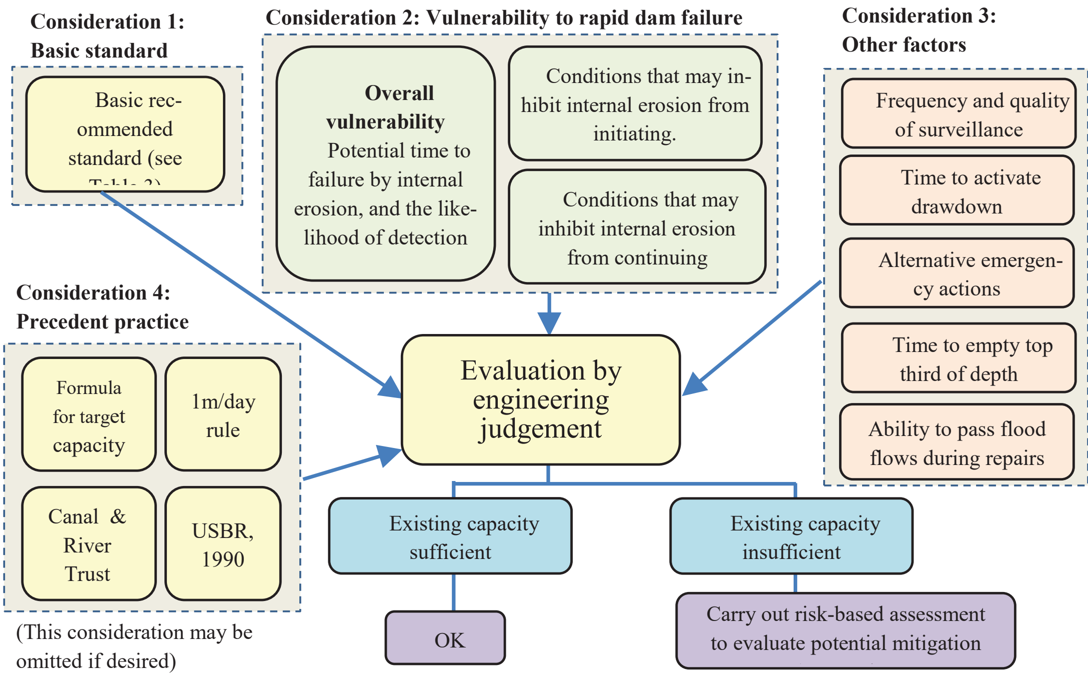

Figure 3 : Flow chart for assessing the adequacy of installed drawdown rate for embankment dams

The first 'consideration' is a set of basic minimum standards which vary depending on the potential consequences of reservoir failure, as shown in Table 3, using the definitions of dam category from ICE, 2015. These basic standards were derived based on the research described above on 'time to failure' and lessons from actual drawdown incidents. They are based on the following assumptions:

- The dam is moderately susceptible to internal erosion (see 'star' in Figure 1), with no designed filter. This is reasonably typical of many UK embankment dams.
- 'Good' surveillance practices are employed, as defined in the guide
- Drawdown can be activated shortly after a defect is detected

Where the circumstances differ from these assumptions, then the adopted drawdown rates should be reviewed based on the guidance.

Table 3 : Basic recommended standard for drawdown rate

Dam category	**Recommended minimum rate from top water level**	**Upper cap on practical draw-down rate** (Note 2)
A (a breach could endanger lives in a community)	5%H/day (Note 1)	1m/day
B (a breach could endanger lives)	3%H/day (Note 1)	0.6m/day
C or D (negligible or no risk to life - Note 3)	2%H/day	0.3m/day

Notes:

1. For low height dams where there is a risk to life the drawdown rate should generally be a minimum of 300mm/day
2. The cap is considered justifiable on the basis that higher dams tend to conform to higher standards of design, construction and general management.
3. For category C or D dams the recommended standard is based on protecting the value of the dam as an asset and avoiding potential reputational losses which may be associated with dam failure.
4. Further notes to the table are given in Section 6.3 of the guide

The next 'consideration' is to consider the vulnerability of the fill materials to erosion which may govern the speed at which an embankment might fail. As noted above the basic recommended standards are based on a dam moderately susceptible to internal erosion and where dams are more or less vulnerable to rapid failure the basic standard may be adjusted, using Figure 1 as a guide.

It is emphasised that the values of D_0 derived from Figure 1 are highly sensitive both to the basis for the assumed hydraulic gradient, and to the value adopted for the erosion rate index, both of which are based on parameters that are often uncertain. The assessment should therefore be made by experienced engineers exercising appropriate judgement.

Guidance is also given on conditions that may inhibit internal erosion, with reference to ICOLD (2013), for example the presence of a properly designed sand filter in the downstream dam shoulder will largely mitigate the risk of internal erosion.

Guidance is also given on other factors which may affect the recommended drawdown rate, including the frequency and quality of surveillance, the time required to activate drawdown and whether there are other alternative emergency actions that could be taken instead.

4.6 Other dam types

Since approximately 80% of reservoirs in the UK are impounded by embankment dams (BRE, 1994) they are the prime focus of the guide. However, Section 7 of the guide considers concrete and masonry dams, and service reservoirs, constructed of non-erodible materials on non-erodible foundations. As such the failure mechanisms are different and tend to fall under two categories, global instability or general ageing and deterioration of the dam materials, rather than internal erosion. It is therefore assumed that the dam is still standing when drawdown of the reservoir is commenced, hence factors of safety for stability must be greater than 1.0 at that time, if only by a small margin. On this basis, the purpose of drawdown should be to prevent water levels from rising and bring about a lowering of water levels to remove the load from the dam, but such a lowering could be relatively gradual. A "basic drawdown rate" is not given for concrete and masonry dams, but guidance is given on potential failure modes and factors affecting the vulnerability to these failure modes., For these reservoirs the allowance for reservoir inflows is more likely to be a key factor in achieving drawdown and it is therefore even more important to carry out sensitivity studies for higher than average inflows.

4.7 Mitigation against insufficient drawdown capacity

Where the installed drawdown rate is judged to be insufficient, Section 8 gives guidance on mitigation measures, which broadly fall into four categories as follows:

(1) Increase the installed drawdown capacity.

(2) Increase the likelihood of detecting failure modes early to allow prompt intervention.

(3) Reduce the consequences of failure by improved emergency planning.

(4) Carry out improvement works, e.g. to reduce the likelihood of internal erosion occurring, or to slow the rate of progression, such that the installed drawdown capacity is judged adequate using the recommended approach (only acceptable where a dam is in satisfactory condition).

In terms of retrofitting additional drawdown capacity to existing dams, installing siphons is often one of the safest, least disruptive and most cost-efficient solutions. Examples of such installations include twin 1600mm diameter siphons at Thames Water's Queen Mary Reservoir (Philpott et al. 2008) and 500 to 1400mm diameter siphons at four reservoirs operated by United Utilities (Kempton et al 2016).

One of the challenging issues in assessing whether to upgrade drawdown capacity at an individual dam is how to quantify the risks of upgrades, against the risk if no upgrade was carried out. A number of reservoir owners requested a method to quantify the benefits of increasing drawdown capacity, necessary to justify inclusion in their five-year risk based business plans. The guide presents several ways of assessing probability of failure, including a notional "index probability of failure" based on the proportion of available capacity to the target capacity, this being the method presented in Peters et al (2016) in a paper on progress in use of risk assessment in UK.

4.8 Summary of main changes

The main changes from previous practice include:

- Applying a consistent, structured approach to assessing required drawdown capacity
- Considering drawdown capacity as percentage of reservoir depth, rather than a fixed depth/ day
- Explicit consideration of vulnerability of the dam to rapid failure
- Explicit allowance for concurrent inflows into the reservoir

5. UPTAKE AND APPLICATION OF THE GUIDANCE

In order to gauge the level of uptake of the guidance a short survey was sent out to the UK Reservoir Safety Managers forum in 2018, which is represented by major UK water companies, enforcement authorities and other significant undertakers. Responses were received from 8 of the 12 Undertakers surveyed. All of them were aware of the guide and most had carried out assessments in accordance with the guidance for at least some of their reservoirs. Most undertakers are employing consultants to carry out drawdown assessments.

Most of the feedback on the guide was positive, with comments that the guide was reasonably easy to use, logical and well laid out for people with varying levels of knowledge.

The results of the survey are presented in Courtnadge et al, 2018. Out of a sample of 212 reservoirs, 165 (78%) met the basic standard, many by a large margin.

6. DISCUSSION AND CONCLUSIONS

The guide has provided a significant advance in dam safety in UK by providing a methodology for consistent assessment of the capacity of drawdown facilities required. For dams where a breach would threaten lives in a community, a basic standard of 5%H/day drawdown rate is recommended, but this should be adjusted on a site-specific basis in relation to various factors using engineering judgement. A primary factor is the dam's vulnerability to rapid failure by internal erosion, which is governed by the hydraulic gradient and erodibility of the fill.

Since its publication, major reservoir owners in the UK have assessed their portfolios against the guidance and upgraded dams which are assessed as deficient. Installing siphons has proven to be an effective and reasonably cost-efficient option for increase drawdown capacity at a number of existing reservoirs.

Key areas for future refinement are improving the ability to quantify the erodibility, and potential rate of erosion/failure of embankment and other types of dams. There is still no universally accepted international guidance on drawdown capacity and it would be a useful topic for a future ICOLD bulletin.

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