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Cradle Mountain Water
Dam Portfolio Risk Assessment

ENTURA-6664B
August 2013

Prepared by Hydro-Electric Corporation ABN48 072 377 158
t/a Entura 89 Cambridge Park Drive, Cambridge TAS 7170 Australia

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Executive summary

Entura was engaged by Cradle Mountain Water (CMW) to undertake a portfolio risk assessment (PRA) on 10 selected CMW dams with a "Significant" to "High" hazard category based on previous studies and assessments.

This PRA study included a desktop engineering assessment of the dams, a review of the consequences of dam failure and other previous studies, and a 'detailed' risk analysis as defined in Table 6.1 of the ANCOLD (2003) *Guidelines on Risk Assessment*.

The PRA aims to identify the highest risk dams in the portfolio and provide a prioritised investigations/upgrade programme to mitigate and reduce the risk to comply with the ANCOLD tolerability limit. It should be noted that there is significant uncertainty in the assessments due to a lack of basic data available for many of the dams and estimates are based on the best currently available information. As investigations are undertaken to address the uncertainties, the relative risk positions of the dams may change.

The key findings of the PRA are summarised below.

Consequence category of dam failure

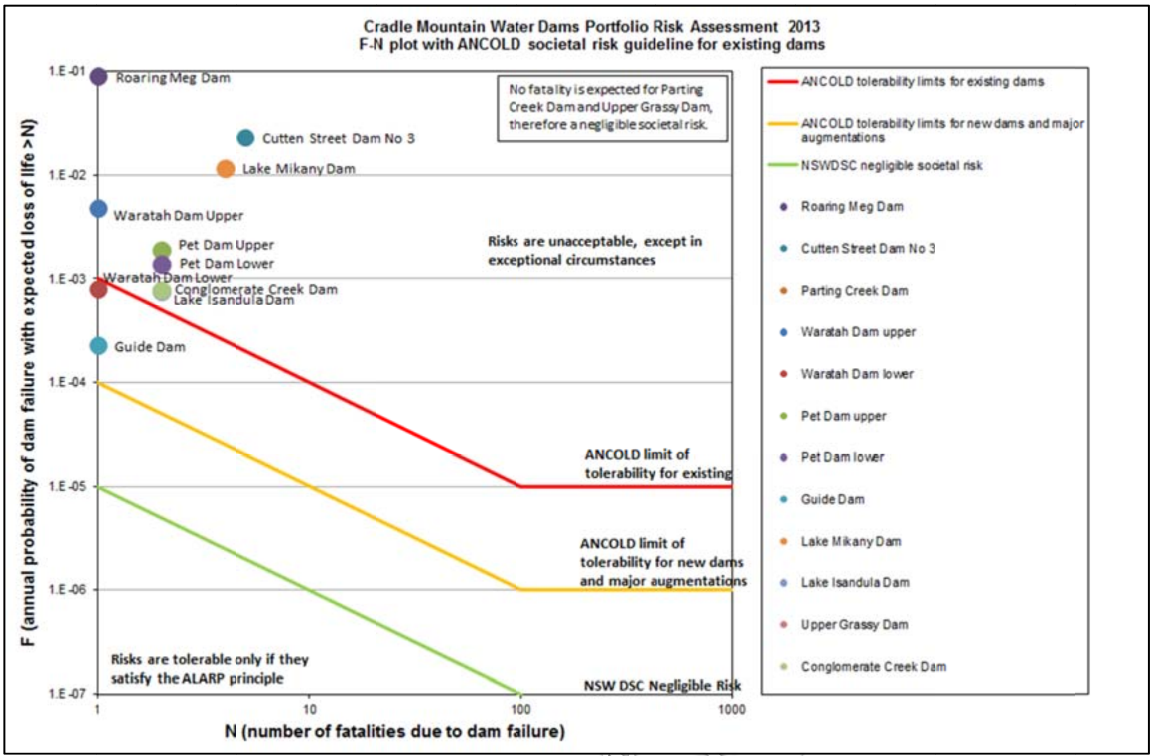
The consequence category was reassessed for each dam included in this PRA in accordance with the ANCOLD (2012) *Guidelines on the Consequence Categories for Dams* as shown in the following table for both sunny day failure and flood failure scenarios.

The dams with consequence category of "High C" and above are highlighted in red.

Dam	Consequence category	
	Sunny Day Failure	Flood Failure
Waratah Dam	Significant	Significant

Summary of societal life safety risk

The societal risks for all dams in the portfolio are plotted against the ANCOLD (2003) limits of tolerability for existing and new dams. For better presentation and clarity of results, only the most critical F-N points for the dams are shown in the plot. The New South Wales Dam Safety Committee (NSWDSC) negligible risk line was also provided for reference purpose.



A number of remarks should be noted about this plot:

- Sensitivity analyses were undertaken for Waratah and Pet Dams (denoted by the "upper" and "lower" descriptions). While for Pet Dam, there is only a small difference in the risk positions. For Waratah Dam, the assumptions made have a significant impact on the dam risk position. This highlights the importance of further investigations for Waratah Dam to justify the risk assessment results.
- The societal risk for Conglomerate Creek Dam was adopted from the recently completed dam safety review (Neupane, 2012).

The following conclusions were made in regards to societal risks:

- Of the 9 dams assessed under this PRA plus Conglomerate Creek Dam, 7 dams were assessed to have intolerable risk when compared to the ANCOLD limit for existing dams. These include Roaring Meg Dam, Cutten Street Dam No 3, Conglomerate Creek Dam, Lake Mikany Dam, Lake Isandula Dam, Pet Dam and Waratah Dam.
- Medium risk was estimated for Guide Dam, being located between the ANCOLD limits for existing and new dams. Guide Dam is considered tolerable provided it satisfies the ALARP principle.
- Parting Creek Dam and Upper Grassy Dam were assessed to have negligible societal risk as no Potential Loss of Life (PLL) was identified due to the failure of these dams. Therefore, these dams are not shown on the F-N summary plot above and are considered tolerable.

Summary of financial risk

The financial risk posed by these dams to CMW was also estimated as shown in the figure below. A financial risk criterion of $10k per annum (based on the Southern Water's Dams PRA) was shown for ranking and comparison purpose.

Note: January 2018

TasWater are actively managing the dams listed above the ANCOLD limit of tolerability. These dams are listed above the red line.

- **Roaring Meg** Decommission complete.

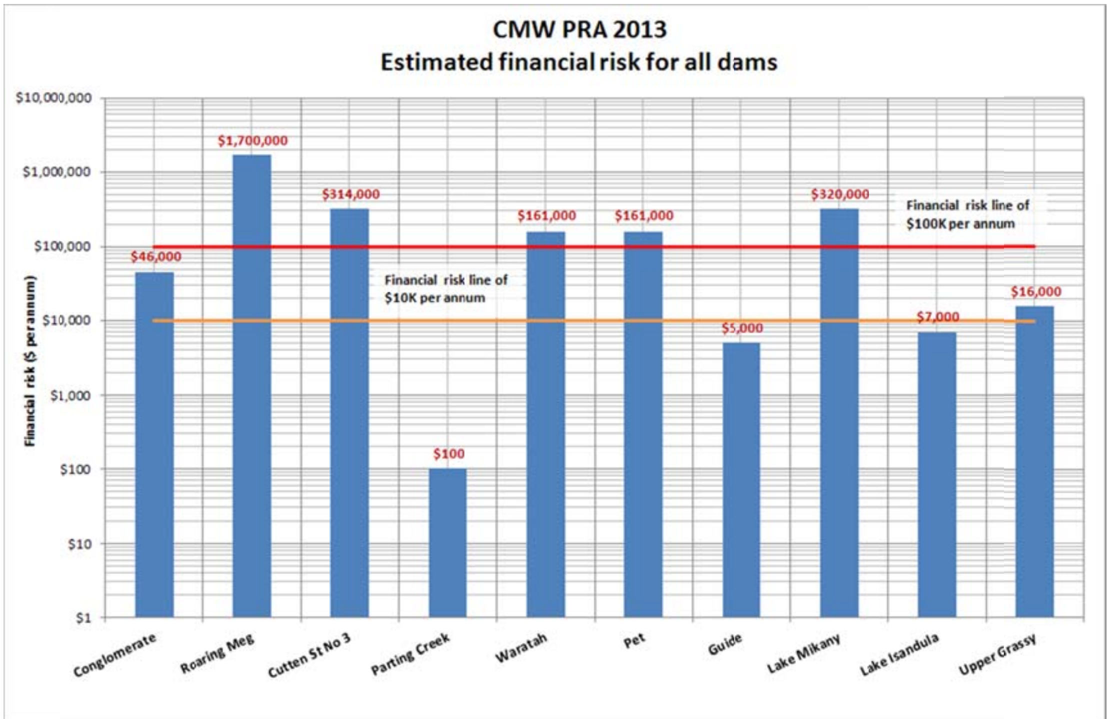
- **Cutten Street 3** Decommission complete.

- **Lake Mikany** Currently in investigation and design stage for the dam's upgrade.

- **Pet Dam (Upper and Lower)** Risks are currently being addressed. An investigation and design stage for the dams upgrade is underway. To manage the flood risk, the scour capacity has been increased and two temporary syphons have been installed.

- **Conglomerate Creek Dam** Is in the final stages of upgrade and will be completed in approximately March 2018.

- **Isundula Dam** Investigation and design stage for the dams upgrade is underway. To manage flood risk, an integrated flood forecasting system has been implemented.



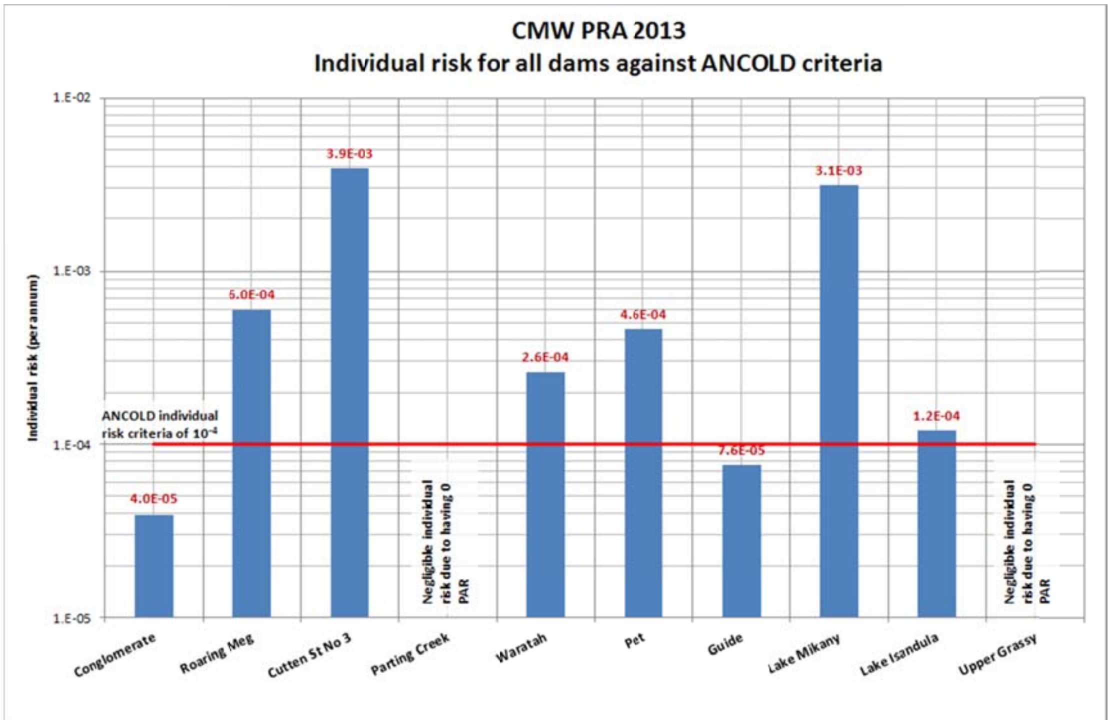
The following conclusions were made in regards to financial risks:

- Based on this assessment, Conglomerate Creek Dam, Roaring Meg Dam, Cutten Street Dam No 3, Waratah Dam, Pet Dam, Lake Mikany Dam and Upper Grassy Dam all have financial risk exceeding the $10k/annum mark, which pose a significant risk to the business.
- Roaring Meg Dam, Cutten Street Dam No 3, Waratah Dam, Pet Dam and Lake Mikany Dam have the highest financial risk in the portfolio with estimated values exceeding $100k/annum.
- The highest financial risk is from Roaring Meg Dam with $1.7M/annum.
- Overall, these dams imply a total financial risk of approximately $2.7M per year to CMW.

Summary of individual life risk

The individual risks for all dams are shown in the following figure. The following conclusions were made in regards to individual risks:

- The individual risk posed by Roaring Meg Dam, Cutten Street Dam No 3, Waratah Dam, Pet Dam, Lake Mikany Dam and Lake Isandula Dam are considered intolerable as they exceed the ANCOLD limit for individual risk of 10^{-4} per annum.
- Individual risk downstream of Conglomerate Creek Dam and Guide Dam are deemed acceptable.
- No individual risk is expected for Parting Creek Dam and Upper Grassy Dam as no population at risk (PAR) has been identified due to the failure of these dams.



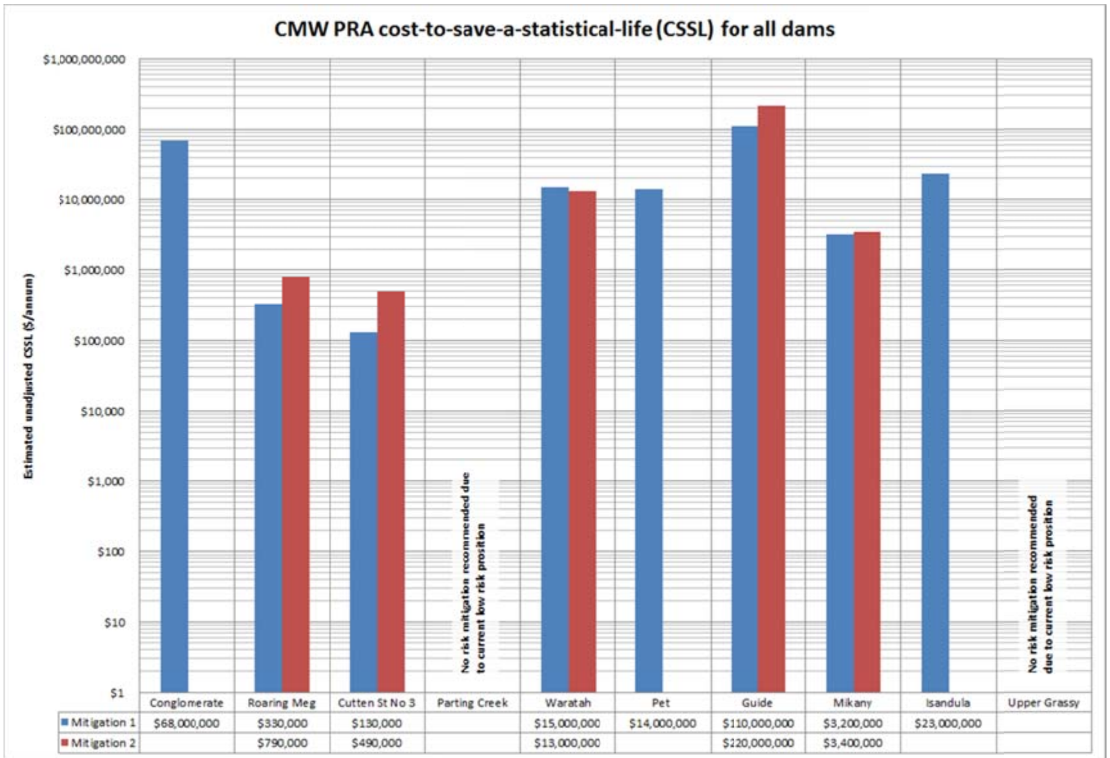
Summary of key failure modes

Key failure modes for all the dams are summarised in the following table, along with the estimated probabilities of failure.

Dam	Failure mode ID	Description of failure mode	Probability of failure	% of total failure probability
Waratah (worst case estimate)	FM03	Erosion of spillway channel	5.4×10^{-3}	10%
	FM05	Piping through a poorly compacted or high permeability layer on the core-foundation contact	2.4×10^{-2}	45%
	FM06	Piping through a poorly compacted or high permeability zone around a conduit through the embankment	2.4×10^{-2}	45%
		TOTAL	**5.4×10^{-2}**	**100%**

Summary of recommended risk mitigations

Based on the current risk positions of the dams, a list of investigations and mitigation measures are provided to mitigate and reduce the risk to align with the ANCOLD (2003) societal risk guidelines as summarised in the following table. The cost-to-save-a-statistical-life (CSSL) was estimated to assist with ranking and comparison of the mitigations in regards to the cost effectiveness of the options in reducing life safety risk. On this basis, the favourable options are highlighted in green and the less-favourable options are highlighted in red.


CMW PRA cost-to-save-a-statistical-life (CSSL) for all dams
Estimated unadjusted CSSL ($/annum)
$1,000,000,000
$100,000,000
$10,000,000
$1,000,000
$100,000
$10,000
$1,000
$100
$10
$1
No risk mitigation recommended due to current low risk position
No risk mitigation recommended due to current low risk position
Conglomerate | Roaring Meg | Cutten St No 3 | Parting Creek | Waratah | Pet | Guide | Mikany | Isandula | Upper Grassy
Mitigation 1 | $68,000,000 | $330,000 | $130,000 | | $15,000,000 | $14,000,000 | $110,000,000 | $3,200,000 | $23,000,000 |
Mitigation 2 | | $790,000 | $490,000 | | $13,000,000 | | $220,000,000 | $3,400,000 | |

Dam	Mitigation 1			Mitigation 2		
	Description	**Estimated cost ($)**	**CSSL ($/annum)**	**Description**	**Estimated cost ($)**	**CSSL ($/annum)**
Waratah	Undertake an investigation to confirm the sources of leakage. Then install filter buttress if required.	$930k	$15M	Mitigation 1 plus provide riprap protection along spillway	$980k	$13M

Based on the estimated CSSL of each measure, the following table summarises the recommended mitigation measures (in the order of priority) in order to bring the life safety risk of each dam below the ANCOLD tolerable limit. The total program cost was estimated to be approximately $10.4M.

Order of Priority	Dam	Mitigation	Estimated CSSL	Estimated cost
4^^	Waratah Dam	Install filter buttress and provide spillway erosion protection	$13M	$980k
			Total	**$10.4M**

^ Based on DSR (Neupane, 2012).

^^ Subject to further investigation to confirm the risk position.

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1. Introduction

1.1 Background

Entura was engaged to undertake a portfolio risk assessment (PRA) on the 10 selected Cradle Mountain Water dams with a "Significant" to "High" hazard category, as listed in Table 1.1.

Table 1.1: "Significant" to "High" hazard category dams

Dam ID	Dam Name	Hazard Category
4806	Waratah Dam	Significant

<u>Note</u> – ^ *The risk assessment for Conglomerate Creek Dam has been completed as part of the recently completed dam safety review. The results have been reviewed for consistency and incorporated into this report.*

1.2 Scope of works

The scope of this project was to undertake a PRA on 10 "Significant" to "High" hazard category dams. The study included a desktop engineering assessment of the dams, a review of the comprehensive assessment of the consequences of failure and other previous studies, and a 'detailed' risk analysis as defined in Table 6.1 of the ANCOLD (2003) *Guidelines on Risk Assessment*.

The key tasks and activities carried out in the 'detailed' risk analysis included data review, site inspection, risk workshops, post workshop risk assessment and final reporting of findings.

A detailed task list is provided in Section 1.4.

1.3 Output

This report forms the main part of the project output which summarises the outcome of the risk workshops and risk assessments. For each dam, this report covers:

- Findings from site inspections.
- Consequence identification and quantification.
- Failure modes analysis and likelihood assessment.
- Risk analysis and results.
- Preliminary assessment and development of options to mitigate individual dam risks together with a high level order of magnitude cost estimate for each option for ranking purposes.

In addition, Entura also provided a spreadsheet software tool and appropriate training for utilising that tool to Cradle Mountain Water staff. This spreadsheet allows CMW to incorporate the results from future risk assessments or risk reduction measures and observe the changes in the overall risk profile.

1.4 Methodology for this risk assessment

The methodology to undertake this PRA was centred on the risk assessment workshops. These were the key elements in risk assessment process that allowed all members involved in the workshops to provide their input. The 10 selected Cradle Mountain Water dams were grouped into two workshop groups based on the locations of the dams, as shown in Table 1.2.

Table 1.2: Risk assessment workshop groups

Workshop Group	Dam Name	Location
West Coast Date of workshops: 15/04/13 – 19/04/13	[redacted]	[redacted]
	Waratah Dam	Waratah
[redacted]		

* Brief review only.

The detailed methodology for this assessment is outlined in the *Cradle Mountain Water Portfolio Risk Assessment – Entura Offer of Services* (dated February 2013). A summary of the methodology is described in the following sections. Figure 1.1 provides a flow chart of the risk assessment process.

1.4.1 Data review and workshop preparation

Data review aimed to identify:

- Key information on the design and construction of the dam, including geology and geotechnical aspects, dam design, construction methodology and construction supervision.
- Available surveillance and monitoring information on the dams that will assist in determining the performance of the dam.
- Key “gaps” in the data and knowledge of the dam that may influence the risk assessment.

In addition to the data review, the following key activities were undertaken in order to have the required inputs for a significant and meaningful risk workshop:

- Determined the hydrological inputs for partitioning the flood loading.
- Determined the seismic inputs for partitioning the seismic loading.

- Assessed the social and economic/business consequences of failure.
- Determined the key properties of the dams and their foundations.

1.4.2 Site inspections and presentation of key information on the dams

Prior to each workshop, a site inspection of the corresponding dams was undertaken with the relevant workshop participants as follows:

- Inspections of Conglomerate Creek Dam, Cutten Street No 3 Dam, Roaring Meg Dam and Parting Creek Dam were undertaken on 15 April 2013. Inspection of Waratah Dam was undertaken on 16 April 2013. The following personnel attended the inspections:
    - **Entura:** Paul Southcott, Shao Ng, Tung Hoang
    - **Cradle Mountain Water:** Phil Benson, Wouter vander Merwe, Michael Eastley, Troy Keating, Damien Finn, Peter Triffitt, Gary Krzysik, Krn Jones
    - **Southern Water:** Neil Smith

1.4.3 Undertake risk workshops

The in-workshop process for each dam involved:

- Reviewing the consequences of failure including potential loss of life, financial and economic losses and intangible losses such as social impacts, environmental impacts and damage to business reputation for each dam.
- Determining and screening the failure modes to assess their credibility to the particular dam.
- Assessing the likelihood of failure for each credible failure mode using the appropriate methods and tools. In particular, the probabilities of flood related failure modes were assessed by developing a flood system response curve. The probabilities of piping failure modes were assessed using the *Piping Toolbox* based on Fell et al. (2008).
- Reviewing the probabilities of failure for each credible failure mode and identifying the key failure modes for the dam.
- Identifying any additional investigations or analyses required to fill important knowledge gaps.
- Brainstorming concepts for reducing the risk of the failure modes.

1.4.4 Develop preliminary risk reduction measures and prepare cost estimates

The following was undertaken:

- Assessing the level of risk reduction after the implementation of the measure.
- Undertaking high level order of magnitude cost estimate to implement the risk reduction measure (including dam decommissioning). The cost estimate will be suitable for options ranking, but may not be suitable for budgetary purposes.
- Including the risk reduction measure on the risk plot, and assess whether the measure meets the risk targets, i.e. the ANCOLD (2003) tolerable limits, Cradle Mountain Water acceptable business risk criteria, and ALARP (As-Low-As-Reasonably-Practicable) principle using CSSL (Cost- to-Safe-a-Statistical-Life) effectiveness principle.

1.4.5 Prepare final report and summary report of risk assessment

The following is reported upon:

- The credible failure modes assessed and non-credible failure modes excluded for each dam.
- The key risks to each dam in terms of probabilities of failure.
- An assessment of the societal and individual risks, including F-N plot, for each dam.
- An assessment of the economic/business risk posed to Cradle Mountain Water by each dam.
- The recommended risk reduction measures for each dam, including level of risk reduction and high level cost estimate to implement.
- An assessment of whether the dam meets the ALARP principle utilising the CSSL principle.

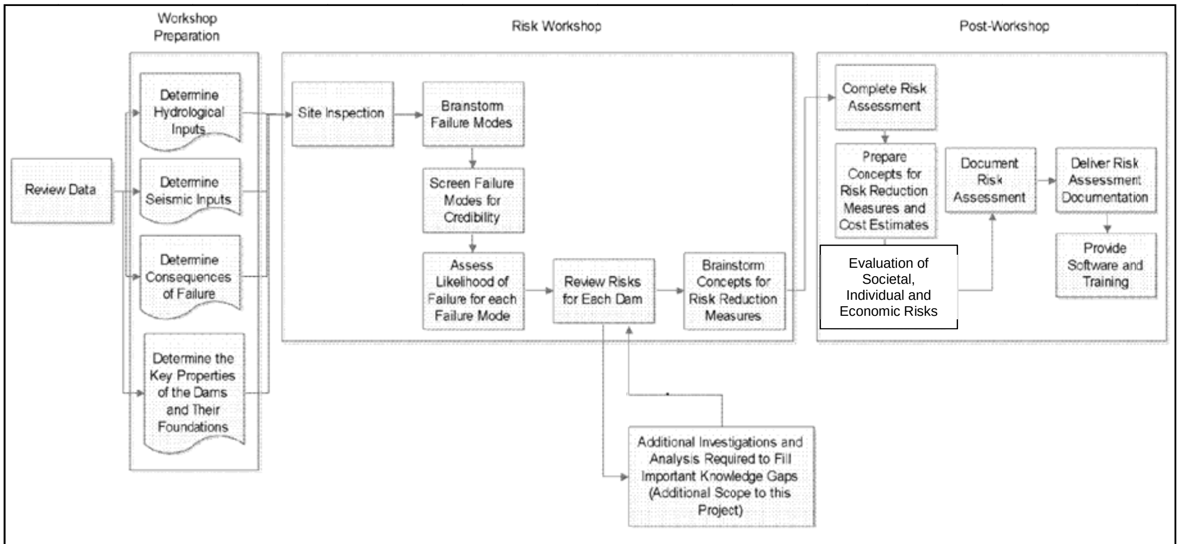


Figure 1.1: Project implementation diagram

2. Waratah Dam

2.1 Dam basic data

Waratah Dam is located 1km southeast of Waratah (approximately 60km southwest of Burnie) on Waratah River (see Figure 2.1). It is the primary source of municipal water supply for the township of Waratah. Cradle Mountain Water (CMW) took ownership of the dam from the Waratah-Wynyard Council in 2010.

A summary of the basic dam data and the current surveillance and monitoring regime at the dam are provided in Table 2.1 and Table 2.2 respectively.

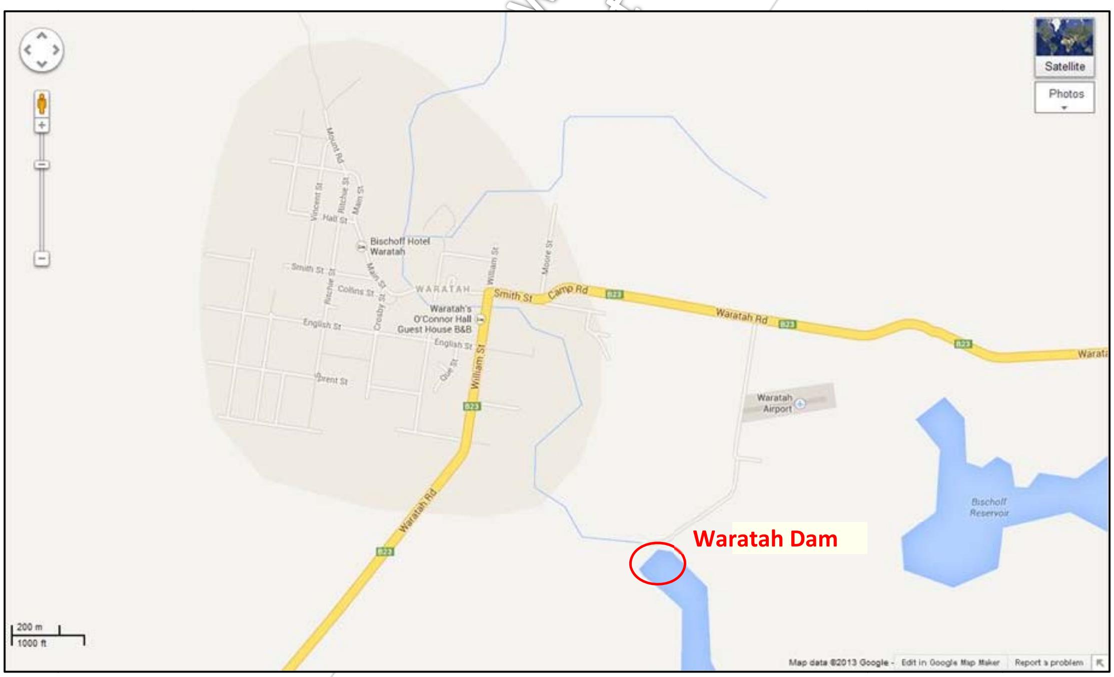


Figure 2.1: Location of Waratah Dam (map obtained from *Google Map*)

Table 2.1: Waratah Dam – basic dam data

GENERAL		
DAM	Waratah Dam	
LOCATION	1 km southeast of Waratah (60 km southwest of Burnie)	
SYSTEM	Waratah System	
CATCHMENT (RIVER)	Waratah River	
YEAR OF CONSTRUCTION	Unknown (dam repaired in 1975/76 following overtopping failure)	
DAM CONSEQUENCE CATEGORY	Sunny Day Failure	**Significant**
	Flood Failure	**Significant**
DAM ID NUMBER	4806	
COORDINATES	E 378 212 m, N 5 409 783 m	
EMBANKMENT		
TYPE	Clay core rockfill	
CREST LEVEL	R.L. 608.8 m	
CREST LENGTH	87.4 m	
CREST WIDTH	8 m	
HEIGHT	6 m	
UPSTREAM SLOPE	1V : 2H	
DOWNSTREAM SLOPE	1V : 2H	
RESERVOIR		
FULL SUPPLY LEVEL (FSL)	Spillway crest level	
CAPACITY AT FSL	800 ML	
SURFACE AREA AT FSL	47.65 ha (0.48 km^2)	
CATCHMENT AREA	9.97 km^2	
ON-STREAM / OFF-STREAM	On-stream	
SPILLWAY		
TYPE	Timber overflow weir discharging into unlined channel	
SPILLWAY CREST LEVEL	R.L. 608 m	
SPILLWAY CREST WIDTH	5.1 m	
CURRENT DESIGN FLOOD	Assumed DCF	
DAM CREST FLOOD (DCF)	≈ 1:2 200 AEP – 5.3 m^3/s	
OUTLET WORKS		
OUTLET	DN450 cast iron outlet pipe and valve	

Table 2.2: Waratah Dam – inspection and monitoring regime

Type	Current inspection/monitoring regime
Routine inspection	Weekly
Intermediate inspection	Yearly – last inspection by Nicholson & Neupane (2012)
Comprehensive inspection	5-yearly – last CSR by Byleveld & Smyth (2010)
Safety review	20-yearly – not yet undertaken
Storage level	Visually monitored during routine inspection
Seepage	Visually monitored during routine inspection
Deformation survey	Not undertaken
Seismological	Continuous monitoring by ES&S

2.2 Current condition and performance

The key findings from recent inspections are summarised below:

- The latest intermediate inspection by Neupane (2012) has revealed that:
  - The upstream face is in an irregular shape with evidence of minor erosion. There is no erosion protection apart from grass cover.
  - The abutments are satisfactory with no signs of slips or erosion.
  - The crest is satisfactory with historic minor depression in the middle of the dam.
  - The downstream face is uneven with minor erosion.
  - Significant leakage presents at a number of locations, mainly along the outlet conduit and to the right of the scour valve. The leakage does not appear to be related to storage level (Byleveld & Smyth, 2010), and is likely to be from the foundation.
  - The spillway is in a satisfactory condition.
  - There is no record of the outlet valve being operated, and the valve was reported as not functioning.
- Cracks and holes were noted during the comprehensive inspection by Byleveld & Smyth (2010), but have now been filled.
- It was reported that the original spillway was constructed on the left abutment of the dam. In 1975/76, the spillway was blocked by debris, leading to overtopping failure of the dam wall. The dam wall has since been reinstated and the new (current) spillway was constructed on the right abutment.
- The following were observed during the PRA inspection:
  - Some remaining concrete structures were observed in the downstream face near the toe, indicating that the dam might have been constructed over an existing concrete structure.
  - The V-notch weir has been removed to prevent leakage ponding at the dam toe.

- The comprehensive surveillance review undertaken by Byleveld & Smyth (2010) assessed that:
  - The dam is unlikely to contain a filter system, therefore has no way of controlling internal erosion should a piping incident occur. Significant leakage was observed along the downstream toe. Piping was considered to be a critical failure mode.
  - The slope of the upstream face was observed to be steeper than modern dam design standards, and may lead to instability during rapid drawdown. Upstream slope instability was considered to be a critical failure mode. A slope stability analysis was recommended.
  - The dam foundation profile appears relatively even, and the presence of any sharp drop-offs which may cause cracking in the embankment due to differential settlement is unlikely. However, Byleveld & Smyth (2010) did notice some cracks and holes along the dam crest, and considered cracking through the crest as a critical failure mode.
  - The probabilities of severe earthquakes initiation piping were expected to be low and earthquake induced failure was not considered to be a critical failure mode.
  - The dam is unlikely to contain a filter system around the outlet pipe to control internal erosion along the pipe.

2.3 Dam failure consequence assessment

No dam break flood mapping has been developed for Waratah Dam. Dam failure consequences for the dam were originally assessed by Byleveld & Smyth (2010), and revised in this PRA.

Based on a car window survey during this PRA, no residential houses have been identified within the likely dam break flood inundation zone. However, itinerants were considered in terms of population in the recreational park downstream of the dam, and traffic crossing the William Street and Smith Street bridges, which would likely be affected during a dam break flood event. The estimated population at risk (PAR), potential loss of life (PLL) and economic and financial costs of dam failure are detailed in Table 2.3.

Table 2.3: Waratah Dam – consequences of dam failure

Scenario	Hours	PAR	Incremental PAR	PLL	Incremental PLL	Total loss
Sunny day failure (SDF)	Business	4	4	0.06	0.06	$3.0M
	After	3	3	0.10	0.098	
Dam crest flood (DCF)	Business	0	-	0	-	-
	After	0	-	0	-	
Dam crest flood with dam break (DCFDB)	Business	4	4	0.08	0.08	$3.0M
	After	4	4	0.18	0.18	

Notes:

- It is assumed that 2 people would be at risk in the recreational park downstream of the river during business hours, and would reduce to zero during after hours. PLL is estimated based on Graham (1999).

- Traffic along William Street and Smith Street is estimated based on the annual average daily traffic (AADT) data obtained from the Department of Transport, DIER, assuming 2 passengers per vehicle.
- No damage is expected under the dam crest flood event without dam failure.
- Based on the size of the dam, the consequences of a sunny day failure and a dam crest flood with dam break event are expected to be similar.

The consequence category of Waratah Dam was assessed as part of this PRA in accordance with the ANCOLD (2012) *Guidelines on the Consequence Categories for Dams*. Table 2.4 summarises the consequence category assessment for the dam. The detailed assessment spreadsheets are provided in Appendix A.1.

Table 2.4: Waratah Dam – consequence category assessment

Dam break scenario	Incremental PLL	Severity of damages and losses	Consequence category
Sunny day failure (SDF)	0.10	Medium	Significant
Flood failure (incremental)	0.18	Medium	Significant

2.4 Engineering assessment

- Geology
  - The 1:50,000 *Geological Map for St Valentines* shows that the dam site is dominated at the surface by tertiary basalt.
- Hydrology
  - A preliminary hydrology assessment undertaken by Byleveld & Smyth (2010) based on the *Tasmanian Regional Method* shows that the dam crest flood is less than the 1:50 AEP flood inflow, with a spillway discharge of approximately 5.3m^3/s. This assessment was based on a broad crested weir spillway, assuming no attenuation within the storage.
  - No other detailed hydrology assessment has been undertaken to facilitate a detailed routing of the flood inflows. A recommendation was made in Byleveld & Smyth (2010) to undertake the next level of hydrology assessment involving a hydrologic rainfall runoff model to allow assessment of the flood critical durations and assess the routing effect of the storage.
  - There is no record of flood overtopping the dam crest since the dam was repaired in 1976, and no signs of overtopping were visible during recent inspections. In addition, based on the size of the reservoir, there is likely to be a significant attenuation of flood inflow within the storage. Therefore, it is believed that the previous assessment by Byleveld & Smyth (2010) is likely to have underestimated the spillway capacity.
  - The flood hydrology was revised as part of this PRA, with the spillway discharge and the peak lake level under each AEP flood estimated from a simplified flood routing model based on an estimated storage rating curve and the previous spillway rating

curve obtained from Byleveld & Smyth (2010). These rating curves are shown in Figure 2.2 and Figure 2.3 respectively. The inflow hydrograph for each AEP flood event was developed by applying a scaling factor (based on the corresponding peak inflow) to the PMF hydrograph obtained from the previous hydrology study, assuming the same critical inflow duration.

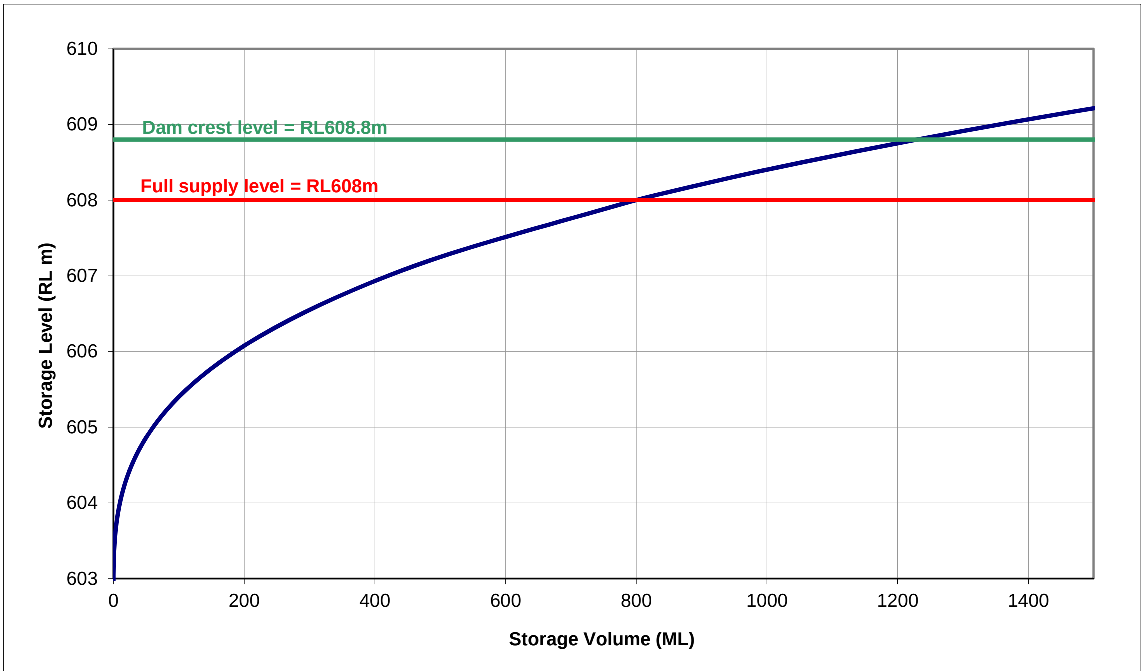


Figure 2.2: Waratah Dam – estimated storage rating curve

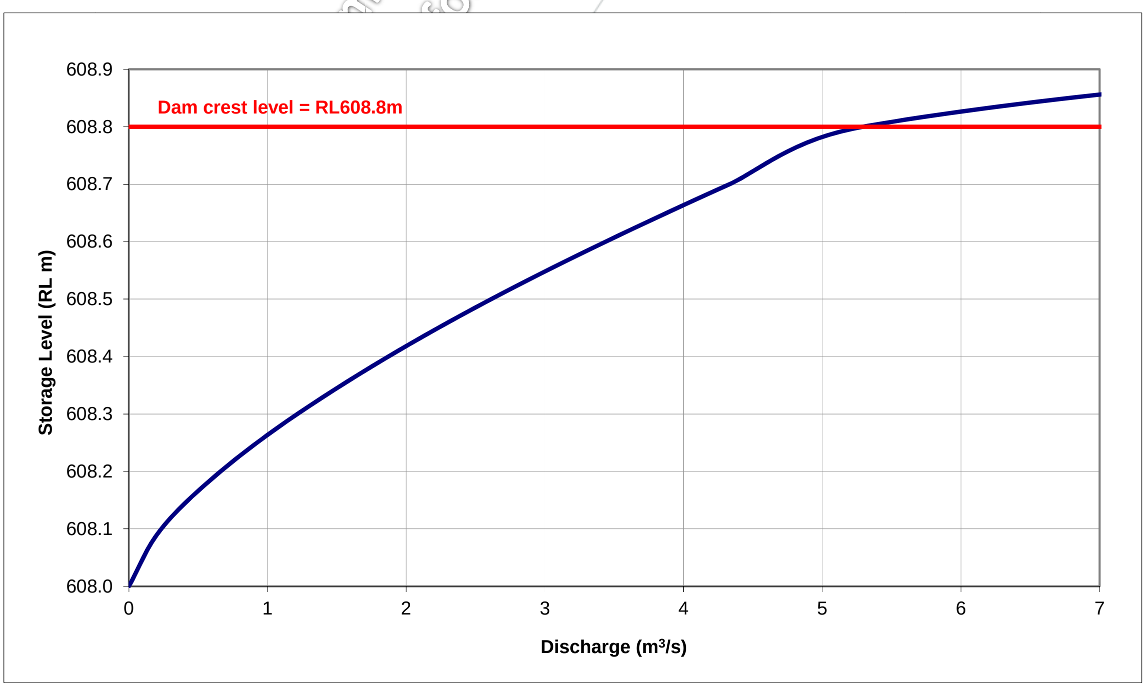


Figure 2.3: Waratah Dam – spillway rating curve (from Byleveld & Smyth, 2010)

- The estimated peak flows and the corresponding peak storage levels under various flood events are tabulated in Table 2.5. The revised assessment shows that the dam crest flood is corresponding to the 1:2,200 AEP flood inflow, with a spillway discharge of approximately 5.3m^3/s.

Table 2.5: Waratah Dam – peak inflows and estimated flood levels with routing effects

AEP	Peak inflow^ (m^3/s)	Peak outflow (m^3/s)	Estimated peak reservoir level (RL m)
1:50	16	1.1	608.2
1:100	19	1.3	608.3
1:1,000	40	3.5	608.6
1:2,200 (DCF)	**54**	**5.3**	**608.8**
1:10,000	82	19.5	609.0
1:100,000	165	80.7	609.5
1:10,000,000	442	305.1	610.3

^ Peak inflows based on Byleveld & Smyth (2010).

- Region seismicity
  - No detailed seismic hazard assessment has been done for Waratah Dam.
  - The *Seismic Hazard Assessment for Crotty and Darwin Dams* undertaken for Hydro Tasmania by the Seismology Research Centre (ES&S, 2009) concluded that the West Coast area of Tasmania has a relatively low seismicity (see Appendix C).

2.5 Failure modes assessment

2.5.1 Screening of failure modes

The risk assessment team screened all possible failure modes for Waratah Dam during the first workshop and selected the most credible failure modes for further analysis and quantification of the risk. The most credible failure modes for Waratah Dam are documented in Table 2.6 along with the reasoning for inclusion. All screened failure modes, including the non-credible failure modes and other failure modes which were assessed to have a negligible risk, are provided in Appendix B.1.

Table 2.6: Waratah Dam – summary of most credible failure modes

Failure mode ID	Piping failure ID	Description of failure mode	Comment
FM01	-	Flood overtopping	Spillway appeared under capacity according to Byleveld & Smyth (2010)
FM02	-	Spillway blockage by debris	Historical blockage of original spillway leading to overtopping failure recorded
FM03	-	Erosion of spillway channel	Evidence of localized erosion at some places. No proper erosion protection along channel
FM04	IM14	Piping through a poorly compacted or high permeability layer in the embankment	No as-constructed drawings/reports are available to demonstrate the compaction quality, sign of seepage observed on the downstream face
FM05	IM15	Piping through a poorly compacted or high permeability layer on the core-foundation contact	Same as above
FM06	IM18	Piping through a poorly compacted or high permeability zone around a conduit through the embankment	Conduit present in the dam embankment, signs of seepage around the outlet conduit
FM07	IM27	Erosion in defects in a rock foundation	Large amount of leakage was observed at the dam/foundation contact, rock outcrops visible near the surface on the downstream left abutment. Hence there is a possibility of the leak coming through the foundation rock

2.5.2 Probability of failure

In order to assess the probability of failure due to flood loading, a flood system response curve which gives the probability of failure versus the flood level is required. For Waratah Dam, the following assumptions have been made based on engineering judgment and discussion during the risk workshop:

- For failure due to flood overtopping (FM01) and spillway blockage (FM02):
  - There is no potential for failure until the water level reaches the dam crest level (i.e. at RL608.8m).
  - Erosion of the dam crest and downstream face would begin when the dam crest is overtopped.
  - When the dam crest is overtopped by 0.15m (i.e. at RL608.95m), there is a conditional probability of failure of 0.1.

   - When the dam crest is overtopped by over 0.4m (i.e. at RL609.2m), there is a conditional probability of failure of 1.
- For failure due to erosion of the spillway channel (FM03):
   - There is no potential for failure until the flow velocity in the spillway channel increases to 1.5m/s for a duration of time long enough to initiate erosion of the core. This corresponds to a reservoir level of RL608.3m.
   - When the flow velocity in the spillway channel increases over 1.5m/s for duration of time, there is a conditional probability of failure of 0.1.
   - When the flow velocity in the spillway channel increases to 2.2m/s for duration of time, there is a conditional probability of failure of 1. This corresponds to a reservoir level of RL608.6m.

For all piping failure modes (FM04, FM05, FM06 and FM07), the probabilities of failure were estimated by using the *Piping Toolbox*.

The estimated probability of each credible failure mode is summarised in Table 2.7, and the estimated risks are shown in Table 2.8. Key failure modes are highlighted in **bold**.

Table 2.7: Waratah Dam – summary of probabilities of failure

Failure mode ID	Piping failure ID	Description of failure mode	Annual probability of failure Pf			Sub Total
			Normal	Flood	Earthquake	
FM01	-	Flood overtopping	-	4.3×10^{-5}	-	4.3×10^{-5}
FM02	-	Spillway blockage by debris	-	5.2×10^{-5}	-	5.2×10^{-5}
FM03	**-**	**Erosion of spillway channel**	**-**	$\mathbf{5.4 \times 10^{-3}}$	**-**	$\mathbf{5.4 \times 10^{-3}}$
FM04	IM14	Piping through a poorly compacted or high permeability layer in the embankment	8.3×10^{-5}	9.0×10^{-6}	-	9.2×10^{-5}
Hypothesis 1: Piping through embankment						
FM05	**IM15**	**Piping through a poorly compacted or high permeability layer on the core-foundation contact**	$\mathbf{2.4 \times 10^{-2}}$	$\mathbf{3.0 \times 10^{-4}}$	**-**	$\mathbf{2.4 \times 10^{-2}}$
FM06	**IM18**	**Piping through a poorly compacted or high permeability zone around a conduit through the embankment**	$\mathbf{2.4 \times 10^{-2}}$	$\mathbf{3.0 \times 10^{-4}}$	**-**	$\mathbf{2.4 \times 10^{-2}}$
Hypothesis 2: Piping through defects in rock foundation						
FM07	IM27	Erosion in defects in a rock foundation	1.4×10^{-6}	1.8×10^{-8}	-	1.4×10^{-6}
TOTAL (hypothesis 1 – worst case scenario)			$\mathbf{4.8 \times 10^{-2}}$	$\mathbf{6.1 \times 10^{-3}}$	**Negligible**	$\mathbf{5.4 \times 10^{-2}}$

Table 2.8: Waratah Dam – summary of life safety, individual and financial risks (worst case scenario)

Loading condition	Life safety risk (lives/annum)	Individual risk (P_{death}/annum)	Financial risk ($/annum)
Normal	4.0×10^{-3}	2.3×10^{-4}	$143k
Flood	8.4×10^{-4}	2.9×10^{-5}	$18k
Earthquake	Negligible	Negligible	Negligible
Total	$\mathbf{4.8 \times 10^{-3}}$	$\mathbf{2.6 \times 10^{-4}}$	**$161k**

At Waratah Dam, it is unknown whether the current leakage is coming through the embankment or through the foundation. Whilst more investigation is required to confirm the source of leakage, the probability of dam failure was assessed for both of these scenarios to illustrate the difference this could generate. The worst case scenario is utilised to compare with other dams in the portfolio to highlight the necessity of more investigation for this particular dam.

The societal risk of Waratah Dam is presented in Figure 2.4 against the ANCOLD (2003) criteria.

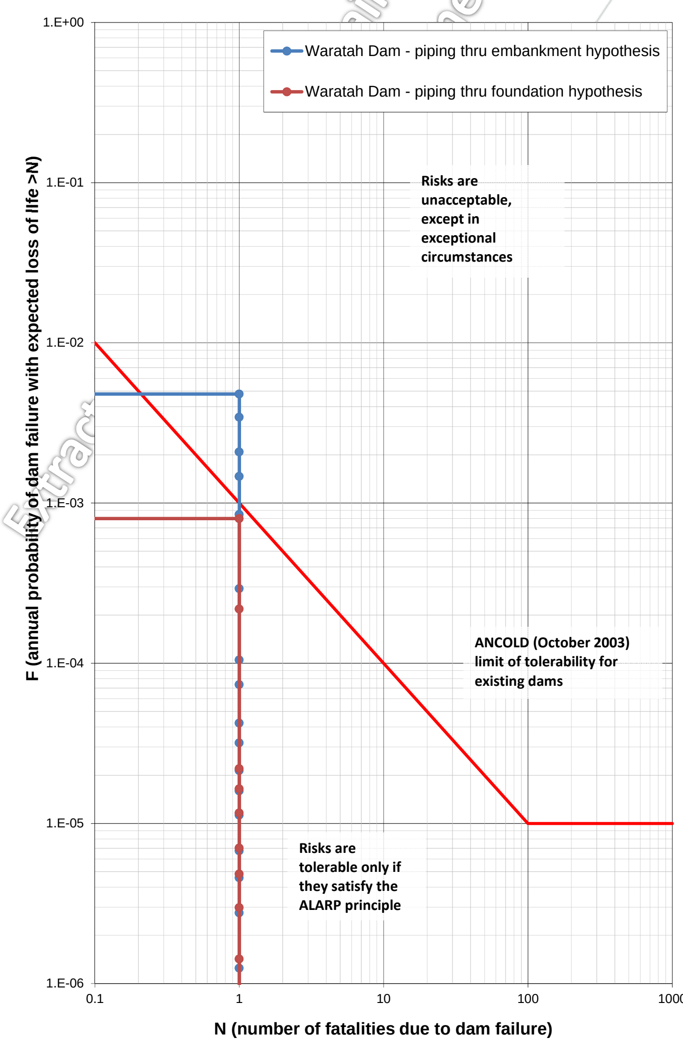


Figure 2.4: Waratah Dam – societal risk against ANCOLD societal risk guideline for existing dams

It is noted that at Waratah Dam the weighted PLL is less than 1 (i.e. 0.1 and 0.18 for SDF and flood failure respectively). On the F-N plot, the PLL was assumed to be 1 person while the actual weighting values of the PLL were applied as a conditional probability to the annual probability of dam failure.

The societal risk posed by Waratah Dam is above the ANCOLD limit of tolerability for existing dams (for the piping through embankment scenario) and is therefore considered unacceptable.

The individual risk downstream of Waratah Dam was identified as an itinerant driving along William Street or Smith Street in Waratah at the time of impact of the dambreak flood wave. The individual risk is calculated as 2.6×10^{-4} per annum which is above the ANCOLD individual risk criteria of 10^{-4}, and is unacceptable.

The financial risk was estimated to be approximately $161k per annum for the worst case scenario.

2.6 Risk mitigation measures

The following risk mitigation measures were discussed during the risk workshop:

- Increase flood capacity by raising the dam crest, widening the spillway or lowering the full supply level.
- Reinstate the original spillway on the left abutment as a secondary spillway.
- Clear the spillway approach channel and install log boom upstream of the spillway to prevent blockage.
- Provide erosion protection along the spillway channel in the vicinity of the embankment.
- Construct filter buttresses, incorporating a filter around the outlet and a foundation filter blanket to control piping.
- Construct downstream rockfill berm.
- Foundation grouting.
- Install upstream membrane to restrict piping flow.
- Wash silty sandy material into upstream face to seal foundation joints.
- The dam is currently the only source of water supply to Waratah, and therefore dam decommissioning was not considered to be a feasible option unless a catchment yield analysis is undertaken to confirm that the natural yield is adequate to supply the town without the dam.

Based on the current estimated risk position of Waratah Dam, the following risk mitigation measures are recommended to address the key failure modes:

- Undertake an investigation to confirm the sources of leakage.
- Mitigation 1: Install filter buttress.
- Mitigation 2: Mitigation 1, plus provide erosion protection along the spillway channel in the vicinity of the embankment.

The new estimated risk position of Waratah Dam post mitigation is shown in Figure 2.5 below.

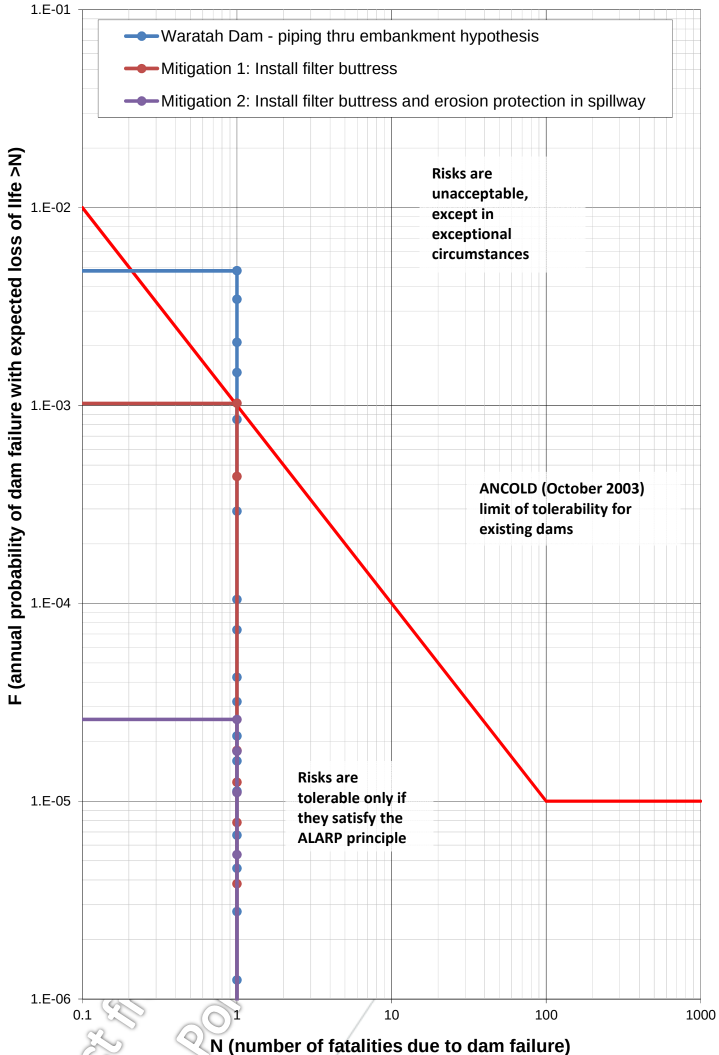


Figure 2.5: Waratah Dam – estimated societal risk post mitigation measures

The cost-to-save-a-statistical-life (CSSL) was also estimated for the mitigation options recommended as shown in Table 2.9. The CSSL was calculated based on a high-level cost estimate to implement the corresponding risk mitigation measure, and the estimated reduction in life safety risk. Based on this estimate, Mitigation 2 appears to be more cost effective than Mitigation 1 in reducing life safety risk.

Table 2.9: Waratah Dam – CSSL estimate

Description	**Mitigation 1**	**Mitigation 2**
Estimated cost of risk mitigation measure ($)	$930k	$980k
Annual life safety risk reduction (lives/annum)	4.0×10^{-3}	4.8×10^{-3}
CSSL ($/life saved)	$15M	$13M

2.7 Summary of knowledge gaps

During the risk assessment process, the following knowledge gaps were highlighted for Waratah Dam:

- No design or as constructed drawings are available. As such, the actual dam zoning, material types in the embankment and foundation, as well as the construction quality are unknown. Further investigations are recommended to verify the risk assessment.
- The details and condition of the outlet works need to be confirmed.
- High leakage flows were observed emerging at the downstream dam toe at the deepest section and also around the outlet conduit. The exact locations of these seepage paths are unknown (i.e. whether through the embankment or the foundation). The exact seepage paths should be confirmed to verify the piping risk assessment.
- The flood hydrology used for the risk assessment was based on a preliminary study undertaken by Byleveld & Smyth (2010) based on the *Tasmanian Regional Method*. A more detailed hydrology assessment is recommended to enable a better estimation of the flood overtopping risk. In addition, a detailed survey and hydraulic modelling of the spillway is recommended to improve the spillway rating estimate.
- It was reported that the dam is spilling at all times, indicating that the natural yield might be adequate to supply the town. The necessity of the dam for water supply can be investigated by undertaking a catchment yield analysis. However, the heritage value of the dam, social values and the need for the dam as a flood retention basin for Waratah should also be investigated prior to a decision being made to decommission the dam.

2.8 Key documents used for risk assessment

Nicholson, E. & Neupane, S. (2012). *Waratah Dam Intermediate Inspection Report*, ENTURA-524A6, Entura, December 2012.

Ng, S. (2013). *Waratah Dam Operations and Maintenance Manual*, 301968-Report-07, Entura, July 2013.

Byleveld, S. & Smyth, R. (2010). *Waratah Dam Comprehensive Surveillance Review*, 300830-Report-02, Hydro Tasmania Consulting, July 2010.

3. Common references and supporting documentation

ANCOLD (2000). *Guidelines on Selection of Acceptable Flood Capacity for Dams*, Australian National Committee on Large Dams (ANCOLD), March 2000.

ANCOLD (2003). *Guidelines on Risk Assessment*, Australian National Committee on Large Dams (ANCOLD), October 2003.

ANCOLD (2012). *Guidelines on the Consequence Categories for Dams*, Australian National Committee on Large Dams (ANCOLD), October 2012.

Byleveld, S. & Ng, S. (2011). *Cradle Mountain Water Dam Safety Emergency Management Plan*, E300830-Report-11, Entura, June 2011.

Fell, R., Foster, M., Davidson, R., Cyganiewicz, J., Sills, G. & Vroman, N. (2008). *A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping*, University of New South Wales.

ES&S (2009). *Darwin and Crotty Dams Seismic Hazard Assessment*, Environmental Systems and Services (ES&S), October 2009.

Graham, W. J. (1999). *A Procedure for Estimating Loss of Life Caused by Dam Failure*, Sedimentation and River Hydraulics, US Bureau of Reclamation (USBR), September 1999.

Neupane, S. (2012). *Conglomerate Creek Dam Safety Review*, ENTURA-40203, Entura, December 2012.

Ng, S. (2011). *Follow Up Inspections and Recommendations*, a memo to Cradle Mountain Water, Entura, March 2011.

Smythe, C. & Cox, G. (2006). *A Regional Flood Frequency Method for Tasmania*, 30th Hydrology and Water Resources Symposium, Australia.

Appendices

A Consequence assessment

A.1 Waratah Dam

A.1.1 Estimated economic losses

WARATAH DAM					
FLOOD EVENT: SDF / Flood failure					
Category	**QTY**	**Units**	**Cost/Unit ($)**	**Total Cost ($)**	**Comments**
Private properties					
Residential (including contents)	0	No	340,000	0	
Business	0	No	400,000	0	
Industrial	0	No	862,500	0	
Public Buildings	0	No	575,000	0	
Historical Buildings	0	No	460,000	0	
Total Private Properties				**0**	
CMW Assets					
Waratah Dam	1	Item	500,000	500,000	Estimated cost to replace dam to required height. Fully rebuild not necessary.
Waratah Treatment plant	1	Item	100,000	100,000	Shed and pump station.
Water (ML)	0	ML	400	0	Water restriction not expected, and water can be trucked in.
Total CMW Assets				**600,000**	
Other Public Infrastructure					
Picnic area	1	Site	100,000	100,000	Recreational/bbq area, footbridge and 2 small embankments and weirs.
Substation (#)	0	No	4,200,000	0	
Telecommunications (#)	0	Properties	1,000	0	
Cemetery (#)	0	No	2,000,000	0	
Sealed Road (km)	0.3	km	360,000	108,000	
Unsealed Road (km)	0	km	175,000	0	
Rail (km)	0	km	575,000	0	
Transmission Line (km)	0	km	625,000	0	
Number of Bridges	3	No	420,000	1,260,000	Old railway crossing, William Street bridge, Smith Street and culvert.
Agricultural Assets (ha)	0	ha	1,500	0	
Total Public Infrastructure				**1,468,000**	
TOTAL ASSETS				**2,068,000**	
Indirect Costs					
Lost Income (% community assets)	65	%	-	954,200	Conservative estimate.
Lost Agricultural Production (ha)	0	ha	230	0	
Temporary Accomodation (#)	0	Night	100	0	
TOTAL INDIRECT				**954,200**	
TOTAL ECONOMIC COST				**$3,000,000**	

A.1.2 Estimated potential loss of life

Consequence Assessment - Potential Loss of Life (PLL) Due to a Vehicle Accident

Dam Name:	Waratah Dam			Prepared	Shao Ng
Dam Type:	Clay core rockfill			Date	12/06/2013
Dam Height:	6.0 m	**FSL Height:**	5.2 m	Checked	
				Business hours per day	10
Loading Condition	Sunny Day Failure			After hours per day	14
Annual probability of failure, Pf					
- Piping through embankment					
- Erosion in a crack in cohesive soil in the foundation					
		Total, Pf	0.00E+00		
Flood inundation zone	William Street				
Population at risk	2 persons per vehicle				

Annual probability of dam failure Pf	Description of population at risk	Temporal spatial probability (PT:S)	Probability of accident (PA:T)	Population at risk PAR	Vulnerability (VD:A)	Potential loss of life (PLL) N
BUSINESS HOURS						
0.00E+00	Vehicle within inundation zone	0.059	0.20	0.02	0.01	0.00
0.00E+00	Vehicle driving into inundation zone during event	1.000	0.02	0.04	0.01	0.00
0.00E+00	Vehicle driving into inundation zone after event	0.0	0.02	0.00	0.02	0.00
			Total	**0.06**	0.01	**0.00**
AFTER HOURS						
0.00E+00	Vehicle within inundation zone	0.010	0.20	0.00	0.02	0.00
0.00E+00	Vehicle driving into inundation zone during event	1.000	0.05	0.10	0.02	0.00
0.00E+00	Vehicle driving into inundation zone after event	1.0	0.05	0.10	0.04	0.00
			Total	**0.20**	0.03	**0.01**

Consequence Assessment - Potential Loss of Life (PLL) Due to a Vehicle Accident

Dam Name:	Waratah Dam			Prepared	Shao Ng
Dam Type:	Clay core rockfill			Date	12/06/2013
Dam Height:	6.0 m	**FSL Height:**	5.2 m	Checked	
				Business hours per day	10
Loading Condition	Sunny Day Failure			After hours per day	14
Annual probability of failure, Pf					
- Piping through embankment					
- Erosion in a crack in cohesive soil in the foundation					
		Total, Pf	0.00E+00		
Flood inundation zone	Smith Street				
Population at risk	2 persons per vehicle				

Annual probability of dam failure Pf	Description of population at risk	Temporal spatial probability (PT:S)	Probability of accident (PA:T)	Population at risk PAR	Vulnerability (VD:A)	Potential loss of life (PLL) N
BUSINESS HOURS						
0.00E+00	Vehicle within inundation zone	0.059	0.99	0.12	0.02	0.00
0.00E+00	Vehicle driving into inundation zone during event	1.000	0.99	1.98	0.02	0.04
0.00E+00	Vehicle driving into inundation zone after event	0.0	0.08	0.00	0.02	0.00
			Total	**2.10**	0.02	**0.04**
AFTER HOURS						
0.00E+00	Vehicle within inundation zone	0.010	0.99	0.02	0.04	0.00
0.00E+00	Vehicle driving into inundation zone during event	1.000	0.99	1.98	0.04	0.08
0.00E+00	Vehicle driving into inundation zone after event	1.0	0.15	0.30	0.04	0.01
			Total	**2.30**	0.04	**0.09**

Consequence Assessment - Potential Loss of Life (PLL) Due to a Vehicle Accident

Dam Name:	Waratah Dam			Prepared	Shao Ng
Dam Type:	Clay core rockfill			Date	12/06/2013
Dam Height:	6.0 m	**FSL Height:**	5.2 m	Checked 0	0
				Business hours per day	10
Loading Condition	Flood Failure			After hours per day	14
Annual probability of failure, Pf					
- Piping through embankment					
- Erosion in a crack in cohesive soil in the foundation					
		Total, Pf	0.00E+00		
Flood inundation zone	William Street				
Population at risk	2 persons per vehicle				

Annual probability of dam failure Pf	Description of population at risk	Temporal spatial probability ($P_{T:S}$)	Probability of accident ($P_{A:T}$)	Population at risk PAR	Vulnerability ($V_{D:A}$)	Potential loss of life (PLL) N
BUSINESS HOURS						
0.00E+00	Vehicle within inundation zone	0.059	0.99	0.12	0.02	0.00
0.00E+00	Vehicle driving into inundation zone during event	1.000	0.99	1.98	0.02	0.04
0.00E+00	Vehicle driving into inundation zone after event	0.0	0.05	0.00	0.02	0.00
			Total	**2.10**	0.02	**0.04**
AFTER HOURS						
0.00E+00	Vehicle within inundation zone	0.010	0.99	0.02	0.04	0.00
0.00E+00	Vehicle driving into inundation zone during event	1.000	0.99	1.98	0.04	0.08
0.00E+00	Vehicle driving into inundation zone after event	1.0	0.08	0.16	0.04	0.01
			Total	**2.16**	0.04	**0.09**

Consequence Assessment - Potential Loss of Life (PLL) Due to a Vehicle Accident

Dam Name:	Waratah Dam			Prepared	Shao Ng
Dam Type:	Clay core rockfill			Date	12/06/2013
Dam Height:	6.0 m	**FSL Height:**	5.2 m	Checked 0	0
				Business hours per day	10
Loading Condition	Flood Failure			After hours per day	14
Annual probability of failure, Pf					
- Piping through embankment					
- Erosion in a crack in cohesive soil in the foundation					
		Total, Pf	0.00E+00		
Flood inundation zone	Smith Street				
Population at risk	2 persons per vehicle				

Annual probability of dam failure Pf	Description of population at risk	Temporal spatial probability ($P_{T:S}$)	Probability of accident ($P_{A:T}$)	Population at risk PAR	Vulnerability ($V_{D:A}$)	Potential loss of life (PLL) N
BUSINESS HOURS						
0.00E+00	Vehicle within inundation zone	0.059	0.99	0.12	0.02	0.00
0.00E+00	Vehicle driving into inundation zone during event	1.000	0.99	1.98	0.02	0.04
0.00E+00	Vehicle driving into inundation zone after event	0.0	0.08	0.00	0.02	0.00
			Total	**2.10**	0.02	**0.04**
AFTER HOURS						
0.00E+00	Vehicle within inundation zone	0.010	0.99	0.02	0.04	0.00
0.00E+00	Vehicle driving into inundation zone during event	1.000	0.99	1.98	0.04	0.08
0.00E+00	Vehicle driving into inundation zone after event	1.0	0.15	0.30	0.04	0.01
			Total	**2.30**	0.04	**0.09**

WARATAH DAM

POTENTIAL LOSS OF LIFE ESTIMATION

Flood Event: SDF - Business Hour

Time warning initiated:	1:00	hh:mm after breach					Warning Cutoff times (hh:mm):			0:15	1:00
Location/Reach	PAR	Flood Severity	Travel Time (hh:mm)	Warning Time (hh:mm)	Flood Severity Understanding	Fatality Rate			Potential Loss of Life		
						Lower Range	Upper Range	Suggested	Lower Range	Upper Range	**Suggested**
William Street	0.1	Low	0:30	0:00	Vague			0.01			**0.0006**
Smith Street	2.1	Low	0:30	0:00	Vague			0.02			**0.042**
Park/bbq area	2	Low	0:30	0:00	Vague	0	0.02	0.01	0.0	0.0	**0.02**
Totals	**4**								**0.0**	**0.0**	**0.063**

Notes:
"Time Warning Initiated" is comprised of travel time for flood to reach William Street plus 30 minutes police contact time.
"Travel Time" is comprised of time to significant increase in flow.
No flood mapping is available. Travel time is based on high level estimate.

Flood Event: SDF - After Hour

Time warning initiated:	10:00	hh:mm after breach					Warning Cutoff times (hh:mm):			0:15	1:00
Location/Reach	PAR	Flood Severity	Travel Time (hh:mm)	Warning Time (hh:mm)	Flood Severity Understanding	Fatality Rate			Potential Loss of Life		
						Lower Range	Upper Range	Suggested	Lower Range	Upper Range	**Suggested**
William Street	0.2	Low	0:30	0:00	Vague			0.03			**0.006**
Smith Street	2.3	Low	0:30	0:00	Vague			0.04			**0.092**
Park/bbq area	0	Low	0:30	0:00	Vague	0	0.02	0.01	0.0	0.0	**0**
Totals	**3**								**0.0**	**0.0**	**0.098**

Notes:
No warning will likely be issued after hour.
"Travel Time" is comprised of time to significant increase in flow based on high level estimate.

Flood Event: Flood Failure (DCF + DB) - Business Hour

Time warning initiated:	0:00	hh:mm after breach					Warning Cutoff times (hh:mm):			0:15	1:00
Location/Reach	PAR	Flood Severity	Travel Time (hh:mm)	Warning Time (hh:mm)	Flood Severity Understanding	Fatality Rate			Potential Loss of Life		
						Lower Range	Upper Range	Suggested	Lower Range	Upper Range	**Suggested**
William Street	2.1	Low	0:30	0:30	Vague			0.02			**0.042**
Smith Street	2.1	Low	0:30	0:30	Vague			0.02			**0.042**
Park/bbq area	0	Low	0:30	0:30	Vague	0	0.015	0.007	0.0	0.0	**0**
Totals	**4**								**0.0**	**0.0**	**0.084**

Notes:
The CMW DSEMP for Waratah Dam requires that the high critial alarm level be raised when storage level reach RL608.5m.
Therefore, warning would have been issued before dam failure due to dam crest flood.
Assumed warning would be issued 30 minutes before dam failure, but it takes 30 minutes for warning to be distributed.
"Travel Time" is comprised of time to significant increase in flow based on high level estimate.

Flood Event: Flood Failure (DCF + DB) - After Hour

Time warning initiated:	10:00	hh:mm after breach					Warning Cutoff times (hh:mm):			0:15	1:00
Location/Reach	PAR	Flood Severity	Travel Time (hh:mm)	Warning Time (hh:mm)	Flood Severity Understanding	Fatality Rate			Potential Loss of Life		
						Lower Range	Upper Range	Suggested	Lower Range	Upper Range	**Suggested**
William Street	2.2	Low	0:30	0:00	Vague			0.04			**0.0864**
Smith Street	2.3	Low	0:30	0:00	Vague			0.04			**0.092**
Park/bbq area	0	Low	0:30	0:00	Vague	0	0.02	0.01	0.0	0.0	**0**
Totals	**4**								**0.0**	**0.0**	**0.178**

Notes:
No warning will likely be issued after hour.
"Travel Time" is comprised of time to significant increase in flow based on high level estimate.

A.1.3 Severity of damage and losses

Applicant Name	Waratah Dam				
Stream Name	Waratah River				
Estimated Capacity at FSL	800 ML				
Dam ID. No. (If existing dam)		**4**	**8**	**0**	**6**
Dam Height (metres)	6 **M**				
Location	1km southeast of Waratah (60km southwest of Burnie)				
Consequence Category Condition	Sunny day failure / Flood failure				
Damage and Loss	**Estimate**	**Severity**			
		Minor	Medium	Major	Catastropihc
TOTAL INFRASTRUCTURE COSTS (costs are indicative only)					
Residential	$ -				
Commercial	$ -				
Community Infrastructure	$ -				
Dam repair or replacement cost	$ 600,000				
Total estimated cost	$ 600,000	YES			
Estimated cost severity level =	**MINOR**				
IMPACT ON DAM OWNER'S BUSINESS					
Importance to the business	Restrictions needed during dry periods	YES			
Effect on services provided by owner	Minor difficulties in replacing services	YES			
Effect on continuing credibility	Some reaction but short lived - 200 people in Waratah	YES			
Community reaction and political implications	Some reaction but short lived	YES			
Impact on financial viability	Able to absorb in one financial year	YES			
Value of water in storage	Can be absorbed in one financial year	YES			
Business impact severity level =	**MINOR**				
HEALTH AND SOCIAL IMPACTS					
Human Health	<100 people affected - minor restrictions	YES			
Loss of services to the community	<100 people affected	YES			
Cost of emergency management	<1,000 person days	YES			
Dislocation of people	<100 person months	YES			
Dislocation of business	<20 business months	YES			
Employment affected	<100 jobs lost	YES			
Loss of heritage	Regional facility - small embankments and weirs, old railway bridge		YES		
Loss of other recreational facilities	Local facility	YES			
Health and sociual impact severity level =	**MEDIUM**				
ENVIRONMENT IMPACTS					
Area of impact	<1km^2	YES			
Duration of impact	<1 year	YES			
Stock and fauna	Discharge from dambreak would not contaminate water supplies used by stock and fauna.	YES			
Ecosystems	Discharge from dambreak is not expected to impact on ecosystems. Remediation possible.	YES			
Rare and endangered species	Species exist but minimal damage expected. Recovery within one year.	YES			
Environment impact severity level =	**MINOR**				
Highest damage and loss severity level =	***MEDIUM***				

Reasons for recommending consequence rating (refer ANCOLD guidelines) which MUST include comments on PAR, buildings, roads, other infrastructure and natural environment downstream of the dam and the potential impacts arising from a dam break: *(Note** Provide photographs to support reasons for recommending consequence rating)***

No flood mapping has been done. Refer to PRA report on PAR and consequence assessment. A sunny day or flood failure of the dam would likely result in an itinerant PAR of 4 and PLL $\geq$ 0.1 during after hours. Likely affected assets include the picnic area, a footbridge, 2 small embankments and weirs, 300m of sealed road, the William Street bridge, the Smith Street crossing and culvert, and the old railway bridge. The total economic loss was estimated to be $3M including indirect cost due to lost infrastructure.

Population at Risk (PAR) PAR includes all those persons who would be directly exposed to flood waters within the dam break affected zone if they took no action to evacuate	**CONSEQUENCE CATEGORY =** N/A - PLL used as risk assessment available	**N/A**

Note 1: With a PAR in excess of 100, it is unlikely that the severity of damage and loss will be minor. Similarly with a PAR in excess of 1000, it is unlikely damage will be classifed as medium

Note 2: Change to "High C" where there is the potential for one or more lives being lost

Probable Loss of Life PLL includes the part of the population at risk that could lose their lives in the event of a dambreak	**CONSEQUENCE CATEGORY =** PLL = 0.18	**Significant**

Note 1: With a PLL equal to or greater than one (1) it is unlikely that the severity of damage and loss will be minor. Similarly with a PLL in excess of 50, it is unlikely damage will be classifed as medium

Completed By	**Tung Hoang, Shao Ng**
Date	**10/04/2013**

B Screening of failure modes

B.1 Waratah Dam

Loading condition	Description of failure mode	Include/ Exclude	Comment
Flood	Flood overtopping	Include	Spillway capacity = 1:2,200 AEP flood. The dam has failed before in the 70s due to flood overtopping.
Flood	Spillway blockage by debris	Include	This has happened before, leading to overtopping failure.
Flood	Erosion along spillway channel	Include	The embankment section adjacent to the spillway channel is unprotected against spillway flows.
Flood	Piping through embankment, foundation and along outlet	Include	Evidence of significant leakage at dam toe. Refer to screening of piping failure modes below.
Flood	Spillway discharge undermining dam toe	Exclude	The spillway downstream channel is located 25m from the dam toe.
Normal	Failure of outlet valve at toe	Exclude	Low discharge rate, approximately $0.92m^3/s$.
Normal	Failure of pipe under embankment	Exclude	Limited information on pipe details. Assumed cast iron pipe in satisfactory condition – to be confirmed by investigations. Water pH = 6.86.
Normal	Piping through embankment, foundation and along outlet	Include	Evidence of significant leakage at dam toe. Refer to screening of piping failure modes below.
Normal	Downstream slope instability	Exclude	Downstream slope is 1V:2H, appears to be rockfill. The dam has a wide crest. A slope failure resulting in a total loss of freeboard is unlikely.
Normal	Upstream slope instability	Exclude	Upstream slope is 1V:2H, appears to be rockfill with grass cover. There are minor signs of wave erosion. The dam has a wide crest. Rapid drawdown is unlikely.
Earthquake	Piping through embankment, foundation and along outlet	Negligible	Low seismic activity. Refer to screening of piping failure modes below.

Loading condition	Description of failure mode	Include/ Exclude	Comment
Earthquake	Deformation/settlement	Exclude	Would not have significant settlement to result in a total loss of freeboard.
Earthquake	Liquefaction	Exclude	Embankment materials are rock or high plasticity silty clay, which are non-liquefiable.
Earthquake	Right abutment slip into spillway channel	Exclude	Spillway channel is shallow and wide, and blockage is unlikely.
Other	Sabotage/terrorism	Exclude	Unlikely.
Other	Reservoir rim stability	Exclude	Low relieve. Material appears to have high plasticity, and any slide would be slow moving.

Failure Path Screening

The purpose of the failure path screening process is to systematically review the potential failure paths/modes that have been identified and eliminate those from further consideration that are assessed to have negligible contribution to risk.

Not all failure paths need to be analysed. Failure paths are screened based on the criteria given in table 3.1 below. Complete this section to show which paths need to be considered further. **See section 3.4 for further info.** Rationale for inclusions/exclusions should be fully documented.

Table 3.1 Internal erosion due to concentrated leaks in TRANSVERSE CRACKS in the UPPER part of embankment

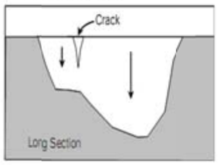
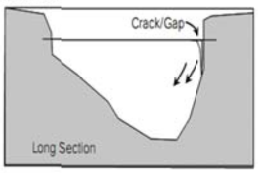
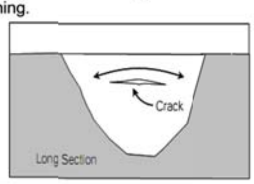
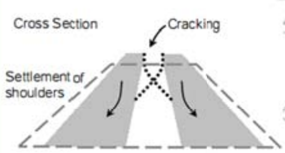
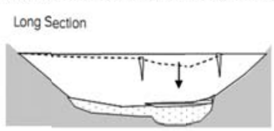
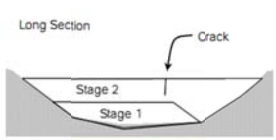
Initiating Mechanism	Exclude If:	Applicable?	Include/Exclude
IM1: Transverse cracking due to cross valley differential settlement. 	***Never Exclude.***	YES	Never exclude this mode, likely to be a low risk, gentle abutment slopes
IM2: Transverse cracking due to differential settlement adjacent to a vertical cliff at the top of the embankment. 	***Exclude if:*** (a) There is no vertical cliff in contact with the embankment. ***(OR)*** (b) A wide bench is present at the base of the cliff (W_t/H_w > 2.5, *refer Figure 5.2*). ***(OR)*** (c) The abutment slope below the cliff is gentle (β_1 < 25°, *refer Figure 5.2*)	No	no vertical cliff
IM3: Trasverse cracking due to cross valley arching. 	***Exclude if:*** The width of valley to dam height ratio W_v/H > 2 (*refer Figure 5.3*)	No	Wv/H > 2
IM4: Transverse cracking resultant on cross section settlement. 	***Exclude if:*** (1) The dam is zoning type homogenous earthfill, earthfill with filter drains or zoned earthfill. ***(OR)*** (2) Evidence from relative settlements of core and shoulders that the materials have a similar modulus. ***(OR)*** (3) Finite Element Analyses have demonstrated that stresses are such that hydraulic fracture is very unlikely.	No	dam zoning uncertain, based on dam type and height likely to be a negligible risk
IM5: Transverse cracking due to differential settlements in the foundation beneath the core. 	***Exclude if:*** There is no compressible soil in the foundation below the core	NO	no signs of cracking onsite, rock outcrop near the surface on the ds area, likely to be rock foundation and no compressible aluvial deposit
IM6: Transverse cracking due to differential settlements due to embankment staging. 	***Exclude if:*** The embankment construction was not staged.	NO	dam was reported to be rebuilt in the past (75/76), assumed dam was reconstructed with no staging, no signs of cracking on crest

Table 3.1 Internal erosion due to concentrated leaks in TRANSVERSE CRACKS in the UPPER part of embankment (Cont).

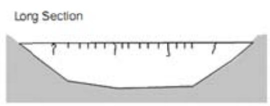
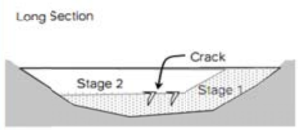
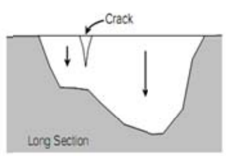
Initiating Mechanism	Exclude If:	Applicable?	Include/Exclude
IM7: Cracking in the crest due to desiccation by drying. 	***Exclude if:*** The reservoir stage being conisdered is below the likely depth of desiccation cracking.	No	wet climate, low freeboard, dam operates near FSL
IM8: Cracking on seasonal shutdown layers during construction and staged construction due to desiccation by drying. 	***Exclude if:*** (1) The reservoir stage being considered is below the level of the seasonal shutdown surface. ***(OR)*** (2) This mechanism only applies above the level of saturation of the core. Below that any desiccation cracks should have swelled and closed. ***(OR)*** (3) This mechanism only applies where there has been a seasonal shutdown during construction, or the embankment has been staged. ***(OR)*** (4) Very good control and clean up practices used - desiccated layers removed from the embankment and replaced with new soil or adequately reworked to specified moisture content.	No	seasonal shutdown unlikely for a small dam
IM13: Cracking due to earthquake. 	***Never Exclude. Complete above IM cases before attempting to complete this mechanism***	YES	Never exclude this mode.

Table 3.2 Internal erosion due to concentrated leaks in TRANSVERSE CRACKS in the MID-LOWER parts of embankment

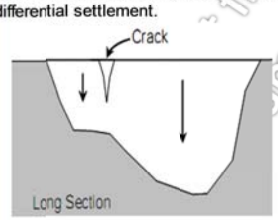
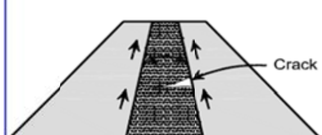
Failure Path/Location	Exclude If:	Applicable?	Reason for Include/Excl
IM9: Transverse Cracking Due to cross valley differential settlement. 	***Exclude if:*** Uniform abutment profile without benches.	No	gentle abutment slopes, potential step in the foundation on the left abutment where the original spillway was reported to be, fairly high up near the crest hence unlikely a big problem
IM10: Transverse cracking due to differential settlement causing arching of the core onto the shoulders of the embankment. 	***Exclude if:*** (1) For all dam zoning types other than central core earth and rockfill (or gravel shells), and puddle core earthfill dams. ***(OR)*** Dam has a wide core (W/H >1.0) ***(OR)*** (3) Core has higher modulus than shells. Shoulders poorly compacted or dumped. Core compacted >98% SMDD	No	dam zoning uncertain, based on dam type and height likely to be a negligible risk
IM11: Transverse cracking or hydraulic fracture in the lower part of the embankment due to differential settlement in the foundation under the core.	Excluded as has already been considered in upper part of the dam.	NO	addressed under IM5

Table 3.2 Internal erosion due to concentrated leaks in TRANSVERSE CRACKS in the MID-LOWER parts of embankment cont.

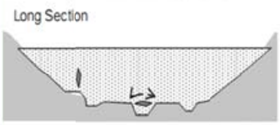
Failure Path/Location	Exclude If:	Applicable?	Include/Exclude
IM12: Transverse cracking at the foundation contact due to small scale irregularities in the foundation profile under the core. 	***Exclude if:*** The persistence of the irregularity across the width of the core is less than 50% of the core base width.	No	rock outcrop exposed on the downstream area, to be considered as poorly compacted layer at dam/foundation contact in IM15

Table 3.3 Internal erosion due to POORLY COMPACTED or HIGH PERMEABILITY zones in the embankment

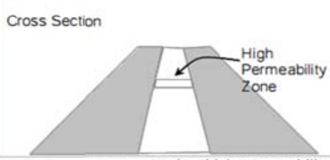
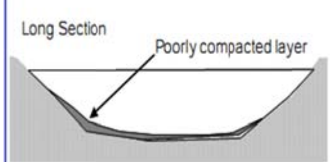
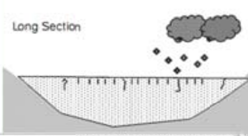
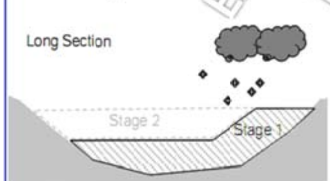
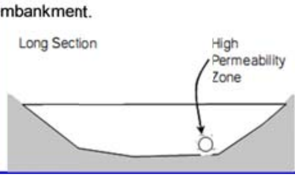
Failure Path/Location	Exclude If:	Applicable?	Include/Exclude
IM14: Poorly compacted or high permeability layer in the embankment. 	***Exclude if:*** All soils are very well compacted with lift thicknesses less than 200mm (8 inches), with good documentation and records: (1) For cohesive soils (Plasticity Index >7), ≥ 98% standard dry density ratio, moisture content 2% dry to 1% wet of OWC. ***(OR)*** (2) For cohesionless soils and soils with PL ≤7, >75% relative density.	YES	
IM15: Poorly compacted or high permeability layer on the core-foundation contact. 	***Exclude if:*** (1) Contact soils are well compacted on a regular foundation surface with good documentation and records. ***(OR)*** (2) Uniform or regular rock surface or surface treated with shotcrete or concrete to correct slope irregularities, and soils well compacted (contact soil compacted using special compaction methods (e.g. rubber tires, use more plastic material, compaction wet of OWC). ***(OR)*** (3) Uniform well compacted soil foundation, with good mixing, bonding and compaction of contact fill. ***(OR)*** (4) Compacted soil foundation.	YES	
IM16: Poorly compacted or high permeability layers in the crest due to freezing. 	***Exclude if:*** (1) The climate is such that temperatures do not fall below freezing point except possibly overnight for a day or two. ***(OR)*** (2) If the reservoir stage being conisdered is below the likely depth of freezing.	No	reason 1
IM17: Seasonal shutdown layers during construction and staged construction surfaces due to freezing. 	***Exclude if:*** (1) The climate is such that temperatures do not fall below freezing point except possibly overnight for a day or two. ***(OR)*** (2) Very good control and clean-up practices were used - Frozen layers removed from the embankment and replaced with new soil or adequately reworked to specified moisture content. ***(OR)*** (3) If the reservoir stage being considered is below the likely depth of desiccation cracking.	No	seasonal shutdown unlikely
Note: Cohesionless soils are soils with zero Plasticity Index			
IM18: Poorly compacted or high permeability zone around a conduit through the embankment. 	***Exclude if:*** (1) There is no conduit passing through the embankment. ***(OR)*** (2) The conduit is totally embedded in a trench excavated in non-erodeable rock, backfilled to the surface with concrete.	YES	conduit present

Table 3.3 Internal erosion due to POORLY COMPACTED or HIGH PERMEABILITY zones in the embankment cont.

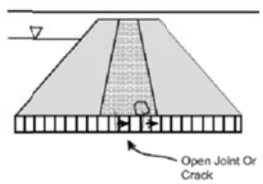
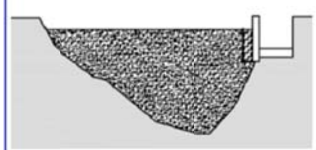
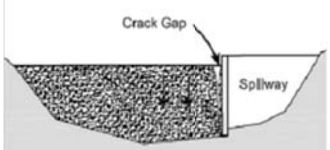
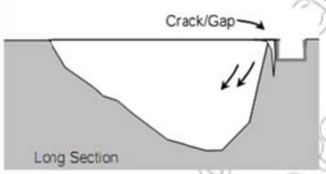
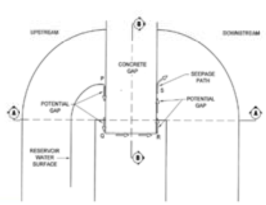
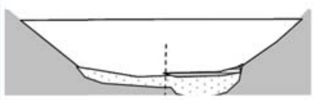
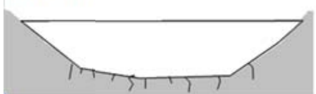
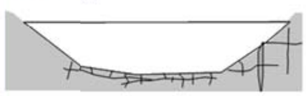
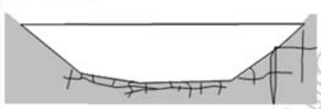
Failure Path/Location	Exclude If:	Applicable?	Reason for Include/Excl
IM19 (A & B): Erosion into a (non-pressurised) conduit. 	***Exclude if:*** (1) There is no conduit passing through the embankment, ***(OR)*** (2) Careful internal inspection of conduit showing no evidence of open joints or cracks.	No	no non-pressurised conduit
IM20: Poorly compacted zone associated with a spillway or abutment wall. 	***Exclude if:*** There is no spillway or abutment wall in contact with the embankment.	No	no walls
IM21: Crack/gap adjacent to a spillway or abutment wall. 	***Exclude if:*** There is no spillway or abutment wall in contact with the embankment.	No	ditto
IM22: Differential settlement adjacent to a spillway or abutment wall. 	***Exclude if:*** (1) There is no spillway or abutment wall in contact with the embankment. ***(OR)*** (2) A wide bench is present at the base of the wall (W_b/H_w >2.5 *refer to Figure 5.2*). ***(OR)*** (3) The abutment slope below the wall is gentle (β_1 <25°, *refer Figure 5.2)*	no	ditto
IM23 : Wrap around details for connection of embankment dam to concrete gravity dam 	***Exclude if;*** (1) There is no wrap around connection of an embankment dam to concrete gravity dam	No	

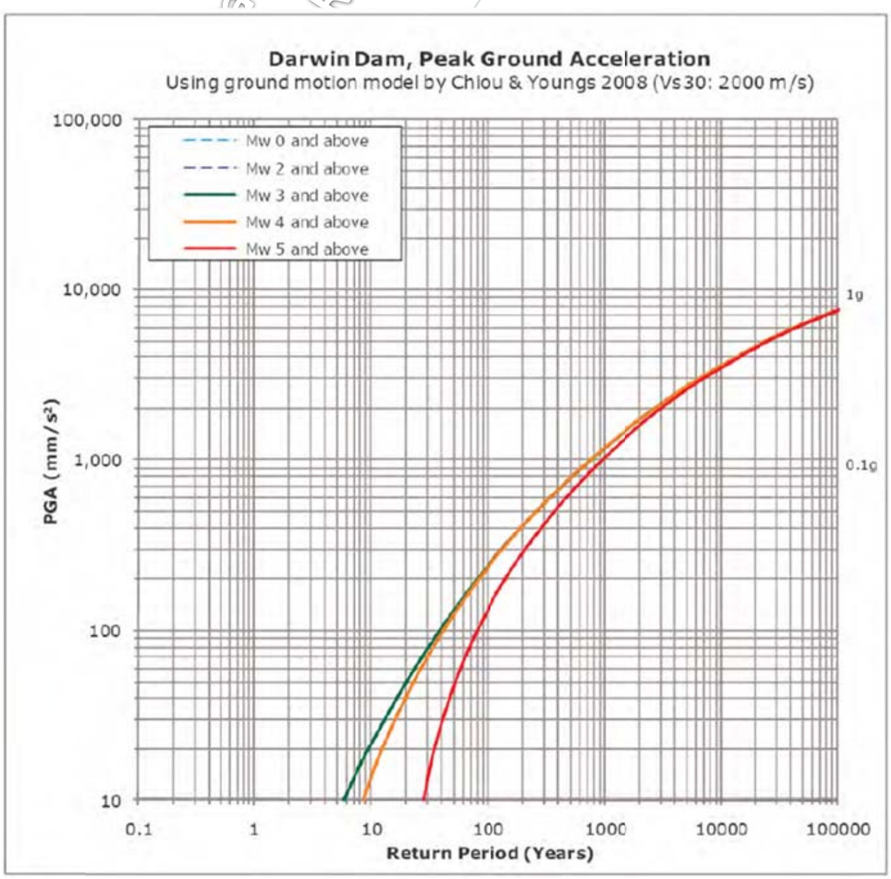
Table 3.4 Internal Erosion through the foundation

Failure Path/Location	Exclude If:	Applicable?	Include/Exclude
All modes of internal erosion of the foundation (backward erosion, suffusion, erosion in a crack)	***Exclude if;*** (1) The soil layer beneath the dam is isolated by a cut-off trench founded in non-erodible rock. (Note that erosion across the cut-off trench is considered separately in internal erosion of the embankment into or at the foundation).	YES	
IM24 – Backward erosion in a cohesionless soil foundation Suffusion in a cohesionless soil in the foundation Long Section 	***Exclude if,*** (1) The foundation soil has a Plasticity Index ≥ 7. **OR** (2) If the cohesionless soil or soil with PI ≤ 7 layer is not continuous below the embankment (i.e. it terminates beneath the dam, refer to Figure 7.1)	no	rock outcrop exposed on the downstream area, hence likely to be rock foundation
IM25 – Suffusion in a cohesionless soil in the foundation Long Section 	***Exclude if,*** (1) The foundation soil has a Plasticity Index ≥ 7. **OR** (2) The proportion of the finer fraction is less than 40% of the total mass of the soil.	no	same as above
IM26 – Erosion in a crack in cohesive soil in the foundation Long Section 	***Exclude if,*** (1) The foundation soil is cohesionless.	No	same as above
IM27 – Erosion in defects in a rock foundation Long Section 	No exclusions apply for a rock foundation	YES	rock outcrop exposed on the downstream area, hence likely to be rock foundation, evidence of significant leakage
IM28 – Internal erosion of the embankment into or at a rock foundation	Exclude if; (1) Rock foundation below the core is comprised of rock containing closed rock defects (<1 mm wide) or defects open less than 3D95 ,of the fine limit of the core OR (2) Rock foundation below the core has been adequately treated (e.g. shotcrete, slush grouting mortar treatment)	YES	rock outcrop exposed on the downstream area, hence likely to be rock foundation, evidence of significant leakage
IM29 – Internal erosion of the embankment into or at a soil foundation	Exclude if; (1) Soil foundation below the core is comprised of fine grained soils with greater than 12% fines (fraction finer than No 200 sieve (0.075mm)), and the soil does not contain macrostructure such as root holes, relic joints or solution features. OR (2) Soil foundation below the core is comprised of sands (SP or SW) which are filter compatible with the embankment materials (i.e. satisfy the No Erosion criteria, refer to Section 10.1.4).	No	rock foundation

C Seismic hazard assessment

No seismic study was undertaken for the Cradle Mountain Water dams in the past. There was a seismic hazard assessment undertaken by Environmental Systems and Services (ES&S) for Hydro Tasmania at Darwin and Crotty dams (ES&S, 2009). These dams are located south of Queenstown and are reasonably close to the Cradle Mountain Water dams. Hydro Tasmania (Topham, 10 July 2012) has given permission to use the data from that report for the use in this PRA. The scope and findings of that assessment are summarised below:

- A probabilistic hazard assessment which employs a seismotectonic model that considers the seismicity and geology of the area was undertaken to estimate seismic activity rates.
- The seismotectonic model allows for calculations of expected ground motion recurrence at the site, including peak ground acceleration (PGA) and response spectra.
- Seismotectonic source contributions were presented to indicate the relative significance of each source with respect to PGA.
- The peak ground velocity and intensity (MMI) recurrence estimation was also presented.
- The following figure shows the computed mean PGA (mm/s^2) as a function of return period (years) using the Chiou & Youngs (2008) ground motion model for bedrock (Vs 30: 2000 m/s).



A minimum earthquake magnitude of Mw 5.0 and a maximum earthquake magnitude of Mw 7.5 were considered for ground motion calculations.

The PGA for Darwin Dam was calculated as being approximately 0.078g for a return period of around 500 years when considering earthquakes of Richter Magnitude ML 4.0 and above for bedrock (Vs30 of 2000 m/s). This value was assessed to be average by Australian Standards.

A de-aggregation plot was developed to provide a representation of the contribution of ground motion that can be expected from different magnitude earthquake at different distances. The result shows that the dominant source of ground motion at the natural frequency of the structure will be produced by earthquakes at a distance between approximately 12 to 24m and magnitude ML 5.0 to 6.0.

Most of the estimated ground motion at the dam site will be due to activity within the West Tasmania seismotectonic zone within which the dam is located.

The dam sites are expected to experience earthquake intensities of MMI3 (vibration which are strong enough to be felt) approximately every 29 years. Intensities of MMI 6 (when standard housing experiences damage) are expected to occur approximately once every 250 years.

Reference:

ES&S (2009). *Darwin and Crotty Dams Seismic Hazard Assessment*, Environmental Systems and Services (ES&S), October 2009.

D Workshop notes

[redacted]

D.4 Waratah Dam

[redacted]

WARATAH DAM

- Dam for water supply and recreational purposes.
- Year of construction unknown. Dam repaired in 1975/76.
- No drawings are available.
- Likely to be clay core rockfill dam – downstream face consists of fine to coarse rockfill, timber logs and concrete remains.
- 6m high, 87.4m long, 8m wide.
- Upstream slope 1V:2H, grassed.
- Downstream slope 1V:2H.
- Storage capacity of 800ML.
- Catchment of $10km^2$.
- Reservoir and dam site consists of tertiary basalt.
- Current dam appeared to be built over existing concrete structure – from concrete remaining on site/in the dam face.

- Timber overflow weir, with upstream approach channel, discharging down natural creek
  - 5.8m at top of log.
  - 6.8m wide at top of bank.
  - 1.1m from top of log to underside of deck.
- Minimal riprap protection along spillway channel.
- Dam crest = RL608.8m / FSL = RL608m
- Spillway capacity of $5.3m^3/s$ = 1:2,200 AEP
  - Less conservative estimate – actual control located upstream of crest.
  - Need survey and modelling to provide better estimate.
- Basaltic material along spillway channel has high erosion resistance.
- Spillway has never stopped spilling
  - Current leakage at the toe is enough to supply water to the town?
  - Necessity for the dam to supply water?
  - Dam for flood retention?
- Outlet consist of DN400 cast iron outlet valve.
- Pipe condition and details to be checked.

- Surveillance and monitoring:
  - Weekly routine inspection.
  - 2-yearly intermediate inspection.
  - 5-yearly comprehensive surveillance review.
  - 20-yearly dam safety review.
  - Storage level – visual monitoring.
  - V-notch weir removed. Seepage visually monitored.
    - Seepage monitoring need to continue in the form of flumes.
    - Reroute spillway flow downstream.
  - No deformation survey.
    - Not detecting key failure modes.
    - Depending on decision and risk position of the dam.
    - To be considered as part of future upgrade.
  - Continuous seismic monitoring.

- Key issues:
  - Minor erosion on upstream face.
  - Depression on dam crest – unchanged for long time.
  - Significant leakage at dam toe – likely to be from foundation.
  - Outlet valve unlikely to be functional.
  - Original spillway constructed on left abutment. The spillway was blocked, resulting in overtopping failure. Dam repaired in 1975/76, with new (current) spillway constructed on right abutment.

- Consequence assessment
  - Only source of water supply to Waratah
    - Serving 200 people in Waratah (per comm. Noel Fagan).
    - Lost of reservoir will not result in significant restriction of supply
      - Current water tank has a storage for > 1 week of supply.
      - Water can be trucked in.
  - Damage and loss:
    - No houses identified within dam break flood inundation zone.
    - William Street crossing would be affected – main road to Carina Savage River – check DIER statistics for both Smith and William Streets.
    - Smith Street would be affected.
    - The two weirs and embankments downstream would likely be destroyed due to overtopping.
    - Downstream recreational areas would be affected – itinerant PAR.
    - Old railway crossing would be washed away – heritage value?
    - New water treatment plant would not be affected except for the existing raw water pump station.

- Itinerant PAR:
  - Sunny day after hour
    - Negligible PAR.
  - Sunny day business hour
    - Estimated PAR = 4 – check DIER statistics.
    - PLL = approx. 1 (no warning, medium severity).
    - Medium severity of damage and loss.
    - **Significant** consequence category.
  - Flood scenario
    - Negligible PAR.
    - DCF = 1:2,000 AEP
    - Extreme weather condition – unlikely to have people presence downstream of the dam.

Extract from Cradle Mountain Water Dam Portfolio Risk assessment

- **Flood loading failure modes**:
  - Overtopping
    - Credible.
    - It has happened before.
  - Spillway blockage
    - Credible.
    - It has happened before.
  - Erosion along spillway channel
    - Credible.
    - Spillway channel adjacent to embankment.
  - Piping through embankment/foundation/outlet
    - Credible.
    - Leakage observed at downstream toe.
  - Spillway discharge undermining dam toe
    - Not credible.
    - Spillway downstream channel located 25m from dam toe.

- **Normal loading failure modes**:
  - Failure of outlet valve at downstream toe
    - Not credible.
    - Low discharge rate = approx. 0.92m^3/s.
  - Failure of pipe under embankment
    - Not credible – to be confirmed following investigation.
    - Limited information on pipe – condition of outlet to be confirmed.
    - Assumed cast iron pipe in satisfactory condition.
    - Water pH = 6.86.
  - Piping through embankment/foundation/outlet
    - Credible.
    - Observed leakage at dam toe.

Extract from Cradle Mountain Water
Dam Portfolio Risk assessment

- <u>Normal loading failure modes (cont.)</u>:
  - Downstream face slope instability
    - Not credible.
    - Slope = 1V:2H.
    - Appeared to be rockfill.
    - Wide crest.
  - Upstream face slope instability
    - Not credible.
    - Slope = 1V:2H.
    - Appeared to have rockfill and grass cover.
    - Sign of wave erosion.
    - Wide crest.
    - Rapid drawdown is unlikely.

- <u>Earthquake loading failure modes</u>:
  - **Seismic induced piping**
    - Credible.
    - Low probability.
  - Seismic induced deformation/settlement
    - Not credible.
    - Unlikely to result in total loss of freeboard.
  - Liquefaction
    - Not credible.
    - Materials are rock or high plasticity silty clay – not liquefiable.
  - Right abutment slip into spillway channel
    - Not credible.
    - Spillway channel is shallow and wide.

- Other failure modes:
  - Sabotage / terrorism
    - Not considered credible.
  - Reservoir rim instability
    - Not credible.
    - Low relieve.
    - Material has high plasticity, any slide would be slow moving.

- Flooding overtopping:
  - DCF = 1:2,000 AEP.
  - No failure until reservoir reaches dam crest level.
  - Conditional probability of failure of 0.1 when reservoir reaches 0.15m above dam crest – 1:50,000 AEP
  - Conditional probability of failure of 1 when reservoir reaches 0.4m above dam crest – 1:20,000 AEP
    - Wide crest.
    - Coarse rockfill, high erosion resistance.
    - Erosion resistance better than Parting Creek Dam, worse than Cutten Street Dam No 3.

- Spillway blockage leading to overtopping:
  - Obtain historic information from previous contractor (Joe Fagan).
  - Search for historic photographs of the dam.
  - Hydrology has only considered short critical duration flood – 5hr
    - need additional hydrology to confirm actual flood scenario – longer duration flood.
  - Estimate probability of debris resulting in 50% spillway blockage
  - Check flood hydrology
  - Rerun flood routing to identify probability of overtopping failure based on the same respond curve.

- Erosion along spillway channel:
  - Erosion along spillway channel:
    - Slope of spillway channel approx. 7%.
    - Flow velocity approx. 2.5m/s.
    - Approx. 300mm diameter cobbles in channel.
    - Erosion of spillway channel is unlikely.
  - Erosion of embankment section:
    - Minimal rock protection downstream of footbridge.
    - Grass cover upstream of bridge.
    - Determine the flood that will result in a flow velocity of greater than 1.5m/s.
    - Conditional probability of failure of 1 with flow at 1.5m/s and duration long enough to erode out the material adjacent to the embankment.

- Piping failure:
  - Dam structure:
    - Assumed earth and rockfill dam based on site observation of significant amount of large rock in the downstream face – to be confirmed by investigation.
    - Pool of record assumed to be 1:50 AEP
      - Dam effectively completely rebuilt in mid 1970's, 50-year old.
  - **IM1**: Never exclude, gentle abutment, low probability.
  - IM2: Not credible, relatively long dam.
  - IM3: Not credible.
  - IM4: Not credible, dam zoning uncertain, low dam, unlikely to have significant differential settlement.

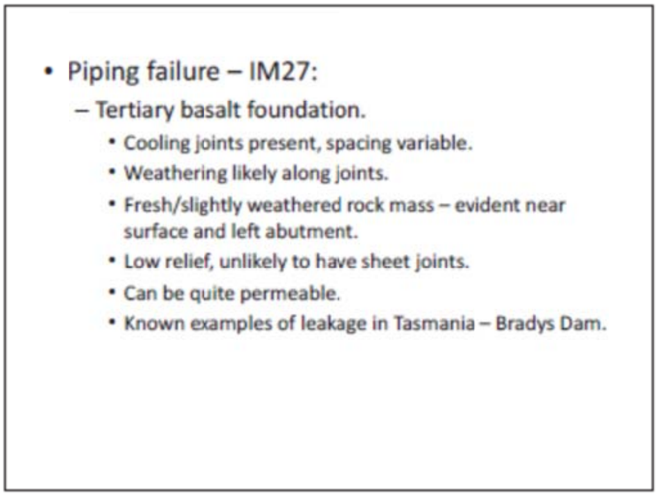
- Piping failure:
  - IM5: Not credible, rock foundation, unlikely to have differential settlement in foundation.
  - IM6: Not credible, dam likely be completely rebuilt in mid-70s with no staging.
  - IM7: Not credible, dam at FSL all time.
  - IM8: Not credible.
  - IM9: Not credible, potential bench on left abutment where the original spillway was, but is relatively high, and is unlikely to result in differential settlement.

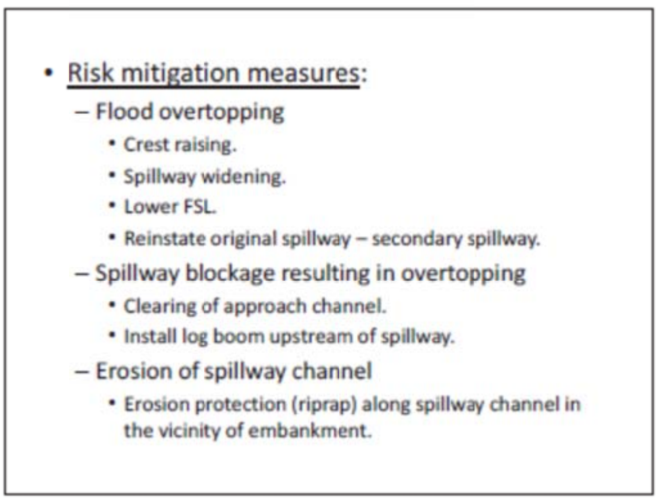
- Piping failure:
  - IM10: Not credible, as per IM4.
  - IM11: Excluded.
  - IM12: Credible, but excluded, to be considered under IM15 – poor compacted layer at foundation.
  - IM13: Not credible, not staged.
  - IM14: Credible.

- Piping failure:
  - IM15: Credible.
  - IM16: Not credible.
  - IM17: Not credible.
  - IM18: Credible.
  - IM19: Not credible, no spillway wall.
  - IM20-IM23: Not credible.
  - IM24: Not credible, rock foundation.

- <u>Piping failure</u>:
  - IM25: Not credible.
  - IM26: Not credible.
  - **IM27**: Credible, erosion possible in basalt foundation, evidence of significant leakage at foundation.
  - **IM28**: Credible, low probability.
  - IM29: Not credible, not soil foundation.

- Piping failure – IM15:
  - D60 = 0.02mm – fine soil
  - D10 = 0.001mm
  - γ_{sat} = 18kN/m^3
  - Layer thickness = 250mm
  - Need to start monitoring leakage using flumes, and re-routing spillway discharge downstream away from the monitoring points.
  - Probability of initiation (hydraulic gradient) is sensitive to dam type i.e. homogeneous versus zoned earth and rockfill.
  - Need investigation to confirm dam type, dam and foundation details.
  - Check with original contractor for information on dam details and construction.


• Piping failure – IM27:
– Tertiary basalt foundation.
• Cooling joints present, spacing variable.
• Weathering likely along joints.
• Fresh/slightly weathered rock mass – evident near surface and left abutment.
• Low relief, unlikely to have sheet joints.
• Can be quite permeable.
• Known examples of leakage in Tasmania – Bradys Dam.


• Risk mitigation measures:
– Flood overtopping
• Crest raising.
• Spillway widening.
• Lower FSL.
• Reinstate original spillway – secondary spillway.
– Spillway blockage resulting in overtopping
• Clearing of approach channel.
• Install log boom upstream of spillway.
– Erosion of spillway channel
• Erosion protection (riprap) along spillway channel in the vicinity of embankment.

- <u>Risk mitigation measures (cont.)</u>:
  - Piping through embankment
    - Construct filter buttresses, incorporating filter around outlet.
    - Construct downstream rockfill berm.
    - Improve leakage monitoring – install flumes and improve drainage.
  - Piping through foundation
    - Incorporate foundation filter blanket in new filter buttress.
    - Improve leakage monitoring – install flumes and improve drainage.
    - Increase monitoring during abnormal condition.
    - Foundation grouting.
    - Install upstream membrane to restrict piping flow.
    - Wash silty sandy material down upstream face to seal joints.
  - Decommissioning
    - Undertake catchment yield analysis to confirm the requirement for the dam.
    - Understand downstream flood mitigation and social impact.
    - Check social and heritage values.
    - Need to develop dewatering options.