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Modelling of environmental water holders' behaviour: A risk-based approach

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Abstract: Incorporating environmental water holder behaviour into hydrologic models is challenging due to inherent uncertainties in human decision-making. Furthermore, it is expected that environmental water holders will react differently under more varying future climates, with the possibility of increased risk appetite when a watering intervention is desperately needed. This study proposes a risk-based approach for capturing decision-making, tested using the Source Murray Model (SMM). Robustness of environmental outcomes with and without the risk-taking method is assessed in the upper Murray catchment of Hume to Yarrawonga in the Murray-Darling Basin. While model improvements are not substantial when using historical inputs, it is recommended that inputs representing future climate conditions be applied, as this would likely present more opportunities to apply the risk-taking approach.

Keywords: *Hydrology, Environmental Water Delivery, Modelling risk-taking, River Murray, Forecast uncertainty, Scenario Analysis*

1. INTRODUCTION

At the Murray-Darling Basin Authority (MDBA), hydrologic river system modelling has been used rigorously to inform policy discussions. Hydrologic modelling allows us to understand what would likely happen if water management policies and rules were changed. Policies are often made based on a vast amount of evidence. Even though modelling analysis is used as one line of evidence, its role is critical to link changes in hydrology to assess impacts on social, economic, environmental and other values due to policy changes.

The Source Murray Model (SMM) is complicated because of the difficulty involved in representing hydrological characteristics along the River Murray, which spans more than 2,500 km. In addition, water sharing and management rules dictate how water resources are shared between different Basin States, adding to the system's complexity. Another ongoing challenge is modelling different irrigation and environmental watering practices under a changing climate.

Irrigation watering practices are represented by annual and permanent crop demands. While water demands for permanent crops are predictable within a reasonable range for climate forecasts over the span of a couple of weeks, annual demands often depend on a business decision in conjunction with predicating seasonal climate conditions and water availability. Modelling of irrigation demands is relatively well established with the use of historical data over more than the last four decades.

However, environmental watering practices are still developing on ground. In addition to the predicted climate conditions and water availability, environmental watering practices are also dependent on system conditions such as expected unregulated flows from upstream. In this paper, a risk-based decision-making process is developed and tested in SMM for robust assessment of possible environmental outcomes.

2. SOURCE MURRAY MODEL

2.1. eWater Source

eWater Source (eWater 2025a) is a tool developed jointly by Australian governments and managed by eWater Group for the Australian governments. In 2008, the Council of Australian Governments adopted a National Hydrologic Modelling Strategy (NHMS) and then revised it in 2018 with eWater Source as the National Hydrology Modelling Platform (NHMP).

The tool is developed using best available research, with its high applicability to Australian catchments and beyond to undertake technical studies, and to understand implications of new policies and rule changes in managing water resources. It has now been adopted broadly across Basin States as a hydrological modelling platform to represent their catchments.

2.2. Source Murray Model (SMM)

SMM is a hydrological model built by the Murray-Darling Basin Authority (MDBA) in conjunction with the Basin States to simulate the Murray and Lower Darling River systems using the Source modelling platform. The MDBA has used the model to inform policy discussions and decisions, in addition to helping river operators make day-to-day decisions in river operations. SMM allows various scenario modelling to assess impacts to water users, including water uses for irrigation activities and environment water holders.

SMM has been reviewed independently (Bewsher, 2017 and Jakeman et. al., 2019). The reviews assessed the model to be suitable for assessing key benchmark scenarios, including 2009 baseline condition and Water Resource Plan (WRP) models. The model includes water sharing and distribution rules between New South Wales, Victoria and the South Australian Murray, which are described in the Murray-Darling Basin Agreement (Schedule 1 of Water Act, 2007). It also has water use representation for urban and irrigation purposes (MDBA 2018a and MDBA 2018b).

Incorporating irrigation water use into the model and predicting irrigation demands are complex as irrigation practices are constantly changing and adapting to several different influences such as climate conditions, domestic and international commodity prices, and competition of water users through the water market. An example of changes in water supply and demand in the southern Murray-Darling Basin can be found in Aither (2019).

Even though irrigation practices are changing all the time and their representative behaviour is difficult to capture in the model, there is historically observed evidence that has been collected over multiple decades, allowing for modelling with sufficient confidence to inform policy discussions and decisions. Relatively speaking, however, water demand modelling for environmental outcomes is new and emerging. It is expected to be more dependent on external drivers including physical and operational system constraints to deliver high flow events, piggybacking opportunity to augment or extend unregulated events, and antecedent ecological conditions. It is also expected that environmental water holder will react differently under changing and more varying climates in future. In this study, a conceptual framework is developed and applied to upper Murray catchment of Hume to Yarrawonga.

2.3. Environmental water modelling in SMM

Environmental flow requirements are represented and managed in eWater Source using two main mechanisms – Environmental Flow Node (EFN; eWater 2025b) and Environmental Flow Manager (EFM; eWater 2025c). While EFN is used to generate water orders to meet environmental flow requirements, EFM manages environmental flow actions that are generated at various EFN's along the system as well as multiple actions created at single EFN. The EFM also handles the prioritisation of different environmental actions and environmental accounting.

As the available water for the environment is limited, delivering all environmental actions may not be possible in each ordering period. In this case, environmental actions are prioritised so that more critical environmental outcomes are managed and delivered. As a default, all environmental actions are ranked based on:

$$R = \frac{A_c}{I} = \frac{exp(-T_S/R_I)}{I}, \quad (1)$$

where R is the rank of an environmental action, A_c is the antecedent condition which is described with T_s, the time since the last successful event; R_I, the specified return interval of the environmental action; I, the importance of the environmental action (which is set to 1 as a default value but can be specified by a user). When $I \leq 0$, the corresponding action is disabled. The return interval is calculated as inversely proportional to target frequency (T_f) described per environmental action (i.e. $R_I = 1/T_f$).

The rank is sorted in ascending order, and smaller ranks take higher priorities in the watering decision. Figure 1 shows typical examples of the antecedent condition (A_C), where the condition reaches to 0.36788 ($= \exp(-1)$) when time since the last event equals to the required return intervals (R_I), regardless of its value. The smaller R_I is, the steeper this decline is, thereby taking higher priority than an action with a higher R_I.

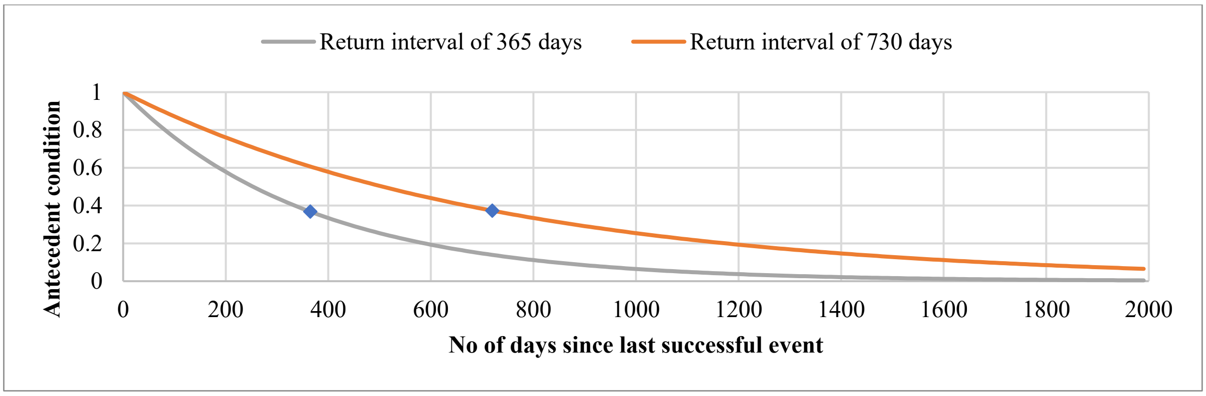

Figure 1: Antecedent condition as a function of time since the last successful event, where blue diamond symbols indicate when the time since the last event equates to the required return intervals

This study uses an environmental flow node at Yarrawonga downstream to represent key selected environmental watering requirements (EWRs) from the long-term watering planning (LTWP) developed by NSW DPIE (2020), as shown in Table 1. NSW DPIE (2020) provides a range of flow regimes and their environmental water requirements, including those that can be met only by natural spill events. However, this study focuses on key bankful and overbank flow requirements that can be managed within plausible constraint flow rates in the future. If required, this risk-based approach can easily be extended to other flow regimes.

It should be noted that Table 1 contains a parameter called resilience period. This risk-based approach uses this parameter to actively make watering decisions. The resilience period is also known as the maximum inter-event period. If time since the last event goes beyond the period, the ecosystem dependent on the specified flow regimes is put under stress and experiences a slower recovery trajectory.

In general, delivering high flow overbank events requires primed conditions provided by unregulated catchments instead of meeting most of the events by releasing water from Hume Dam. In the study area, the system is primed by the Kiewa and Ovens catchments when seasonal rainfall events occur. This allows environmental water holders to piggyback off primed conditions due to unregulated flow events to extend flow durations or augment flow peaks.

Table 1 Bankful and overbank flow environmental watering requirements (EWRs) for the Murray River – Yarrawonga to Barmah (NSW DPIE 2020). EWRs that are not greyed out are considered in this study.

Flow Regime	EWR code	Flow Threshold (F_t, ML/d)	Minimum Duration (D, day)	Seasonality[1]	Target Frequency (T_f, %)	Resilience Period (R_p, year)
Bankful	BK1_10GL	> 10000	45	Aug-Nov	75	2
	BK2_29GL	> 29000	45	Aug-Nov	75	3
Overbank	OB1_15GL	> 15000	45	Aug-Nov	75	2
	OB2_9GL (After OB1)	> 9000	105	Sep-Nov	60	2
	OB3_25GL	> 25,000 for 21 days and 15000 for 90 days		Aug-Nov	70	3
	OB4_35GL	> 35000	14	Aug-Nov	65	3
	OB5_35GL	> 35000	30	Aug-Oct	35	5

1. In LTWP, this is specified as preferred period for optimal environmental outcomes. However, the model relaxes this condition to all year round to allow unregulated events from Kiewa and Ovens that are just outside of the specified period to be utilised.

3. RISK-BASED APPROACH FOR ENVIRONMENTAL WATERING

As presented in Figure 1, the modelling platform has a capacity to prioritise environmental watering actions and deliver more urgent actions first if there is not enough water available in the environmental account to meet all listed actions.

However, it requires much more information than just antecedent conditions used in Eq. (1) for planning when environmental demands should be triggered, and which events should be targeted. Typically, the SMM would need:

1. Forecasts of future hydrologic conditions leading to an assessment on the likelihood of water availability at a given time.
2. Primed conditions from unregulated catchments for an event opportunity.
3. The ability to service the environmental demands from Hume Dam (e.g. there is enough volume available in the reservoir that can be released within physical and operational constraints).

For example, if an environmental watering action is scheduled, but it is not likely to have favourable hydrologic conditions in the season, environmental water that was set aside to achieve the action becomes "overcommitted" and may interfere with other environmental watering action potentials. It is also possible to have the opposite situation; the action may lead to missed opportunities when not directly scheduled, meaning there is inefficient use of the available environmental water. It should be noted that environmental watering planners are exposed to this situation in making decisions, and they must work with uncertain future conditions. The aim of this study is to systematically model this decision-making process. To this end, a risk-based approach is adapted.

This approach starts with acknowledging the uncertainty of future forecasting. In Figure 2, season conditions are projected within a range of different possible outcomes. The possibility of future forecasts being eventuated is expressed with 25th and 75th percentile regression equations and a line of best fit. Figure 3 shows the possible forecasts calculated every month. In this case, monthly total inflow to Hume Dam over the last two months and current month was used as the independent variable (predictor as denoted in figure 2) to forecast the total seasonal inflow to the dam from June to December.

The monthly relationship in Figure 3 allows seasonal forecasts to be updated at the beginning of every month. As seasons progress, the range of forecasts and their uncertainty is reduced. The seasonal forecasts are then classified into four different statuses – Extreme Dry, Dry, Medium and Wet. To this end, three flow thresholds (T_{High}, T_{Med} and T_{Low}) are used. The thresholds are developed by interrogating the two modelling scenarios – Without Development (a what-if scenario that estimates pre-regulation outcomes) and Current Condition (best estimate of current management and operations) models and their outcomes in achieving the EWRs (NSW DPIE 2020) across different hydrologic regimes. The analysis indicates that $T_{\mathrm{High}} = 5{,}100\ \mathrm{GL}$, $T_{\mathrm{Med}} = 3{,}100\ \mathrm{GL}$ and $T_{\mathrm{Low}} = 1{,}100\ \mathrm{GL}$ are reasonable representation of the four classifications.

For delivering bankful and overbank flow indicators, four cases are considered (Figure 2):

1. Case (a): Hydrological conditions are likely wet and environmental outcomes are likely delivered naturally without environmental demands being placed;
2. Case (b): Hydrological conditions are likely dry. Therefore, primed conditions to enhance unregulated flows are likely unavailable. Due to dry conditions, environmental water availability in its account is unlikely to be sufficient to deliver EWR;
3. Case (c): Future hydrological conditions are in medium-wet where there will be significant chances of receiving primed conditions to enhance environmental outcomes; and
4. Case (d): Future hydrological conditions are likely lower than the medium wet conditions, but the upper end of future forecasts indicate there may be sufficient conditions available to augment unregulated flows to enhance environmental outcomes.

The importance function (I) is set to zero for Cases a and b so that environmental watering actions are turned off and not scheduled, while it is set to one for Case c allowing for the flow manager to look for an opportunity to enhance environmental outcomes if there is enough water available in the account.

For Case d, hydrological conditions are less favourable than what would be expected under Case c. In this case, environmental watering actions are triggered with an increased risk of not being able to fully deliver intended outcomes. Therefore, it will only be accessible to environmental actions that need interventions urgently where their frequency has extended beyond the resilience period identified in Table 1. To reflect its urgent requirements, the importance function is set to higher than one as below:

$$I = \frac{T_s}{R_p},$$

where R_p is the resilience period as specified in Table 1.

When an EWR is not maintained within its target frequency and goes without a watering event beyond the resilience period, the increase in the importance value allows the event to be prioritised higher than the other events. This risk-based approach also allows the EWR to be activated even if the system is less than optimal to deliver the event. Instead of waiting for a fully primed condition (defined when expected flow exceeds EWR's flow threshold), it takes a risk of not successfully delivering the targeted environmental outcomes by triggering water delivery even if expected flow is less than the flow threshold. This is to reflect environmental holder's behaviour of increased risk appetite when a watering intervention is desperately needed. It is assumed that the risk appetite is also increased as the time since the last event is elongated. In the model, this is expressed by reducing EWR's flow threshold inversely to the importance function (i.e. F_t/I).

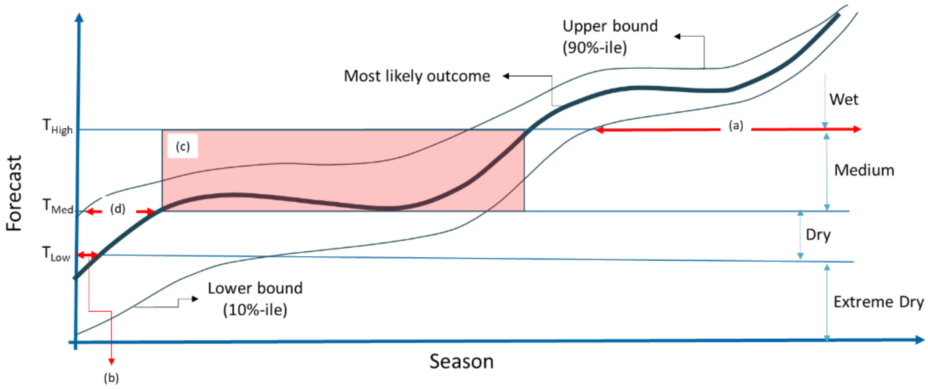

Figure 2: Seasonal forecast with uncertainty and environmental watering decisions depending on seasonal forecast.

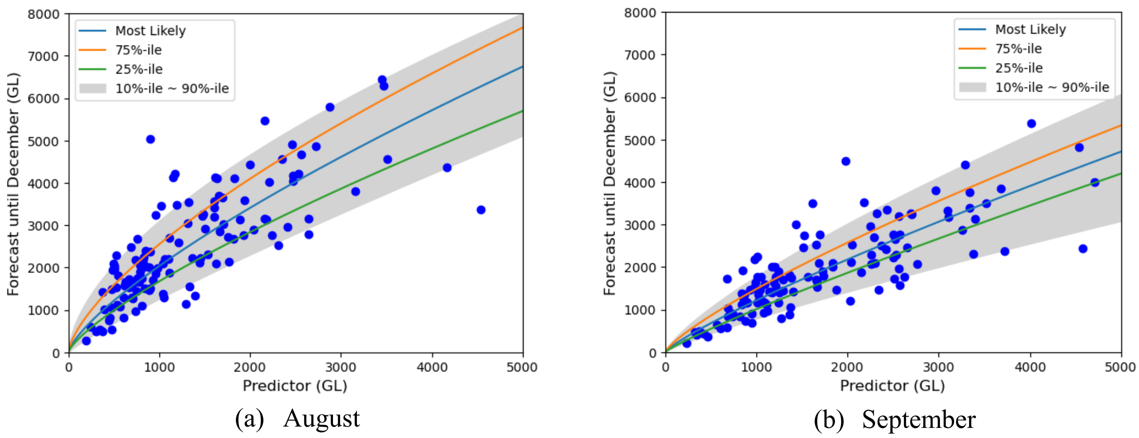

Figure 3: Monthly seasonal forecasts ((a) August and (b) September). The predictor is taken as total inflow over previous 2 months and current month. The seasonal forecast is based on a cumulative measure until December from the current month.

4. MODELLING EXPERIMENT

The risk-taking approach was applied to MDBA's SMM which simulates river systems for the Murray and Lower Darling system. For this study, a modelling period between July 1895 and June 2024 was utilised. Climatic conditions were derived based on historical data while the current river operations and policy settings are assumed to be applied over the entire period with the exception of river constraint rates. To test this risk-taking approach, this study uses relaxed constraint rates of 30,000 ML/d and 35,000 ML/d at Doctor's Point and Yarrawonga downstream.

There are four scenarios developed – two different upper bounds in the seasonal forecasts and with/without the risk-taking approach. For the upper bounds, 75 and 90 percentile estimates of seasonal forecast are used.

Figure 4 presents median values of monthly seasonal forecasts over the entire modelling period (1895~2024). Noting that this study focuses on overbank flow interventions, the tenth-percentile values as an option for the lower bound are not presented. As this figure was developed by treating every month independent to others, it doesn't show auto-correlations and cannot draw any conclusions about how successive monthly estimates affect overall seasonal forecasts. However, it shows that:

- Most likely, forecasts closely trace the corresponding historical truth,
- At the beginning of a season, there are bigger uncertainties for forecasts and as the season progresses, over- or under-predictions are corrected gradually,
- It indicates that this risk-taking approach is effective and applicable only in early season, and
- Selection of the upper bound of the season forecasts (in this example, it is between the 75 %-ile and 90 %-ile forecasts) will decide how actively the risk-taking approach is applied.

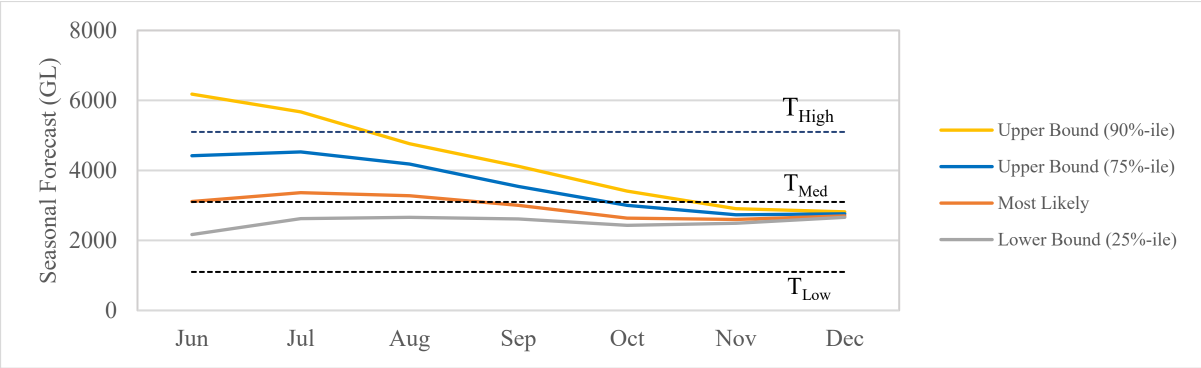

Figure 4: Medium values of seasonal forecast from a modelling run spanning from 1895 to 2024 with $T_{\text{High}} = 5,100$ GL, $T_{\text{Med}} = 3,100$ GL and $T_{\text{Low}} = 1,100$ GL.

It is expected that the higher percentile estimate used as the upper bound of the seasonal forecast presents more cases to take opportunistic intervention in an event, even if prevailed conditions are not optimal (Figure 4). This comes at a cost of not enhancing a smaller intervention event, even though an opportunity is present to deliver the event. Hence, it is called a risk-taking opportunity. This is also demonstrated in **Error! Reference source not found.** where the importance function of the OB3_25GL rule is presented. The scenario without the risk-taking approach caps the importance to one, while it goes beyond one if a risk-taking approach is adapted and when the time since the last event is longer than its corresponding resilience period.

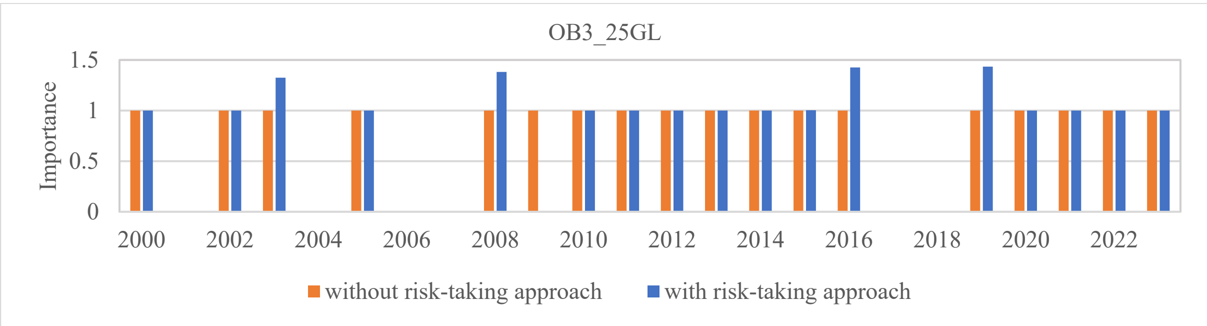

Figure 5: Importance function outputs of OB3_25GL rule when the upper bound of the seasonal forecast is taken from the 90%ile estimate

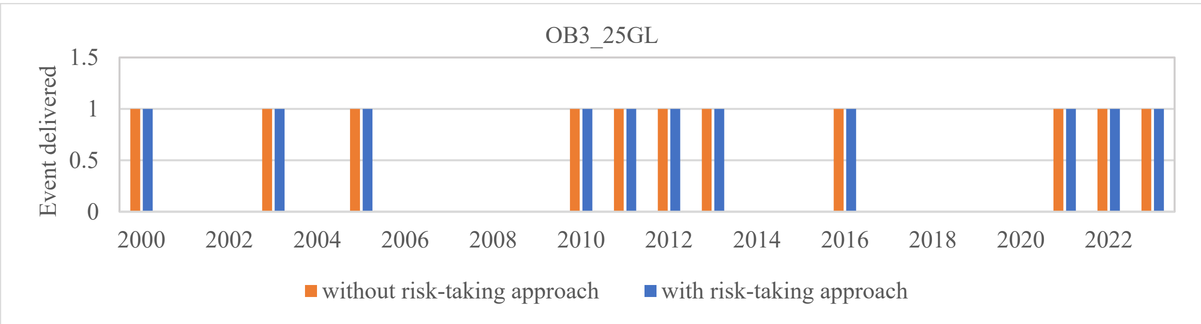

Figure 6: Achievement of environmental event (OB3_25GL) (1=delivered and 0=not delivered) when the upper bound of the seasonal forecast is taken from the 90%ile estimate

Error! Reference source not found. shows the achievement of the OB3 EWR corresponding to the importance presented at **Error! Reference source not found.**. It shows that there are 4 potential cases (2003, 2008, 2016 and 2019) to uptake a risk and prioritise this EWR. However, **Error! Reference source not found.** indicates that none of the cases are realised as a successful delivery. In more detail, these cases are:

1. In 2003, the higher EWR (OB5_35GL) is aimed to deliver and because of delivering the OB5 event, the OB3 EWR is also achieved for both model runs of with/without risk-taking approach,
2. In 2008, even though an opportunity presents and the OB3 EWR is prioritised, lack of unregulated flow prevails to initiate the environmental water delivery. In this case, environmental water availability is quite low to successfully deliver this event,

3. In 2016, an opportunity is taken up and an event is intervened when the risk-taking approach is used. However, the intervention is not continued because of a spill event, and
4. In 2019 (similar to the case of 2008), an opportunity cannot be realised due to lack of primed conditions to initiate an environmental intervention.

Following analysis of the four scenarios, there were no significant changes in frequencies achieved and duration between events. The most noticeable improvement was observed with the OB3 EWR, where there was a ~2% increase in frequency when a risk-taking approach was used. This further improved to ~5% when the 90%-ile estimate of the seasonal forecast upper bound was applied.

As shown in **Error! Reference source not found.**, however, the success of delivery of environmental events depends on several factors including environmental water availability, primed river system conditions and interactions with other environmental actions. The limitation of water availability may be alleviated if multi-year planning is included where carry over policies can be incorporated to bank environmental water for later years when the current system is wet and usefulness of delivering high overbank flow events is tested.

5. CONCLUSIONS AND RECOMMENDATIONS

In this study, plausible environmental water holder behaviour is modelled systematically, where uncertainty of future forecast is incorporated, and its risk-based decision process are considered. While differences in modelled outcomes using the risk-based assessment were not substantial, the approach still better captures environmental water holder behaviour in certain cases. The modelling experiment relied on historical input data, which provided limited opportunities to demonstrate improvements through the risk-based methodology. For future analysis, climate-adjusted data could be used, as this would likely result in more Case d scenarios where the risk-taking framework can be applied, demonstrating more evident improvements in model performance.

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