LIFE LOSS SIMULATION MODELLING : LESSONS AND APPLICATION IN DAM SAFETY EMERGENCY PLANNING

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ABSTRACT

Recent emergency management reforms in the Australian state of Victoria aimed at better serving the community through improving agency cooperation and the resilience of organisations and infrastructure, is positively influencing the activities dam owners are taking towards continuous improvement within their dam safety management programs. This paper briefly draws the link between emergency management reforms and its relationship with dam safety management.

As part of their efforts to continuously improve their emergency preparedness and understanding of dam safety risk, Southern Rural Water commissioned life loss simulation modelling, using HEC-LifeSim, for their high and extreme hazard category dams. Agent based life loss simulation models, such as HEC-LifeSim, provide a platform to intersect outputs from hydraulic models with information from dam safety emergency plans or flood warning systems and evacuation plans, with the uncertainties of human response and population redistribution. This makes it easy to test a number of 'what if' scenarios which allows for better understanding of how the interaction of these components influence the outcome.

This paper discusses the development of modelling inputs for HEC-LifeSim which represent the warning and evacuation timeline, the value of engaging local emergency services personnel early to capture site specific information, followed by lessons learned from undertaking life loss simulation modelling from the dam owner perspective and how it contributes toward continuous improvement and understanding of critical infrastructure risk.

1. INTRODUCTION

Southern Rural Water (SRW) is a State Government owned Water Corporation in Victoria, Australia that owns and manages seven large dams. As part of their continuous improvement efforts to ensure their understanding of risk and dam safety emergency planning is informed by contemporary engineering techniques and leading industry practice, SRW has partnered with Jacobs to undertake life loss simulation modelling across their portfolio using the HEC-LifeSim software (Fields, 2016) developed by the U.S. Army Corps of Engineers (USACE). A primary objective of the modelling is to produce robust estimates of potential life loss (PLL) across SRW's portfolio which consider the warning and evacuation constraints specific to a region. PLL estimates produced and modelling insights gained will inform dam safety planning and decision making and support broader project objectives to:

- Identify potential improvements to the warning triggers within SRW's Dam Safety Emergency Plans (DSEP)
- Understand how sensitive consequences are to warning system implementation
- Identify whether there is any significant change in societal risk at the various dams and if any further action may be required to investigate or lower risk;
- Improve internal and external stakeholder understanding of societal risk posed by SRW's large dam's portfolio; and,
- Strengthen relationships with emergency services across SRW's footprint.

Warning and evacuation of a population at risk in the event of a dam failure is a complex process which is further complicated by the uncertainties of human behaviour. HEC-LifeSim, has the ability to explicitly model the elements of the warning and evacuation timeline and allow for analysis of each element's influence on the outcome. In doing so, there is potential to identify if and where along the timeline improvements can be made. It is important the warning and evacuation process and uncertainties are well understood by both dam owner and practitioner so that inputs to simulation models adequately reflect the real-life actions and decision making which is likely to take place during these events.

This paper considers the preparation of inputs to the warning timeline, particularly the hazard identification, warning and evacuation parameters for a large dams portfolio where site specific life loss and evacuation calibration data is not available. The value of capturing site specific information, including input provided by emergency services to characterise the entire warning system, in lieu of calibration data is discussed. Quantitative results are presented to demonstrate the sensitivity of model results to the warning inputs. This paper also provides insight to lessons learned from the dam owner's perspective on life loss simulation and how it assists in efforts towards continuous improvement and understanding of critical infrastructure risk.

2. BACKGROUND

Over the past two decades, operators of critical infrastructure within Victoria (incl. water corporations) have been subject to two major legislative reform programs that have changed the scope and professionalism required of their emergency risk management systems. The first reform followed the September 2001 terrorist attacks in the United States and required critical infrastructure owners to proactively manage security risks to their assets. The second followed several catastrophic natural disasters including fatal bushfire and flooding events in Victoria between 2009-11. These events, and subsequent inquiries, culminated in new legislation and a new philosophy for emergency management in Victoria. This redirected and sharpened focus is underpinned by the 'all communities, all emergencies' approach to emergency management which places emphasis on greater levels of preparedness by 'all agencies' for 'all hazards' including identifying and planning for systemic consequences arising from critical infrastructure failure or service disruption, improved agency interoperability, improved understanding of risk posed by more immediate hazards than ter-rorism, such as extreme weather events, and system wide risk informed evidence of continuous improvement (a thorough overview of these reforms and their impact to dam owners in Victoria is discussed in Mannix et al., 2018).

The Needham et al. 2018 discussion of warning and evacuation during the Oroville Dam failure notes: *"Understanding and making informed decisions related to life safety risk not only requires a clear understanding of the engineering aspects…., but also the human aspects"*. As part of SRW's commitment to continuous improvement under Victoria's critical infrastructure resilience arrangements and its obligation to exercise due care in the understanding and management of risk[1], life loss simulation modelling has been applied across its large dams portfolio using the HEC-LifeSim software. Agent based life loss simulation models, such as HEC-LifeSim, provide a platform to intersect outputs from hydraulic models with information from dam safety emergency plans or flood warning systems and evacuation plans, with the uncertainties of human response and population re-distribution. A key feature of the software, is the opportunity to explicitly consider each component of the warning and protective action initiation timeline (Mileti and Sorensen, 2015; Needham et al., 2016 and shown in Figure 1). The efficiency with which the timeline progresses during a disaster is dependent on human response, ability and behaviour which will be influenced by many factors including age, mobility, willingness to take risk, previous experience, etc. All of which contributes to uncertainties associated with the timeline.

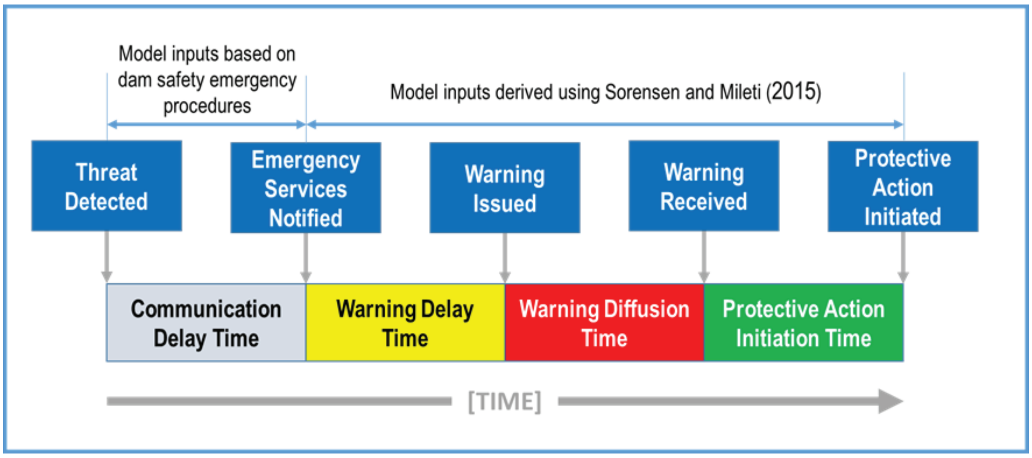

Figure 1 : The warning and protective action initiation timeline simulated in HEC-LifeSim for a dam failure scenario (from Mileti and Sorensen, 2015, adapted by Kavanagh et al., 2017)

1. Fleming's Law of Torts, 10th ed., 2011, p396 (emphasis added): "The statutory immunity is lost if the grantee fails to avoid all unnecessary harm. He must observe the strictest safety standards, proportional to the high degree of risk involved….and to this end , is expected to avail himself of all accessible scientific aid, including independent experts".(from Manchester Corp. v Farnworth AC 171 (1930).

3. INFORMING THE WARNING TIMELINE

Consider Figure 1 in the context of a dam failure scenario. The identification of an initiating event which has the potential to result in dam failure (threat detection), the internal dam owner verification of the potential dam failure event (communication delay time) and communication to the external organisations tasked with advising the public of the hazard (emergency services notification), are generally managed by the dam owner. Warning issuance, public response and evacuations are primarily managed by emergency services. Each element is captured and simulated in the HEC-LifeSim software by distributions, warning diffusion curves and response curves which can be informed by empirical relationships or tailored using site specific information.

Input distributions are used to capture the uncertainty bounds for each element. For example, threat detection can be simulated using a triangular distribution where the minimum detection time, most likely and maximum can be defined. Figure 2 demonstrates how distributions for the threat detection, communication delay and warning delay for a given event, combine to determine a possible window in which warnings could be issued to the public. The time at which warning issuance occurs is dependent on the cumulative outcome of these preceding elements of the warning timeline. Therefore if the preceding elements progress quickly, a warning can be issued soon after the threat is detected in contrast to slow progression of the preceding elements resulting in later warning issuance. As such, Figure 2 shows the warning issuance window overlapping the preceding elements.

A summary of the information sources considered in developing the distributions is provided in Table 1. The process engaged to capture the information for each element is described in the following sections.

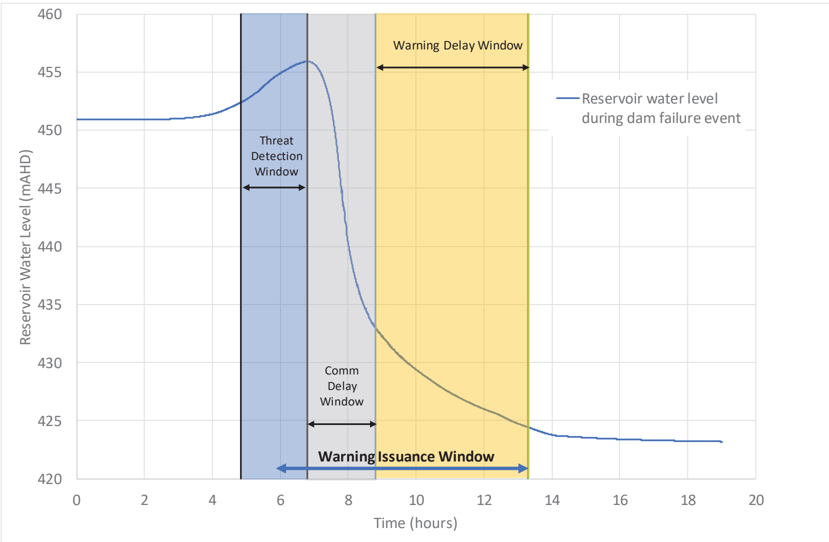

Figure 2 : Combination of the threat detection, communication delay and warning delay in determining the warning issuance window

Table 1 : Information sources for inputs to the warning timeline distributions

Warning timeline element	Key information source	Data and information sources	Key considerations when defining input parameters
Threat detection (or hazard identification)	Dam owner	Dam Safety Emergency Plans Dam Safety Management Manual Flood forecasting procedures	Flood forecasting information incl. catchment size Inspection frequency
Communication delay	Dam owner	Dam Safety Emergency Plans SRW internal incident management procedures	Process for internal verification
Warning delay time	Emergency Services/Dam owner	Mileti and Sorensen (2015) questionnaire Emergency services SRW	Emergency services tools and procedures
Warning dissemination	Emergency services and Dam owner	Mileti and Sorensen (2015) questionnaire Emergency services SRW Local Government	Emergency services tools and procedures
Protective action initiation	Emergency services and Dam owner	Mileti and Sorensen (2015) questionnaire Emergency services SRW Local Government	Demographic of population at risk Previous experience with flooding

3.1 Threat detection and communication delay

Inputs to the warning timeline up to the notification of emergency services were primarily informed by the documented processes and procedures captured in SRW's Dam Safety Emergency Plans (DSEPs). The DSEPs were used to identify the triggers which would initiate dam safety emergency actions by SRW. For example, in the event of an extreme flood, a series of reservoir water level or spillway discharge triggers are documented which relate downstream flood levels to emergency management actions and notifications to agencies responsible for the evacuation of downstream populations. These triggers were used to inform the hazard identification as described in the distributions. Robust inputs to these distributions are critical as they initiate commencement of the warning timeline in the model relative to the arrival of the flood wave.

In the modelling of theoretical and extreme scenarios such as those considered in dam break and consequence assessments, the circumstances which lead to the detection of a possible dam failure and the decision to evacuate downstream populations can result from a range of possible scenarios and occur in a range of possible time frames. An advantage of life loss simulation models such as HEC-LifeSim is the ability to consider this uncertainty as a distribution input to the model and provide an understanding of the various 'what-if' outcomes. When modelling, it is important the distribution adopted, particularly with regards to the threat detection, is well informed and understood by the dam owner and practitioner when defining the parameter boundaries. The factors which were considered in defining the hazard identification distribution are summarized in Table 2:

Table 2 : Factors which were considered when defining the hazard identification and communication delay windows of the HEC-LifeSim warning timeline

Sunny day failure	Flood related failures
• Failure mode (e.g. seismic vs. piping) • Surveillance and telemetry • Inspection frequency • Presence of onsite staff • Internal corporate incident management plans	• Failure mode (e.g. overtopping and piping related failure) • Surveillance and telemetry • Inspection frequency • Presence of onsite staff • Critical storm duration for scenario modelled • Flood forecasting abilities and response to warn-ings from the weather bureau related to extreme events • Advance evacuation from those located in the incremental flood extent in response to weather warnings not necessarily related to dam failure warnings • Internal corporate incident management plans

In the experience of the authors of this paper, while information related to trigger levels and the initiation of particular actions was identifiable from the DSEPs and other documented procedures, discussion between the dam owner and practitioner was critical in constructing the timeline and informing the distribution. Through workshops to discuss initial assumptions related to the warning timeline, the authors were able to consider factors which may have otherwise been overlooked if considering the dam failure warning processes in isolation. Notable considerations which emerged from discussions and contributed to changes in assumptions included:

- Experience and understanding of the general flood warning system and how far in advance evacuation warnings would be disseminated to the population as a result of extreme weather warnings not necessarily related to dam failure
- Operating levels and airspace availability potentially allowing for additional lead time ahead of overtopping failure
- Some dams have reservoir keepers in residence and so for these dams, the identification and internal verification process may occur faster than others
- The characteristics of the storm event being modelled for a particular dam break scenario (i.e. shorter critical storm event may mean that there is not as much lead time in identifying the threat)

A thorough understanding of the threat detection or hazard identification process and uncertainties was found to be critical. This process initiates the warning timeline in the model which then significantly affects the warning issuance time. It was found that initial modelling assumptions applied to the SRW portfolio did not adequately consider the flood warning process related to natural floods which may commence well in advance of a dam failure warning. As a result, warning initiation was commencing late during the flood event which forced sampling of warning issuance to be limited to scenarios where the population was receiving little or no warning. Figure 3 shows the range of life loss estimates sampled before and after adjustment of these assumptions. This finding and subsequent adjustment builds on work completed by Hill et al. (2019), which discusses the benefits of using HEC LifeSim to determine the effectiveness of implementing a total flood warning system to reduce potential life loss from flooding.

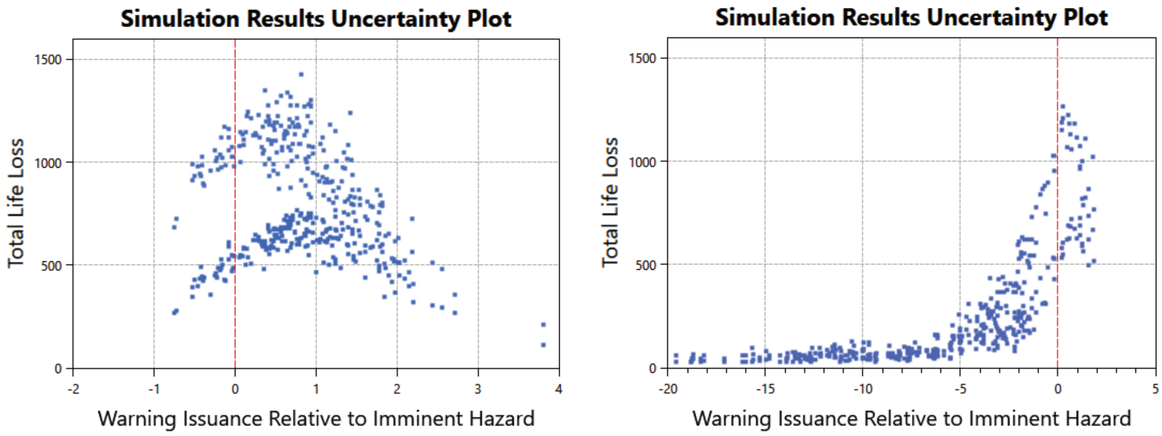

Figure 3 : Range of life loss estimates before and after workshopping of the initial threat detection and communication delay components of the warning timeline

3.2 Warning delay, warning diffusion and protective action initiation

Relationships for the warning delay time, warning dissemination, and protective action initiation were initially informed by the Mileti and Sorensen questionnaire (Mileti and Sorensen, 2015 & Needham et. al., 2016). Responses to the questionnaire are used to weight the factors specific to a population which influences these components. The warning and mobilization curves produced by the Mileti and Sorensen questionnaire are empirically based and have been verified against case histories. However, Needham et al. (2017) points out that the data on which these models are based is scarce. As such, the situations where these models are valid may have different characteristics to the regions actually being assessed. If data is available for calibration, these relationships can be adjusted to reflect the historic experience of the region being assessed. An example of this is documented in Risher et al. (2017) where a HEC-LifeSim model was calibrated to real life data from the Joso levee failure in Japan which caused loss of life.

For the SRW dams assessed, there were no historic events on which to base the relationships. Responses to the 52 questions, were initially prepared by SRW emergency planning, dam engineering, incident management and dam operations staff in consultation with senior personnel from the Victoria State Emergency Service (VICSES)[2] for each region considered in the assessment. An independent expert reviewer was subsequently engaged by SRW to review the initial outputs. The decision was made by SRW to manually adjust the curves produced by the Mileti and Sorensen questionnaire, as they were considered to overestimate preparedness levels, warning system effectiveness and protective action expected for the regions being assessed.

The pre and post adjustment curves are shown in Figure 4. The warning issuance delay and the warning dissemination curves were adjusted to reflect slower rates which are expected to be observed in the regions. The adopted relationships were supported by anecdotal information captured from discussions with the VICSES and expert reviewer. The lower evacuation rates adopted (protective action initiation curves) are supported by information collated from Australian flood events which indicated that a significant portion of the population, in the range of 30% to 50%[3,4], would choose not to evacuate in the event of a flood. The adopted curve assumes a higher overall evacuation rate than suggested by the Australian events because HEC-LifeSim does not account for rescue. The impact of the model not accounting for rescue is further discussed in Risher et al. (2017) which noted that rescue efforts during the Joso event, which reduced the actual life loss, contributed to life loss being overestimated by the model.

2. The designated agency in Victoria responsible for incident control for flooding downstream of dams – Emergency Management Manual Victoria Part 7 Agency Roles: https://www.emv.vic.gov.au/policies/emmv
3. North Queensland flood survey from Feb, 2019 found that half of people did not evacuate: https://www.abc.net.au/news/2019-02-22/preliminary-survey-results-north-qld-floods/10831934
4. State survey of Queensland found that 33% of respondents said they would never evacuate in the event of a flood: https://www.qra.qld.gov.au/sites/default/files/2018-10/resilient-queensland-2018-21-final_0.pdf

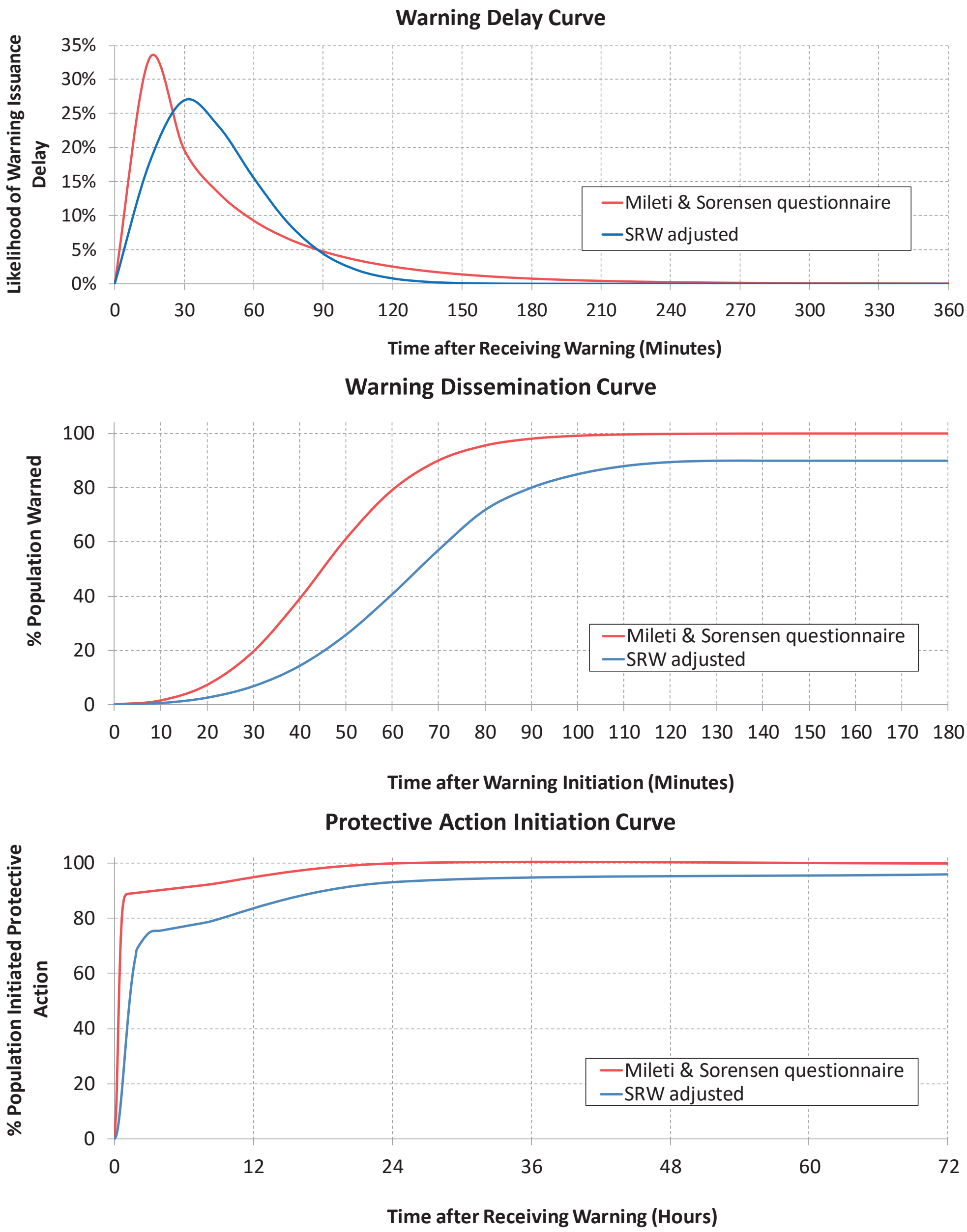

Figure 4 : Example of warning delay, warning dissemination and protective action initiation model input curves before and after manual adjustment

4. LESSONS LEARNED FROM THE DAM OWNER'S PERSPECTIVE

Important lessons learned from the dam owner's perspective during the project included:

- The dam owner cannot expect to achieve a realistic set of curves from the Mileti and Sorenson questionnaire without input from emergency response agencies as it requires specific knowledge of how an evacuation is planned and executed, in-depth knowledge of the systems and tools available to emergency services, the effectiveness of these systems and tools, and knowledge of the population demographics impacted, amongst other things.
- The threat detection and communication delay component of the warning timeline determined by the dam owner, requires specialist knowledge of the different infrastructure components and systems (i.e. the dam, how it operates, surveillance technology, flood forecasting system, etc.) as well as an in-depth whole of systems understanding of how and when a dam failure is identified and communicated to emergency services. This is critical in defining realistic uncertainty distributions for model simulations and requires careful selection of the personnel involved.
- It is important for the dam owner to ensure warning triggers associated with flood failure scenarios included in DSEPs provide a level of flexibility in terms of when a dam failure warning is issued to emergency services to ensure PLL estimates are not overestimated. In practical terms, language used to initiate a warning of dam failure is more useful when it is expressed as; '...if the water level is likely to reach and exceed xxRL' rather than specific level triggers such as '...when the water level exceeds xxRL'. This enables engineering judgement to be applied

more flexibly and ensures that the triangular uncertainty distributions adopted for warning initiation (early, most likely, late) appropriately reflects the uncertainty associated with such events. The benefits of this approach to warning system design and initiation is shown in the PLL plots above in Figure 3.

- It is important for flood forecasting systems to be optimized for dam operations so that they can properly interface with DSEPs to initiate early warning. This may help in reducing PLL in the incremental flood extent as warnings associated with natural flooding prior to dam failure will implicitly account for the passage of the flood through the dam. Flood forecasting systems that do not allow for flow routing through dams, are less likely to be effective at initiating warning to the PAR within the incremental flood extent as the dams catchment hydrology, water level response and spillway hydraulics are not embedded in the warning, which is the case for systems optimised for dam operations.

5. CONCLUSION

Life loss estimates produced using HEC-LifeSim for the SRW large dam portfolio, were found to be particularly sensitive to assumptions and inputs related to hazard identification and the warning timeline. Of these elements, adjustment of the hazard identification assumptions was found to have the most impact. Effort was focused on capturing realistic processes within the warning timeline parameters so they are adequately simulated within the model. This required thorough consideration of not only the SRW processes and procedures during a dam failure, but also consideration of processes engaged by external organisations and behavior of the human receptors when constructing a tailored warning timeline for each system. Early engagement of personnel familiar with the local warning systems and emergency management processes proved valuable in verifying assumptions and developing robust model inputs.

Overall, the process of gathering insights from the modelling and engaging with external organisations to inform the inputs has supported objectives to:

- Identify potential improvements to the warning triggers within SRW’s Dam Safety Emergency Plans (DSEP)
- Understand how sensitive consequences are to warning system implementation
- Identify whether there is any significant change in societal risk at the various dams and if any further action may be required to investigate or lower risk;
- Improve internal and external stakeholder understanding of societal risk posed by SRW’s large dams portfolio; and,
- Strengthen relationships with emergency services across SRW’s footprint.

The work completed by SRW is an example of how the critical infrastructure resilience arrangements now embedded in Victoria are helping to drive continuous improvement and positively contribute to the ‘all communities, all emergencies’ philosophy that underpins Victoria’s emergency management sector.

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