STRATEGIC RISK ASSESSMENT FOR THIRTEEN VICTORIAN DAMS

Richard R. Davidson[1], Shane McGrath[2], Adrian Bowden[3], Andrew Reynolds[4]

ABSTRACT

Goulburn-Murray Water (G-MW) manages thirteen major dams for the State of Victoria. As part of its Dam Improvement Program (DIP), five priority dams were identified for detailed safety and performance evaluation. Over the last three years, the design reviews have been completed and a series of dam safety issues have been identified which pose societal and financial risk. Substantial financial resources will be required to be applied over a considerable period to bring these dams into compliance with established international and Australian standards. Which of these dam safety issues should be addressed first? In what sequence and with what urgency should the actions be implemented? Can cost-effective interim targets be set? How can the remaining eight dams, which could also pose societal and financial risk, be prioritised for future detailed investigation? To answer these questions a quantitative risk assessment approach was used. The approach utilised expert engineering and consequence panels and included input to and review of the process and outcomes by a stakeholder reference panel reporting directly to the Board of G-MW. The implementation of a strategic risk management process has now begun to progressively and systematically reduce the dam safety risk across the entire dams portfolio. This process recognises that available funding for risk reduction measures is very limited, so the highest risks are reduced in an incremental fashion to achieve interim risk targets and eventually meet contemporary dam safety standards.

1. INTRODUCTION

Goulburn-Murray Water (G-MW) is the largest of the successor bodies to the Victorian Rural Water Corporation and is responsible for the operation, maintenance, renewal and dam safety programs for thirteen State owned dams and four Murray-Darling Basin Commission storages. The assets, including Eildon dam, the largest state storage and Dartmouth, the highest earth-rockfill dam in Australia, have a current replacement cost of $1.5 billion.

When G-MW was allocated responsibility for managing the dams in 1995, the Authority was faced with a number of major challenges including: a number of design deficiencies across the portfolio; inadequate funds held by the Authority to quickly address the backlog of deficiencies; and a need to prioritise the necessary works.

G-MW chose to use a comprehensive Business Risk Assessment of all its dams as a framework for planning decisions on maintenance, renewals and dam safety reviews. The details of that process were published in ANCOLD Bulletin No. 107 (ANCOLD 1997). However, whilst the methodology was used to compile the ongoing minor capital and maintenance programs, no funding source had been identified for major design deficiency upgrading works.

In October 1997, the Victorian Government announced, as part of a State-wide Water Reform Package, that it would grant G-MW $18.5 million toward a Dam Improvement Program for the thirteen State-owned dams over the following five years. A condition of the grant, was that customers would contribute approximately an equal amount to the Program through price increases.

Subsequently G-MW has undertaken a risk assessment process including review by an independent Stakeholder Reference Panel. The risk assessment has provided a clear direction for a future program of dam upgrade works highlighting the already recognised fact that the identified program will exceed the initial funding grant.

[1] *Senior Principal and Vice President, URS Australia Pty Ltd, BSE MS Eng (Civil)*
[2] *Manager Dam Improvement Program, Goulburn - Murray Water, BEng (Civil)*
[3] *Senior Principal, Business Risk Strategies Div. Of URS, PhD*
[4] *Project Team Leader, Goulburn – Murray Water, BEng (Agr)*

2. DAM IMPROVEMENT STRATEGY

G-MW has developed a strategy to reduce the risk posed by its dams using risk assessment to support a standards based approach to dam safety. The strategy uses varying levels of assessment for the purposes of determining investigation and works priorities.

The strategy uses an initial risk assessment process, commonly referred to as "portfolio risk assessment" to determine design review priorities and to provide an indication of potential works. Following the completion of design reviews, a more detailed quantitative risk assessment is used in conjunction with acceptable risk to life guidelines to:

- Assist in determining the severity of a risk, by comparing the calculated risk to indicative targets for acceptable risk to life and then deciding an appropriate time frame for reducing risk;
- Assist in devising interim, or short term, risk reduction measures that achieve a level of "acceptable" risk until funds are available to undertake standards based works; and
- Assist in deciding when business risks might be addressed ahead of low risks to life.

The process of detailed risk assessment and developing a risk reduction program had to meet the following requirements:

- Clearly present the current status of risk and how cost effective measures could be implemented to reduce risk;
- Be subject to review and allow for inputs regarding consequence assessments, by key stakeholders;
- Be to a level of detail that would provide for confidence in decision making and be defendable under scrutiny; and
- Provide risk and consequence information in sufficient detail to support funding submissions to Government.

While the formal risk assessment process was only applied in detail to the organisation's portfolio of dams this process is consistent with management's approach to evaluation of risks in other business areas and allows the G-MW Board to consider the priority of dam upgrades in relation to other issues.

3. RISK ASSESSMENT PROCESS

The risk assessment process comprised the following elements and guiding principles:

- Individual risk assessments of the five priority dams for which design reviews were complete to guide formulation of risk reduction strategy.
- Portfolio risk assessment to prioritise design reviews for the remaining eight dams.
- Use of two separate, consistent measures of risk: societal risk and financial risk.
- Application of a defensible and consistent process.

The overall risk assessment approach was to develop a quantitative understanding of the key contributors to risk at each of the priority dams and to then prioritise the risk events across the entire range of priority dams so that a risk-based risk management strategy could be developed. Specifically, the process for the priority dams risk assessment was as follows:

- Engineering information including detailed design reviews for each dam was reviewed by an expert Engineering Panel to apply event tree analysis to identify the probability of each potential type of failure.
- A broad range of potential consequences was evaluated by an expert Consequences Panel with respect to 1) loss of life and 2) financial cost.
- A measure of risk was derived for each failure type and for each dam; and risk profiles were generated that show the total risk presented by each major dam and the risk for all dam failure types, ranked in order of decreasing risk.
- The event trees and risk profiles were used to develop a prioritised list of risk reduction actions (a risk management strategy) for all failure types applicable to the priority dams.
- The risk reduction benefits and the costs of achieving the benefits were compared and used to develop a schedule of risk management actions.

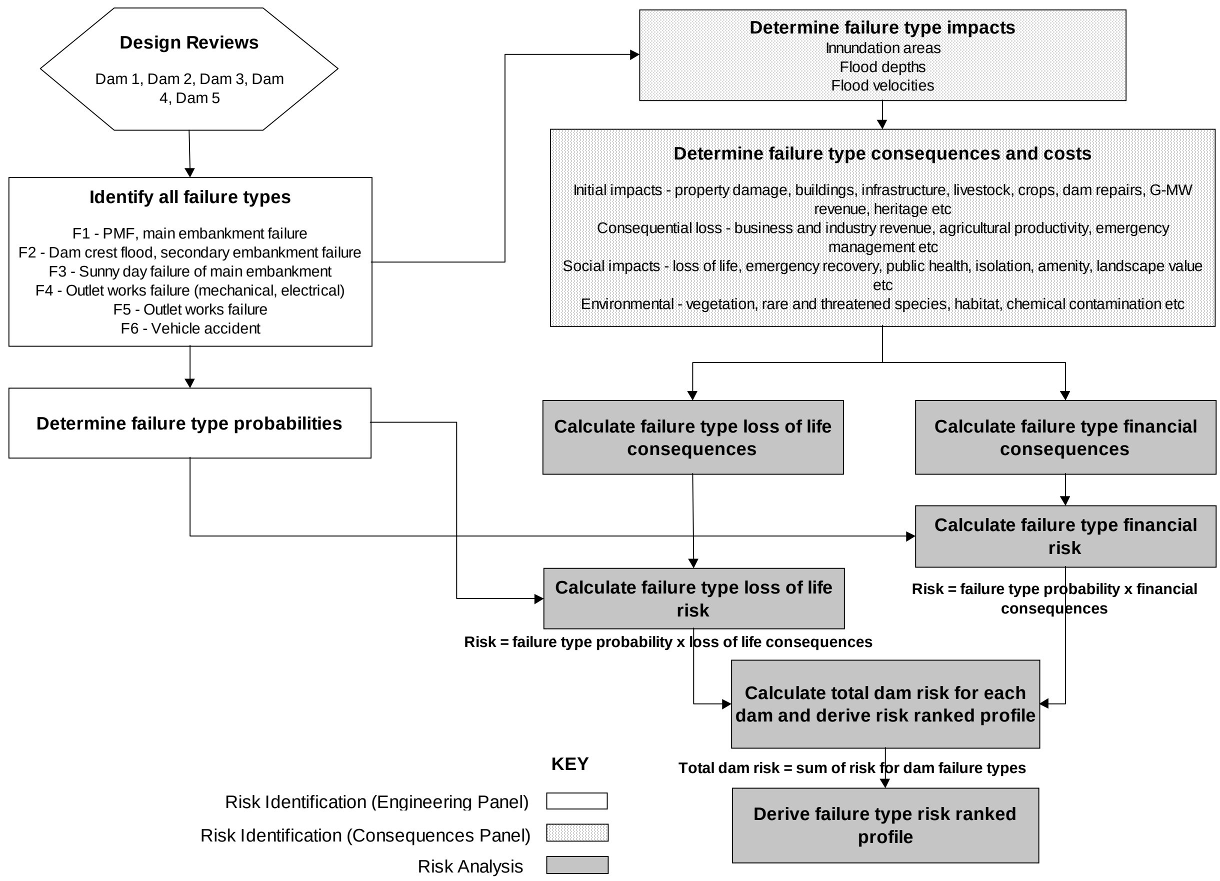

Figure 1. Risk Assessment Process

The dams risk assessment process was reviewed throughout its progress by a G-MW Board-appointed Stakeholder Reference Panel. The panel included a broad range of local authorities and interest groups.

Figure 1 summarises the links between the Engineering Panel, the Consequences Panel and the risk analysis process, and it shows how the dam risk profiles and the failure type risk profiles were developed.

The method used to perform the priority dams risk assessment followed the process established by the RISQUE method (Bowden et al. 2001). The RISQUE method follows a systematic methodology and is defensible with respect to current worlds best practice. It complies with the Australian Standard on risk assessment (AS/NZS 4360:1991). The use of expert panels was fundamental to this quantitative risk assessment because inputs to risk modelling (such as probability of occurrence and magnitude of consequences) based on actuarial information were not available for the identified risk events.

The risk assessment and formulation of the risk management strategy proceeded as a staged process.

Stage 1 Establish the Context. Established the background to the risk management process and determined the required level of detail for the assessment. Stakeholders were identified and the risk management aims and structure were developed.

Stage 2 Risk Identification. Expert panels identified and characterised the key failure scenarios using event trees. For each event, the probability of occurrence and the consequences were assessed. Documentation of the panel's findings was consolidated onto a risk matrix that described each risk event and indicated probabilities and consequences.

Stage 3 Risk Analysis. The probabilities and consequences for each substantive risk event were quantified and modeled. The risk model derived a range of outputs that included risk profiles, exposure profiles and risk maps.

Stage 4 Develop Risk Management Strategy. Formulation of risk management strategy utilised the results of the risk analysis process to evaluate various actions to treat key risk events. The benefits (risk reduction) of implementing the action plan were estimated by modifying and re-running the risk model until the interim risk targets were achieved. The severity of risks was compared to indicative guideline targets in developing a timeframe for implementation.

Stage 5 Implement Strategy. Implementation of the risk management strategy will be determined by the G-MW Board and may progressively involve actions such as engineering remedial works, review of dam operations, further investigations, establishment of emergency action plans, installation of detection systems, and community consultation.

4. ENGINEERING ASSESSMENT

The engineering assessment of each dam was conducted in workshops by an Engineering Panel comprised of five senior dam engineers covering the full range of geotechnical, structural, hydraulic and mechanical issues inherent in dam safety. The well proven expert panel process, Barneich et al. (1996), systematically identified and provided an understanding of key dam failure events, particularly their probability of occurrence and the nature and extent of flooding. The ultimate goal of these panel workshops was to quantify risk event probability and consequences using the collective judgement of the panel participants.

Review of Design Information. Prior to commencing the detailed risk assessment of the five priority dams, G-MW undertook design reviews and produced dam break inundation maps for each of the dams. The Engineering Panel reviewed the available information for each dam, which included design review reports, failure mode analyses, hydrology and dam break analysis reports, issues reports, remedial works concept designs, geotechnical investigation reports, current and historic instrumentation data, construction information and photos, discussions with original design and construction engineers, incident reports, and dam safety emergency plans. Technical representatives of each of the priority dam design review teams conducted a detailed briefing of the panel and actively participated in the risk workshop.

Identification of Dam Failure Scenarios. The Engineering Panel used the background information in the workshops to identify all conceivable failure scenarios. Actual dam performance was assessed and supporting engineering analyses were reviewed to evaluate the probability of various failure scenarios and their impacts. For all dams reviewed, failure scenarios were grouped into four primary sets of issues: hydrology / hydraulics; structural; seismic; and geotechnical. In some cases, numerical analyses of the probability of failure scenarios were not practical, so subjective assessments based on panel experience and experience of the international dam community were required. In order to be consistent, a proven guideline to estimation of event probabilities was used, as shown in Table 1.

Table 1 - Event probability guidelines

Description	Probability
Occurrence is certain	1
Occurrence of the condition or event are observed in the available database.	10^{-1}
The occurrence of the condition or event is not observed, or is observed in one isolated instance in the available database; several potential failure scenarios can be identified.	10^{-2}
The occurrence of the condition or event is not observed in the available database. It is difficult to think about any plausible failure scenario; however, a single scenario could be identified after considerable effort.	10^{-3}
The condition or event has not been observed, and no plausible scenario could be identified, even after considerable effort.	10^{-4}

The process was collaborative in that each expert provided their opinions and discussion ensued until consensus was achieved. G-MW personnel, including the operational staff for each dam, provided factual information to assist panel members' deliberations.

Development of Event Trees for Each Dam Failure Scenario. Event trees were prepared to capture dam failure scenarios starting with the initiating event and carrying through the required sequence for a failure event that follows. Event trees were prepared for:

- Flood induced failure scenarios, such as probable maximum precipitation (PMP) design flood and dam crest flood causing overtopping of embankments and breach.
- Significant mechanical and electrical failure scenarios, such as failure or inoperability of spillway gates, bulkhead failure, pipe rupture, guard gate failure, loss of power to the spillway or outlet tower, or various valve failures.
- Events such as deformation and cracking of embankments, instability in the upstream or downstream slopes, or piping with storage level at full supply, historic high or other intermediate levels.
- Seismic events focusing on existing dam features that are susceptible to seismic deterioration or collapse such as the embankment or foundation; spillway structure, walls or hoist bridge columns; outlet tower, conduit and penstocks, bridge, and pump or power station failure.

Figure 2 shows an example of an event tree which develops the probability and progressive outcomes of gate failure caused by an earthquake. Failure can be achieved under a multiplicity of conditions shown by the various pathways of the event tree. The event tree indicates the probability of the outcomes for each path along the event tree. Similar event trees were developed for each of the hydrologic, structural, geotechnical and mechanical failure modes, including operational and intervention activities, under various initiating events. Failure probabilities were then summed for each contributing initiating event to produce total probabilities.

Where the analysis identified unacceptable high probability of failure G-MW considered the requirement for immediate action to reduce the risk.

5. CONSEQUENCE ASSESSMENT

The purpose of the Consequences Panel was to assess the consequences of dam failure in terms of financial cost and loss of life. The panel evaluated the entire range of substantial consequences (social, environmental and financial) that would be inflicted by each dam failure type. Inundation maps from dambreak analyses, tables of flood flow rate and depth, and various downstream cross sections, and estimates of population at risk and potential loss of life were key data used in the process.

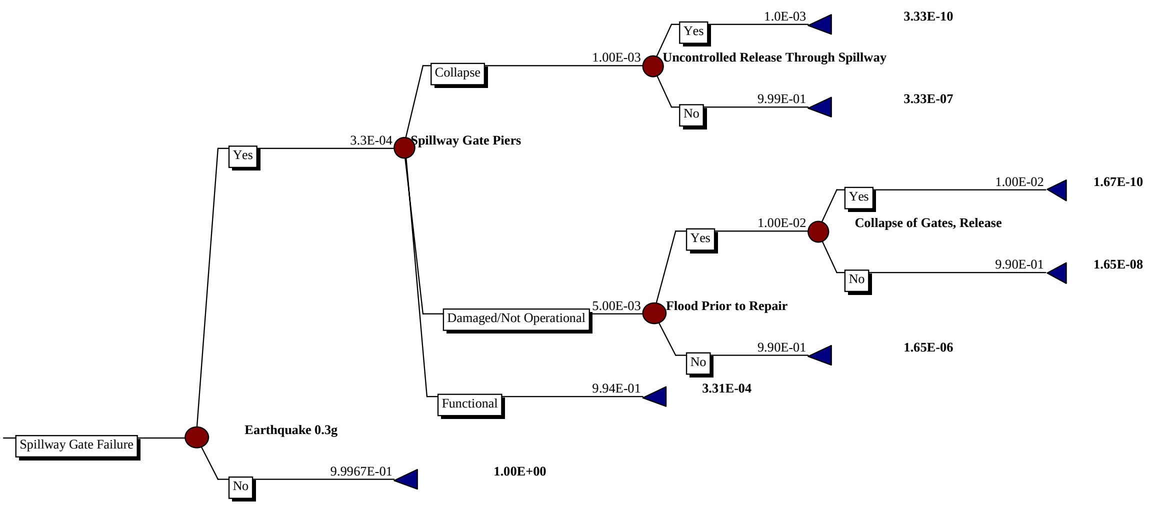

Figure 2. Typical Event Tree for Spillway Gate Failure Scenario

The Consequences Panel always used the same nine members to ensure consistency of approach and style. Each panel member represented a specific area of expertise. The process followed by the Consequences Panel was as follows:

Inspection of Site and Inundation Areas

At each site a briefing on the findings of the Engineering Panel was provided with a description of the dam, dam construction, dam operation, applicable failure scenarios, flood inundation areas, flood flow rates and flood depths. The briefing was followed by a trip down the valley to gain a first-hand impression of the nature and extent of potential dam break consequences. At selected points within the inundation areas, the panel discussed potential flood extents, flood characteristics and potential damage.

Consequence Data Collection

While the expert consequence panel process was adopted to provide consistency in the consequence evaluation across the G-MW portfolio of dams, it was important that the data on which the consequence assessment was done had a consistent and justifiable basis. This was achieved by using GIS based data obtained from the Victorian Department of Natural Resources and Environment Corporate Geospatial Data Library, local governments, and public utilities. Reference was also made to aerial photography and site inspections to qualify information obtained from GIS.

For each flood reach, data collected included infrastructure (eg. roads, bridges, rail, electricity and other utilities), structures (houses, schools, industrial facilities), land use information (agriculture, forestry, industry), environmental features (wetlands, water courses, remnant vegetation, endangered flora and fauna species), archaeological issues and social data (population). Dam break inundation maps were used to develop loss of life estimates and assessments of financial consequences. The inundation maps were extended downstream of the dam to a point where additional loss of life from incremental flooding due to dam failure was calculated to be negligible. This extent was also used for the financial consequence assessment. Clearly there could be considerable additional financial consequences resulting from the continued flow of flood water although the severity of the flood wave would be greatly reduced. This issues was recognised but judged that it would not affect the relative magnitude of total consequences at each dam and therefore would not affect the determination of priorities for upgrade works.

Identification and Quantification of Consequences

The Consequences Panel developed a checklist of consequences that was applied to each failure type. The severity of consequences within each reach was estimated by considering the destructive force of floodwater for given depths and flow velocities. Other factors were the destructive effects of debris, such as trees and buildings, which become entrained within the floodwaters. The proportion of the specified features within the inundation area that would be destroyed, damaged, or undamaged was estimated based on an assessment of the severity of the flood and used as a factor in estimation of consequential cost.

Both direct and indirect damages were assessed. Agricultural production losses were assessed as the farm gate value of lost production. Multiplier effects for value adding on farm production were not included. Environmental damage was assessed by estimating the re-establishment cost of affected species.

Cost Uncertainty

A probabilistic costing approach, where costs are expressed as probability distributions was used to account for inherent uncertainty associated with the consequences of dam break events. For consequential costs, panel members were asked to provide two estimates of cost which reflect the uncertainty and range of potential costs.

The first cost estimated was the median cost, or best estimate. The median cost estimate is the 50% confidence level estimate, or there is a 50% chance that the indicated cost will be exceeded. The second cost estimate was a very conservative estimate, which indicates a high end cost, but not the highest conceivable cost. The 95% confidence level estimate would be expected to be exceeded in only 5% of similar cases.

The spread between the two selected confidence levels provides a measure of the judgement of uncertainty. The costs were assumed in the risk model to be distributed as log normal distributions with attributes defined by the median and the 95th percentile values provided by the panel.

Lives Risk Criteria

Current ways to present risk to life include:

- Annualised lives risk (or lives risk quotient is also a form of societal risk);
- Societal risk (in terms of F-N curves); and
- Individual risk.

Lives risk was assessed and presented in all three ways to allow comparison. Annualised lives risk was found to be the most straightforward manner in which to compare risk between dams and failure types.

At present, the types of risk where guidance on risk criteria can be found are societal and individual. Central to the process is the requirement to satisfy the ALARP principle in demonstrating that the risk has been reduced as low as reasonably practicable.

ANCOLD's individual risk criteria (ANCOLD 2000) were used as a check on the prioritisation of G-MW's proposed dam upgrading actions. All three measures of lives risk provided consistent risk ranking.

The approach taken to the calculation of Loss of Life (LOL) complies with the procedure set down in ANCOLD 2000 and Graham 1999. Although these methods have many limitations and uncertainties they were applied consistently across the entire dams portfolio and provide a useful means of comparison. Key inputs to the Graham method are population at risk (PAR) and warning time. Population at risk estimates incorporated both seasonal and temporal effects. Expected warning times were developed through discussions with relevant emergency services agencies and considered factors such as current level of preparedness, means by which warning message would be distributed and location of population. Uncertainty in PAR and warning time was included in the modelling as probability distribution functions in a similar manner to other consequence determinations.

Compilation of Cost Data

The entire range of costs for all consequences for each dam was compiled into a central spreadsheet file. The file contained a cost matrix for each failure type. The cost matrices show, where applicable, the estimated cost of all identified consequences for each affected reach downstream of the dam. Future consequence costs (such as lost agricultural productivity) were calculated in the data input spreadsheet in net present value (NPV) terms.

6. RISK ANALYSIS

Risk analysis involved quantification and modelling of the constituent probabilities and consequences for each identified risk event. A number of techniques were applied to derive ranked profiles of risk quotients as both societal risk and financial risk.

A spreadsheet model was the most appropriate tool for incorporating risk modelling into the priority dams risk assessment. Probabilistic calculations in the analysis were performed using the Crystal Ball simulator, which is a commercial add-on software package to Microsoft Excel. The simulation software computed spreadsheet solutions for 2000 trials, using the Monte Carlo sampling strategy. Simulation using Crystal Ball was used in the risk models to treat costs as probability distributions.

The techniques that have been applied in the risk assessment have been selected for their suitability to define dam failure risk events (failure types) in financial terms, so that some appropriate form of provision can be made that accounts for their probability of occurrence and consequences; and account for uncertainty in the magnitude of the consequences of a dam failure type.

Outputs of the modelling process express the risk relationships between the dam failure types and show the magnitude of combined risk presented by all of the dam failure types. For each major dam the outputs of risk modelling included:

- An exposure profile, that shows the range of cost for the dam failure types. The model outputs are presented at three levels of confidence (optimistic -50%, planning - 80% and pessimistic - 95%).
- A risk profile that shows the calculated societal risk for each dam failure type and the dam as a whole.

- A risk map showing the relationship between probability of occurrence, loss of life consequence and societal risk quotient for each dam failure type.
- An exposure profile, that shows the range of consequential financial cost for the dam failure types.
- A risk profile that shows the calculated financial risk quotient for each dam failure type.
- An exposure profile that shows the contribution to the overall financial risk cost of the major consequence groupings (initial impacts, consequential loss, social impacts and environmental degradation).
- A risk map showing the relationship between probability of occurrence, financial consequence and financial risk for each dam failure type.

Risk modelling results from each of the priority dams were combined to allow comparison of societal risk and financial risk for dam failure types across the entire range of G-MW priority dams.

7. RISK ASSESSMENT OUTCOMES

The need for G-MW to implement interim measures required establishment of useful target risk levels. Reference was made to the ANCOLD position paper on revised criteria for acceptable risk to life (ANCOLD 1998) in establishing interim risk targets for the G-MW risk reduction strategy.

The following interim goals for failure type risk were set to progressively reduce societal and financial risk for the priority dams: Firstly, reduce the risk of all failure types to levels below an indicative guideline "unacceptable" limit (threshold) of 0.001 lives per year. Secondly, reduce the risk of all failure types to levels below an indicative guideline "objective" of 0.0001 lives per year. Thirdly, eventually achieve modern design criteria in that all failure types comply with industry deterministic standards. The societal risk ranked profile for the five priority dams of Figure 3 shows that:

The ranking of priority dams according to risk was the same for both societal risk and financial risk.

- The societal risk posed by three dams is greater than the indicative guideline unacceptable limit of 0.001 lives per year.

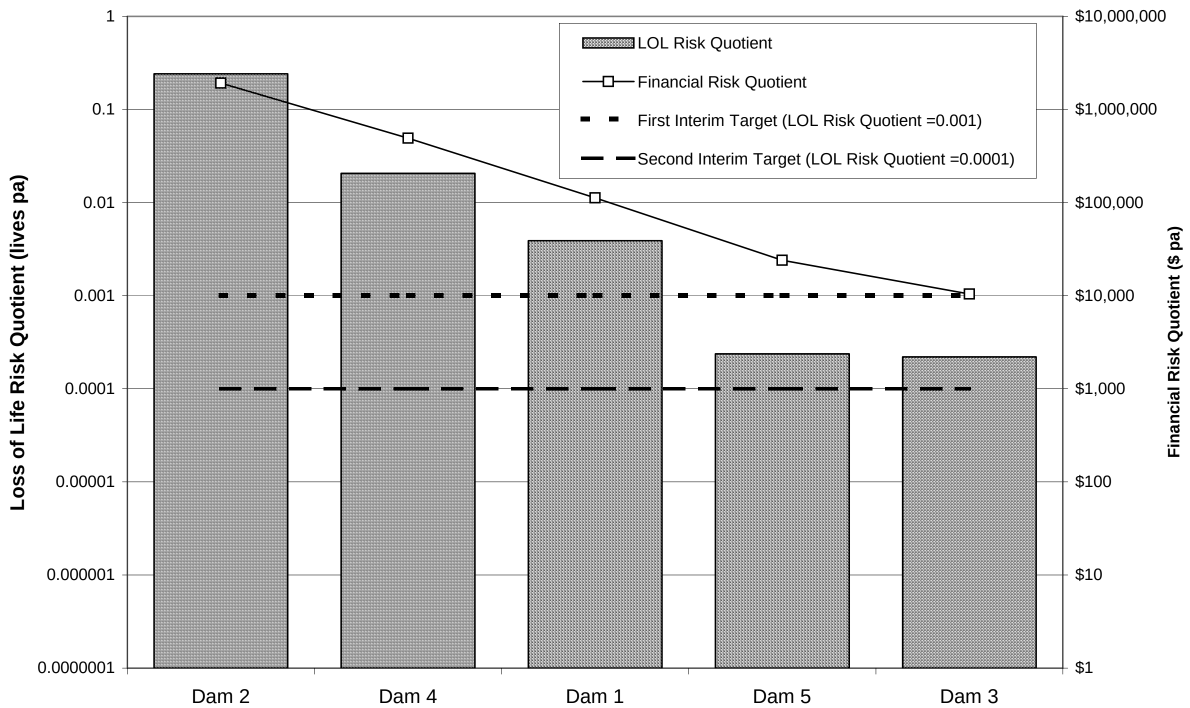

Figure 3. Priority Dams Risk Profile

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- The highest risk dam presents around 500 times (2.5 orders of magnitude) more risk than the indicative limit.
- The risk posed by the last two priority dams must be judged against the ALARP principle.

The societal risk ranked profile for all of the failure types in Figure 4 shows that:

- The ranking of failure types according to risk is similar for both societal risk and financial risk.
- Seven failure types individually present greater societal risk than the first interim target (unacceptable limit) of 0.001 lives per year.
- Five failure types fall within the risk zone between the two interim targets. The risk for each of the remaining 16 failure types is less than the second interim target (objective) of 0.0001 lives per year.

On the basis of the failure type risk profile, a list of 15 actions that could be progressively implemented to achieve standards-based design for the priority dams was identified by the Engineering Panel and G-MW.

The reductions in societal risk and financial risk for all failure types that would be achieved by complete engineering upgrades to industry standards are shown on Figure 5.

Figure 6 shows the progressive reduction in societal risk that would be achieved through implementation of the initial prioritised list of actions, against the cumulative cost. The total cost to implement all of the risk reduction actions is estimated to be approximately $100 million. The graph of Figure 6 shows that greater risk reduction is achieved by earlier actions on the prioritised list. The first five actions, where the societal risk for every failure type is greater than the first interim target of 0.001 lives per year, cause a reduction in risk of around 2.0 orders of magnitude. Also Figure 6 shows that a large proportion of the societal risk could be reduced (to around 3% of the current risk) if the first four actions were to be implemented for a relatively low cost of around $ 9 million.

The dams risk reduction strategy is based on the preliminary prioritised list of actions, taking funding availability and project logistics into account.

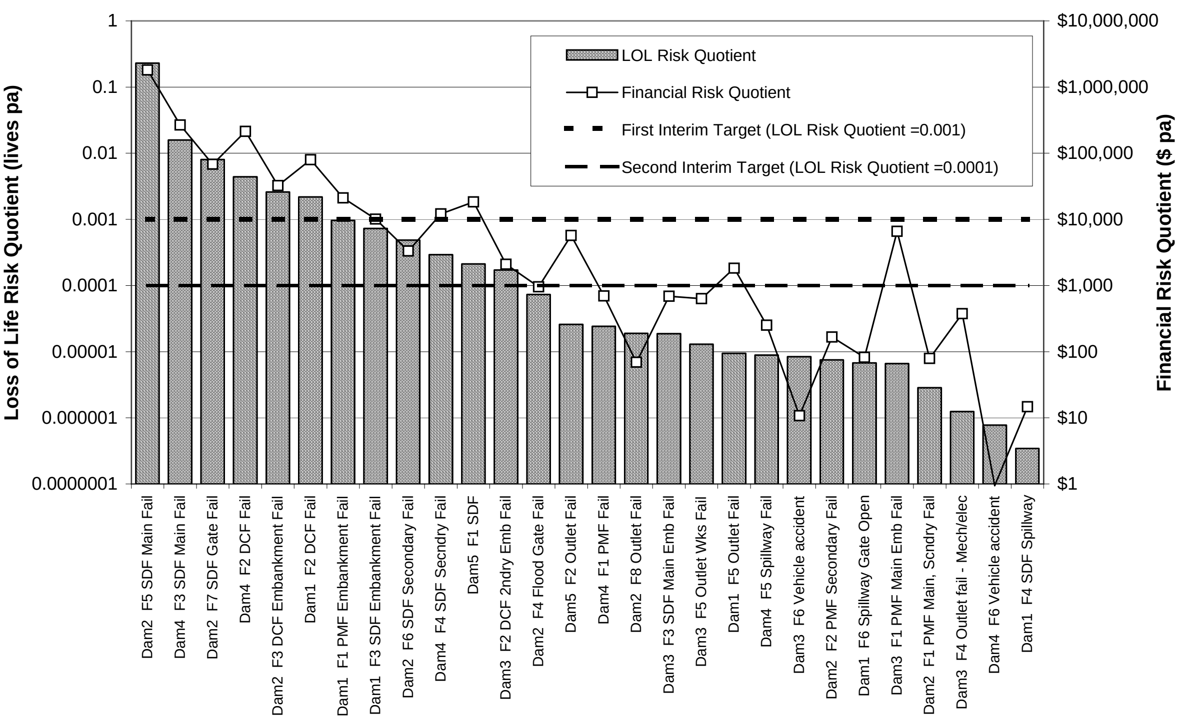

Figure 4. Risk Ranking of Failure Types

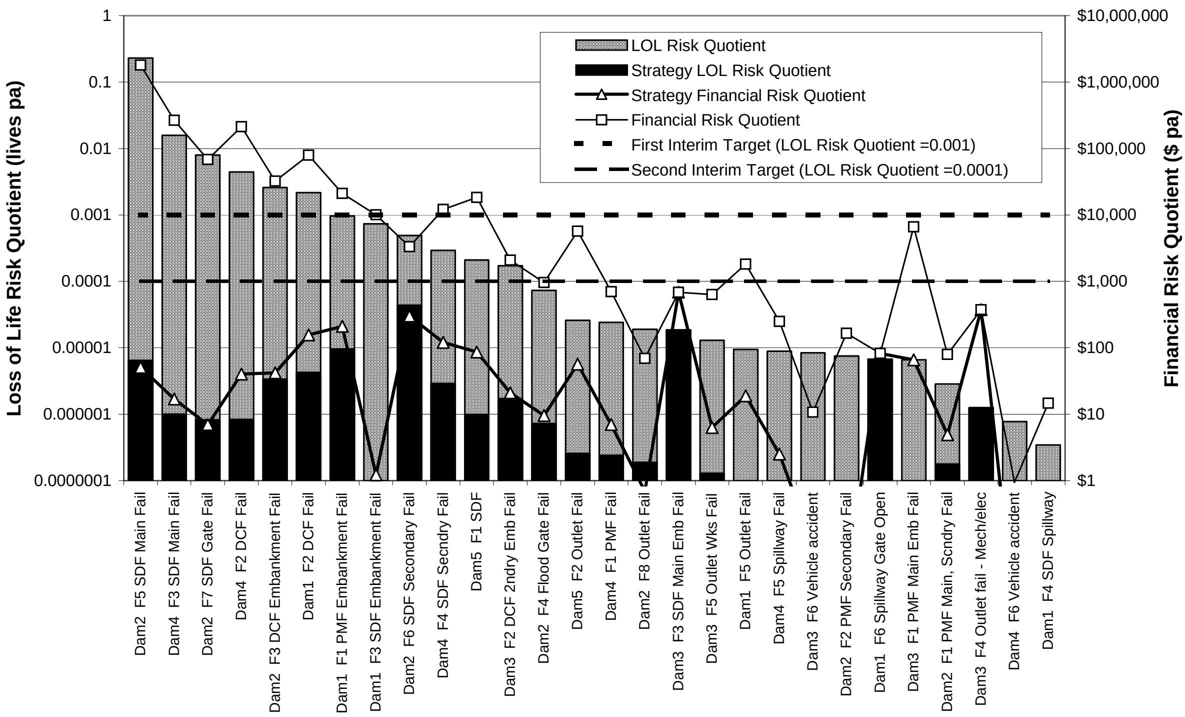

Figure 5. Risk Profile After Implementation of Action Plan

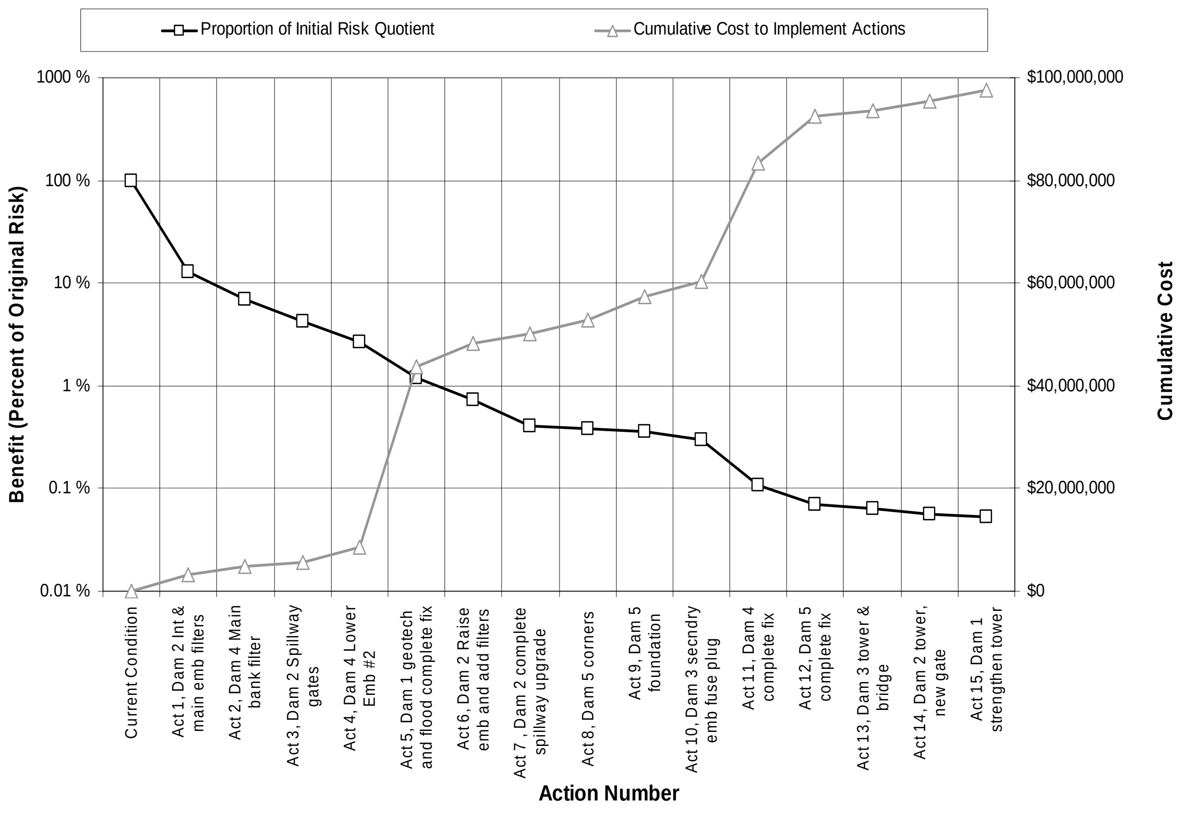

Figure 6. Cumulative risk reduction for each dam upgrade action

Recommended timeframes for implementation of upgrade works have been developed with regard to the current level of risk at each dam.

- Immediate actions will be implemented where the calculated societal risk greatly exceeds the unacceptable limit. Such actions include operational limits, increased surveillance and upgrade of dam safety emergency plans.
- Interim actions will implemented as soon as possible over the next three years to reduce the societal risk posed by all failure types to less than the indicative guideline unacceptable limit 0.001 lives per year
- Interim actions have also been planned for implementation within a reasonable timeframe (3 to 7 years) to reduce the risk posed by all failure types to less than the indicative guideline risk objective of 0.0001 lives per year.
- Actions have been planned and will be implemented within the ultimate timeframe (15 years) to achieve compliance with standards-based criteria.

8. PORTFOLIO RISK ASSESSMENT

Similar results were developed for the remaining eight dams, but with a much more limited base of information on the dam and its failure consequences. Design reviews had not been completed. The Engineering Panel conducted a much more limited review of existing design and performance data, and had to judge failure modes and scenarios much more subjectively. The consequences were judged based on comparable information developed for the priority dams in similar catchment and with similar downstream development in the inundation area.

However, even with this limited information it was possible to identify the priority for the remaining design reviews and to identify a number of crucial dam safety and business risk issues for immediate attention. G-MW have used this information to fast track assessments of these issues within the on-going dam improvement program.

Given the significant difference in detail of the portfolio and detailed risk assessments, comparison of the quantified risk is not possible.

9. STAKEHOLDER REFERENCE PANEL

Many proponents of risk assessment testify to the value of stakeholder involvement in the risk assessment process. History shows that unless risk assessment procedures include an element of interactive participation with stakeholders then the results and conclusions reached are more likely to be challenged by those affected by the resultant decisions. G-MW recognised that the resultant program of works would affect a diverse range of people, many of whom have little understanding of the risks posed by dams. For the DIP risk assessment process to fulfil its desired purpose it was essential that broad acceptance of the risk assessment process and the specifics as applied to the G-MW portfolio be gained by internal decision makers and the wider community.

To assure the G-MW Board that the risk assessment process delivered a defensible output and that information was presented in a form appropriate for the proposed audiences, G-MW convened a Stakeholder Reference Panel. The Panel membership was established by issuing invitations to relevant organisations of which twelve provided representatives. The Panel was chaired by Mike Fitzpatrick with membership drawn from G-MW's customer water services committees, local government, Victorian Farmers Federation, catchment management authorities, State Emergency Services, Victoria Police, and DNRE. Panel membership was deliberately targeted at senior personnel from the various organisations, recognising the detail and potential sensitivity of the information to which the Panel would be exposed.

While working collaboratively with G-MW, the Panel was not required to reach consensus on issues raised and dissenting views were recorded in the Panel's final report.

The Panel was given a series of briefings over six meetings. Briefings covered the engineering and consequence assessment process and specific details of deficiencies at each of the five dams studied. While the method of determining probabilities of failure was discussed, the Panel's influence on the results of the work was confined to the consequence determinations.

In some instances Stakeholder Panel members provided feedback on specific details from their own local knowledge. This information was subsequently incorporated in the risk assessment process. In other cases more general feedback on the methodology led to modifications to the consequence assessments.

The use of societal risk as the primary driver for prioritisation of works was accepted by the Panel. The Panel did however note that the presentation of financial risk should prove valuable in seeking further funding and for emergency management/response planning.

At the conclusion of the process the Panel reported to the G-MW Board that they endorsed the use of risk assessment as a tool to prioritise works. The Panel was comfortable with the transparency and consistency of the risk process and satisfied that consequence estimates were reasonable.

10. LESSONS LEARNED

Many lessons were learned during the project:

- The owner must have a clear understanding of what level of detail is required for the risk assessment which will depend upon the proposed use of its outcomes. To ensure the necessary level of confidence required for detailed, costed dam upgrading programs, design reviews should be available along with concept remedial works designs and consequence data.
- Appropriate resources must be utilised for the engineering and consequence assessments including both industry experts and owner's operational and technical staff.
- The increasingly popular portfolio risk assessment process should be used with caution where comprehensive design reviews and consequence assessments have not been undertaken, because the scope and costing of upgrade works could change significantly once these studies have been completed. However, as a means of prioritising design reviews and assessments, portfolio risk assessment is a powerful tool.
- Although quantification of dam failure risk and its consequences can be a daunting and frustratingly subjective process, there are now powerful tools and processes available that allow this work to be done more consistently between dams and between owners and portfolios.
- Qualitative measures of risk are subject to far more subjectivity and bias. While suitable for some applications they are limited if comparisons to acceptable risk criteria are required.
- The utility of the ALARP principle has been demonstrated in making risk based decisions and defining interim levels of risk reduction.
- If a reference panel approach is taken, it is important to allow sufficient time to fully brief the panel members on the process and to have meaningful input to the study. The six-month period for this process would be the minimum practical time.
- The risk assessment model is very useful during the development of design concepts and works programs to take account of risk issues such as stability and operating water level during remedial works.
- It should be possible to "cull" low financial impact consequences early in the study to focus on the main issues.
- Good documentation is essential for a consistent and efficient process as panels move from one dam to another. The process of assembling the dam design and performance data alone is a very useful process.
- Much is learned from past incidents. A non-threatening, open and comfortable forum for communication and sharing of the lessons learned from these experiences is essential
- Often the most useful outcome of risk assessments are the discussions of dam failure scenarios which focus all parties on the causes of the problems and get them to know their structures much better. It is not uncommon that simple non-structural solutions present themselves which can dramatically reduce risk exposure.

11. ACKNOWLEDGEMENTS

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