Guideline for the use of rainfall forecasts to make releases from dams in Victoria

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Southern Rural Water

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Guideline for the use of rainfall forecasts to make releases from dams in Victoria

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1.0	April 2022	DELWP	Original created
1.1	March 2024	DEECA	Amendment to Executive Summary – Seasonal target curves
			Amendment to Section 2.1 Legal requirements for water corporations
			Amendment to Section 2.2 Hypothetical operating options
			Amendment to Section 6.1 Risk management
			Amendment to Section 6.4 Filling curves

This document will be reviewed every five years to ensure that it remains up to date and reflects best practice.

Contents

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Executive Summary

The purpose of this guideline is to assist Victorian dam owners in setting policies and procedures for the use of rainfall forecasts in making release decisions. It should be noted that all of the gated public dams in Victoria were originally designed and constructed primarily to harvest water, without any explicit flood mitigation function. They have continued to be operated primarily in a manner that is consistent with their focus on water harvesting, although in many cases dam owners have developed policies to manage dams so that flood attenuation is provided in some circumstances. In this regard, public dams in Victoria are distinct from some other dams in Australia and internationally that were explicitly designed for both water harvesting and flood mitigation functions, such as Somerset and Wivenhoe dams in the Brisbane River catchment.

Legal context

In all cases where the Minister has appointed a water corporation as the storage manager, the water corporation has legal responsibilities both as the Authority and as the storage manager. The requirements for storage managers are set out in section 122ZL of the *Water Act* (Victoria, 1989). The water corporation must have regard to not only the four items under section 122ZL(2) but also any other relevant mandates associated with any other part of the *Water Act* or associated instrument, including the *Statement of Obligations for Victorian Water Corporations*. These legal requirements on water corporations should be given effect in policies, procedures, manuals and practices implemented to manage public dams in Victoria, in order to avoid or minimise potential civil liability.

Victorian water corporations should note that the *Water Act* applies statute to over-ride the Common Law with regard to legal civil liabilities for the flow of water in Victoria. The relevant sections of the Water Act (sections 16 and 157) set out strict liabilities.

Dam Flood Operations Manuals for Victorian dams, discussed below, should contemplate the prioritisation of strategic command principles and adoption of release plans that appropriately take into account the strict liability provisions that water corporations in Victoria are currently subject to. Procedures for developing strategic command principles and release plans should apply appropriate techniques, such as flow and rainfall forecasts (if sufficiently accurate) in a manner that robustly achieves the least amount of overall flood damage whilst not unreasonably jeopardising the requirement to maximise the harvesting of water for customers, so that the water corporation would then be strictly liable for less damage, if any occurs.

Procedures

Storage managers should operate dams, in accordance with linkages to various policies, principles and procedures as shown in **Figure ES- 1**. All gated dams must have a Dam Flood Operations Manual (DFOM). The DFOM should provide storage managers with clear direction on assessing the relative priorities associated with the strategic command principles and in adjusting the release plan in order to meet the priorities. There must be clarity in the interface between the DFOM and any other manual or procedure associated with operation of the dam and its appurtenant works, such as operations and maintenance manuals or Dam Safety Emergency Plans.

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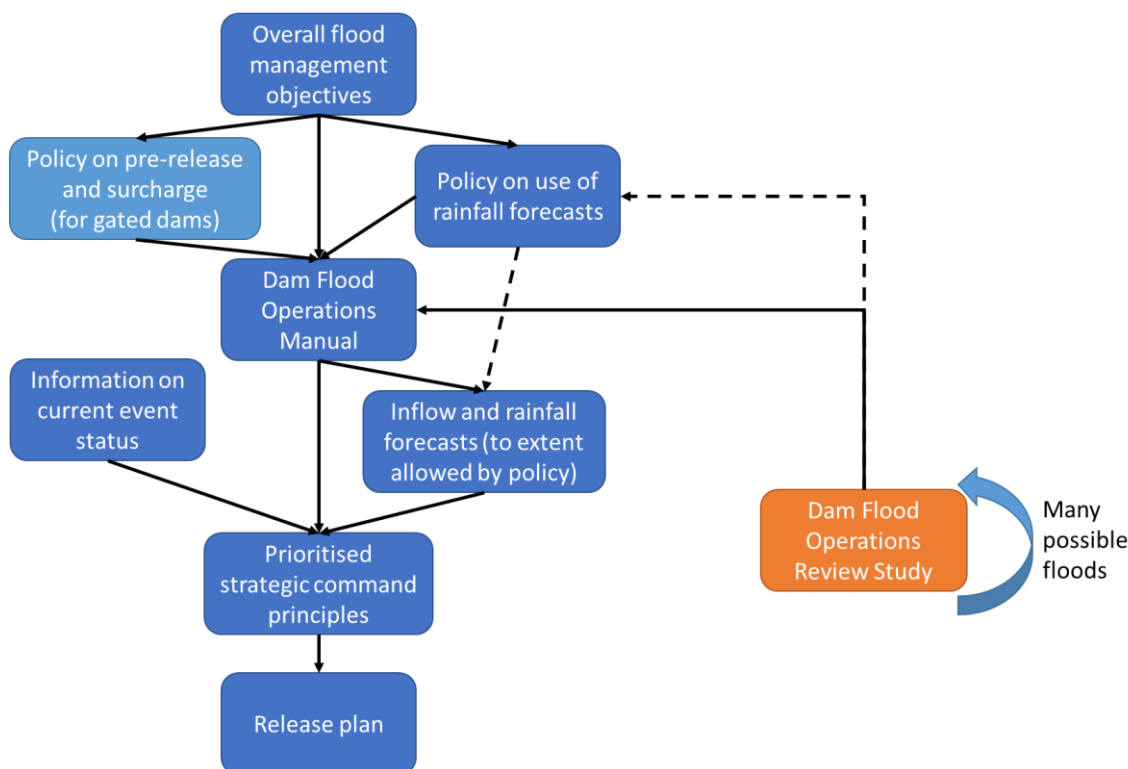
Figure ES- 1 Recommended relationship between documents

Storage managers should have overall flood management objectives for the dam, which are consistent with their statutory and regulatory obligations, relating to both flood impacts and harvesting water.

The highest overall flood management objective in the DFOM should be prevention of structural failure of the dam(s). This is the highest objective because structural failure would almost certainly breach all of the obligations set out in the legislation, as well as obligations under the *Occupational Health and Safety Act 2004*.

At key times during each flood event, the DFOM should direct the storage manager to re-assess and document the relative priority of the different strategic command principles for the event. It is possible that given the situation at a dam during the management of a flood event and technical and physical constraints in operating the dam, there may be conflict between simultaneously satisfying all flood management objectives. When this is the case, any adjustment to the priority attached to the strategic command principles that steer response through the Incident Action Plan should be guided by a risk management approach.

At key points in the lead up to and during the management of a flood event, the DFOM should direct the storage manager to review, set and document a release plan. The release plan should define the releases that the storage manager intends to make over the remainder of the flood event. The release plan should be consistent with the strategic command principles. Some iteration may be required in prioritising strategic command principles, testing a release plan that is consistent with those priorities, assessing the degree of compliance of the proposed release plan against the priorities, testing an alternative set of priorities and then repeating the cycle.

Rainfall forecast products

The Bureau of Meteorology (BoM) provides several different rainfall forecast products that are currently available to registered users from the BoM:

1. ACCESS Numerical Weather Prediction model rainfall forecast outputs

2. Australian Digital Forecast Database (ADFD)

3. Probability Matched Ensemble (PME) and

4. Rainfields

The BoM's rainfall products were developed for a range of different user communities. However, none of the currently available products are specifically designed for quantitative ensemble flood forecasting (with uncertainty) for dam operations. Several products that are in development look promising, such as Seamless

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Rainfall ensemble forecasts, precipitation post-processing technologies developed by CSIRO and The University of Melbourne, and 7-day ensemble streamflow forecasts. However, further developments are needed to adapt these to produce ensemble rainfall and flood forecasts, which would be required to manage dam operations in a manner that allows for the provision of quantitative forecasts with uncertainty. Until it is possible to obtain ensemble-based forecasts which are bias-corrected for the catchments of interest, the current forecast products are best suited to only providing situational awareness to dam owners.

The (backward looking) quantitative precipitation estimates provided by Rainfields are likely to be useful for dam owners that would model inflows using rain-on-ground forecasts. Dam owners should consider Rainfields as a useful adjunct to any ground-based rain gauge telemetry systems that they may have in place because Rainfields performs an optimal merging of rain gauge and radar data. The value and accuracy associated with Rainfields data will be a function of catchment specific properties such as distance from the nearest radar, location and density of rain gauges and catchment size.

Despite the shortcomings of the ADFD rainfall forecast product for true ensemble forecasting, it is recognised that the ADFD 50th, 25th and 10th percentile gridded rainfall forecasts are a convenient product. As a simplified approach, a storage manager may choose to run three scenarios, populated from the ADFD 50th, 25th and 10th percentile rainfall forecast grids, averaged from the gridded data over the catchment(s) of interest. If this approach is adopted, the forecast inflow and outflow hydrographs should be labelled as low, medium and high forecast rainfall, in preference to referring to them as 50%, 25% or 10% probability of exceedance rainfall forecasts. It is also recommended that consideration be given to supporting these products by having other BoM products available to be used for comparison purposes.

Flood forecasting systems

There are four types of forecast approaches that may be implemented by storage managers, as shown in **Figure ES- 2**. These four approaches form a hierarchy, with an increasing degree of complexity involved in implementing each approach, with each move up the "staircase". Hence, the volume of data, model complexity, level of expertise, computational resources, systems and training required to implement each approach increase, as the decision is made to move up the hierarchy. It is not necessarily the case that a more sophisticated approach to forecasting will produce more favourable outcomes across all potential impacts, for all flood events. It is also possible that a combination of the approaches may be used.
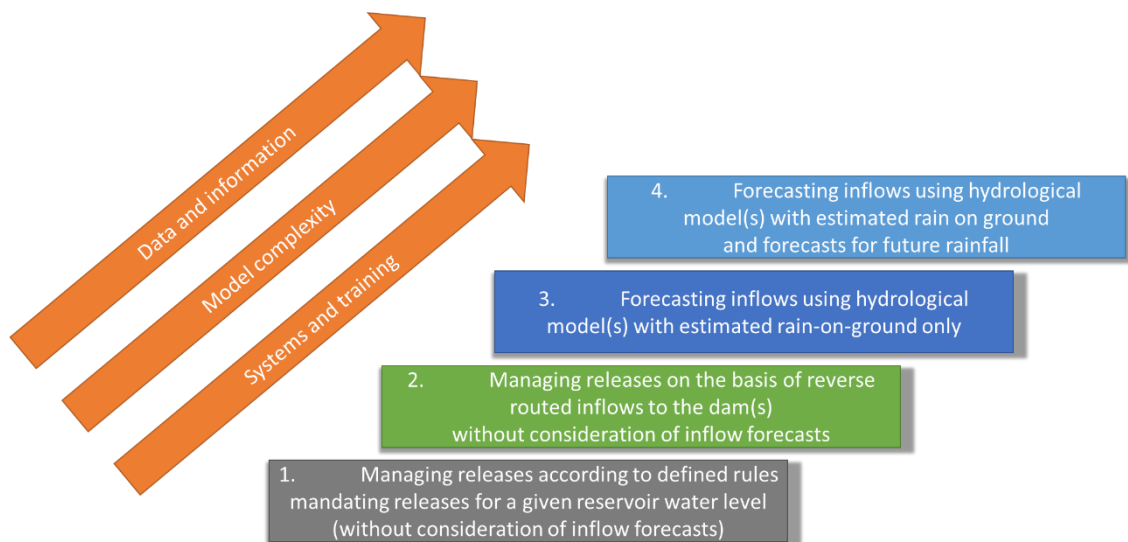
Figure ES- 2 "Staircase" hierarchy of flow forecasting approaches

Water corporations should make an assessment of the costs and benefits that would be associated with moving to each increment of complexity in forecasting approaches. The policy to use forecasts should be re-examined after risk, feasibility, and implementation studies and work are completed. If levels 3 or 4 of the hierarchy of flow forecasting are applied, models will be used to forecast flows, using rain-on-ground only or with forecast rainfall., which can then be used to assist in decision making for storage management. Flow forecasting models and methods should be consistent with the general guidance provided in the *World Meteorological Organisation Manual on Flood Forecasting and Warning* (2011).

Australian-specific recommended performance requirements for infrastructure to undertake flood warning in Australia are provided in the *Flood Warning Infrastructure Standard* (National Flood Warning Infrastructure Working Group, 2019). The recommendations of this standard should be applied by Victorian water

corporations for flood operations, with a few specific adaptions (provided in this guideline), to make them suitable for managing dams during floods.

Data collection, quality control of the data, flood modelling, ongoing staff training and reservoir release planning are all components of an integrated system for flood operations. Good practice integrates these components using a purpose-built software system.

It is likely to be difficult for a storage manager, in many situations, to make a well-considered assessment of risks in the process of managing an individual flood event. Flood operations are likely to involve complex decisions about re-prioritisation of the flood management objectives, strategic command principles and release plan, which may be difficult to make in real time. It is therefore recommended that a dam flood operations review study (DFORS) should be undertaken periodically, to inform the guidance on these matters in the DFOM. The DFORS should provide the basis for selection of the priorities associated with the flood management objectives, strategic command principles and release plan, for a given set of circumstances during a flood event.

The DFORS should define triggers for changing the priorities associated with strategic command principles. For a given set of priorities, the DFORS would define the constraints for setting the release plan, including the maximum period for any surcharge to be drained, the likely downstream consequences, the minimum and maximum permissible streamflow rates and the maximum rates of increase and decrease in streamflow.

The study should assess the procedures for prioritisation of the strategic command principles and implementation of release plans across a wide range of different floods, from those that only just have the potential to cause minor flooding to extreme floods that may threaten dam safety.

Seasonal target curves

Some Victorian dams have target filling curves, which set the desired maximum reservoir level in the reservoir over the late winter and early spring period with the aim of being full by the commencement of increased demand for water and the reduction in reliable inflows. Target filling curves are typically set based on an analysis of historic inflows, from which the Storage Manager calculates predicted future inflows, coupled with predicted future demands to calculate the target filling curve.

BoM seasonal flow forecasting products can be used to set a dynamic target filling curve that varies from year to year, for example this is done for the target filling curve arrangements at Lake Eildon. The DFORS should analyse options for applying seasonal flow forecasts in setting the target filling curve, in place of target filling curves that are informed only by antecedent recorded inflows.

Storage managers must balance various obligations under the *Water Act* and associated instruments relating to dam safety, water management, flood mitigation and environmental protection. Dam safety would take the highest priority because of the strong mandates in the Statement of Obligations and also because, if a dam fails, all other considerations would automatically not be met, and with devastating consequences. In undertaking the function of harvesting water to supply entitlement holders, the storage manager should not avoid making pre-releases if the storage manager has reliable information available about forecast inflows that would likely replace these releases.

Pre-releases

The procedure discussed below contemplates pre-releasing on the basis of any of the rainfall forecasts reaching Full Supply Level (FSL), in situations where pre-releases are limited to below minor flood flows between the dam and downstream communities or assets. Such an approach would give priority to dam safety (by creating or maintaining airspace in the dam) and flood mitigation (by creating or maintaining airspace that may be used later in the event to contain potential inflows). However, pre-releasing on the basis of a rainfall forecast, rather than rain on ground only, creates a risk that the inflows will not be sufficient to have the dam reach FSL by the conclusion of the event or by another specified target date.

Adding to the complexity of pre-release decisions, inflows can be dependent on the assumptions that are made in the flood forecasting model about losses in the catchment. Relationships between soil moisture and initial loss should be investigated as part of the dam flood operations review study (DFORS) to see if they are suitable for use. Guidance on the recommended relationship should be included in the DFOM. Such a relationship should only be recommended for use before significant runoff has been recorded in a flood event and the DFOM should recommend that loss parameters are recalibrated to recorded flows and storage levels, as the event progresses.

During the lead up to a flood event, storage managers could consider using the BoM's seven-day streamflow forecasting product, as a means of estimating inflows and hence assessing the level of pre-releases that should be made.

Forecast informed decision making

The BoM's various rainfall forecast products provide convenient sources of forecast rainfall. Hypothetically, if the likely uncertainty in each of the rainfall forecast products, for a particular catchment area and forecast period could be assessed, then those rainfall forecasts could be weighted in the forecasting process. However, it is currently not possible to assess the uncertainty in any of the current rainfall forecast products for very heavy rainfall events that are likely to give rise to flood events.

It is acknowledged that, despite the considerable uncertainty associated with rainfall forecasts, dam owners will from time to time be in a position where operational decisions may benefit from consideration of these forecasts. Whilst forecast inflows based largely on forecast rainfall (as opposed to rain on ground) may be used operationally at any point during a flood event, there are three typical strategic command principles where the benefits and consequences of making decisions informed by forecast rainfall are most critical. These are:

- Pre-releasing to lower the reservoir water level prior to or in the early stages of inflows in order to provide flood mitigation

- Absorbing the flood within the reservoir to provide flood mitigation and capture storage

- Surcharging the reservoir water level to provide flood mitigation

Given the range of potential consequences and the regulatory environment associated with these decisions, there is no appropriate level of conservatism that can be invoked to offset the considerable uncertainty in forecast rainfall. One conservative approach is simply not to make decisions on the basis of forecast rainfall; for example, setting in place a policy where pre-releases are not made until there is sufficient rain on ground to demonstrate both the magnitude and spatial pattern of the storm. However, such a policy may be unacceptable from the perspective of community and regulatory expectations. As such, dam owners should contemplate a framework that guides decision making in situations where inflow forecasts are heavily dependent on forecast rainfall.

Basing pre-release decisions on forecast rainfall inputs alone, which have inherently low spatial accuracy, runs the risk that the forecast rainfall will not occur over the dam catchment but instead will impact an adjacent catchment or the catchment downstream of the dam. In this case, the pre-releases would add to the natural flooding in a manner that would not have happened had the pre-release not been made. This runs the risk of being publicly perceived as a 'dam made flood', and the dam owner is likely to be strictly liable for any increased flood damage. Instead of attempting to quantify the uncertainty associated with rainfall forecast products, and therefore how much weight should be given to each of them, an alternative risk-based approach to forecast informed decision making is therefore recommended. The rain on ground forecast provides the lower limit, in terms of inflows, peak water level in the reservoir and peak releases. An indication of the upper limit could be produced by considering the range of outcomes from the highest forecast rainfall, which may be the 10th percentile ADFD forecast.

Where one of the ADFD or PME rainfall forecast products is being used for flow forecasting, the rainfall forecast used for modelling should be updated at each time that the revised BoM forecast is provided, i.e. twice per day. Where the dam owner adopts this pragmatic approach, as time progresses through the first 12 hours or so of the forecast period, the rain on ground data will gradually overlap with the ADFD or PME rainfall forecast. Decisions to pre-release (when levels are below FSL) or release could then be made using a decision framework, such as the checklist provided in these guidelines. Such decisions will need to give due account to any asymmetry in the consequences associated with the risks of the forecasts being over-estimated versus the risks of them being underestimated. These consequences may include flooding caused by releases that hindsight shows did not need to occur, or a failure to harvest adequate water. It should be noted that completion of a dam flood operations study (DFORS) may supersede the approach outlined here with a specific procedure for individual dams based on a more detailed understanding of forecast rainfall uncertainty that is specific to the catchment of the dam.

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1. Introduction

1.1 Purpose of this guideline

The purpose of this guideline is to assist Victorian dam owners in setting policies and procedures for the use of rainfall forecasts in making release decisions.

This guideline was prepared by a consortium from Hydrology and Risk Consulting Pty Ltd (HARC), University of Melbourne, University of South Australia and RJN Hydrology, in response to a tender prepared by Southern Rural Water, on behalf of Goulburn-Murray Water, Coliban Water, DELWP and other Victorian dam owners.

The most immediately obvious application of these guidelines is to dams that have spillway gates, where the dam owner has significant capacity to control the releases from the dam(s) during a flood event and and/or in the lead-up to a forecast flood event. However, these guidelines also consider:

- Flood operations procedures relevant to all dams in Victoria, whether they have gated spillways or they have only uncontrolled spillway(s) for passing flood flows. This recognises that ungated dams may have other facilities for managing the flood, such as outlet works or pipes for transferring flows to another reservoir or that decisions can sometimes be made well in advance of a flood that may impact on flood flows.

- Guidance related to a broader range of possible forecasting approaches during the management of floods, including:

    - not forecasting inflows at all,

    - forecasts of flows prepared by the water corporation using rain-on-ground only,

    - forecasts of flows prepared by the water corporation, informed by rainfall forecasts provided by an external agency such as the Bureau of Meteorology (BoM)

    - forecast flows that could be provided by an external agency such as the BoM.

The guideline considers the relevant Victorian legislation and regulations, including the *Water Act* (Victoria, 1989), *Water Industry Act* (Victoria, 1994), *Emergency Management Act* (Victoria, 2013), *Statement of Obligations for Victorian Water Corporations* (Minister for Environment Climate Change and Water Victoria, 2015), *Occupational Health and Safety (OH&S) Act* (Victoria, 2004), *Wrongs Act* (Victoria, 1958) and the *OH&S Regulations* (Victoria, 2017). The relevant legislation and regulations make distinction between the legal requirements on the owners of public dams and private dams. Due to the particular requirements of the Victorian legislation and regulations, much of this guideline is only relevant to public dams that are owned and managed by water corporations in Victoria. Different guidance may apply to private dams in Victoria and dams in other jurisdictions.

It should be noted that all of the gated public dams in Victoria were originally designed and constructed primarily to harvest water, without any explicit flood mitigation function. They have continued to be operated, in a manner that is consistent with their focus on water harvesting, although in many cases attempts are made to provide some level of flood mitigation. In this regard, public dams in Victoria are distinct from some other dams in Australia and internationally that provide both water harvesting and flood mitigation functions, such as Somerset and Wivenhoe dams in the Brisbane River catchment (Queensland Department of Energy and Water Supply, 2014a).

1.2 Definitions

For clarity, definitions of terms used in these guidelines are provided below:

Authority is a water corporation, as defined in the *Water Act* (Victoria, 1989).

Storage manager is the Authority that is appointed under Part 6C of the *Water Act* (Victoria, 1989), or an Authority where it is exercising its functions under Part 8 of the *Water Act* (Victoria, 1989).

Dam Flood Operations Manuals (DFOM) are currently referred to by various water corporations as *Flood Incident Management Plans (FIMP)* or *Flood Plans*. DFOM set out procedures that are to be undertaken by storage managers in the lead up to and during the management of all floods at the dam where

"management" encompasses activities necessarily undertaken to pass the flood through the reservoir and downstream. Under extreme flood conditions, the DFOM links with the Dam Safety Emergency Plan (DSEP).

Rainfall forecast policy is a statement that defines the current position of the storage manager with respect to the use of rainfall forecasts to determine reservoir inflow and/or outflow forecasts.

Overall flood management objectives are general objectives set by the storage manager for managing all floods at a dam, in response to the legal obligations on the storage manager. These are defined in the dam flood operations manual and do not change during flood events.

Prioritised strategic command principles are the principles that the storage manager is intending to satisfy, ranked in order of priority, with the prioritisation informed by the situation at that time. As such, they form the basis of an Incident Action Plan established by the storage manager for managing a flood through the reservoir. Strategic command principles and their priorities should be guided by the overall flood management objectives.

Release plan defines, at any particular time in the lead up to or during a flood event, the releases that the storage manager intends to make over the remainder of the flood event, given the situation at that time. The release plan should be consistent with the storage manager's rainfall forecast policy, the DFOM, DSEP and the strategic command principles.

Dam flood operations review defines how a risk management process should be implemented, across the possible range of floods that could occur at the dam, to prioritise the strategic command principles and define the release plans. The review study should aim to meet the overall flood management objectives, across a range of different flood events, to manage the overall risk to the storage manager and the community.

Pre-releases comprise water released from a dam before the dam has reached full supply level, in response to forecast inflows and/or rainfall conditions.

Surcharge is water temporarily held above a dam's Full Supply Level (FSL), during the passage of a flood.

Situational awareness is the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their future status (Endsley, 1995). This guideline refers to application of situational awareness in mostly a qualitative sense, rather than quantitative modelling or forecasting.

Strict liability is a concept applied in both civil and criminal law that holds a defendant responsible for their actions regardless of their intent at the time of the action. It means that somebody could be held accountable for a result they never intended.

Rain-on-ground. As a real-time event unfolds, rainfall gauges will record the rain which has fallen. This is typically referred to as "rain-on-ground", to distinguish it from forecast rainfall.

Reverse routing is a computation that calculates the estimated inflow for a period of time as the balancing term, after allowing for the recorded or estimated releases from the dam and the estimated change in reservoir volume over the period. The reservoir volume is normally estimated from recorded water levels in the reservoir. In some cases, evaporation from the reservoir and rainfall estimated to occur directly on the dam surface area may also be included. Reverse routed inflows can be subject to appreciable uncertainty, particularly when computed over short time intervals, as temporal fluctuations in reservoir water surface levels and/or spatial variation in the water level across the reservoir may cause appreciable uncertainty in the change in storage component of the volume balance. In addition, for reservoirs with large surface area, there may be uncertainty in estimating the rainfall falling directly on the reservoir surface from rain gauges.

Predictive uncertainty is the uncertainty that remains on the future realization of a physical parameter, or status of a system, after using all available information, which is usually, but not necessarily, embedded in a mathematical model. Realizing the role of uncertainty in the decision making process is of fundamental importance because the quantity needed for appropriately taking decisions is the expected damage cost, not the cost computed in the expected "most likely scenario" (International Commission on Large Dams, 2016, p.95).

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2. Legal framework

2.1 Legal requirements for water corporations

This section contains a summary of the legal framework for managing public dams in Victoria. Further details are provided in Appendix A.

In all cases where the Minister has appointed a water corporation as the storage manager, the water corporation has legal responsibilities both as the Authority and as the storage manager. The primary purpose of Victoria's water storages is to provide a secure and safe water supply for irrigators, towns and the environment. However, in undertaking the role of storage manager, storage managers are required to also weigh up other considerations set out in legislation and associated instruments.

The requirements for storage managers are set out in s. 122ZL of the *Water Act* (Victoria, 1989). The water corporation must have regard to not only the four items under s. 122ZL(2) but also any other relevant mandates associated with any other part of the *Water Act* or associated instrument, including the *Statement of Obligations for Victorian Water Corporations* (Minister for Environment Climate Change and Water Victoria, 2015). The water corporation must, where possible, consider:

- Dam safety, per Part 5-3 of the *Statement of Obligations* and link to Part 5/ s 80 of the *Water Act*

- Water supply, per s. 122ZL (2)(b) of the *Water Act* and link to Part 8 as well as to Bulk Entitlement agreements per Part 4

- Flood mitigation, per s. 122ZL (2)(d) of the *Water Act* and link to Parts 5-2.2 and 7-2.4 of the Statement of Obligations and back-link to Div. 4 of Part 10 of *Water Act* and

- Environmental protection, per s. 122ZL (2)(a) and (c) of the *Water Act*.

The first consideration would take the highest priority because of the strong mandates in the Statement of Obligations and also because if a dam fails, all other considerations would automatically not be met.

These legal requirements on water corporations should be given effect in policies, procedures, manuals and practices implemented to manage public dams in Victoria in order to avoid or minimise potential civil liability.

The *Water Act* applies statute to over-ride the Common Law with regard to legal civil liabilities for the flow of water in Victoria. Civil liabilities are addressed in two different places in the *Water Act*: the main general sections on "Liabilities" under Division 2 of Part 2 (ss. 16–21) and/or s. 157. With regard to public dams, the *Water Act* essentially over-rides the Common Law, saying per s. 17(1) that civil liability can only go as far as either s. 16 or s. 157.

It is also important to note for any situation that may attract s.157 liability is the s.157(4)(b) provision which states that "the proportion (if any) of the responsibility of the Authority for the injury, damage or loss must be assessed and only that proportion of the assessed damages must be awarded against the authority". This establishes a requirement for the courts to "assess" a proportion of responsibility for the injury, damage or loss.

In managing any given flood event, a storage manager will be making trade-offs to manage their releases. The purpose of larger earlier releases, or pre-releases, would be to reduce the incremental damage that would occur had decisions been made to keep releases lower and to utilise more of the surcharge capacity early in the event but then resulted in the need to make larger releases later in the flood than would have otherwise been necessary. There is a risk in making these decisions that flooding may result that was larger than actually needed to be the case or that supply requirements under the bulk entitlement are not met.

Dam Flood Operations Manuals for Victorian dams, discussed below, should contemplate the prioritisation of strategic command principles and adoption of release plans that appropriately take into account the strict liability provisions that water corporations in Victoria are currently subject to. Procedures for developing strategic command principles and release plans should apply flow and rainfall forecasts (if sufficiently accurate) in a manner that best balances the strategic command principles, so that the water corporation would be strictly liable for less damage, if any occurs.

2.2 Hypothetical operating options

An example of management of a hypothetical flood that could occur is considered here. **Figure 2-1** shows hydrographs for inflow to a gated dam for a hypothetical flood and the water level and outflow hydrographs that would result if the dam were managed using reverse routed inflows. The hypothetical inflow flood has a peak inflow of about 190,000 ML/d. If the dam was managed to use all of the 0.6 m surcharge capacity, releases would peak at about 120,000 ML/d.

Figure 2-2 shows two (of the many) potential alternative options for operating the dam. Both of the alternative options presented utilised all of the available 0.6 m surcharge capacity. Both of the alternative options also comply with the same rules for maximum rates of increase and decrease in flood releases. The reverse routed and two alternative options also return the reservoir to FSL within about 6 days of the inflow peak and about 5 days of the peak water level.

The green hydrograph on **Figure 2-2** shows the releases peaking at about 78,500 ML/d, which is about 41,500 ML/d less than the peak release under reverse routing. This release plan could be achieved only with a rain-on-ground forecast of inflows to the dam, as the peak release occurs after the end of the rainfall for the hypothetical event. If rainfall could be forecast accurately for the last 24 hours of the hypothetical rainfall event, the yellow hydrograph could be achieved, which results in a peak release of 56,000 ML/d, which is about 65,000 ML/d less than the peak release under reverse routing. In this hypothetical example, achieving the yellow hydrograph would rely upon inflows to be forecast using rain-on-ground up to about 9 am on 8 February, followed by a perfect forecast of rainfall for the remainder of the rainfall event (from 9 am on 8 February to 9 am on 9 February).

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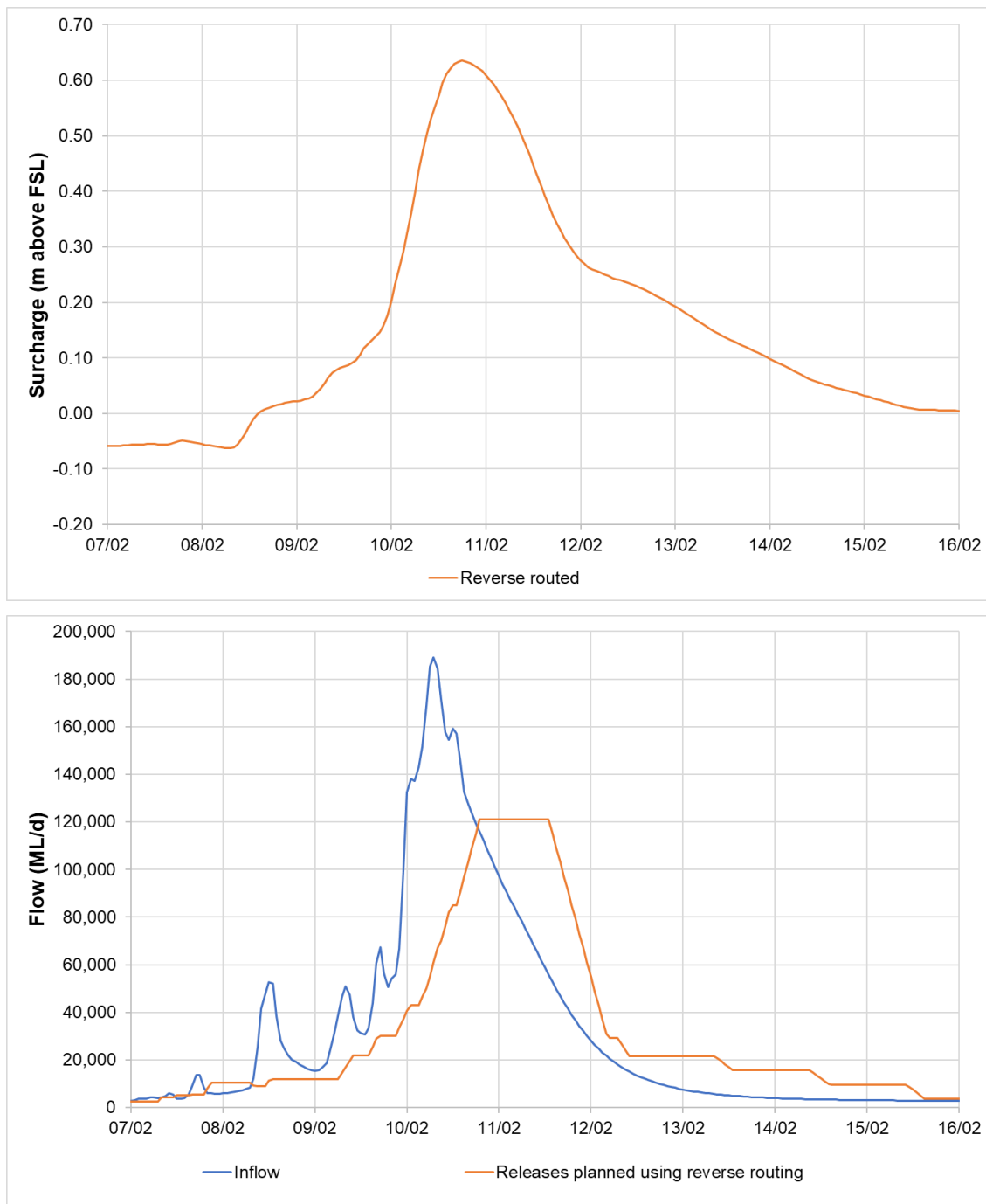
Figure 2-1 Hypothetical flood event for gated dam, managed using reverse routed inflow forecasts. The top panel shows the reservoir water level and the bottom panel shows modelled inflows and outflows.
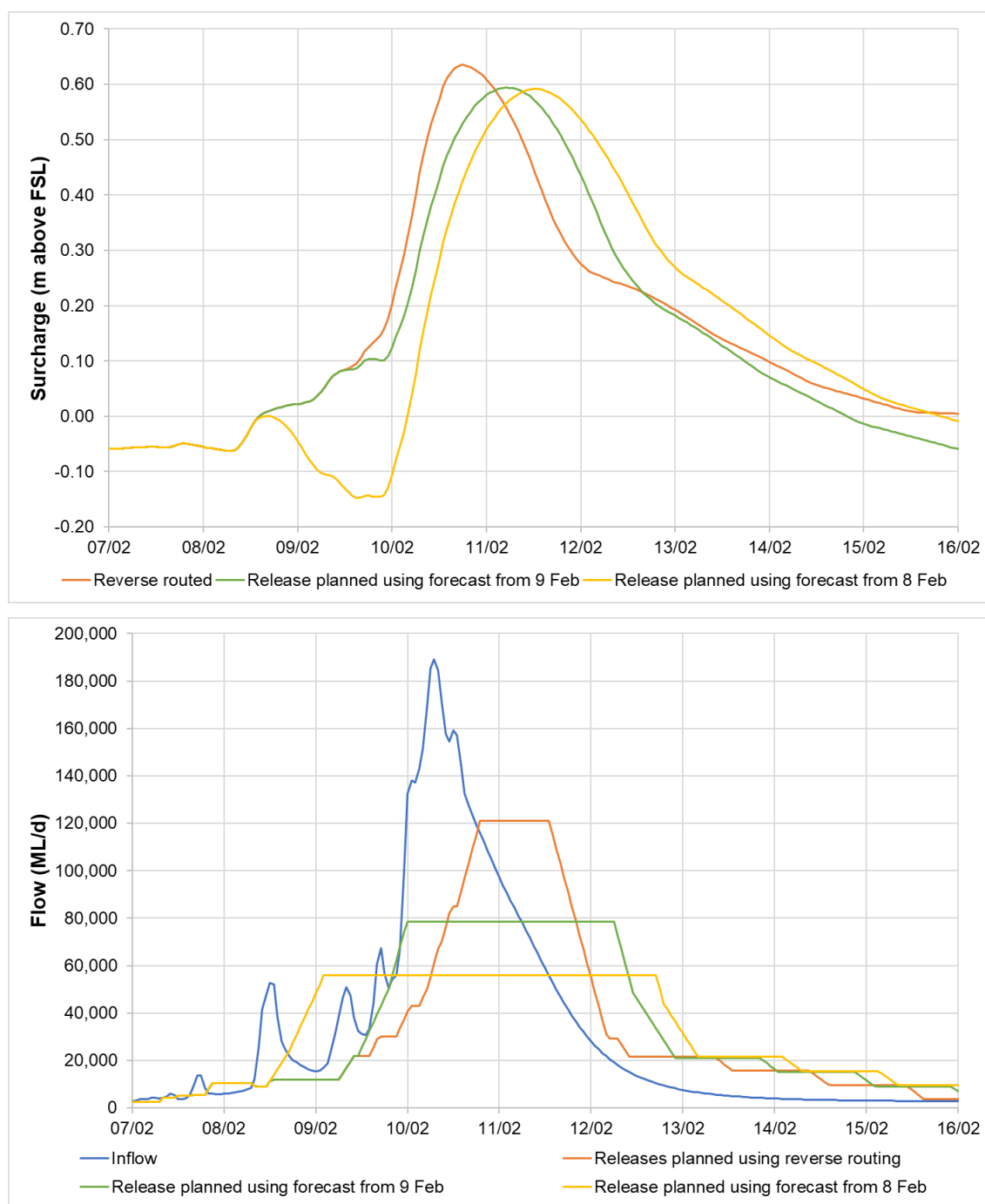
Figure 2-2 Comparison between hypothetical flood event for a gated dam, managed using reverse routed inflows, with potential alternative management arrangements that allow releases informed by inflows forecast from 9 am on 8 February or 9 am on 9 February. The top panel shows the reservoir water level and the bottom panel shows modelled inflows and releases.

The alternative flood operations also modify the duration of peak flood releases. There may be some assets, such as crops, which may be able to sustain a particular duration of inundation before suffering damage. In this hypothetical example, there may be a field that is inundated for releases of 40,000 ML/d from the dam. That field would be flooded for about 4 days under the yellow release plan alternative on **Figure 2-2**, about 2 ½ days under the green release plan alternative and about 2 days with reverse routing (orange hydrograph).

The hypothetical flood scenario described here mirrors, somewhat, the January 2011 flood event in the Brisbane River catchment. In that situation, plaintiffs downstream of Wivenhoe and Somerset dams claimed that flooding to their properties would have been reduced or avoided completely had flood operations occurred in a different manner. The plaintiffs reconstructed alternative release plans for the dams to demonstrate the changes in flood outcomes that could be achieved, in a similar manner to the hypothetical flood discussed above. Under the law that operated in Queensland at that time, to be successful in their legal action, the plaintiffs also had to demonstrate that the dam operators failed to comply with the Flood

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Operations Manual for Wivenhoe and Somerset dams. It is important to note that under the law that currently operates in Victoria, with the strict liability provisions that apply in the Water Act, a Victorian water corporation is unlikely to be protected from liability by demonstrating compliance with an equivalent flood operations manual.

In managing any given flood event, a storage manager will be making trade-offs to manage their releases. As the above hypothetical example demonstrates, making larger releases earlier in the event (green or yellow release hydrographs) or pre-releasing water (yellow hydrograph) might result in a reduction in the peak release from the dam. The purpose of larger earlier releases, or pre-releases, would be to reduce the incremental damage that would occur had decisions been made to keep releases lower and to utilise more of the surcharge capacity early in the event.

It is likely that a storage manager that decided not to pre-release, in order to perform their water supply reliability function (s.122ZL(2)(b)) ahead of their flood mitigation function (s.122ZL(2)(d)), hence consuming more of the surcharge early in the event and requiring larger releases later, would be strictly liable[1] for incremental releases above what could have been achieved with alternative release plans[2].

There would appear to be nothing prohibiting a storage manager from making a pre-release, if the dam was below FSL and inflows were forecast. However, a storage manager making a pre-release should consider the potential legal liabilities that could eventuate from making releases that could exceed later inflows, if inflows were not as large as forecast.

Some of the flood flows can be due to releases from the dam(s) and some from the catchment downstream of the dam. A water corporation may therefore need to consider how releases might affect flooding at multiple locations downstream of the dam, not only at the toe of the dam wall. Section 3.5.4 of the *WMO Manual on Flood Forecasting and Warning* (World Meteorological Organisation, 2011) discusses this situation,

"To operate for flood control in a multi-functional reservoir it is imperative that forecast estimates of the incoming flood are available. It is necessary that such forecasts are integrated with those for downstream riparian areas, as flooding in these areas may occur independently of any release from the upstream reservoir. The flooding scenario downstream of the reservoir must be assessed to decide on quantities of flood water to be released from the reservoir to avoid aggravation of the downstream conditions. Generally, the objective in such flood control operations is not necessarily to retain the peak of the incoming flood hydrograph within the reservoir. It is rather to ensure the greatest possible attenuation at one or several downstream locations with an acceptable lag time."

DFOM for Victorian dams should contemplate the prioritisation of strategic command principles and adoption of release plans that appropriately take into account the flood outcomes that might occur at multiple locations downstream of the dam(s).

Procedures set out in the DFOM should be tested across a wide range of different hypothetical flood events, with different peak inflows, rainfall event durations, temporal patterns, spatial patterns, antecedent catchment conditions and starting levels in the reservoir(s).

2.3 Overview of stakeholders' roles

Arrangements for flood forecasting and warning in Victoria are summarised in Bureau of Meteorology (2018a, Appendix 4). This section summarises the relevant information from that document, the *Intergovernmental Agreement on Provision of Hazard and Warning Services* (Council of Australian Governments, 2017) and the *Service Level Specification for Flood Forecasting and Warning Services for Victoria* (Bureau of Meteorology, 2020a).

The Victorian Floodplain Management Strategy (VFMS) outlines policy, actions, accountabilities, and funding arrangements for the Total Flood Warning System in Victoria.

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[1] Even if the statutory interpretation issues discussed in 0could be resolved such that a storage manager in performing its Part 6 functions firstly could never be subject to the s.16 strict liability, and secondly when subject to the s.157(1)(a) and (3)(a) strict liability the "intentional conduct" is interpreted to mean **intent to cause** injury, damage or loss (hence making it relatively easy to discharge such criminal-like liability on the basis of the lower 'balance of probabilities' proof standard), the storage manager nevertheless will probably still be liable under the negligent conduct provisions of s.157(3)(b) for incremental releases above what could have been achieved with alternative release plans (essentially alternatives which would be regarded as a part of the state of scientific knowledge consideration per s.157(3)(b)(i)). The 2011 Queensland floods case (subject to the current appeal process) provides some relevant supporting precedent in this regard: it is for **not** implementing such alternative release plans (based on rainfall forecasts and for which their flood manuals provided for) that the defendants were held to be liable in negligence.

[2] Per the s157(4)(b) "proportional responsibility" provision, as discussed in 0.

The Department of Environment, Land, Water and Planning (DELWP) has the accountability for the coordination of, and performance reporting on, the Total Flood Warning Service at the state level. The Catchment Management Authorities (CMAs) and Melbourne Water coordinate regional floodplain management strategies in partnership with the Victorian State Emergency Service, local governments and local communities. These strategies include agreed priorities for flood warning system improvements at the regional and local levels, which align with each local community's risks, and with community's willingness to fund.

The *State Emergency Management Plan* (Emergency Management Victoria, 2020a) contains the policy and planning documents for emergency management in Victoria. It provides details about the roles and responsibilities of different organisations in the emergency management arrangements that apply in the State. Arrangements for responding to floods in Victoria can be found in *State Emergency Response Plan – Flood Sub-Plan* (Emergency Management Victoria, 2020b), which outlines arrangements for ensuring an integrated and coordinated approach to the State's response to flood events.

The Bureau of Meteorology (BoM) has responsibility for flood prediction and the preparation of flood warnings for all catchments in Victoria, with the exception of Port Phillip and Westernport catchments, for which Melbourne Water is responsible. The BoM is responsible for the dissemination of flood forecasts and warnings throughout the period of flooding, including those prepared by Melbourne Water. These forecasts and warnings are disseminated to State agencies, CMAs, local governments, water corporations and selected private entities and the media in accordance with the service levels as set out in the *Service Level Specification* (Bureau of Meteorology, 2020a) and the *Intergovernmental Agreement* (Council of Australian Governments, 2017).

For locations downstream of major storages impacted by storage operations, the storage managers inform the BoM of planned releases in accordance with the *Service Level Specification* (Bureau of Meteorology, 2020a).

The BoM is responsible for maintaining the currency of the operational flood forecasting system, including the real-time data ingestion system. This includes updating the calibration of forecasting models as new data and other information becomes available and for continuing improvement to the efficiency of operational processes (Bureau of Meteorology, 2018a).

Bahramian *et al.* (2021) neatly summarise the difference in requirements for flood warning agencies, such as the BoM, and storage managers for dams with appreciable capacity to manipulate releases (e.g. dams with gated spillways), as follows,

"Flood warnings are issued to provide the general public and agencies with information about impending floods to minimize the possible negative impacts. The provision of flood warnings may be deemed effective when the endangered communities are provided with an understanding of potential flood risks in a timely manner. However, when forecasts are required for active flood management" [e.g. making decisions on releases from gated dams that influence downstream flows]*, "there is an increased need to quantify uncertainty in the timing,"* [volume and peak flow] *"of the forecasts so that decision-makers can evaluate management options, often in the face of strong asymmetry in the consequences of over- or under-estimates (Demeritt et al., 2007). For example, if the magnitude of a flood is under-estimated, then operators of a dam are less likely to take pre-emptive action, and this increases the likelihood that the dam may be overtopped and fail catastrophically. Conversely, if the forecasts are over-estimated, then operators may release more floodwater than necessary, and this may incrementally increase the consequences of downstream flooding. The trade-offs involved in balancing the benefits of pre-emptive warnings with the costs of false negatives represent a 'duality of errors' (Demeritt et al., 2007) and reinforces the importance of explicitly including uncertainty in forecast products* (Krzysztofowicz, 2001; Montanari and Grossi, 2008; Zhao et al., 2015) *and in decision-making (Dietrich et al., 2009)."*

The BoM flood warning service provide quantitative forecasts of peak flood level and timing of when that flood is likely to occur, with less attention typically paid to forecasts of flow rate, hydrograph shape or flood volume. BoM operate at state and nation-wide level, so resources can be stretched when multiple catchments within a state, or nationally, are in flood. BoM forecasts can also typically afford to be somewhat conservative, forecasting a flood level that could be biased high and communicated with appropriate caveats, which would typically permit relatively low-cost actions such as evacuation of people and animals from, and relocation or protection of property within, the area forecast to be inundated. By contrast, a storage manager will be actively making decisions on the rate of release (or even not to release), which could materially change the degree to which their legal obligations are met under the *Water Act* (Victoria, 1989). A Victorian water corporation operating a public dam therefore has different obligations to those of the BoM, which must translate into differences in approach, with regard to flood forecasting and use of forecast rainfall

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in preparation of those forecasts. A storage manager may find that there are situations when adopting a conservatively high rainfall or flood forecast may produce a non-conservative result, which could include higher releases and more flood damages.

3. Procedures

3.1 Policies, plans and manuals

Storage managers should operate dams, in accordance with linkages to various policies, principles and procedures as shown in **Figure 3-1**. All gated dams (or dams where operations can make a significant difference to flood impacts) must have a Dam Flood Operations Manual (DFOM).

The DFOM should provide storage managers with clear direction on assessing the relative priorities associated with the strategic command principles and in adjusting the release plan in order to meet the priorities.

There must be clarity in the interface between the DFOM and any other manual or procedure that defines non-flood operations of the dam, such as operations and maintenance manuals.

The statutory context of the DFOM should be explained. The approval process and authority for a DFOM should be defined in the manual.
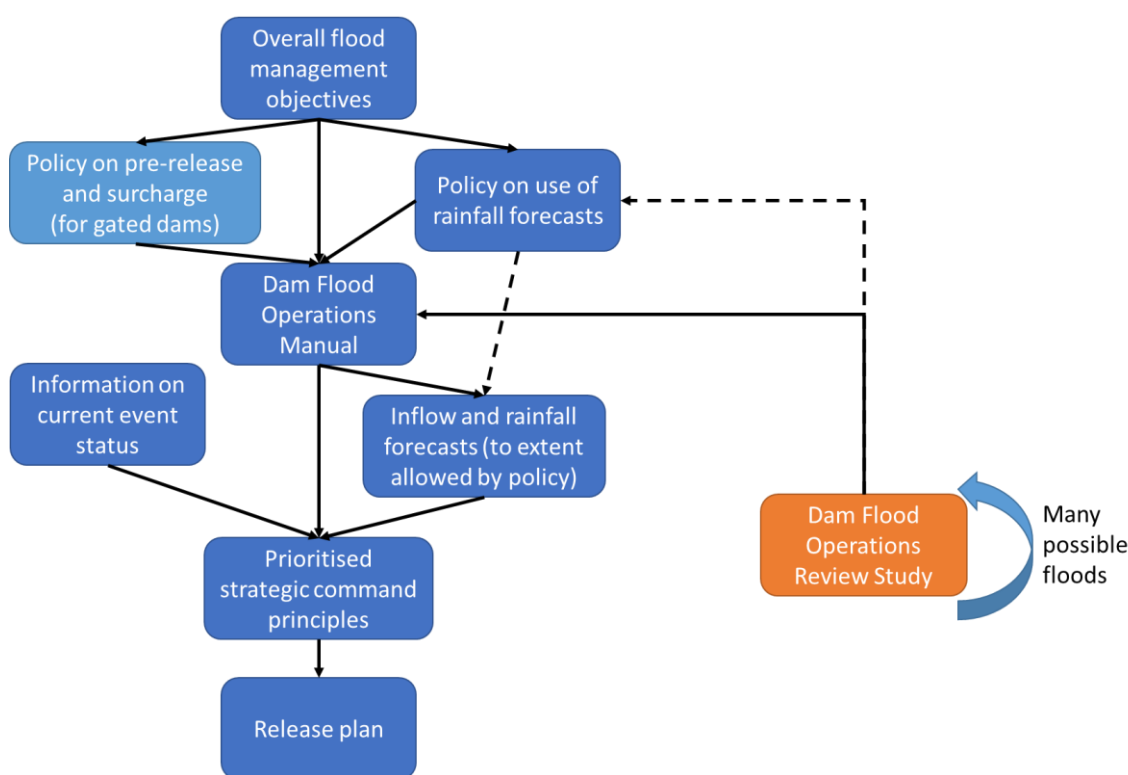
Figure 3-1 Recommended approach to release planning for dams

3.1.1 Overall flood management objectives

The DFOM should state overall flood management objectives for the dam, which are consistent with the storage manager's statutory and regulatory obligations, under the *Water Act*, *Water Industry Act* (Victoria, 1994) and the *Statement of Obligations* (Minister for Environment Climate Change and Water Victoria, 2015).

The highest overall flood management objective in the DFOM should be prevention of structural failure of the dam(s). This is the highest objective because structural failure would almost certainly breach all of the obligations set out in the legislation (see below) as well as obligations under the *OH&S Act 2004* (as discussed under Section 2.1 above).

As discussed in Section 2.1, the overall flood management objectives should give effect to the obligations on storage managers, as set out in s. 122ZL (2) of the *Water Act*. Water Corporations should review the overall flood management objectives in their DFOM, to ensure that they give effect to their legislative obligations. Examples of possible overall flood management objectives are provided in **Table 3-1**. It should be noted that

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there is no particular priority given to the list of obligations for storage managers in s. 122ZL (2) of the *Water Act.*

Table 3-1 Examples of possible overall flood management objectives

Legislative obligation on storage manager	Example of overall flood management objective to give effect to this obligation
Protecting the ecological values of the water systems relating to the land specified in the instrument of appointment	**Limiting the maximum level and/or rate of rise in the reservoir (to protect environmental assets around the reservoir margin or upstream)**
Protecting the reliability and quality of water supply	**Ensuring the storage(s) is/are at full supply level (or the level of the target filling curve, if lower) at the conclusion of the flood event**
Subject to water supply needs, minimizing the impact on the environment of the carrying out of any such function and maximizing the benefit to the environment of the carrying out of any such function	**Setting maximum rates for increase in releases and/or decrease in releases, to protect the downstream river channel and floodplain**
Developing and implementing strategies to mitigate flooding, where possible	**Using available airspace below FSL or the defined surcharge capacity within the reservoir to mitigate flooding**

DFOM should consider provisions for alternative procedures, such as providing the storage manager with the ability to formulate departure from the DFOM, when it is identified that the documented procedures may not meet objectives for a particular flood. Alternative procedures can deviate from the standard set of procedures but the alternative procedures must still be aimed at meeting the overall flood management objectives.

3.1.2 Clarity in specifying mandatory and discretionary criteria

DFOM should have clarity on mandatory ("must") criteria versus discretionary ("may") criteria. The mandatory criteria define hard constraints, and the discretionary criteria define the permitted alternative considerations.

3.1.3 Policies

Storage managers should have two policies in place to guide management of floods for dams:

- a policy on use of rainfall forecasts in management of dams (which may also set the policy for the forecasting approach to be applied, from the four options explained in Section 5.1) and

- for gated dams, a policy on pre-release and surcharge. This policy is required for gated dams under item 5.2.2 of the *Statement of Obligations.*

The overall flood management objectives and the two policies should guide the DFOM for the dam (or group of dams). Operations should be conducted by the storage manager in accordance with the DFOM and information that is collected on the current status of the event. The storage manager may also be guided by forecasts of inflows and rainfalls, to the extent permitted by the policy on use of rainfall forecasts and as directed by the DFOM.

3.1.4 Strategic command principles and release plans

At key stages during each flood event[3], the DFOM should direct the storage manager to re-assess and document the relative priority of the different strategic command principles for the event. In effect, to revisit the Incident Action Plan and reassess incident objectives. The strategic command principles and their priorities should be guided by the overall flood management objectives. However, it is possible that given the situation at a dam during the management of a flood event and technical and physical constraints in operating the dam, there may be conflict between simultaneously satisfying all flood management objectives. When this is the case, any adjustment to the priority attached to the strategic command principles that steer response through the Incident Action Plan should be guided by a risk management approach. The DFOM should provide guidance on how a risk management approach should be implemented to set the strategic command principles and the relative priorities. The priority of the strategic command principles may change

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[3] The frequency of reassessment often varies significantly during the progression of the event. Reassessments are likely to be required more often when inflows are changing rapidly, such as during periods when rainfall intensities are high and/or there are rapid changes in rainfall intensities across the catchment(s).

during a flood event, in response to changing circumstances, but they should always be guided by the DFOM.

At key stages in the lead up to and during the management of a flood event, the DFOM should direct the storage manager to set and document a release plan and carry out updates as required. The release plan should define the release strategy that the storage manager intends to make over the remainder of the flood event. The release plan should be consistent with the strategic command principles and ensure there is no confusion or inconsistencies with any overlapping or linked plans.

3.1.5 Defining start and end of flood operations for events

DFOM should contain a clear definition, with suitable tolerances, to determine the start and end date and time of operations for a flood, including:

- Distinguishing between the start and end date and time for flood operations under the DFOM, and any other broader incident definition start and end date and time (if there are relevant differences).

- Clarify if any intended pre-emptive release is part of the flood event operation period, or alternatively authorised under some alternative procedure[4].

- Define trigger points between operations under the DFOM and the DSEP, such as defined water levels in the reservoir.

3.1.6 Multiple dams in one catchment

The *WMO Manual on Flood Forecasting and Warning* (World Meteorological Organisation, 2011) notes that,

"In the case of a cascade of more than one reservoir on one river, or a number of reservoirs located on different tributaries of the same river, the operation becomes more complex but also provides more flexibility in operation. In such cases, all the reservoirs must be considered as comprising a single system, as coordinated operation of all reservoirs will perform much more efficiently."

If there are multiple dams in one river catchment[5] (either in series or parallel situation) risks can arise to the dam operator (and affected stakeholders) if there is a separate DFOM for each dam. These risks include:

- Inconsistencies in the procedures for each dam between the respective DFOM, if the operations (objectives and procedures) are co-dependant and/or

- Increased probability of inconsistencies, if the review processes for each DFOM are not synchronised.

Increased robustness for clarity of flood operations is likely be provided if a single combined DFOM covers the combined operations of multiple dams in relevant situations[6]. Consideration should therefore be given to a DFOM covering the combined operation of multiple dams in the same river catchment where relevant. Another advantage of a combined DFOM for relevant combinations of dams is that it can simplify and reduce effort for any obligations for post event reporting and post event reviews. To the extent that it aids in clarity and consistency of operations, a single DFOM may also cover multiple dams in different catchments.

3.1.7 Notification

The DFOM should provide advice on requirements for notification that are consistent with all statutory requirements and local agreements, including the incident management doctrine detailed in the *Emergency Management Manual Victoria* (2018), the *State Emergency Management Plan* (Emergency Management Victoria, 2020a) and the Incident Notification Protocol between Water Corporations and DELWP (DELWP, 2018).

3.1.8 Specification of maximum surcharge period

In situations where the Authority has determined that the dam may be surcharged above FSL for the purposes of flood mitigation, the DFOM should provide guidance on the maximum permissible time for the dam to remain in a surcharged state before it is drained back down to FSL or the target filling curve. This guidance should be consistent with the Authority's policy on surcharge. The Dam Flood Operations Review (see section 3.2) should assess the lead time at which rainfall and streamflow forecasts can be used to foresee subsequent flood events, after the event that is being managed. In the absence of further analysis,

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[4] If the any intended pre-emptive release is to be authorised and guided by some procedure other than the DFOM, it will require clarity on the transition from pre-emptive release to flood event operations.

[5] Relevance depending on one or more having gated spillways or other outlets for controlling releases.

[6] Relevant situations would be where the operation of one dam must take account of the operation of another dam.

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current technologies for rainfall forecasting demonstrate negligible skill beyond seven-days. The surcharge policy and DFOM should therefore direct that any surcharge above FSL never exceeds seven days beyond the forecast date, and may be less depending on the surcharge policy of each assessment. The DFOM and surcharge policy should also have appropriate regard for any rules regarding how flow recession is managed, in order to protect the downstream environment including the river bed, banks, flora and fauna (see Section 3.1.9).

The period limit for surcharge needs to consider whether the period starts upon:

- Start of pre-release
- When dam first goes over FSL (even if pre-release started before that)
- Time of peak inflow (which may create difficulties in multiple peaked events)
- Time of peak reservoir level (which is typically the easiest to apply but can be manipulated by prior decisions about releases).

None of the above will ensure the best outcomes for all floods but the latter two usually have practical utility over the former two options, as the former two options may result in increased downstream flooding for long duration flood events.

3.1.9 Specification of release rates and rates of change in release rates

The DFOM should contain clear guidance on minimum and maximum permissible release rates, for each of the strategic command principles. Wivenhoe and Somerset dams, provide a practical example of guidance on specification of minimum and maximum release rates (see Section 3.3 for further explanation of this example). Maximum release rates during pre-release periods may be stricter than those that apply after significant inflows to the dam have occurred. The maximum and minimum release rates may be linked to other variables (e.g. inflow) that allows them to be flexibly applied to the conditions being experienced.

The DFOM should contain clear guidance on the downstream consequences associated with a range of outflows or releases from the storage. Ideally, guidance would extend to the maximum flood magnitude covered under the DFOM, noting that larger floods are possible and procedures for managing these events would generally be incorporated into the DSEP.

The DFOM should also contain clear guidance on permissible maximum rates of increase in flood releases. Maximum permissible rates of increase in releases should be informed by operational constraints on the infrastructure at the dam, the time required for adequate warning and relocation of downstream communities, environmental considerations and the range of critical infrastructure and essential services that could be affected by the releases. Maximum rates of increase may vary according to the release rate. For example, rates of release may increase more quickly when releases are already high than when release rates are low. They may also have triggers that allow them to be overridden such as when the safety of the dam or flood mitigation may dictate.

The DFOM should contain clear guidance on permissible maximum rates of decrease in flood releases. Maximum permissible rates of decrease in releases should be informed by operational constraints on the infrastructure at the dam and potential environmental impacts downstream of the dam, such as slumping of river banks. Maximum rates of decrease may vary according to the release rate. For example, rates of release may decrease more slowly when release rates are likely to be within the river channel than when releases are above channel capacity.

The Dam Flood Operations Review should consider how various options for these release rates and rates of change of release rates affect the risks of failing to achieve the overall flood management objectives, across a range of different potential flood events.

3.1.10 Contingencies for loss of communications

The DFOM should contain clear guidance on procedures to be followed in the event of loss of communications between the dam and the Authority's incident management team which may be located remotely from the dam.

3.2 Flood operations review studies

It is likely to be difficult for a storage manager, in many situations, to make a well-considered assessment of risks in the process of managing an individual flood event. Flood operations are likely to involve complex decisions about re-prioritisation of the flood management objectives, strategic command principles and release plan, which may be difficult to make in real time. It is therefore recommended that a dam flood operations review study (DFORS) should be undertaken periodically, to inform the guidance on these matters in the DFOM. The DFORS should provide the basis for selection of the priorities associated with the flood management objectives, strategic command principles and release plan, for a given set of circumstances during a flood event.

The DFORS should define triggers for changing the priorities associated with strategic command principles. For a given set of priorities, the DFORS would define the constraints for setting the release plan, including the maximum period for any surcharge to be drained, the likely downstream consequences, the minimum and maximum permissible streamflow rates and the maximum rates of increase and decrease in streamflow.

The DFORS should consider relevant consequences to flood operations, which may include:

- flooding downstream of the dam
- flooding upstream of the dam[7]
- dam safety
- potential reductions in security of water entitlements
- costs to reinstate security of water entitlements, via alternative water supply sources
- impacts on the downstream environment
- impacts on social and economic wellbeing and
- impacts on indigenous values.

Many of the above consequences will impact upon third party stakeholders. The storage manager should consider legal liabilities that may be conferred on them, due to impacts on third parties (see Section 2.1 and Appendix A).

It may be difficult for a storage manager, in many situations, to make a well-considered assessment of risks in the process of managing an individual flood event, to inform the setting of priorities for the strategic command principles and release plan. The study should therefore assess the procedures for prioritisation of the strategic command principles and implementation of a release plan across a wide range of different floods, from those that only just have the potential to cause minor flooding to extreme floods that would cause dam failure. The DFORS should take into account the severe increase in consequences that are likely to result from a dam failure event, over an event that is managed to avoid dam failure.

Where there are benefits to be gained and the storage manager has the expertise, capability and systems to do this, the DFORS should consider potential operational strategies that apply to each of the four types of forecasting approaches listed in Section 5.1. It may be that a particular storage manager only has the expertise, capability and systems to use a relatively simple system, for example forecasting based upon observed water levels or reverse routed inflows. However, some storage managers are likely to have sufficient resources and expertise to use more sophisticated systems, based upon inflow or rainfall forecasts. In this case, the DFORS should be used to objectively test choices made about the forecasting approach and supporting infrastructure that is to be used to manage flood operations.

With any gated spillway (or other controlled outlets with significant flow capacity) it is possible to devise large variations and permutations in possible release plans. Giving the highest priority to dam safety (notably managing risks of extreme floods) will often be a constraining factor. Nonetheless there are still likely to be multiple variations of gate operations procedures that would maintain a similar risk profile presented by extreme floods but would provide varying levels of mitigation for more common floods. In addition, different gate operations procedures are likely to cause different impacts on different parties, who are at different locations and may be affected by different magnitudes and durations of flooding. It is difficult to near impossible to define or achieve gated dam flood operation procedures that would be optimal for all flooding conditions for all affected parties, as there are almost always trade-offs involved. The DFORS should attempt to find a robust and defensible approach to identifying and managing these trade-offs.

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[7] For many dams, these may be negligible and could therefore be ignored

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3.3 Examples of flood operations review studies

Further insight on the potential scope of a DFORS may be gleaned by considering some similar examples.

3.3.1 Lake Eildon

An investigation of options for the volume of the surcharge compartment at Lake Eildon was undertaken by SKM (2010). This study was a DFORS, in a limited sense. The study only considered four potential surcharge compartment options (0, 0.6, 0.9 and 1.2 m depth). However, the 2010 study did not consider other potential management options, such as alternative methods for forecasting inflows, variations in full supply level or variations in maximum rates of increase or decrease in release rates. SKM (2010) only looked at peak release rates, water levels and storage volume at the end of the event and only considered three potential hydrographs: the October 1993 observed flood and single representative hydrographs for each of the 1 in 100 and 1 in 500 design flood events.

3.3.2 South-East Queensland

Optimisation studies were undertaken for North Pine, Wivenhoe and Somerset dams (Queensland Department of Energy and Water Supply, 2014a, 2014b). In these studies, several options for dam operations were assessed against competing objectives, balancing dam safety, security of urban water supply, impacts downstream of the dams, environmental performance and economic outcomes. **Figure 3-2** shows the 32 different options for operational strategies that were investigated for operation of Wivenhoe Dam, in the *Wivenhoe and Somerset Dams Optimisation Study (WSDOS)*. The options considered in WSDOS tested variations in the size of each of the storage compartments in the reservoir: the water storage compartment (below FSL); compartments to be utilised for mitigating flooding of urban areas (in Brisbane and Ipswich); compartments used to manage flooding of six different bridges (in rural areas, between Wivenhoe Dam and the outskirts of Brisbane) and the compartment reserved for protecting the safety of the dams. *WSDOS* found that reducing the full supply volume of Wivenhoe Dam reduced expected flood damage and impact costs. However, the reduced flood cost was of similar magnitude to, or less than, the expected increase in bulk water infrastructure and operational costs; and given the order of accuracy of the work completed. Therefore, the total cost comparison did not support a permanent reduction in the full supply volume of Wivenhoe Dam.
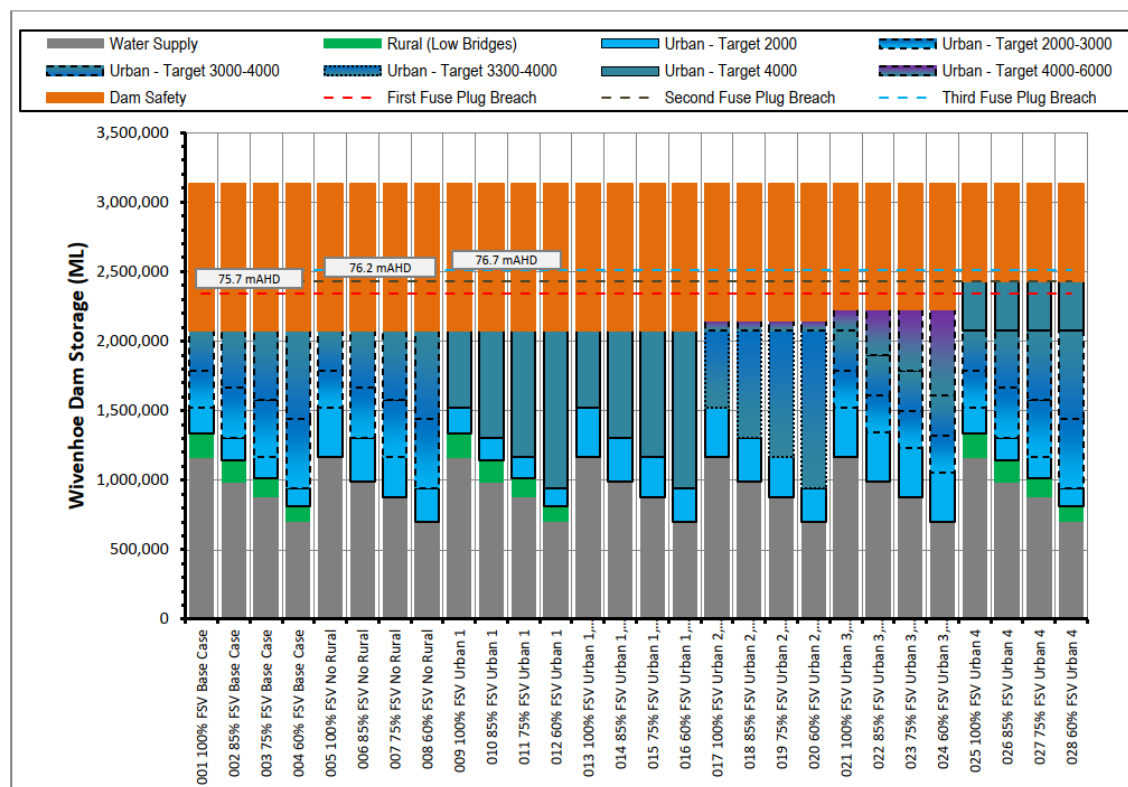
Figure 3-2 Operational strategies investigated in the *Wivenhoe and Somerset Dams Optimisation Study*, **reproduced from Figure S2 of (Queensland Department of Energy and Water Supply, 2014a) and Figure 5-12 of (Seqwater, 2014)**

WSDOS also considered variations in strategies for targeting minimum and maximum flows in the Brisbane River at Moggill, on the upstream margin of Brisbane's suburbs. The Wivenhoe and Somerset Dam study identified a preferred strategy (called alternative urban 3), which produced improved flood mitigation outcomes across a wide range of different floods. The current DFOM for Wivenhoe and Somerset dams implements the recommendations of the optimisation study, with the preferred strategy represented via a target flow guide curve, reproduced in **Figure 3-3**. The guide curve provides minimum and maximum acceptable flow rates at a key forecast location downstream of Wivenhoe Dam (Moggill), resulting from the proposed release plan, given the forecast peak level in Wivenhoe Dam. The optimisation study found that specifying a target maximum flow at Moggill of up to 6,000 m³/s (the alternative urban strategy 3) provided improved overall flood mitigation benefits than the base case strategy, which targeted a maximum release at Moggill of 4,000 m³/s and a transition to the dam safety strategy for a Wivenhoe reservoir level of 74 m AHD.

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— Flood Mitigation Strategy Target Line (based on the Alternative Urban 3 Target Line)

■ Release Plan Acceptable

■ Release Plan Not Acceptable

■ Release Plan Acceptable only if the rainfall event is judged likely to be complete or nearly complete and it is expected the Drain Down Strategy will be selected in the next 12 hours

■ Release Plan Acceptable only if the selected Target Maximum Flow at Moggill is less than the estimated peak flow in the Brisbane River excluding releases from Wivenhoe Dam

■ Release Plan Not Acceptable, Strategy must transition to the Dam Safety Strategy.

Figure 3-3 Target flow guide curve at Moggill in the DFOM for Wivenhoe and Somerset Dams, reproduced from Figure 5.3.1 of Seqwater (2019)

The *North Pine Dam Optimisation Study (NPDOS)* considered just eight potential options, with the water supply compartment varying between 42%[8] and 100% of the nominal full supply volume for the base case (going into NPDOS in 2014). Three of the options were similar to a non-seasonally defined target filling curve (using Victorian terminology), with the water supply compartment operated to start between 42% and 85% full but flood releases not commencing until simulated flow forecasts indicated that the reservoir will reach 100% of the water supply compartment volume. North Pine Dam may be a more relevant analogue for several of the gated dams in Victoria than the Wivenhoe/Somerset dam system, as North Pine Dam does not

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[8] 42% full represented the fixed spillway crest level for North Pine Dam, which therefore was the lowest level that could practically utilised as the lower bound for the flood mitigation compartment.

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have a designated flood storage compartment (i.e. no surcharge, to use Victorian terminology), it is the only gated dam in its catchment and there is a relatively short distance between the dam and the first of the potentially flood affected properties.

NPDOS analysed flood outcomes for eleven flood hydrographs: the five largest historical floods with suitable data (1974, 1989, 1999, 2011, 2013) and six design flood events (1 in 20, 100, 500, 1,000 and 2,000 AEP events and the Probable Maximum Flood). NPDOS found that the flood mitigation benefits, in terms of properties impacted, of lowering North Pine Dam full supply volume from 100% to either 85% or 75% were, "marginal and accrue mainly due to reductions in transport infrastructure damage." However, a semi-permanent lowering of the dam full supply volume to around 90% was recommended because it provided operational flexibility to pass some small floods and it improved the dam's ability to pass extreme floods. Short-term impacts on urban water supply security of a lowering to between 75% and 90% of full supply volume were identified as being small. It was recommended that the water supply impacts were reassessed, once dam safety upgrades had been completed at North Pine Dam, which may allow consideration of returning back to the original full supply volume.

The relevance of the studies for Wivenhoe, Somerset and North Pine dams are that they provide examples of the:

- Overall framework for DFORS, including consultation with all of the different stakeholder groups and incorporating the different types of consequences and benefits (water supply security, flood mitigation, dam safety, environmental etc.)

- Importance of specifying both minimum and maximum target flow rates, which inform the setting of flood management objectives, and the prioritisation of strategic command principles and release plans, on achieving downstream flood outcomes.

- Importance of testing options for transitions between the boundaries of each of the storage compartments (water supply, surcharge / flood mitigation and dam safety).

- Relevance of considering a wide range of different rainfall events and floods, considering overall rainfall event magnitude and the space-time pattern of rainfall across the catchments of the dams and tributaries downstream of the dams. The WSDOS study used 600 different space-time rainfall patterns, which were used to generate more than 5,000 different potential flood events that were used to test flood mitigation performance (Jordan *et al.*, 2014).

The WSDOS Report (Queensland Department of Energy and Water Supply, 2014a) noted that,

"Advice was sought from the BoM about simulations to test the robustness of relying on rainfall forecasts for operational decision making at the dams. While the science underpinning rainfall forecasts is continually being improved, BoM advised that forecast models 'have less skill for higher rainfall intensities and while guidance may indicate that a heavy rainfall event is possible, it is only guidance and should be used in that way.' *At present, temporal and spatial uncertainties exist with forecast rainfall which undermines confidence in their use for flood operations. Thus, Seqwater has been in discussion with BoM about potential collaborative research and investigation into the potential future use of rainfall forecasts in dam operations."*

It is our current understanding that BoM and Seqwater are continuing work together to scope out the research that would be required for future use of rainfall forecasts in dam operations.

3.3.3 Callide Valley, Central Queensland

The *Callide Valley Flood Mitigation Study* (Queensland Department of Energy and Water Supply and Sunwater, 2017) considered operational strategies for Callide Dam, which has six radial spillway gates, along with other potential flood mitigation options in the study area. The Callide Valley also includes Kroombit Dam, which has an ungated spillway, and the options considered in the study included alternative operations at Callide Dam, infrastructure upgrade options to raise Callide or Kroombit dams or construction of a new flood mitigation storage and local flood mitigation options, including construction of levees, raising of building and roads and voluntary property buy-back.

The Callide Valley study had a simpler hydrological framework than the Wivenhoe and Somerset dam studies, in that the options were only tested for ten different flood hydrographs: six historical flood events and four design events, with nominal AEPs of 1 in 50, 100, 500 and 2,000. The Callide Valley study simulated flood inundation outcomes using a calibrated TUFLOW hydraulic model. Option assessment incorporated reduction in direct and indirect flood damage costs, capital and operating costs for infrastructure upgrades and economic impacts due to potential reductions in reliability of water supply delivered to irrigators.

3.3.4 Western United States of America

Forecast Informed Reservoir Operations (FIRO) is a collaborative project being undertaken in the western states of the USA, with a goal of developing reservoir operations strategies that better informs decisions to retain or release water by integrating additional flexibility in operation policies and rules with enhanced monitoring and improved weather and water forecasts (Center for Western Weather and Extremes, 2021). One of the first investigations undertaken by FIRO was investigation of various strategies for releases and pre-releases, for Lake Mendocino, in the Russian River Basin, California (Delaney *et al.*, 2020). Further investigations are being undertaken by FIRO for Prado Dam, in the Santa Ana River Basin, and the Yuba-Feather River Basins (both in California).

The FIRO study for Lake Mendocino analysed the improvement in flood mitigation and water supply outcomes that could be achieved by pre-releases informed by 15-day flow forecasts. The pre-release policy was informed by the flow forecasts, as a potential alternative to the equivalent of what would be referred to in Victoria as target reservoir filling curves, which vary seasonally across each year. For Lake Mendocino, the model found a 33% increase in median stored volume in the water supply compartment at the end of the filling season by adopting FIRO over fixed seasonal filling curves, without marked changes in flood frequency for locations downstream from Lake Mendocino (Delaney *et al.*, 2020). The Lake Mendocino study demonstrated the importance of using ensembles that appropriately represent the bias and spread of the probability distribution of forecast rainfall and flows, in order to reliably estimate the changes in outcomes that would be delivered from forecast products.

3.3.5 Other relevant international studies

Todini (2014) sets out the mathematics behind a conceptual framework for optimising dam operations for multiple objectives, informed by forecast products. Todini (2014) then goes on to provide very brief overviews of the practical benefits delivered from the optimisation approach applied to two reservoirs: Lake Como, Italy, and the High Aswan Dam, Egypt.

3.3.6 Relevance of these examples to Victoria

In the studies discussed above from Queensland and the USA, a common feature is the need to consider multiple objectives and the importance of engaging with all of the stakeholders that could be impacted by dam operations. However, it should be noted that legislation differs in other jurisdictions, which impacts upon how risks are allocated between the dam owner and other stakeholders. For example, legislation in Queensland protects the operators of Wivenhoe, Somerset and North Pine dams from legal liability for flooding caused by releases, where the dams are operated in accordance with the relevant DFOMs. By contrast, the strict liability provisions in the *Water Act* (Victoria, 1989) are unlikely to offer the same level of legal protection to Victorian water corporations, even if a Victorian dam were to be operated in accordance with its relevant policies and manuals.

Given the current level of legal protection afforded storage managers in Victoria under the *Water Act* (Victoria, 1989), DFORS undertaken in Victoria might usefully consider how the consequences and benefits would accrue to different stakeholder groups, under each of the potential strategies.

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4. Rainfall forecast products

4.1 BoM rainfall forecast products

This section reviews the various BoM rainfall and streamflow products (shown by the green boxes on **Figure 4-1**), from a standpoint that ensemble forecasts are essential for risk assessments of dam operating options, with respect to meeting multiple objectives.

The BoM provides several different rainfall forecast products. Most of these products are available, for a fee, to registered users via file transfer protocol (FTP) services. The registered user services allow registered users to directly intersect the rainfall forecasts with their locations or catchments of interest and obtain numerical values of the forecast.

Some products, or aspects of these products, are also available for free on the BoM's public website. Where free access to products is provided, it is often in the form of contour maps of rainfall ranges, rather than providing numerical values. The products on the BoM's public website may therefore be useful for situational awareness but unsuitable for quantitative modelling of floods by water corporations.

There are four rainfall forecast products that are currently available to registered users from the BoM:

1. ACCESS Numerical Weather Prediction model rainfall forecast outputs

2. Australian Digital Forecast Database (ADFD)

3. Probability Matched Ensemble (PME) and

4. Rainfields

Discussion of each of these products is provided below. The following criteria are used to describe each of the products:

- Domain: spatial coverage of the forecast product

- Spatial resolution: horizontal dimension of the grid-cell elements in the forecast product

- Temporal resolution: duration of each time step in the forecast product

- Forecast horizon or lead time: period that each forecast is provided for, from the time the forecast is issued

- Forecast update: time of each day, or number of times each day, that the forecast products are updated and reissued

- Latency: time delay between when a forecast is created and when it is issued by the BoM

- Type: deterministic (single forecast), ensemble (multiple forecasts, providing all spatial and temporal data for the forecast period) or probabilistic (only statistics of the forecast)

As will be explained in further detail in this section and Section 4.3, the range of currently available rainfall forecast products are unsuitable for probabilistic modelling which would be required to inform quantitative decision making. However, they may provide useful situational awareness to flood forecasters.

4.1.1 ACCESS Numerical Weather Prediction model rainfall forecast outputs

BoM runs a suite of Numerical Weather Prediction (NWP) models, known as the Australian Community Climate and Earth-System Simulator (ACCESS) suite (Bureau of Meteorology, 2021). Characteristics of the most relevant four ACCESS models, from the Australian Parallel Suite version 3 (APS3) are listed in **Table 4-1** (Bureau of Meteorology, 2020b, 2021).

Table 4-1 Characteristics of ACCESS Numerical Weather Prediction models

Model	Domain	Type	Spatial resolution	Forecast horizon	Forecast update
ACCESS-G3	Global	Deterministic	12 km	10 days	4 times a day
ACCESS-GE3	Global	Ensemble (36 members)	33 km	10 days	4 times a day
ACCESS-C3 VICTAS	Victoria and Tasmania	Deterministic	1.5 km	~3 days	4 times a day
ACCESS-C3 VICTAS	Victoria and Tasmania	Ensemble (12 members)	2.2 km	~3 days	4 times a day

Raw forecasts from these NWP models are subject to bias. In case of ensemble forecasts, the ensemble spread is also likely to be unreliable. Therefore, post-processing is necessary to correct the bias and ensemble spread through statistical calibration. Bias and ensemble spread correction should be undertaken in a manner that preserves the coherence in forecast rainfall for ensemble members between catchments that are upstream and downstream of the dam(s). Ensembles can also be created through statistical calibration, in the case of deterministic NWP forecasts.

The BoM's calibration process for ACCESS uses statistical models, established on archived NWP data and observation data. Statistical calibration can be carried out for a point, grid cell, sub-catchment or a catchment. The calibration is usually done separately for different locations and lead-times. Therefore, the calibrated ensemble members need to be linked spatially and temporally to give realistic structures. This can be achieved by using a popular empirical method called Schaake shuffle developed by the USA National Weather Service (Clark *et al.*, 2004).

For the BoM 7-day streamflow forecasting, discussed in Sections 4.4.2 and 6.3, the Catchment Hydrologic Pre-Processor (CHyPP), developed by CSIRO, is used (Robertson *et al.*, 2013; Shrestha *et al.*, 2015). For the BoM Australia-wide gridded runoff forecasting (being established, see Section 4.4.3), the Seasonally Coherent Calibration model developed by the University of Melbourne is used (Wang *et al.*, 2019; Yang *et al.*, 2021). These calibrated ensemble precipitation forecasts are made available to some registered users.

Additionally, the BoM also has licences to use raw forecasts from several overseas NWP models, but generally cannot provide original data to third parties. It may be possible for water agencies to arrange access to the data with the overseas forecast providers directly, although this may be complicated and expensive to organise.

4.1.2 Australian Digital Forecast Database (ADFD)

The Australian Digital Forecast Database (ADFD) provides an assembly of forecasts for Australia. The ADFD is a database of official weather forecast elements produced by the BoM, such as temperature, rainfall and weather types, presented in a gridded format. "The forecasts use a blend of Australian and international model data with the latest science, technology and expert meteorologist input to best represent expected weather", at each point in the grid (Bureau of Meteorology, 2020c).

ADFD provides individual forecast for point locations across Victoria, on a 0.03° (about 3 km) grid spacing. Spatial and temporal correlations in forecasts across the grid cells are not necessarily preserved, which presents difficulties when attempting to characterise uncertainty in the forecasts. So, for example, averaging the ADFD 25th percentile rainfall forecasts for a group of grid cells across a catchment will not give the 25th percentile rainfall forecast for that catchment. Similarly, the sum of the 10th percentile rainfall forecasts for the 3-hour blocks in each day will not give the 10th percentile rainfall forecast for the whole day. Aggregating the low probability rainfall amounts for an extended periods of several days can readily lead to unrealistically high estimates of forecast rainfall.

Characteristics of the ADFD rainfall forecasts are provided in **Table 4-2**. Statistics of forecast rainfall, provided on grids at 3 km resolution, are made available and updated whenever grids are published. In addition, all grids are refreshed at around 6 am and 6 pm Australian Eastern Standard Time (AEST) each day (Bureau of Meteorology, 2020c).

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Table 4-2 Characteristics of ADFD rainfall forecasts (Bureau of Meteorology, 2020c)

Domain	Type	Spatial resolution	Temporal resolution	Forecast horizon	Forecast update
Victoria	Deterministic and probabilistic (not Ensemble)	3 km	3 hours and 1 day	7 days	At least 2 times a day: about 6 am and 6 pm AEST

ADFD provides the following rainfall statistics at each grid cell:

- Mean rainfall total, for each day and each 3-hour period
- 75, 50, 25 and 10% probabilities of exceedance for daily rainfall depths
- 50, 25 and 10% probabilities of exceedance for 3-hourly rainfall depths
- Probability of any rainfall in each day or 3-hour period and
- Probabilities in each day of at least 1, 5, 10, 15, 25 and 50 mm of rainfall

There are some characteristics of the ADFD rainfall forecasts that make them unsuitable for driving flow forecast models for dam operations during floods:

1. As discussed above, ADFD provides individual forecast for point locations and does not preserve spatial or temporal correlations. It is therefore unsuitable for catchment level rainfall forecasts.

2. ADFD provides statistics from the probability distributions, but it doesn't provide ensemble members. Each of the individual ensemble members would be required as input to flow forecasting models, in order to perform probabilistic simulation of flows, dam releases and assess risk.

3. The ADFD are produced from forecasts that assemble results from different NWP and assessment of conditions by BoM meteorologists. The NWP products used for ADFD have, and are likely to continue, to evolve over time. The forecast skill from the NWP and the forecasters is also likely to vary on a day-by-day basis. Even if ADFD provided ensemble members (which it currently doesn't), it may be difficult to represent the true bias and ensemble spread, as this is likely to change over time.

Whilst the ADFD is currently unsuitable for probabilistic modelling, it may provide useful information for making rainfall forecast informed operational decisions. This can be obtained via the registered user product. The BoM's public website also displays it's free "MetEye" data viewer, which displays ADFD daily rainfall forecasts for the next 7 days and 3-hourly rainfall forecast for about 2 days from the time of each update. For situational awareness purposes, the MetEye product may be sufficient, without the water corporation requiring registered user access. The outputs provided for free from MetEye to public users may change in future.

4.1.3 Probability Matched Ensemble (PME)

Probability Matched Ensemble (PME) (or Poor Man's Ensemble) forecasts are derived from a combination of NWP models from Australia (ACCESS-G), the United Kingdom, USA, Canada, Europe, and Japan (Bureau of Meteorology, 2018b, 2019).

PME provides the following rainfall statistics at each grid cell:

- Expected (mean) rainfall total, for each day and each 3-hour period
- 75, 50, 25 and 10% probabilities of exceedance for daily and 3-hourly rainfall depths
- Probabilities in each day and 3-hour period of at least 0.2, 0.4, 0.6, 1, 2, 5, 7, 10, 15, 25 35, 50, 75, 100, 125, 150. 300 and 500 mm of rainfall

PME provides individual forecast for point locations across Australia, on a 0.25° (about 25 km) grid spacing. Spatial and temporal correlations in forecasts across the grid cells are not necessarily preserved. So, for example, averaging the PME 25th percentile rainfall forecasts for a group of grid cells across a catchment will not give the 25th percentile rainfall forecast for that catchment. Similarly, the sum of the 10th percentile rainfall forecasts for the 3-hour blocks in each day will not give the 10th percentile rainfall forecast for the whole day.

Characteristics of the PME rainfall forecasts are provided in **Table 4-3**.

Table 4-3 Characteristics of PME rainfall forecasts (Bureau of Meteorology, 2019)

Domain	Type	Spatial resolution	Temporal resolution	Forecast horizon	Forecast update
Australia	Deterministic and probabilistic (not Ensemble)	0.25° (25 km)	3 hours or daily	8 days	2 times in the morning and 2 times in the evening each day: 5:30 am, 7:40 am, 6:05 pm, 7:45 pm

The PME shares some similar characteristics to the ADFD rainfall forecasts that make them unsuitable for driving flow forecast models for dam operations during floods:

1. PME provides individual forecasts for point locations and does not preserve spatial or temporal correlations. It is therefore unsuitable for catchment level rainfall forecasts.

2. PME provides statistics from the probability distributions, but it doesn't provide the ensemble members. Individual ensemble members would be required as input to flow forecasting models, in order to perform probabilistic simulation of flows, dam releases and assess risk.

3. PME are produced from forecasts that assemble results from different NWP that have, and are likely to continue, to evolve over time. Even if PME provided ensemble members (which it currently doesn't), it may be difficult to represent the true bias and ensemble spread, as this is likely to change over time.

The PME rainfall statistics are calibrated against previous performance of the NWP models, providing more weight to those models that have had stronger past performance and less weight to those with poorer performance. Calibration of the probabilities in the PME changes each day, using the rainfall for the previous 35 days and the 71 days centred on the same date of the previous year (Bureau of Meteorology, 2018b). Whilst the PME therefore has some level of bias and spread correction, unless the 106 days happen, by chance, to include a large rainfall event, it will be limited in its usefulness for applying appropriate bias correction for heavy rainfall that could give rise to floods.

4.1.4 Rainfields

Rainfields produces real-time quality controlled, rainfall estimates and forecasts using radar, rain gauges and NWP models (Bureau of Meteorology, 2020d). It generates:

- Calibrated radar rainfall, which uses bias corrected radar reflectivity from real-time rain gauge observations.

- Merged rain gauge and radar rainfall, which blends real-time rain gauge observations with calibrated radar rainfall.

- Rainfall forecasts incorporating ensembles and probabilistic information.

Characteristics of the Rainfields products are provided in **Table 4-4**.

Rainfields products can be obtained for a Victorian mosaic, which would cover all of the Victorian dam sites, at 1 km spatial resolution. In addition, for some products there is data available for a 256 x 256 km domain centred on some of the Victorian radars: Laverton, Yarrawonga, Bairnsdale, Mildura and Rainbow. Rainfields derived rainfall accumulation products for 5-min resolution, 1-hour resolution, 24-hour period to 9 am and for the period since 9am are also available on the BoM's website (http://www.bom.gov.au/australia/radar/), for radars that support these Rainfields products. The (backward looking) quantitative precipitation estimates provided by Rainfields are likely to be useful for dam owners that would model inflows using rain-on-ground forecasts. The accuracy of rainfall estimates derived using radar, in combination with rain gauges, will depend upon a number of factors, including the distance of the radar from the catchment of interest, meteorological conditions and the number of rainfall gauges recording rainfall across the radar domain that are used in the radar/rain gauge merging process (Jordan, 2000; Jordan *et al.*, 2003). Dam owners should consider Rainfields as a useful adjunct to any ground-based rain gauge telemetry systems that they may have in place because Rainfields performs an optimal merging of rain gauge and radar data[9]. In many

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[9] Post-processing of rainfall data for an event may include additional pluviograph and daily-read rainfall gauges in the radar/rain gauge merging process, which may improve the accuracy of the rainfall field for post-event analysis.

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situations, it is likely that Rainfields, informed by both the radar and the gauges, will provide a better picture of the spatial and temporal pattern of rainfall that has fallen across the catchment than the gauge data available to the water corporation. Rainfields products are updated very often, every 5 to 15 minutes depending the product, with very small latency (typically a few minutes).

Rainfields provides two sets of (forward looking) ensemble rainfall forecasts: a 30-member ensemble for the next 2 hours and a 10 member ensemble for the next 12 hours. The Rainfields ensemble forecasts are derived from extrapolation of the movement of the rainfall cells on the radar and statistical downscaling from the ACCESS-C3 NWP forecasts. As Rainfields provides the ensemble members, the forecasts could be useful for Victorian dam owners, with further work. Before they could be applied to forecasting by Victorian water corporations, the number of ensemble members would probably need to be increased and algorithms would need to be applied to correct the bias and spread of the ensemble members. The bias and spread correction should be focussed on heavy rainfall events and events where heavy rainfall was forecast but did not eventuate.

The other significant limitation of Rainfields rainfall forecasts for dam operations are their short lead times, with the 10 ensemble member forecasts extending out for only 12 hours. Forward looking ensemble rainfall forecasts from Rainfields are updated frequently (every 5 to 10min), and are available just after each new radar volume scan is completed and processed, so dam operators have new rainfall predictions available every few minutes. The 12-hour lead time of Rainfields forecasts is too short to be useful, on their own, for flood operations at dams. Rainfields forecasts would therefore need to be merged, in some way, with other rainfall forecast products to extend to lead times that would be useful for dam operations (i.e. out to 7 or 8 days).

Table 4-4 Characteristics of Rainfields products

Domain	Type	Spatial resolution	Temporal resolution	Forecast horizon	Updated
Victoria mosaic OR 256 km centred on each radar: Laverton, Yarrawonga, Bairnsdale or Rainbow	Calibrated radar rainfall	500 m	5 and 60 min and daily	None (past data)	Every 5 min
Victoria mosaic OR 256 km centred on each radar: Laverton, Yarrawonga, Bairnsdale or Rainbow	Merged rain gauge and calibrated radar	500 m	15, 30, 60 and 180 min and daily	None (past data)	Every 15 min
256 km centred on Laverton	Ensemble forecast (30 members)	500 m	5 min	2 hours	Every 5 min
Victoria mosaic	Ensemble forecast (10 members)	1 km	10 min	12 hours	Every 10 min

An updated version of Rainfields is currently in development, which will update the rainfall forecasting processes. BoM are investigating changes to the forecasting algorithm and computational infrastructure, which will potentially allow for more ensemble rainfall forecast members to be produced (Velasco-Forero *et al.*, 2020). BoM have completed a verification of the proposed update to Rainfields, which analysed the application of the proposed new algorithms to radar data for the October 2019-March 2020 period for ten weather radars, including Laverton. The verification concentrated on rainfall forecasts of 5-minute rainfall intensities for 1 km grid cells, with lead times of 60 to 90 minutes. The verification report (Velasco-Forero *et al.*, 2020) was more focussed on verification of the updated Rainfields forecasting algorithm for use in public weather services, thunderstorm warnings and forecasting of flash floods on smaller catchments, rather than flood forecasts for large catchments. In this context, the proposed update to Rainfields demonstrated

excellent skill in forecasting rainfall, although the skill declines for rainfall intensities around 50 mm/h. Velasco-Forero *et al.* (2020) note that, "it is important to note that there is a significant variation in the quality of the predictions, and verification results vary from radar to radar and from event to event depending of the nature of the radar, event, accumulation threshold, and lead-time." Further work would be required to verify the accuracy of rainfall forecasts from the proposed update to Rainfields (Rainfields3-ADV) for application to dam operations in Victoria, considering the catchment areas for these dams and the relevant time resolution and lead times that are of specific interest to dam owners.

4.2 BoM flood warnings

BoM's flood warnings, issued during flood events, are based on rainfall on ground and precipitation forecasts as advised by duty meteorologists. Duty meteorologists prepare a forecast policy that includes expected rainfall ranges based upon a range of NWP solutions, which are then shared with BoM hydrologists. Normally, the same forecast policy prepared by the duty meteorologists is reflected in the ADFD and other public-facing forecast products. Whilst rainfall forecast products that are available to the public or registered users will normally be consistent with the rainfall forecasts used internally within the BoM for preparation of flood forecasts, there may be some divergence, particularly when meteorological conditions are changing rapidly. There is no systematic means currently in place to ensure that a water authority is able to access the same quantitative rainfall forecast as those that are being adopted by the BoM for flood warning.

BoM's flood warnings provide forecasts that are categorical for each forecast location (i.e. classified as below flood level, minor, moderate or major) with some quantitative information, such as the predicted peak level (or level range) and timing of the peak, timing of transition to the next flood class or timing of flood recession. Forecast hydrographs are not provided in the public facing flood forecasts.

BoM have recently developed a new product, the Flood Scenarios Outlook., which provides two scenarios for forecast flooding: "most likely" and "higher possible" or "credible alternative". The forecasts are categorical for each forecast location (below flood level, minor, moderate, major), with some quantitative information (highest modelled levels), but without giving forecast hydrographs. The forecasts also provide a diagram of modelled forecast flood class (below minor, minor, moderate or major), in 6-hour blocks, for the following 7-day period.

BoM's Queensland flood warning office have recently developed an operational trial product providing forecast hydrographs (currently for some Queensland catchments only). The forecast hydrographs provided in this product are deterministic and based on precipitation forecasts as advised by the duty meteorologists[10]. BoM are currently considering extending the product to other regions, including Victoria.

Whist the BoM does sometimes carry out ensemble hydrological modelling for flood forecasting, the standard flood warning and forecast products cannot be considered ensemble forecasts and therefore are not suitable for use as inputs into detailed ensemble modelling for risk assessment of dam operations. As with the currently available rainfall forecast products, they may be useful for situational awareness. In addition, as discussed in Section 2.3, the BoM have different requirements for their flood forecasts and warning products to Victorian storage managers.

It is noted that there are often direct discussions between BoM flood forecasters and storage managers during flood events. These discussions may often provide useful situational awareness to the storage manager. DFOM should be clear about how information obtained by the storage manager in such conversations may, or must, be applied in planning releases. The DFOM should also be clear about the processes and procedures for documenting and archiving information that is exchanged in these conversations with the BoM.

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[10] There are a small number of catchments in Queensland, for which systems have been established for the BoM to provide the rainfall forecast policy, prepared by the duty meteorologists, to dam owners. Systematic arrangements for providing the same rainfall forecasts used by BoM flood forecasters to registered users, such as dam owners, have not yet been established beyond South-East Queensland. Even with this system in place, some situations have arisen in Queensland where differences have occurred between the rainfall forecasts used within BoM for flood warning and the rainfall forecasts used by dam operators for flood operations.

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4.3 Assessment of forecast rainfall reliability

As discussed in Section 4.5, none of the rainfall or flow forecast products produced by the BoM are well-designed to meet the specific requirements of ensemble flood modelling that would be best practice for dam operations in floods.

In the context of dam operations, rainfall forecasts may be used for two purposes:

1. Quantitative forecasting of dam inflows, to be used directly in release planning or

2. To provide situational awareness of the possible range of forecast inflows, which are not used for release planning.

As discussed in Section 2.1, storage managers are required under s. 122ZL of the *Water Act* to consider multiple objectives in managing dams. An ideal approach is to make probabilistic assessment of consequences of dam operating options, in relation to the objectives, and make informed choices. For example, the DFOM may pre-specify thresholds of consequences and levels of risk tolerance. In real time, the storage manager would assess the probabilities of crossing the thresholds under certain operating options and compare them with levels of risk tolerance. The assessments would then lead to adoption of a release plan, which is consistent with the prioritisation of strategic command principles at that particular time in the flood.

There is evidence in the academic literature demonstrating that for many dam owners and flood forecasters to be able to make accurate and reliable risk assessments, ensemble modelling is essential (Cloke and Pappenberger, 2009; Bahramian *et al.*, 2021). **Figure 4-1** shows a flow-chart of the process for translating externally generated rainfall data and forecasts into an adopted release plan from dams, which would allow for forecast uncertainty, which was adapted from the Cloke and Pappenberger (2009) review. As shown by the grey boxes on the flow chart, there are several gaps in the process that require significant further development before rainfall forecasts could be quantitatively applied to release planning for dams.

The first missing link is post-processing of rainfall forecasts, to produce potential rainfall forecasts (ensemble members) that have an equal chance of occurring over the specific catchment of interest. The model is run with one member of the input ensemble to give a model output, and this is repeated for all input ensemble members to give a collection (ensemble) of model outputs. The ensemble spread of model outputs should then accurately represent the uncertainty of model results. In the case of ensemble precipitation forecasts, each member is associated with a spatial and temporal pattern of precipitation that may possibly eventuate. In the case of ensemble river flow forecasts, each member is also associated a spatial and temporal pattern; here the spatial pattern refers to how flow hydrograph in the main river and hydrographs of the tributary inflows will coincide with each other. The temporal patterns provide valuable information on the uncertainty around the timing of the flood peak. For risk assessments, consequences should be modelled or estimated from each of many possible spatial and temporal patterns, as represented by the full ensemble. For this reason, there is an important distinction between ensemble and probabilistic forecasts. While ensemble forecasts (with sufficient ensemble size) may be easily converted to probabilistic forecasts, probabilistic information alone does not give the individual spatial and temporal patterns of the ensemble forecasts. Therefore, forecast products that provide only probabilistic information are not sufficient for adequately assessing the risks that water corporations and the community are exposed to.
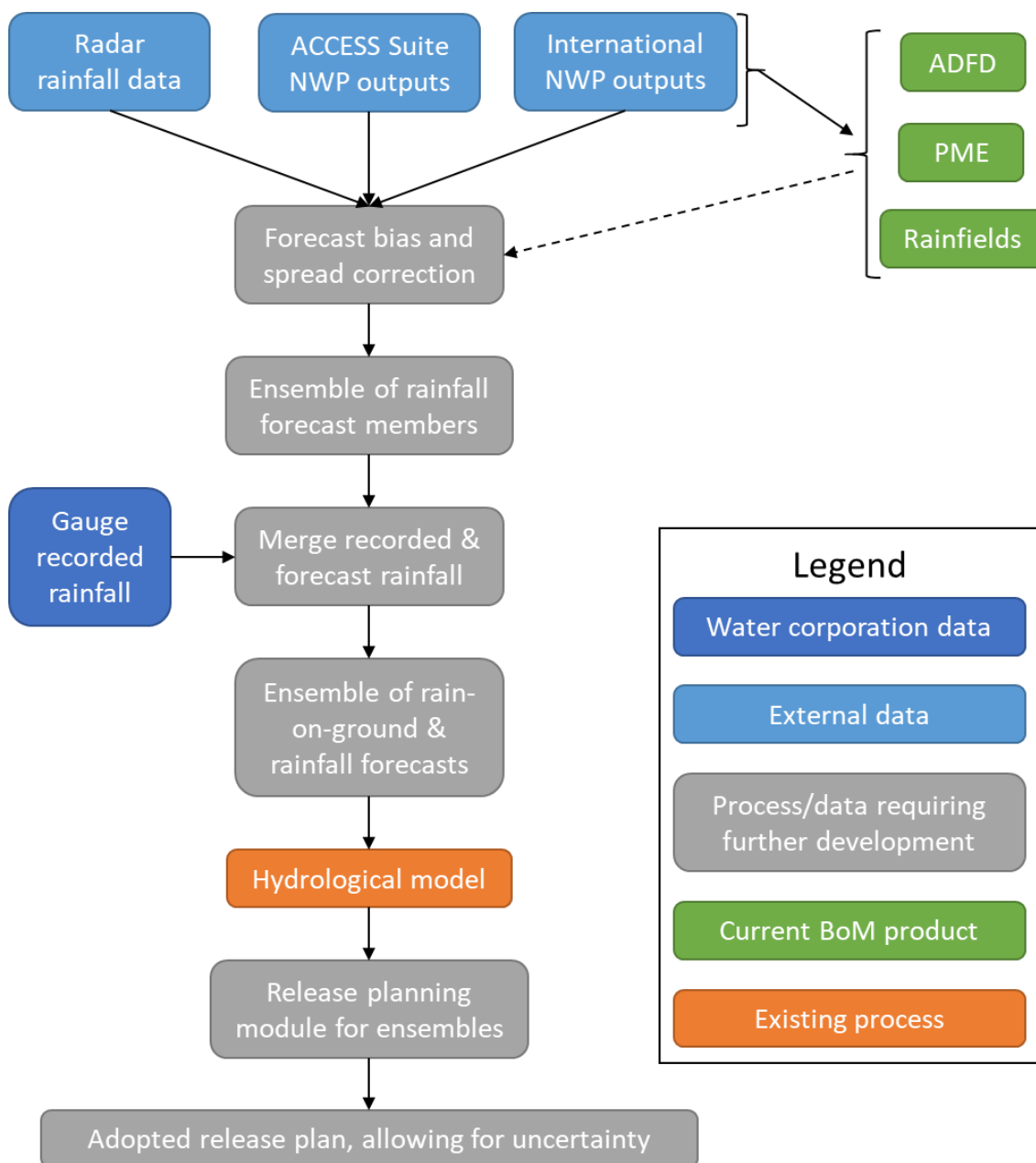
Figure 4-1 Flow chart of process for translating forecast rainfall products into an adopted release plan for a dam, which allows for uncertainty

Further work on bias and spread correction, merging of rain-on-ground with rainfall forecast and reservoir release planning with ensembles, is required before rainfall forecasts may be used. Section 5.8 discusses a recent Australian example of implementing PME rainfall forecasts for flow forecasting in an undammed catchment.

4.4 Potential future developments in rainfall forecasting

4.4.1 Seamless rainfall

BoM have indicated that a new longer-term precipitation forecast product is under development, named Seamless Rainfall, which will initially create ensembles of forecast rainfall fields across Australia at 1-hour time steps and 2 km resolution for up to 8 days ahead by merging rainfall predictions of ACCESS-G3 and ECMWF NWP models. Seamless Rainfall forecasts are expected to be available to registered users during the first half of 2022. This longer-term precipitation forecast product may potentially be useful for driving ensemble modelling to provide risk assessment.

Around mid-2022, the Bureau plans to operationally replace its current rainfall forecasting algorithm (Gridded Operational Consensus Forecasts, or GOCF) with 'IMPROVER' (Integrated Model post-PROcessing and VERification). IMPROVER will output similar rainfall probabilities to GOCF (calibrated to be reliable at the point scale), and utilise both rain gauges and gauge-calibrated radar data as training data. It is also intended that IMPROVER provide test outputs of calibrated model-realistic rainfall for each input ensemble member from mid-2022, which could be suitable for some hydrological processing.

4.4.2 Ensemble rainfall forecast inputs to seven-day streamflow forecasts

For the BoM 7-day streamflow forecasting, a rainfall post-processor developed by CSIRO is used to post-process precipitation forecasts of the ACCESS-G and European Centre for Medium-Range Weather Forecasts (ECMWF). Calibrated hourly ensemble forecasts of precipitation are generated for sub-areas of catchments. The forecasts are then used to force a hydrological model to produce streamflow forecasts. The calibrated precipitation forecasts are not publicly available and do not cover well the total inflow catchments of gated dams in Victoria. However, the technology has the potential to be applied for the catchments of Victorian dams and then provided to registered users.

4.4.3 Ensemble rainfall forecast inputs to AWRA-L

The BoM is working to establish a gridded short-term hydrological forecasting service (out to 7 days) based on AWRA-L. The precipitation forecast inputs to the AWRA-L are 5km gridded ensemble daily forecasts derived from post-processing ACCESS-G forecasts. It covers the whole of Australia. The post-processing uses the Seasonally Coherent Calibration model developed by the University of Melbourne. The post-processed forecasts are not publicly available and currently provides only daily forecasts. The technology can be easily applied to forecasts from international NWP models and adapted to combine forecasts from multiple NWP models.

4.5 Summary

The BoM has a range of precipitation, streamflow and flood forecasting products, which were developed for a range of different user communities. However, none of the currently available products are designed to meet the need of ensemble flood modelling that is required for dam operations in floods. Several products that are in development look promising, such as Seamless Rainfall ensemble forecasts, precipitation post-processing technologies developed by CSIRO and The University of Melbourne, and 7-day ensemble streamflow forecasts. However, further developments are needed to adapt these to produce ensemble rainfall and flood forecasts for specific catchments, which would be required to manage dam operations in a quantitative risk assessment framework.

Although they are not suitable for quantitative rainfall and flood forecasting, the currently available rainfall forecast products may provide useful situational awareness to dam owners.

The (backward looking) quantitative precipitation estimates provided by Rainfields are likely to be useful for dam owners that would model inflows using rain-on-ground forecasts. Dam owners should consider Rainfields as a useful adjunct to any ground-based rain gauge telemetry systems that they may have in place because Rainfields performs an optimal merging of rain gauge and radar data.

Despite the shortcomings of the ADFD rainfall forecast product for true ensemble forecasting, it is recognised that the ADFD 50th, 25th and 10th percentile gridded rainfall forecasts are a convenient product. As a simplified approach, a storage manager may choose to run a three-member "ensemble" of low, medium and high forecast rainfall, populated from the ADFD 50th, 25th and 10th percentile rainfall forecast grids, averaged from the gridded data over the catchment(s) of interest. An analysis of past forecasts is required to determine how best to ensure that the 50th percentile forecast is representative of "typical" forecast accuracy.

5. Flood forecasting systems

5.1 Flow forecasting approaches

There are four types of approaches to making release decisions that may be implemented by storage managers:

1. Managing releases according to defined rules mandating releases for a given reservoir water level without consideration of inflow forecasts

2. Managing releases on the basis of reverse routed inflows to the dam(s), without consideration of inflow forecasts

3. Forecasting inflows using hydrological model(s) with estimated rain-on-ground only

4. Forecasting inflows using hydrological model(s) with estimated rain-on-ground and forecasts for future rainfall.

Figure 5-1 shows that these four approaches form a hierarchy, with an increasing degree of complexity involved in implementing each approach, with each move up the "staircase". Hence, the volume of data, model complexity, level of expertise, computational resources, systems and training required to implement each approach increase as the decision is made to move up the hierarchy.
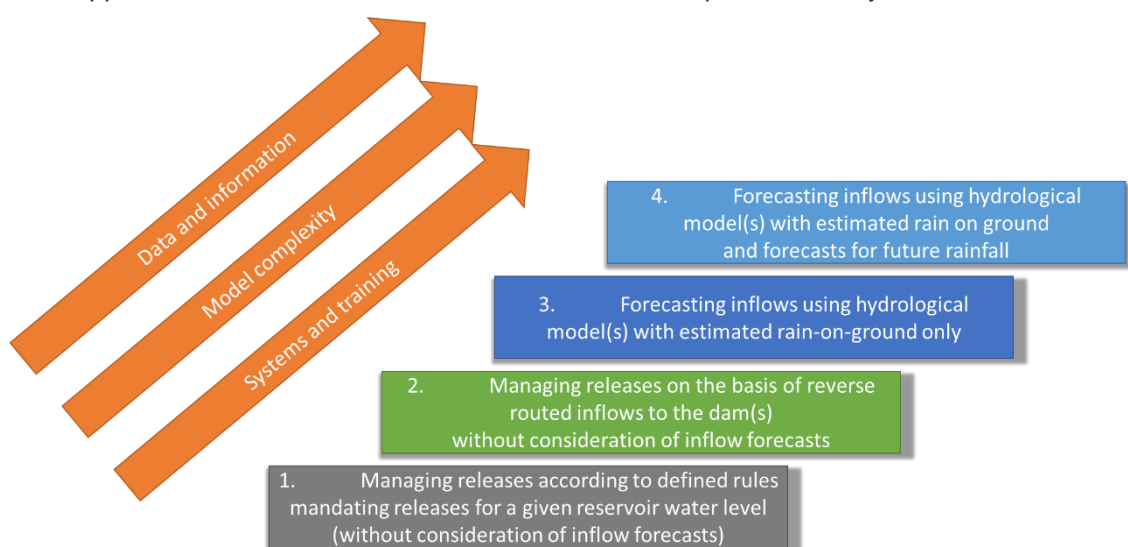
Figure 5-1 "Staircase" hierarchy of flow forecasting approaches

It is not necessarily the case that a more sophisticated approach to forecasting will produce more favourable outcomes, across all potential impacts, for all flood events. It is also possible that inflow forecasts may be used qualitatively (i.e. to enhance situational awareness, plan for the response to the flood event as it unfolds, allocate resources and inform discussions with the wider incident management cohort) or quantitatively (i.e. all of the above, as well as a basis for decision making around whether to pre-release or not, or whether to surcharge a dam or not). Generally speaking, dams with more complex strategic command principles and operations are likely to obtain greater benefits from more sophisticated approaches to flood forecasting. Water corporations should therefore make an assessment of the costs and benefits that would be associated with moving to each increment of complexity in forecasting approaches. The policy to use forecasts should be re-examined after risk, feasibility, and implementation studies and work are completed.

5.2 Flood modelling

The *World Meteorological Organisation (WMO) Manual on Flood Forecasting and Warning* (2011) provides guidance on developing and operating systems for flood forecasting and warning. Victorian water corporations have a role to play in flood forecasting and warning, as discussed in Section 2.3 above, so the *WMO Manual* is directly relevant to that role. The good practices set out for flood forecasting in the *WMO Manual* are also relevant to flood operations undertaken by water corporations for their dams, even where the responsibility for warning then falls to the BoM, under the *Service Level Specification* (Bureau of Meteorology, 2020a) and the *Intergovernmental Agreement* (Council of Australian Governments, 2017).

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If levels 3 and 4 of the hierarchy of flow forecasting (see **Figure 5-1**) are applied, models will be used to forecast flows, using rain-on-ground only or with forecast rainfall. Flow forecasting models and methods should be consistent with the general guidance provided in Chapters 3 and 4 of the *WMO Manual*.

Good practice for flood forecasting in Australia currently applies rainfall-driven catchment models or combined catchment and routing models, which are discussed in Sections 3.2 to 3.4 of the *WMO Manual*. Section 3.2.1 of the *WMO Manual* provides general guidance on rainfall monitoring and forecasting. More specific information on rainfall forecasting products provided in Australia by the BoM is provided in Section 4.1 of this guideline.

Flood forecasting practices in Australia have almost exclusively focussed on event-based rainfall runoff modelling. The most common models applied for flood forecasting in Australia include URBS, RORB and RAFTS, all of which have relatively similar rainfall runoff routing frameworks. The guidance provided in Chapter 3 of the *WMO Manual* should be applied to developing and applying such models, as summarised in **Figure 5-2**.

During an event, flood forecasts should be updated regularly, as new rainfall or flow data is received or rainfall forecasts are updated. Flow forecasts should therefore be updated more frequently in the early stages of rainfall or rising streamflow, or when rainfall intensities are high. With the conceptual rainfall runoff models typically applied in Australian practice, it is common to adjust the loss parameters, and sometimes the routing parameters to accommodate for differences in catchment response between events, as the flood event progresses. For example, in general the losses are likely to be larger after a long period of dry conditions than when the catchment is wet. The DFOM should provide guidance on recommended ranges for loss and routing model parameters.
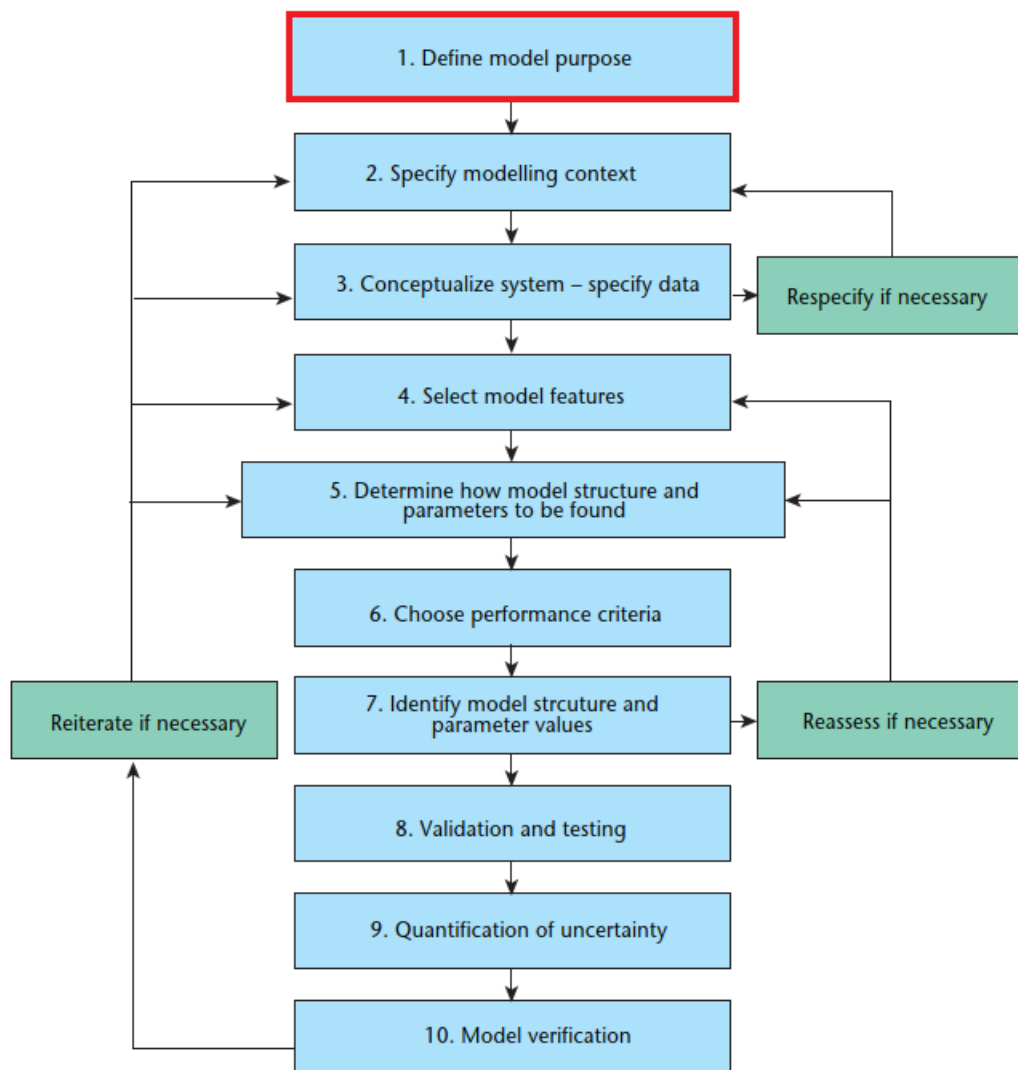
Figure 5-2 Process for developing a flood forecasting model, reproduced from Figure 3.1 of the *World Meteorological Organisation (WMO) Manual on Flood Forecasting and Warning* **(2011)**

5.3 Flood warning gauge networks

General guidance on monitoring networks and data collection and transmission requirements for flood warning services are provided in Section 2.2 and Chapters 5 and 6 of the *WMO Manual* (World Meteorological Organisation, 2011).

Australian-specific recommended performance requirements for infrastructure to undertake flood warning in Australia are provided in the *Flood Warning Infrastructure Standard* (National Flood Warning Infrastructure Working Group, 2019). The recommendations of this standard should be applied by Victorian water corporations for flood operations, adapted in accordance with the specific recommendations provided below.

The *Flood Warning Infrastructure Standard* was written to guide agencies that provide flood forecasts and warnings. Whilst much of this standard is directly relevant, water corporations in Victoria are required to operate their dams in accordance with their legal responsibilities, as discussed in Section 2.1. Their contribution to working with the BoM to provide flood warnings is only one of those responsibilities. In some situations, a different standard of performance may be justified for flood warning infrastructure in order for Victorian water corporations to meet all of their legal obligations.

In most cases, dams owned and managed by Victorian water corporations will be on catchments that are sufficiently large or have reservoir storage capacities that are sufficiently large, for the flooding to be managed as "Riverine flooding", with a time of concentration in the 12 to 24 hours range, according to the definitions provided in the *Flood Warning Infrastructure Standard* (see Table 1, National Flood Warning Infrastructure Working Group, 2019). Accordingly, the latency of reporting should be between 15 and 60 minutes.

Accuracy requirements for rain and flow gauges should be consistent with the requirements in Section 3.5 of the *Flood Warning Infrastructure Standard*, applying the "high accuracy" forecasting requirements.

The flood forecasting system for dams should perform across all floods, including those in the extreme flood range. The default guidance in the *Flood Warning Infrastructure Standard* is for the maximum design intensity to be set according to the 1% AEP design depth. However, for dam flood operations, the maximum design intensity should be set according to the 1-hour duration point Probable Maximum Precipitation (PMP) depth at the site. Similarly, for flow gauges, the "highest anticipated flood level", which is used as one criterion for setting the upper limit of the recording range, should be set by an estimate of the Probable Maximum Precipitation Flood (PMPF) level or the Probable Maximum Flood (PMF) level at the site, if available.

5.4 Transitioning between rain on ground and forecast rainfall

As an event progresses, rain-on-ground data becomes an increasingly important component of the total rainfall timeseries. As shown in **Figure 5-3**, early in the event rain-on-ground data would be blended with forecast rainfall information to produce a composite rainfall timeseries for the event if forecasts are intended to be used for flood operations. As the event unfolds, rainfall forecasts become progressively less important and the rain-on-ground data provides the major contribution to flood estimation.

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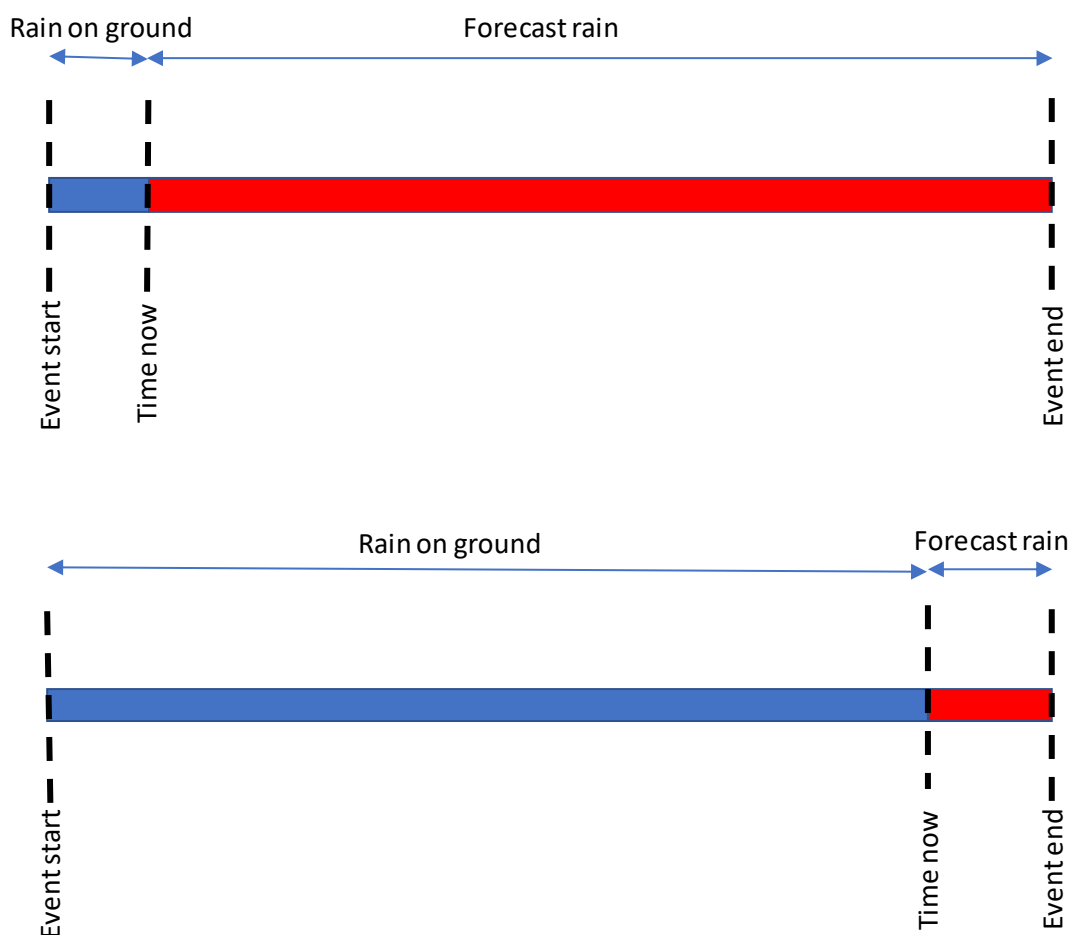
Figure 5-3 Composite rainfall time series at the start (above) and end (below) of a real-time event

The BoM's ADFD and PME rainfall forecast products are provided at temporal resolutions of 3 hours and 1 day and each of these products is currently updated about twice per day, once in the morning and once in the afternoon. Where one the ADFD or PME rainfall forecast products is being used for flow forecasting, the rainfall forecast used for modelling should therefore be updated at each time that the revised BoM forecast is provided, i.e. twice per day. Where the dam owner adopts this approach, as time progresses through the first 12 hours or so of the forecast period, the rain on ground data will gradually overlap with the ADFD or PME rainfall forecast.

A pragmatic approach to resolving this issue would be to:

1. Interpolate the forecast rainfall for the 3 hourly periods from the BoM product (ADFD or PME) on to the same time step as is used in the flood forecasting model (typically this will be 1 hour, or possibly ½ hour)

2. As the data from the recorded rain on ground overlaps the forecast data, replace the interpolated rainfall forecast with the data from rain on ground. For example, for the first flood forecast run after 8 am local time, the forecast rainfall for the first two hours of the forecast period (6 am to 8 am local time) would be replaced by recorded rainfall data.

3. Roughly every 12 hours, new rainfall forecast information would be available from the BoM. At this point in time, replace all of the rainfall forecast with the revised forecast and return to step 1, above.

It should be noted that timing and location errors in rainfall forecasts can contribute significantly to the overall errors that have been observed in forecast rainfall. It is possible that the rainfall forecast total, for example across a 24-hour period, could be correct but the forecast rainfall could occur too late in the forecast period, resulting in "double counting" of the rain on ground (early in the period) and the forecast rainfall (later in the period). Conversely, a rainfall forecast may occur to early in the forecast period, resulting in "missing" forecast rainfall over-written by low rain on ground early in the forecast period. It is difficult to provide general guidance on how these situations should be addressed.

5.5 Reservoir release planning

Having established the inflow hydrograph to the dam(s) (or ensemble of hydrographs, with forecast rainfall), it will be necessary to route these through the storage to derive a release plan. As discussed in Section 3.1.4, the release plan should define the indicative releases that the storage manager intends to make over the remainder of the flood event. The release plan should be consistent with the overall flood management objectives for the dam and thus also with the strategic command principles. The release plan should also be consistent with the requirements set out in the DFOM.

Some iteration may be required in prioritising strategic command principles, testing a release plan that is consistent with those priorities, assessing the degree of compliance of the proposed release plan against the priorities, testing an alternative set of priorities and then repeating the cycle.

Relatively simple procedures, such as defined rules on releases for a given reservoir water level (level 1 in the hierarchy of **Figure 5-1**) may be substantially automated within a spreadsheet or hydrological model. For example, RORB contains gate operations procedures that have been developed for several Australian gated dams, implementing a water level to release rate relationship. RORB may be implemented within WaterRIDE™ (see Section 5.7 below).

More sophisticated forecasting approaches, involving planning releases in response to forecast inflows (and also sometimes forecast flows downstream of the dam(s)), will typically require a human forecaster to drive a decision support tool. An example of this is the RTC-Tools module (Deltares, 2021), which is available within Delft-FEWS (see Section 5.7 below).

Considerable care should therefore be applied in adopting spreadsheet-based approaches to release planning for dams. The dangers of errors in spreadsheets that are applied to make important decisions are well documented in the literature (e.g. see Panko, 1998, 2008; Powell *et al.*, 2008). Any spreadsheet template that is used for release planning must be thoroughly checked before it is used. Controls must be implemented in the spreadsheet, to minimise the chances of forecasters introducing errors in the computations during the management of a flood event. Spreadsheet based release planning systems are likely to be unsuitable for ensemble forecasting with multiple hydrographs incorporating rainfall forecasts (level 4 of the hierarchy of **Figure 5-1**).

5.6 Integration systems

Data collection, quality control of the data, flood modelling, ongoing staff training and reservoir release planning are all components of an integrated system for flood operations. Good practice integrates these components into an integrated software system (*WMO Manual*, 2011, Section 5.3.7).

Figure 5-4 shows the components of an integrated flood forecasting and dam operations system, for a system that is driven by rain-on-ground flow forecasts only. The pale-yellow shape shows the boundary of all of the components that sit within the integrated system. The integrated system should:

- facilitate data manipulation processes, such as:
  - serving data
  - undertaking quality control checks (both automated and manual)
  - conversion of water levels to flows or storage volumes using rating curves
  - estimating initial catchment wetness and initial loss
  - interpolating point data to spatial estimates and
  - intersection of gridded rainfall estimates with model sub-area boundaries.
- automate processes for archiving all:
  - data
  - forecaster decisions and
  - the forecasts themselves.
- facilitate forecaster-driven processes, including:
  - forecaster driven checks of data quality
  - hydrological model calibration

- release planning from the dam

- prioritisation of the strategic command principles

- communicating the adopted release plan to the BoM and other agencies and

- post-event analysis and reporting.

Figure 5-5 shows the components of an integrated flood forecasting and dam operations system, for a system where forecast rainfall inputs are added. Such a system would require access to the BoM's rainfall forecast products via FTP or similar. Those rainfall forecast products would then need to be combined with the rain-on-ground estimates by the integrated system. Further discussion on this process is provided below. The integrated system would also need to facilitate ensemble runs of the hydrological model, which the system would then need to incorporate into the release planning module.
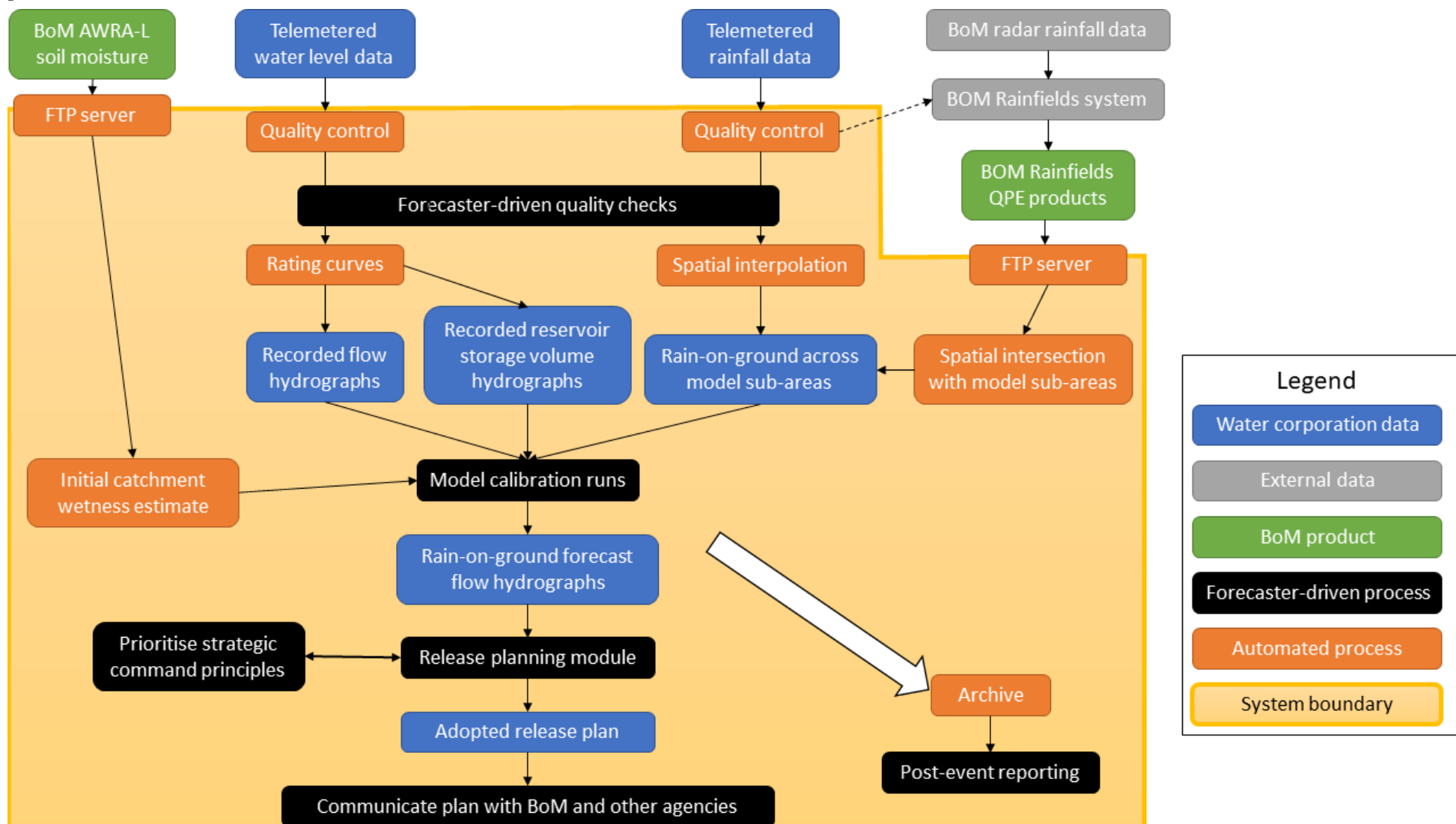
Figure 5-4 Integrated flood forecasting system for dam operations, for a system implementing rain-on-ground forecasting only
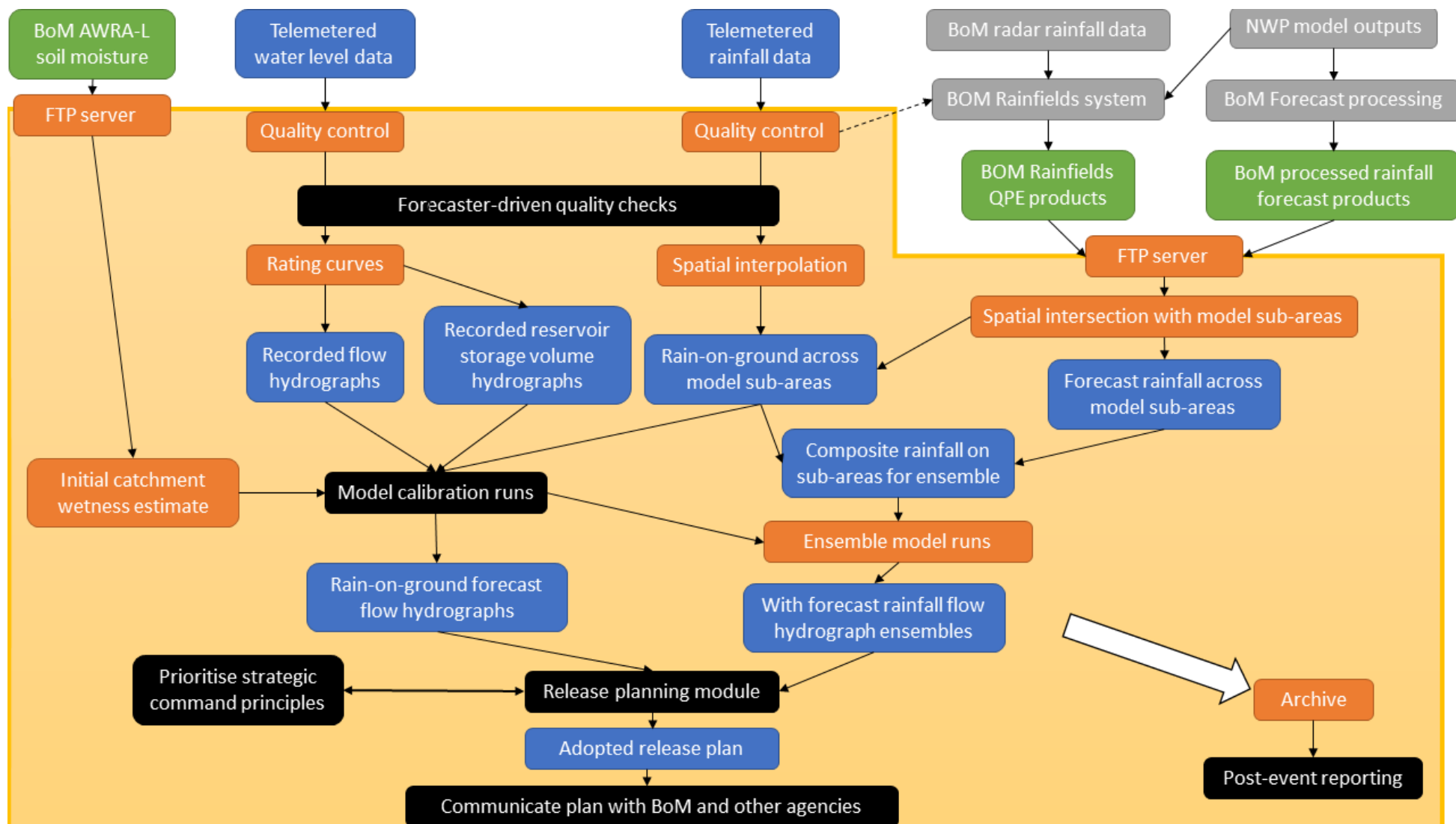
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Figure 5-5 Integrated flood forecasting system for dam operations, for a system implementing rain-on-ground and rainfall forecast generated flows

The modelling system will need to ingest, quality control and analyse data from numerous sources. This will typically include rainfall, water level and streamflow data being recorded in real-time at the portfolio of event reporting rainfall and river level sensors (e.g. an ALERT system) owned by water corporation, the BoM and possibly other organisations that are sharing data via the data collection network. Typically, this data will be received in real-time into a system, such as Enviromon, which undertakes some basic quality control and database storage functions. Additionally, it will be necessary to obtain, store and analyse forecast rainfall information presented as gridded data from the BoM, which are discussed in Section 4.1. The BoM products are currently provided in NetCDF format via file transfer protocol (FTP), so the integration system should have the capacity to automatically ingest the NetCDF data from the FTP site, unpack it from compressed format and allow the user to map or display it, over the catchment(s) of interest.

The integration system should then include an algorithm which produces complete rainfall timeseries estimates over each catchment to be used for forecasting, smoothly transitioning from rain-on-ground recorded at the sensor network to forecast estimates based on BoM data (in situations where rainfall forecasts are to be applied). If rainfall forecasts were to be used to inform quantitative decision making, it will typically be necessary to produce an ensemble of rainfall time series that combine the rain-on-ground (same for ensemble members), with each of the different ensemble members for the remainder of the forecast outlook period.

The rain-on-ground data will need to be spatially interpolated to derive rainfall depths and temporal patterns across each sub-area in the hydrologic models. This is typically done using a technique such as Thiessen polygons. This approach should be set up prior to a flood event and needs to be sufficiently flexible to cope with situations such as new rainfall gauges being added to the network and/or gauges becoming inoperable or providing invalid data for (and possibly part-way through) a flood event.

Basic output checks will also be required so that flood forecasters can easily manually review and plot rain-on-ground records and check for erroneous or inconsistent data.

5.7 Examples of integration systems

Given the number and interaction of processes required in these systems (see **Figure 5-4** and **Figure 5-5**), an integrated software solution to manage this is essential. In Australia, the most commonly deployed systems for flood forecasting are Delft-FEWS and WaterRIDE™.

Delft-FEWS (Forecast and Early Warning System) is a Dutch product which has gained a significant foothold in the Australian flood warning industry over the last five years. There is an active Australian user base for FEWS. It has been adopted by the BoM as the basis for their flood forecasting operations and many of the major dam owners have set up and actively use FEWS for real time operations, including GMW and SRW. There are other agencies such as Melbourne Water and several local governments who use it for flood forecasting.

WaterRIDE™ is produced by Advisian out of their offices in Sydney. The software is primarily designed for management of flood modelling results but has an additional "Forecast Console" module. Use of this module allows the software to be used in a real time manner. There are between 20 and 25 other organisations using WaterRide for real time flood operations across Australia. It already has the ability to incorporate both RORB and RAFTS models and could relatively easily be adapted to run MIKE FLOOD models in real time. A WaterRIDE™ system has been adapted for flood operations by Townsville City Council for Ross River Dam (Jordan *et al.*, 2020) and is currently being implementing for Scrivener Dam in Canberra (Lake Burleigh Griffin).

5.8 Ensemble approaches

Best practice forecasting for dam operations would utilise an ensemble of flow and rainfall forecasts. Implementation of ensemble flow forecasting would require preparation of forecast rainfall ensemble members.

Bahramian *et al.* (2021) recently released a paper that demonstrates the implementation of aspects of the ensemble flow forecasting process. They modelled flood forecasts for the 3,876 km² Gregor's Creek catchment, in the Upper Brisbane River basin. They simulated forecast rainfall for a 3-day period, which was used to simulate the forecast accuracy in generating flood hydrographs, for a library of 31 different observed floods over 20 years. The bias and uncertainty in the rainfall forecasts was simulated by comparing forecasts from the PME with AWAP gridded rainfall data across the catchment, derived by analysing the library of PME rainfall forecasts prepared over a 6-year period (2010-2016). Flow forecasts were modelled using the RORB

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rainfall runoff routing model. Loss parameters in the RORB model were informed by AWRA-L simulated soil moisture, which was identified as a useful predictor of initial loss and continuing loss rate.

Bahramian *et al.* (2021) found that, "the uncertainty from forecast average catchment rainfall depth is dominant. The impact of uncertainty from antecedent conditions is of a similar magnitude to the impact of uncertainty from spatial-temporal patterns of rainfall, but overall, these sources of uncertainty are of modest importance compared to forecast average depth." **Figure 5-6** shows an example of the cumulative rainfall and flow forecast hydrographs produced by Bahramian *et al.* (2021) to forecast one flood event. The considerable scatter between the different forecast hydrographs should be noted.

The Bahramian *et al.* (2021) paper provided a practical demonstration, on an Australian catchment with familiar models and data sets, of how some of the aspects of modelling with forecast uncertainty could be undertaken. However, it should be noted that the scope of this paper was limited to producing flow forecast hydrographs at one location, for a catchment with no dams. Further research and development would be required to fill in the remaining gaps in the forecasting process from **Figure 4-1**. Once this work is completed, further work would be required to pass forecast ensemble of inflows through a reservoir routing and operations model to test the resulting outcomes for floods downstream of the dams and reservoir level at the conclusion of the flood events, which feeds back into potential outcomes for water supply security. Further research and development will be required to extrapolate the process across a wider range of magnitudes of events, in order to assess the impact on risks from larger floods, which may threaten the safety of the dam.

It should also be noted that the Bahramian *et al.* (2021) method would be applicable to looking at pre-release or releases in the early part of the forecast period. Extensions to their framework would be required to incorporate progressive updating of forecast rainfall depths, spatial and temporal patterns, in order to test how flood events might be adaptively managed, with progressive transition from forecast rainfall only to a combination of rain-on-ground and forecast rainfall. In more complicated catchments, the framework may need to be extended to consider flows generated from catchments upstream of more than one dam and/or catchments between the dam(s) and potentially affected locations.
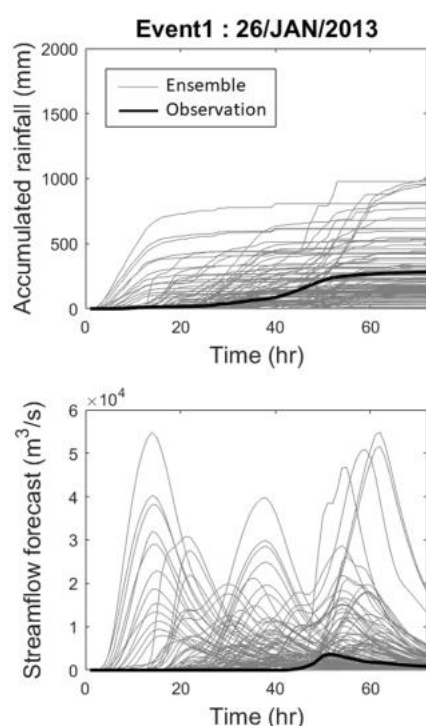
Figure 5-6 Example of accumulated forecast rainfall and forecast inflows for one rainfall event, reproduced from Figure 5 of Bahramian et al. (2021)

5.9 Simplified approach applying ADFD rainfall grids

Rainfall forecasts produced by the BoM's ADFD are reviewed in Section 4.1.2. It was noted that spatial and temporal correlations in forecasts across the ADFD grid cells are not necessarily preserved, which presents difficulties when attempting to characterise uncertainty in the forecasts. So, for example, averaging the

ADFD 25th percentile rainfall forecasts for a group of grid cells across a catchment will not give the 25th percentile rainfall forecast for that catchment.

It is acknowledged, however that the ADFD 50th, 25th and 10th percentile gridded rainfall forecasts are a convenient product that may appear to provide an indication of low, medium and high forecast rainfall. As a simplified approach, a storage manager may choose to run a three-member forecast rainfall ensemble, populated with the ADFD 50th, 25th and 10th percentile rainfall forecasts. If this approach is adopted, the forecast inflow and outflow hydrographs should be labelled with generic qualitative identifiers (e.g. low, medium and high forecast rainfall in preference to referring to them as 50%, 25% or 10% probability of exceedance rainfall forecasts).

6. Seasonal Target Curve considerations

6.1 Risk management

Storage managers may be placed in a position where they need to trade-off the risks of pre-releasing before a flood, with the aim of maintaining airspace in the reservoir to mitigate inflows later in the event, against costs associated with causing flooding that may not have otherwise occurred and/or finishing the event with a reservoir that is not at full supply or the target storage level from the filling curve. As discussed in Section 2.1, storage managers must balance various obligations under the *Water Act* and associated instruments relating to dam safety, water management, flood mitigation and environmental protection. Dam safety would take the highest priority because of the strong mandates in the Statement of Obligations and also because, if a dam fails, all other considerations would automatically not be met, and with devastating consequences. In undertaking the function of harvesting water to supply entitlement holders, the storage manager should not avoid making pre-releases if the storage manager has reliable information available about forecast inflows that would likely replace these releases.

The processes discussed in Section 5.8 can be applied to the lead up period before a flood event, when pre-releases may be considered. The procedure discussed in Section 5.8 contemplates pre-releasing on the basis of any of the rainfall forecasts reaching FSL, in situations where pre-releases are limited to below minor flood flows between the dam and downstream communities or assets. Such an approach would give priority to dam safety (by creating or maintaining airspace in the dam) and flood mitigation (by creating or maintaining airspace that may be used later in the event to contain potential inflows). However, pre-releasing on the basis of a rainfall forecast, rather than rain on ground only, creates a risk that the inflows will not be sufficient to have the dam reach FSL or the desired storage level by the conclusion of the event. The storage operator must assess what level of risk this poses and compare it to the benefits that may be gained and decide if they are willing to take the risk.

6.2 Antecedent conditions and losses

Adding to the complexity of pre-release decisions, inflows can be dependent on the assumptions that are made in the flood forecasting model about losses in the catchment. Section 5.3.4 of the *WMO Manual* discusses the use of antecedent precipitation index methods for estimating the initial catchment wetness, as a predictor of initial loss, prior to floods. In Australia, the BoM and other agencies, such as Townsville City Council, SeqWater and SunWater, have moved toward the use of Australian Water Resources Assessment (AWRA) modelled soil moisture as a convenient and sufficiently accurate predictor of initial loss for flood forecasting. Relationships between AWRA soil moisture (or other products that may be available) and initial loss should be investigated as part of the dam flood operations review study (DFORS). Guidance on the recommended relationship should be included in the DFOM. Such a relationship should only be recommended for use before sufficient runoff is observed to obtain a suitable real time calibration of initial loss in a flood event. Once sufficient rainfall has occurred in an event, the DFOM should recommend that loss parameters are recalibrated to recorded flows and storage levels, as the event progresses.

6.3 BoM seven-day streamflow forecast products

During the lead up to a flood event, storage managers could consider using the BoM's 7-day streamflow forecasting product, as a means of estimating inflows and hence assessing the level of pre-releases that should be made.

The BoM provides streamflow forecasts with a lead time of seven days, to assist river users and water managers. This service covers selected locations across Australia. Forecasts are updated between 10:30

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and 11:30 am each day. Currently hourly forecasts are available to download in the form of probabilistic forecasts (5, 25, 50, 75 and 95% probabilities of exceedance) (see **Figure 6-1**, for an example). The BoM will provide the ensemble members to registered users on request. Water corporations could become a registered user and access the ensemble members from the BoM, which could be used by the water corporations in addition to the processed hydrograph statistics. Currently, the BoM do not regard the 7-day streamflow forecasts as a flood forecasting product.
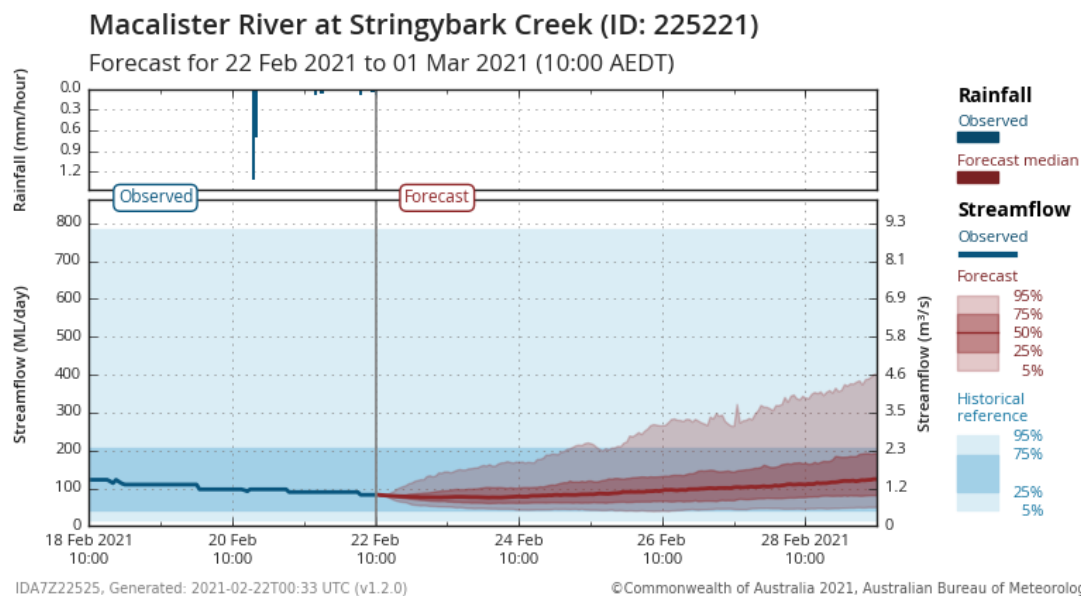
Figure 6-1 Example hourly flow probabilities from 7-day streamflow forecast for Macalister River at Stringybark Creek gauge (225221)

The 7-day streamflow forecast service is currently not set up to provide total forecast inflows to any of Victoria's gated dams. In some cases, there are 7-day streamflow forecasts available for gauges that may capture part of the catchment upstream of a dam. Examples of this include the Loddon River at Newstead (upstream of Cairn Curran dam), Buffalo River at Abbeyard (upstream of Lake Buffalo) and Macalister River at Stringybark Creek and Glenmaggie Creek at the Gorge (both upstream of Lake Glenmaggie).

Water corporations could negotiate with the BoM to extend the service to provide 7-day streamflow forecasts for the total catchment inflow to dams that are of interest to them. To facilitate this, it is likely that the water corporation would need to provide a long time series (several years) of derived hourly inflows to the dam(s) of interest, which would probably be computed from reverse routed inflows, rainfall runoff models and/or transposed from upstream gauge sites.

In preparing the 7-day streamflow forecasts, the BoM create ensemble members that are designed to correct the bias and ensemble spread. However, the bias and spread correction processes are tuned across the whole flow range, rather than being tuned toward floods or forecast potential floods. If ensemble 7-day flow forecasts were to be provide by BoM in future for inflows to a dam, for water corporations to apply the forecasts to flood management further work should be undertaken to investigate, and if necessary, tune the bias and ensemble member spread for floods. **Figure 6-2** shows an example of the forecast skill of the 7-day flow forecasts. It should be noted that the forecast skill is for daily total inflows, so forecast skill is likely to be lower periods shorter than one day. In addition, the verification is performed across a relatively short period of data (four years) and would have considered the full range of flows, so that performance in floods may be different.
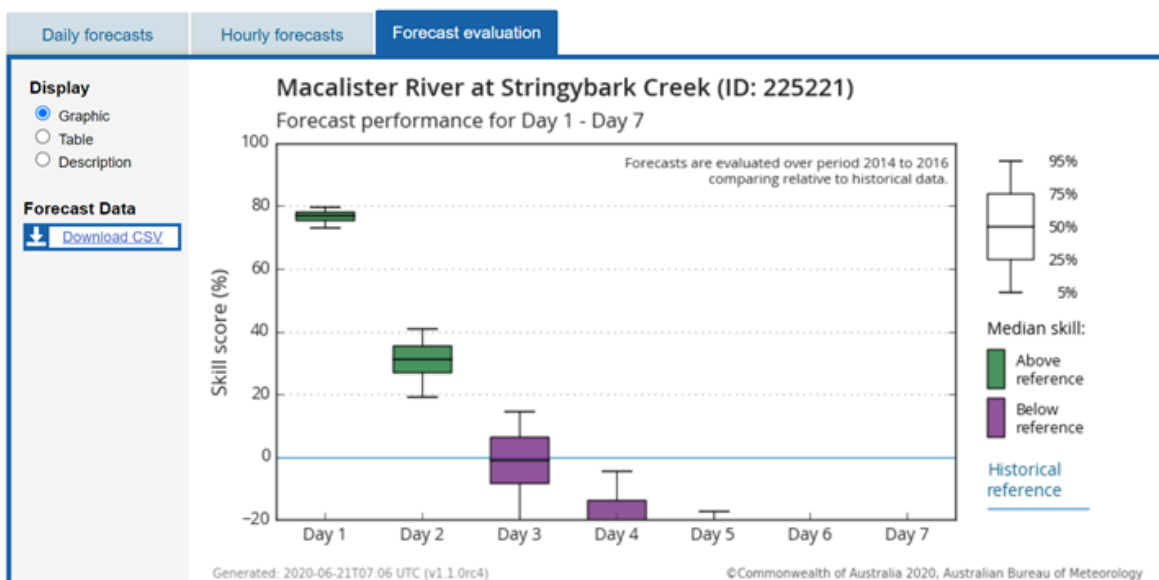
Figure 6-2 Example of evaluation of forecast skill for daily total inflows for Macalister River at Stringybark Creek gauge (225221)

6.4 Filling curves

Some Victorian gated dams have target filling curves, which set the desired maximum reservoir level in the reservoir over the late winter and early spring period. The objective of the target filling curves is to have the reservoir at FSL by the start of the irrigation season, whilst maintaining airspace in the reservoir over winter and spring that can be used to mitigate floods that could occur.

Target filling curves are typically set based on an analysis of historic inflows, from which the Storage Manager calculates predicted future inflows, coupled with predicted future demands to calculate the target filling curve. BoM seasonal flow forecasting products can be used to set a dynamic target filling curve that varies from year to year. This is done for Lake Eildon but not for other storages with filling curves. The DFORS should analyse options for applying seasonal flow forecasts in setting the target filling curve, in place of target filling curves that are informed only by antecedent recorded inflows.

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7. Forecast informed decision making

The BoM's various rainfall forecast products, as discussed above, provide convenient sources of forecast rainfall. Hypothetically, if the likely uncertainty in each of the rainfall forecast products, for a particular catchment area and forecast period could be assessed, then those rainfall forecasts could be weighted in the forecasting process. However, it is currently not possible to assess the actual uncertainty in the rainfall forecast products. This is because:

- the NWP used to produce the underlying rainfall forecasts evolve over time

- the methods for producing the BoM products from the NWP also change over time

- as a result, the database of very heavy rainfall events, at dam catchment scale, for assessing rainfall forecast uncertainty is very small and

- uncertainty / errors in the rainfall forecasts are likely to vary considerably between catchments of different areas, for different forecast lead times and for different seasons, in ways that will be difficult to quantify.

Further research would be required to answer the above questions, some of which could be explored as part of a dam flood operations review study.

It is acknowledged that, despite the considerable uncertainty associated with rainfall forecasts, that dam owners will from time to time be in a position where operational decisions must be made which are informed by these forecasts. Whilst forecast inflows based largely on forecast rainfall (as opposed to rain on ground) may be used operationally at any point during a flood event, typical circumstances where the benefits and consequences of making decisions informed by forecast rainfall are most critical:

- Pre-releasing to lower the reservoir water level prior to inflows in order to provide flood mitigation

- Absorbing the flood within the reservoir to provide flood mitigation and capture storage or

- Surcharging the reservoir water level to provide flood mitigation.

Given the range of potential consequences and regulatory environment associated with these decisions, there is no appropriate level of conservatism that can be invoked to offset the considerable uncertainty in forecast rainfall. One approach would be simply not to make decisions on the basis of forecast rainfall; for example, setting in place a policy where pre-releases are not made until there is sufficient rain on ground to demonstrate both the magnitude and spatial pattern of the storm. However, such a policy is unlikely to be acceptable from the perspective of community and regulatory expectations. As such, it is necessary for Victorian dam owners to adopt a framework that guides decision making utilising the available rainfall forecasts, in at least some circumstances.

Instead of attempting to quantify the uncertainty associated with rainfall forecast products, and therefore how much weight should be given to each of them, an alternative risk-based approach to forecast informed decision making is recommended. To apply this approach, the following inputs are necessary:

- The ability to estimate forecast inflows using hydrological models informed by both rain on ground and forecast rainfall (i.e. a 'Level 4' approach described in Section 5.1).

- At least three forecast inflow scenarios based on forecast rainfall, including at least the 10th, 25th and 50th percentile exceedance ADFD forecast rainfall data.

- Detailed understanding of the potential flooding consequences associated with different ranges of flows downstream of the dam.

Operational decisions, such as whether to pre-release or surcharge, could be informed by following the flow chart provided in **Figure 7-1**:

- Phase 1: involves considering the context, with increasing justification to consider releases on the basis of BoM advice of heavy rainfall and/or flooding and the activation of emergency management arrangements.

- Phase 2: If the context provides justification to consider releases, phase 2 involves verifying the inputs to the forecasting model. This phase involves checking the rainfall forecast(s), checking the assumptions in the hydrological model (such as estimates of loss parameters) and running the model with rain-on-ground (if any rainfall has already fallen).

- Phase 3: Once hydrological model inputs have been verified, the next process involves running the model for at least two possible rainfall forecast scenarios, low and high forecast rainfall. The low rainfall plus rain-on-ground forecast provides an indicative lower limit, in terms of inflows, peak water level in the reservoir and peak releases. An indication of the upper limit would then be provided by considering the range of outcomes from the highest forecast rainfall, which may be the 10th percentile ADFD forecast. Forecasts provided by BoM meteorologists, during discussions with the BoM flood forecasting team, could also be included in the mix of possible rainfall forecasts.

- Phase 3 may involve testing one or more iterations of the release plan, run with the low and high rainfall forecasts. If no releases have yet been made, the first iteration may involve a plan for no releases, to check the maximum levels in the dam(s). This may be followed with testing alternative potential release plans, to forecast levels in the reservoir(s), releases and possibly also forecast flows at downstream locations. Depending upon the peak modelled level in the reservoir for each of the two forecast rainfall scenarios, there would be varying level of justification to make releases and/or consider using the available surcharge capacity (if any is defined in the DFOM). Before adopting the release plan, other factors should be considered, such as rain on ground since forecasts were issued, updated rainfall forecasts, the range of modelled inflow, dam level and outflow scenarios, emergency management arrangements and how downstream community impacts might be influenced by the available warning time and time of day that flooding is forecast to occur.

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1. Assess context

BoM is forecasting heavy rainfall for the catchment

BoM has issued a Flood Watch for the catchment up or downstream of the dam

BoM has issued a flood warning for the catchment up or downstream of the dam

Emergency management arrangements at incident, regional or state level been activated, due to forecast flooding

Increasing justification to plan for release

Abbreviations
BoM = Bureau of Meteorology
FSL = Full Supply Level
MASL = Maximum Allowable Surcharge Level
DSEP = Dam Safety Emergency Plan
ADFD = Australian Digital Forecast Database

2. Verify model inputs

Make reasonable efforts to verify forecast rainfall depths with BoM

Make reasonable efforts to check the loss assumptions in the hydrological model, given catchment conditions (soil moisture, gauged flows, recent rainfall etc.)

Check rain on ground data, run hydrological model and check forecast flows with rain on ground

3. Run forecast model, calculate possible releases and consider actions

Run hydrological model with one or more rainfall forecasts (e.g. ADFD 50th, 25th and 10th percentile)

Calculate dam water levels in accordance with DFOM:
(1) without releases
(2) with planned releases

Test potential release plans

Forecast peak water level in dam for:	
Smallest rainfall forecast run	**Largest rainfall forecast run**
Below target filling level and FSL	Below target filling level and FSL
Below target filling level and FSL	At or above FSL but below MASL
Hit target filling level or FSL	At or above FSL but below MASL
Hit target filling level or FSL	Above DSEP activation level
At or above FSL but below MASL	Above DSEP activation level
At or above DSEP activation level	Above DSEP activation level

Plan for no releases, continue to monitor

Plan releases to achieve FSL for smallest forecast

Consider larger releases to mitigate potential flooding later

Plan releases and consider activating DSEP

Plan releases and activate DSEP

Increasing justification for larger releases and/or use of surcharge capacity

Adopt and communicate release plan

Figure 7-1 Flow chart of approach to deciding on pre-release or release decisions, informed by rainfall forecasts

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Appendix

Appendix A   Legal framework for managing floods at public dams in Victoria

A.1 Legal requirements for water corporations managing public dams

Section 122ZK (in Part 6C) of the Water Act allows the Minister to appoint an Authority (including a water corporation) as a storage manager for a dam. This appointment confers the functions of the storage manager, which are set out in s. 122ZL of the Water Act. As at February 2021, the Minister had used instruments to appoint:

- Goulburn Murray Water as the storage manager for Lake Eildon, Cairn Curran and Buffalo dams and several other ungated dams

- Southern Rural Water as the storage manager for the Macalister Irrigation District Headworks System, which includes Lake Glenmaggie and

- Coliban Water as the storage manager for the Coliban Headworks System, which includes Upper Coliban, Lauriston and Malmsbury reservoirs.

In all cases where the Minister has appointed a water corporation as the storage manager, including those listed above (which currently capture all of the public water supply dams in Victoria with gated spillways), the water corporation has legal responsibilities both as the Authority and as the storage manager. The water corporation must have regard to not only the four items under s.122ZL(2) but also any other relevant mandates associated with any other part of the Water Act or associated instrument, including the Statement of Obligations (per s.122ZL(1)).

An Authority which is the dam owner broadly includes the storage manager as well as responsibility for dam safety and, in the case of Melbourne Water, responsibility for floodplain management, per the other relevant Parts of the Water Act and the Statement of Obligations.

The requirements for storage managers are set out in s. 122ZL (in Part 6C) of the Water Act. This section is quoted below.

122ZL Functions of storage managers

(1) The functions of a storage manager appointed under this Part in respect of the land to which the appointment relates are

(a) to control and manage any water storage on the land specified in the instrument of appointment and any water or works on the land so specified, in a manner that is consistent with this Act and that will maintain the water quality of any water storage on the land;

(b) to carry out any other functions that are conferred on the storage manager by or under this Act or any instrument made under this Act.

(2) An Authority, in performing its functions under subsection (1) must have regard to—

(a) protecting the ecological values of the water systems relating to the land specified in the instrument of appointment; and

(b) protecting the reliability and quality of water supply; and

(c) subject to water supply needs, minimizing the impact on the environment of the carrying out of any such function and maximizing the benefit to the environment of the carrying out of any such function; and

(d) developing and implementing strategies to mitigate flooding, where possible.

A.2 Potential criminal liabilities

It is also important to note that water corporations can be subject to other statute laws that may include potential criminal liability and penalties for the conduct of water corporations. For example, the Victorian workplace health and safety/ work cover legislation per the *Occupational Health and Safety (OH&S) Act* (Victoria, 2004), *Wrongs Act* (Victoria, 1958) and the *OH&S Regulations* (Victoria, 2017). Under the *OH&S Act 2004* employers have a general duty under s.20(1) to ensure health and safety by either eliminating risks so far as is reasonably practicable or, where this in not possible, reducing risks so far as is reasonably practicable. More specifically this duty per s.21(1) is to "so far as is reasonably practicable, provide and maintain for employees of the employer a working environment that is safe and without risks to health" and per s.23 to ensure so far as is reasonably practicable "that persons other than employees of the employer are not exposed to risks to their health or safety arising from the conduct of the undertaking of the employer." Under s.20(2) to determine what is "reasonably practicable" in ensuring health and safety regard must be had to,

"(a) the likelihood of the hazard or risk concerned eventuating;

(b) the degree of harm that would result if the hazard or risk eventuated;

(c) what the person concerned knows, or ought reasonably to know, about the hazard or risk and any ways of eliminating or reducing the hazard or risk;

(d) the availability and suitability of ways to eliminate or reduce the hazard or risk;

(e) the cost of eliminating or reducing the hazard or risk."

The Worksafe Victoria (2020) Guideline on "How WorkSafe applies the law in relation to Reasonably Practicable" provides further guidance and in particular states that matters will be assessed,

*"***with a clear presumption in favour of safety***" (emphasis from the Worksafe Guideline).*

The Guideline goes on to state that,

"Once the likelihood and degree of harm from a hazard or risk is understood, and the availability and suitability of a relevant safety measure to eliminate or reduce the hazard or risk is established, that safety measure should be implemented unless the cost of doing so is so disproportionate to the benefit (in terms of reducing the severity of the hazard or risk) that it would be clearly unreasonable to justify the expenditure." Further*, "If the degree of harm is significant, e.g. death or serious injury is highly likely, then it is extremely unlikely that the cost of eliminating or reducing the risk would ever be so disproportionate to the risk to justify a decision not to implement an available and suitable control measure. Moreover, the question of what is 'reasonably practicable' is to be determined objectively, and not by reference to the duty-holder's capacity to pay or other particular circumstances."*

Per s.146 of the *OH&S Act* water corporations would be regarded as "employers" and proceedings for breaches of the Act can be brought against them by the OH&S Authority established under the Act. Sanctions can include infringement notices per s.147, court orders requiring offenders to improve OH&S per s.136, fines such as under s. 23 or even imprisonment such as under s.39G. As the functions/conduct of storage managers that work for water corporations can place the health or safety of people downstream at risk (e.g. when releasing water from dams), it is important for water corporations to be aware of these duties under the *OH&S Act* 2004 to ensure compliance and avoid the potential penalties and criminal liability. Based on the above Worksafe Victoria (2020) guidance it is clear that the standard of care to eliminate or reduce risks to others is very high when possible death or serious injury is involved, effectively requiring the dam safety function and possibly even the flood mitigation function of water corporations to be elevated to a very high priority over and above any cost implications associated with their water supply function.

Whilst it is important to be aware of all potential liabilities faced by water corporations including criminal ones, the scope of the guidelines being developed here is more to avoid the sort of civil liability that attached to the conduct of the storage managers in the 2011 Queensland floods. Hence, the next sections will focus on the potential civil liabilities for Victorian water corporations.

A.3 Potential civil liabilities

Unless barred by statute, individuals are entitled to sue other people or the state, for the purpose of obtaining a legal remedy. Negligence is one of the torts that may be pursued under the Common Law, in more usual circumstances.

The Water Act applies statute to over-ride the Common Law with regard to legal civil liabilities for the flow of water in Victoria (per s. 17(1)). Civil liabilities are addressed in two different places in the Water Act: the main general sections on "Liabilities" under Division 2 of Part 2 (ss. 16–21) and/or s. 157, which could apply to water corporations under specific circumstances.

A.3.1 Potential civil liabilities under sections 16-20 of the Water Act

Section 16 of the Water Act establishes civil liability arising out of flow of water from the land of a person onto any other land when the flow is "not reasonable" (s.16(1)). It can also arise via an "interference" either negligent or otherwise of a reasonable flow of water that leads to a flow that is "not reasonable" (s.16(2)). As long as the flow is not reasonable in accordance with the s. 20(1) criteria then the liability becomes a strict liability. If the cause of action were one of strict liability, "the defendant would be held liable even though they were not at fault, that is, the defendant's actions were not intentional, reckless or negligent." (Australian Law Reform Commission, 2014). In other words, the flow can be considered not reasonable, regardless of whether the actions of the water corporation were, or were not, intentional, reckless or negligent.

A.3.2 Potential civil liabilities under section 157 of the Water Act

Section 157 of the Water Act is quoted in full below:

> *157 Liability of Authorities arising out of flow of water*
>
> *(1) If—*
>
> *(a) as a result of intentional or negligent conduct on the part of an Authority in the exercise of a function under Part 8, Part 9, Division 2, 3 or 5 of Part 10, or Part 11 or any corresponding previous enactment, a flow of water occurs from its works onto any land; and*
>
> *(b) the water causes—*
>
> *(i) injury to any other person; or*
>
> *(ii) damage to the property (whether real or personal) of any other person; or*
>
> *(iii) any other person to suffer economic loss—*
>
> *the Authority is liable to pay damages to that other person in respect of that injury, damage or loss.*
>
> *(2) If it is proved in a proceeding brought under subsection (1) that water has flowed from the works of an Authority onto any land, it must be presumed that the flow occurred as a result of intentional or negligent conduct on the part of the Authority unless the Authority proves on the balance of probabilities that it did not so occur.*
>
> *(3) For the purposes of a proceeding brought under subsection (1)—*
>
> *(a) a flow of water is to be taken to have occurred as a result of intentional conduct on the part of an Authority if the flow—*
>
> *(i) was designed or intended by the Authority; or*
>
> *(ii) inevitably and without intervening cause resulted from the exercise of a power by the Authority; and*
>
> *(b) in determining whether or not a flow of water occurred as a result of negligent conduct on the part of an Authority, account must be taken of all the circumstances including any omission or failure, in the planning, design, construction, maintenance or operation of the works, to provide reasonable standards of capacity or efficiency or exercise reasonable care or skill having regard to the following matters—*
>
> *(i) the state of scientific knowledge and knowledge of local conditions at any relevant time;*
>
> *(ii) the nature and situation of the works;*
>
> *(iii) the service to be provided by the works;*
>
> *(iv) the circumstances and cost of—*
>
> *(A) the works; and*
>
> *(B) the maintenance and operation of the works; and*

> *(C) works which it would have been necessary to construct to avoid the occurrence of any relevant injury, damage or loss.*
>
> *(4) The following provisions apply with respect to a proceeding brought under subsection (1)—*
>
> *(b) the proportion (if any) of the responsibility of the Authority for the injury, damage or loss must be assessed and only that proportion of the assessed damages must be awarded against the Authority;*
>
> *(c) in assessing damages in respect of damage to property or economic loss the measure of damages is the direct pecuniary injury to the person bringing the proceeding by the loss of something of substantial benefit accrued or accruing and does not include remote, indirect or speculative damage;*
>
> *(d) if damages are assessed in the proceeding in respect of any continuing cause of action, they may, in addition to being assessed down to the time of assessment, be assessed in respect of all future injury, damage or loss and, if so, the Authority is not liable to pay any further damages in respect of that injury, damage or loss;*
>
> *(h) a person, not being a party, in whose favour a determination is made may enforce the determination by the same means as if the person were a party.*

The liability in s. 157 of the Water Act is similar to the liability in s. 16 in that they both have aspects of strict liability associated with them, although there are different criteria in each part of the act for assessing when the liability applies: s. 16 when a flow is "not reasonable" and s.157 when a flow that causes damage/harm is the result of intentional or negligent conduct.