Examining Trade-Offs in Piggybacking Flow Events while Making Environmental Release Decisions in a River System

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Abstract: High flow pulses (or spells or freshes) play a crucial role in maintaining the ecological health of a river system. Impoundment of water in a reservoir and release or diversion of water for human water needs has significantly altered the magnitude and frequency of flow pulses in many river systems, often reducing river ecological health. A limited volume of water is sometimes available for release into the river to reintroduce pulses specifically aimed at meeting ecological requirements (*environmental water*). If aiming to achieve maximum environmental benefit, such releases from the reservoir should be timed to augment or piggyback natural unregulated catchment flow events. These decisions must be made in presence of uncertainty of near-future unregulated catchment inflows entering the river. Making flow release decisions under this uncertainty poses the risk of either not achieving the benefit of the environmental flow release because too little environmental water is released, or of causing flood damage because too much is released. To date, assessment of risks associated with piggybacking environmental flows have focused solely on the flooding risks. This paper considers assessment of trade-offs between environmental risks and flooding risks while making piggybacking decisions. The key contribution of the paper is a risk framework that allows for the assessment of both flooding and environmental risks when piggybacking of natural flow pulses occurs. The risk framework is used to assess rules or rules with varying levels of piggybacking on the trade-offs between environmental outcomes and flooding risks when releasing piggybacking flows under these rules for flow events under near-future forecast uncertainty. Spawning flows for a key fish species in the Yarra River in southeast Australia is used as a case study to compare three piggybacking rules. **DOI: 10.1061/(ASCE)WR.1943-5452.0001048.** *© 2019 American Society of Civil Engineers.*

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Introduction

Increased river regulation for flood control, hydropower generation and extraction of water to meet industrial and consumptive demands has significantly altered the natural flow regime of many rivers worldwide (Stewardson et al. 2017). This flow alteration adversely affects ecological processes and aquatic and riparian biota (Poff et al. 1997; Bunn and Arthington 2002). These effects are likely to be exacerbated by increasing demands for water and climate change (Arthington et al. 2006). The provision of environmental flows is now a policy in many countries around the world (Harwood et al. 2017; Wallace et al. 2003; Le Quesne et al. 2010; Horne et al. 2017b). A major challenge for implementing these policies is balancing the needs of the environment and other uses of the river and floodplains (Wallace et al. 2003).

While early environmental flow studies focused attention on maintaining the minimum flows for environmental purposes, there is increasing attention on the need to provide medium to high flow pulses (also known as flow events, spells, pulses, or freshes). These can be an important flow component for river biota and other environmental assets such as wetlands and floodplains (Watts et al. 2009). Among other effects, flow pulses are required to flush sediments and clear algal biomass from river channels, to provide spawning and migration cues to fish species, to maintain connectivity between river channels and floodplains, and to maintain vegetation growth and protect habitat for water birds (Watts et al. 2009; Rolls and Bond 2017). River regulation often alters the volume, timing, and frequency of flow pulses. Downstream of a major impoundment, environmental flow releases aim to reintroduce these pulses into the flow regime.

Ideally, one would deliver environmental flow releases to achieve the best possible outcomes with as little environmental water released as possible. This maximizes the water available for other uses. To achieve this, environmental water releases can be timed to augment naturally high streamflows caused by rainfall

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events that create unregulated catchment inflows to the river downstream of the storage. In other words, the environmental release can *piggyback* upon a natural catchment runoff event (Harman and Stewardson 2005) to achieve maximum efficiency. This also allows the environmental flow regime to retain some natural timing, which may be beneficial in achieving the intended ecological responses. We note also that examples of river systems exist where piggybacking of natural flows is necessary to get any benefit for the environment because the target flow pulse volumes are so high that they can only be achieved through piggybacking (e.g., because of limited capacity of flow releases that can be made from dams and reservoirs along the river) (Hardwick et al. 2001; Bowmer 2004). However, the strategy of piggybacking has associated risks of unintended flooding because the environmental release will coincide with natural storm runoff, which is unpredictable.

Identifying an appropriate flow event upon which to piggyback environmental flows is a complex process. Currently, a number of criteria (for example, the time of year, rainfall forecast, channel and release capacities, volume of environmental water required, and risk to private properties and croplands) are analyzed in conjunction with requirements of the environmental process or endpoint targeted by the piggybacked flow event (Jensen 2009; Ausseil et al. 2013; DIPNS 2004; CEWO 2004; OEH 2013).

Environmental water releases must be made amid uncertainty as to how the near-future downstream catchment rainfall and resulting downstream river inflows will unfold. However, most of the time environmental water release decisions are made based on the most likely near-term future forecast (e.g., rainfall forecasts, streamflow forecasts) with the requirement that flooding of adjacent properties must not occur. It is not known how this strategy performs under near-term forecast uncertainty. There is not only a consequent risk of flooding adjacent properties and/or public infrastructure (Cottingham et al. 2003), but also a risk that the catchment response may not provide a flow event adequate to meet the environmental flow target (Fig. 1). Thus, it is important to identify the flow events that may be piggybacked, considering the trade-off between the marginal environmental benefit achieved by piggybacking an event and the possible cost of flooding private properties under the full spectrum of near-future forecast uncertainties (Mackay and Van Kalken 2014).

To date, the assessment of risks associated with piggybacked environmental flow releases has largely focused on the potential

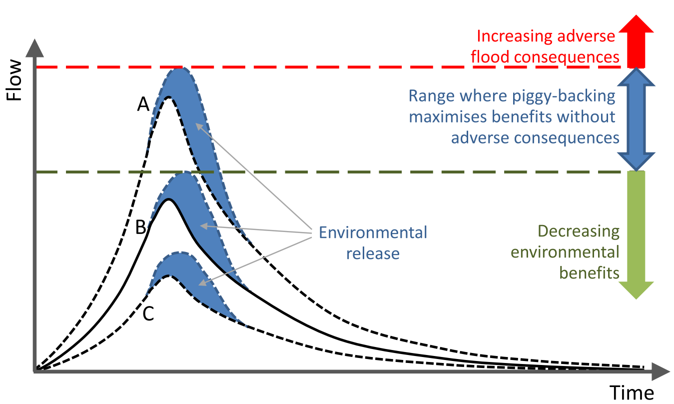

Fig. 1. Predicted river flow due to a runoff event in a catchment [where solid black line represents best estimate of event (B), and dotted lines are possible outcomes above (A) and below (C) the best estimate]. Proposed environmental release is solid area above these lines.

for adverse flood impacts, and ignored trade-offs with environmental risk of not delivering the pulse event (Jacobs 2015). In order to address this shortcoming, this paper proposes a risk framework and optimization model that allows for the assessment of both flooding and environmental risks when piggybacking events occur. A simple case study is then used to demonstrate the framework.

The remainder of the paper is structured as follows. The section entitled "Framework for Considering Risks" describes the risk framework for managers to accommodate uncertainties in flow forecasts when assessing the environmental benefits and flood risks of piggybacking. The methodology, which uses an optimization approach to assess the environmental risks of piggybacking flows, is presented in the section entitled "Evaluating Environmental and Flooding Risks for Piggybacking Events." The risk framework is applied to the Yarra River in southeast Australia as a case study to demonstrate the frameworks potential. The section called "Case Study and Model Setup" presents the details of the case study, piggybacking rules, and the model setup. The results and the future work including the challenges of implementing the complete framework under climatic uncertainty are discussed in the sections entitled "Results and Discussion" and "Conclusion and Future Work," respectively.

Framework for Considering Risks

Risk assessment and management has become central to many aspects of public policy (Beck 1986; Godden et al. 2013). The risk is a combination of the likelihood (the probability of an unwanted event) (Apel et al. 2004) and consequence (the potential loss or impact caused by that event). It is not possible to avoid uncertainty when making decisions, however assessing the uncertainty can lead to a better consideration of costs and benefits of the decision (Kaplan and Garrick 1981). In the context of environmental water delivery, there is an environmental risk in not delivering an event [Fig. 2(a)], and a potential flood risk in delivering the event [Fig. 2(b)].

The likelihood that an environmental water release that piggybacks' *exogenous* flows (i.e., all flows in the river except environmental flows such as unregulated flows and flows released to meet human consumption) will lead to a particular outcome depends on the level of certainty around the forecast of streamflows over the duration of the watering event (Jacobs 2015). However, in reality there is a skill level in our streamflow forecasting ability, with increasing uncertainty the longer the forecast lead times (Bennett et al. 2014). There is both *aleatory* uncertainty (the inherent randomness in the climate systems that cannot be predicted), and *epistemic* uncertainty (gaps in knowledge around system processes such as catchment response to rainfall) (Ascough et al. 2008). The aleatory uncertainty cannot be reduced; this is an inherent attribute of modeling natural systems. In the context of piggybacking, the dominant source of aleatory uncertainty is that associated with the streamflow forecasts (ensemble or otherwise) relevant to the watering event. Determining the likelihood that an environmental water release will lead to a particular flow outcome requires an understanding of the level of skill in streamflow forecasting. This can be represented statistically and incorporated within environmental water release decision making.

The consequence of an environmental water release leading to property and infrastructure flooding is a combination of the level of damage caused to social and economic values (Schanze et al. 2006). The damage to social values refers to "loss of life, health impacts (injuries), loss of vitality, stress, social impacts . . . .and loss of cultural heritage," while the economic damage relates to "direct

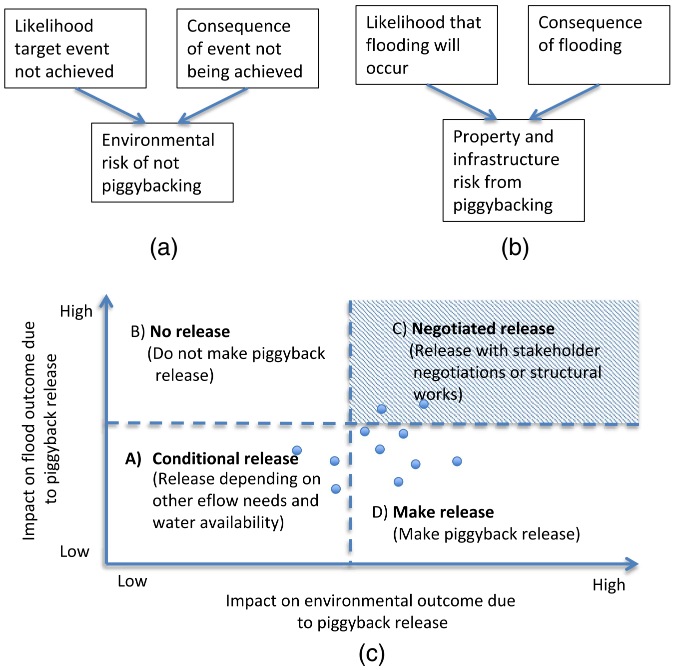

Fig. 2. Framework to decide on piggyback release strategy based on both environmental and property and infrastructure flood risk: (a) environmental risk; (b) property and infrastructure flood risk; and (c) management framework to consider risk. A dot represents outcome for a given member of a forecast ensemble. Distribution of dots shows likelihood of achieving environmental target and flooding. Together, this provides information on level of risk.

and indirect financial losses by damage to property assets, basic material and goods, reduced productivity . . . " (Schanze et al. 2006, p. 3). There is also a need to consider the perception of risk from those potentially impacted. Different people within the community will perceive risk differently. This leads to different levels of perceived vulnerability should a flood eventuate (Messner and Meyer 2006). This is an important consideration for environmental water programs as the success of the programs requires ongoing public support (Doolan et al. 2017; O'Donnell and Garrick 2017).

The environmental outcome from a particular environmental water release is influenced by the antecedent condition and life-history transition of the target species or river reach as a whole (Horne et al. 2018b). The risk of not providing the event depends on the current condition of the species, and also on the likelihood that a similar environmental event will be able to be delivered at a subsequent time, providing the required environmental outcome. Consider for example, a fish species with a three-year life span. If a fish spawning event occurred last year, the environmental consequences of missing a spawning event this year could be considered low. However, if the species is stressed, with no spawning events for the previous two years, the environmental consequences of not providing a spawning event this year could be extreme.

Both the social and economic risks of flooding and the environmental risk of not providing a flow event should be considered when making an environmental water release decision. Fig. 2(c) shows a management framework where the two competing risks can be considered. Note that the thresholds (both for x and y axes) defining the four quadrants in the framework are the choices that need to be negotiated among stakeholders based on the antecedent condition of the target ecological species and their tolerance to flooding risks. A data point on the plot gives the impact (consequence) on environmental and flooding outcomes with respect to one of the streamflow forecasts from the ensemble for a flow event. The spread of these data points across the four quadrants of the risk framework indicates the likelihood of meeting the environmental target and the likelihood that flooding will occur while making the piggybacking release for the forecasted event. When data points lie in one quadrant, the decision to release water will be straightforward. Where risks are low, release decisions can be made depending on the volume of environmental water available and the other environmental flow needs (quadrant A). Where the environmental risk is low but flood risk is high, an environmental release should be avoided (quadrant B). Similarly, where environmental risk is high but flood risk is low, an environmental release should occur (quadrant D). When both environmental and flood risks are high (quadrant C), other options need to be explored to allow the release to proceed while minimizing the chances of both forms of negative impacts. The key challenge is when the data points span more than one quadrant of the risk framework. This is even in the case where the majority of data points lie in one quadrant indicating low risk, with one or two showing potential flood risks. In such cases, the piggybacking releases can be made in view of the risk tolerance of the environmental water manager, after weighing out the flooding risks against the environmental benefits. For example, where a species is in very poor or critical condition and an environmental flow event will have significant benefit, one or two data points showing a possibility of flooding risk may be tolerated and the piggyback event permitted. In contrast, where flood risks are high and only a few data points indicate a potentially adverse environmental outcome if the event is not delivered, the manager may hold of releasing environmental water despite these points.

Evaluating Environmental and Flooding Risks for Piggybacking Events

A major challenge in identifying natural flow events for piggybacking is how to understand their potential impact on the magnitude and duration of flow events that can be delivered, and the associated benefits to the environment. In this section, we present a method that enables one to do this, with the general procedure shown in Fig. 3. We propose optimization as a tool to explore the environmental benefits of piggybacking natural flow events. Specifically, we adapt the SEWDS model, a mixed integer programming (MIP)-based optimization model used in Horne et al. (2017a) and Horne et al. (2018a) (Fig. 3).

The SEWDS model takes the water resource model of a river system and ecological models of key endpoints of the river system as input, and finds an environmental release schedule that maximizes the likelihood of improvement in the condition of key ecological endpoints of the river, while ensuring no flooding occurs in any river reach. The ecological model for each endpoint is given as a conditional probability network (CPN) (Horne et al. 2018b). A CPN for a species is a network of *nodes* (representing the flow components that may affect the species, the intermediate ecological stages to its lifespan, and the overall ecological condition) and directed *links* (modeling a cause-effect relationship between the nodes they connect). Each node has a predefined conditional probability table (CPT) that defines the probability of the node being in each of its states given the states of the nodes feeding into it. An environmental water release schedule creates a unique flow series in the river, defining the probability distribution of the CPN nodes representing the flow components. Given the probability distributions of the flow-component nodes, the node-link structure, and the CPT of nodes, the CPN calculates the probability distribution of the

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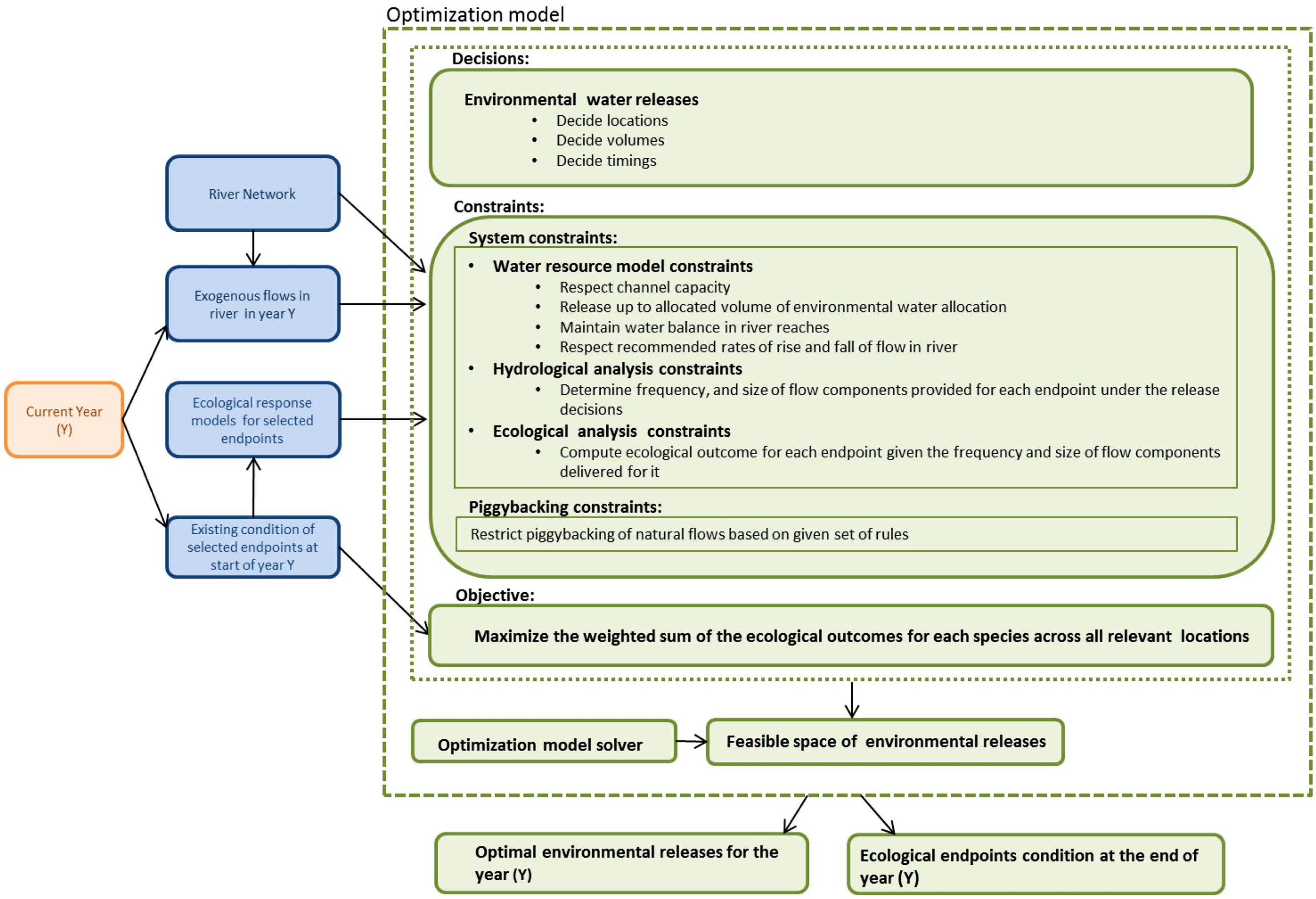

Fig. 3. Conceptual structure of optimization model to support environmental flow release under piggybacking restrictions.

node representing the overall ecological condition of the species. The MIP model finds the best environmental release schedule with the objective of achieving maximum likelihood of improvement in the conditions of the key species and assets across the river, while using minimum volume of environmental water. Refer to Horne et al. (2018a) for details of the optimization model developed for the case study river system.

In this paper, we adapt the preceding MIP model to include piggybacking rules (i.e., rules that may include restrictions on when the flow in the river can or cannot be piggybacked). We formulate the mathematical constraints for each restricted piggybacking rule and include them in the optimization model (see the "Current Year" box in Fig. 3).

Fig. 4 shows the procedure used to determine the likelihood of flooding and the likelihood of good environmental outcomes for an environmental flow release made under a given piggybacking rule. We first obtain a near-future streamflow forecast ensemble for a flow event and select a piggybacking rule. Each forecast flow series of the ensemble is passed to the optimization model (adapted to the selected piggybacking rule) to obtain an environmental water release schedule that maximizes the environmental outcomes under the selected piggybacking rule, but ensuring that no flooding occurs. This step generates an environmental water release schedule for each forecast series. The environmental flow release schedules so obtained are applied to the actual flows to get a set of data points representing a distribution of environmental outcomes and flooding outcomes for the piggybacking rule. These data points are mapped onto the risk framework presented earlier. The spread of these data points across the four quadrants of the risk framework is used to assess the environmental and flooding risks associated with making flow releases according to the selected piggybacking rule.

Case Study and Model Setup

Yarra River

The Yarra River is located in southeastern Australia, with the lower reaches flowing through the city of Melbourne. An environmental flows study for the Yarra River (SKM 2012) established a number of objectives for environmental water releases and identified six key reaches with the majority of environmental water releases targeted at Reach 2 and Reach 5. Each year, 17000,000 cubic meters of water is allocated to the environment to maintain river health. This environmental water allocation is actively managed, with a designated water manager making decisions on the timing, volume, and location of water releases from multiple reservoirs. In addition, river managers can make a cease-to-harvest order at points in which water is pumped from the river for irrigation and consumptive purposes to allow a natural flow event to pass through. The total volume of water released from the reservoirs or removed from harvesting for environmental purposes is debited against the total allocation of environmental water.

There are five key ecological endpoints identified for the Yarra River (SKM 2012)—healthy populations of macroinvertebrates,

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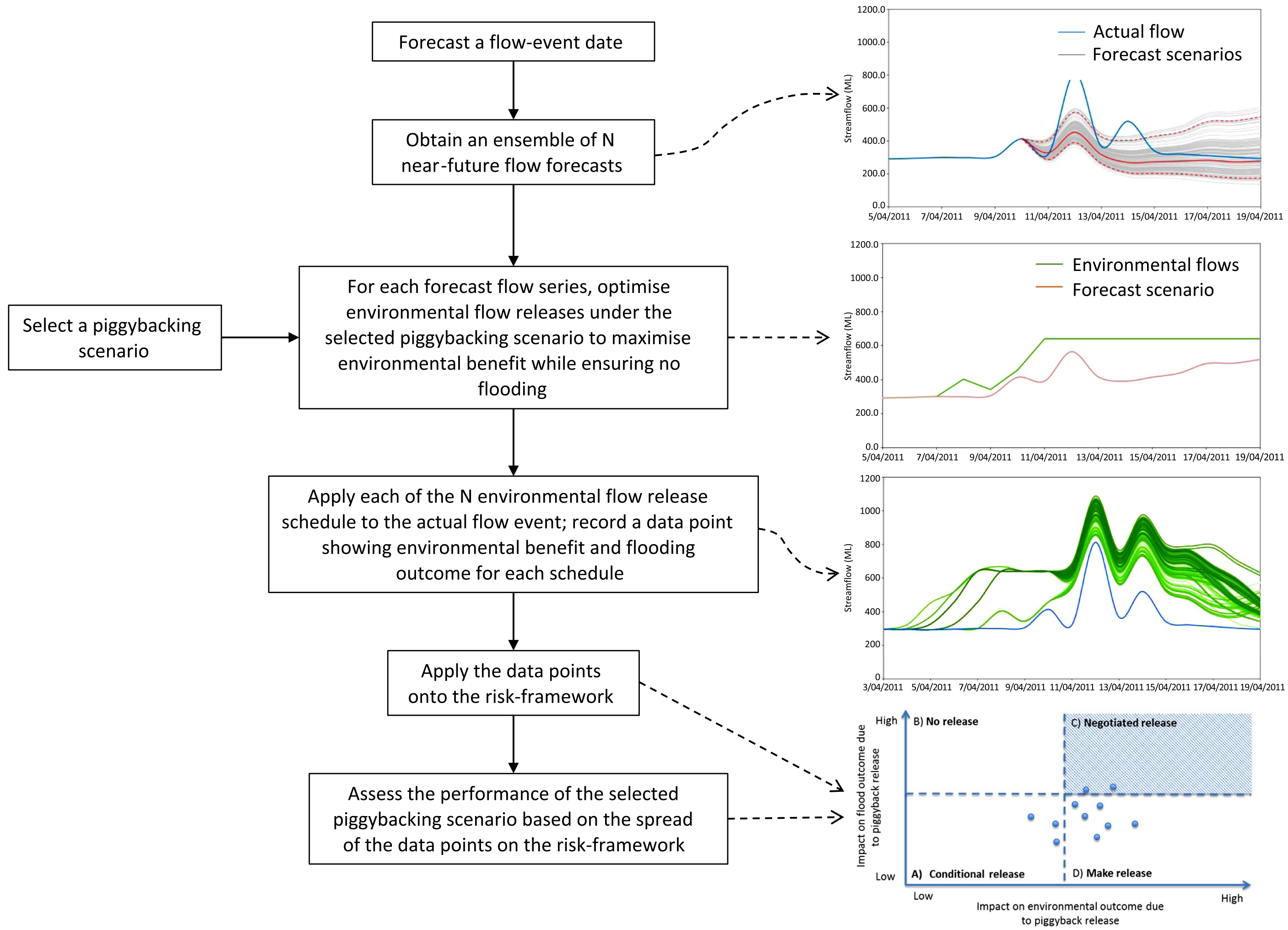

Fig. 4. Methodology for applying risk framework to a flow pulse under a piggybacking rule.

Australian grayling, Macquarie perch, blackfish, and channel maintenance (sediment management). Channel maintenance is applicable to Reach 1 and all other endpoints are applicable to Reaches 2 and 5. The overall health of these endpoints depends on the provision of a number of flow events. Among the three key fish species, Australian grayling (an endangered fish species) has a life span of three years, which is the shortest life span and is most affected by the provision of flow events. The ecological outcomes for Australian grayling hinge on a number of fresh events including an autumn flow pulse to trigger downstream migration and spawning of adults. The autumn flow pulse for Australian grayling can be delivered at different flow thresholds and for different durations. Table 1 illustrates the range of flow magnitudes and durations at which the flow pulse is believed to be effective.

Current management policy in the Yarra River restricts piggybacking of environmental water releases onto natural flow events. The release rules specify that the environmental water can be released into the river only if the river has stable flows and there is no significant rainfall forecast (MW 2014). While the current policy intends to minimize flooding risks along the river, this is done at the cost of increasing the risk of not providing necessary flow events within the river. The analysis presented in this paper may help the managers to identify high flow pulses that can be piggybacked to deliver flow events without unduly increasing the risk of flooding private properties.

Table 1. Flow events required for Australian grayling

Parameter	Value
Flow event	Autumn pulse
Flow magnitude recommendations (mL/d)	
Reach 2	300–640
Reach 5	1,000–1,900
Duration (days)	6–21
Timing	March to June

Source: Data from Horne et al. (2018a).

Piggybacking Rules

For the Yarra River, we designed three piggybacking rules—unrestricted piggybacking and two restricted rules (Fig. 5). The unrestricted piggybacking (Rule 1) represents the best possible environmental outcome based on predicted flow events, allowing the model to piggyback upon natural events with no restrictions. The restricted rules are designed to capture periods of stable flows in the river as per the current management policy in the Yarra River. This requires the identification of flow peaks in the river that should not be piggybacked. We define the restricted piggybacking rules based on the commonly used criterion: (1) the flow threshold that flow events exceed (Rule 2), and (2) the rates of rise and fall of flow in the river system (Rule 3). Rule 2 is the most conservative

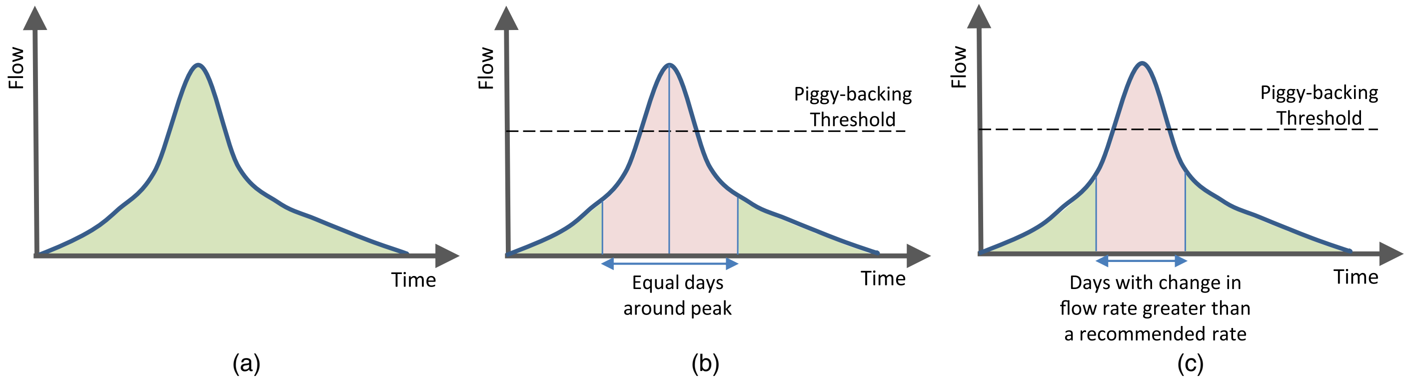

Fig. 5. Conceptual representation of a flow pulse and timing where piggybacking is permitted or restricted for each rule: (a) Scenario 1; (b) Scenario 2; and (c) Scenario 3.

approach that leads to effectively no piggybacking around the peak of a flow pulse. Rule 3, on the other hand, is an intermediary approach between Rules 1 and 2, allowing piggybacking of flow pulses as long as the rates of rise and fall criteria are met. The details of each rule are given next, together with the mathematical constraints to model them.

- *Rule 1—Unrestricted piggybacking:* This rule does not include any additional restrictions on the release of environmental water in the base optimization model. The optimal solution obtained under this rule can potentially piggyback all natural occurring flow events in the river in order to provide a combination of flow components (thresholds, frequencies, durations, timings) that maximizes the likelihood of improvement in the conditions of key species and assets while using the smallest volume of environmental water.
- *Rule 2—Flow constrained piggybacking:* In this rule, we use flow thresholds to determine the flow pulse that cannot be piggybacked. More specifically, natural flow events in a river reach that exceed the given flow threshold cannot be piggybacked. To model this we include a modeling parameter that restricts delivery of environmental water for a specified number of days around the peak above the given threshold to ensure no piggybacking of corresponding pulse occurs. The following constraints are added to the base optimization model to include this rule

$$x_{ad'} \leq e_{ad'} \quad \forall\ d' \in \{d-\pi_a, d+\pi_a\}, d \in D_{t_a}, a \in A_r \quad (1)$$

where $e_{ad'}$ is the exogenous flow in river reach a on day d', $x_{ad'}$ is the total flow (exogenous flows + environmental flows) in river reach a on day d', D_{t_a} is the set of days the flow peak exceeds threshold t_a, π_a is a parameter that restricts the number of days around the peaks in D_{t_a} for piggybacking, and A_r is the set of reaches in the river system. For each river reach, the parameter π_a can be obtained by analyzing the recommended rates of rise and fall in the reach and the size and duration of fresh events required by the ecological endpoints in the reach. For the Yarra River, we take threshold levels of 350,000 and 600,000 cubic meters for Reach 2 and Reach 5, respectively, to restrict piggybacking. These thresholds are chosen based on the minimum passing flow values and the historical flow patterns in the two reaches. In addition to this, topping-up of exogenous flows is restricted for four days on either side of the peaks of the events that are not piggybacked.
- *Rule 3—Flow rate constrained piggybacking:* This rule restricts the topping up of flow in a reach on a day if the exogenous flow on the day is greater than a given threshold *and* the rate of change of flow (the rate of rise or fall) for the following day is greater than a given percentage. While adding environmental flow on the falling limb would not increase the flooding risk, our aim here is to define a no-piggybacking rule using the rate of change of flow, and hence we restrict addition of environmental flows to rapidly falling flows. To model this, we add the following constraints to the base optimization model

$$x_{ad} \leq e_{ad} \quad \forall\ a \in A_r, d \in D\colon e_{ad} > t_a, \quad \text{and}$$
$$\frac{\max\{e_{ad}, e_{a(d+1)}\}}{\min\{e_{ad}, e_{a(d+1)}\}} \geq 1 + RecRate_a \quad (2)$$

where e_{ad} is the exogenous flow in river reach a on day d, x_{ad} is the total flow (exogenous flows + environmental flows) in river reach a on day d, t_a, and $RecRate_a$ are the recommended threshold and rate of change of flow to select the piggybacking events in reach $a \in A_r$. For the case study, we take threshold levels of 350 and 600 mL for Reaches 2 and 5, which are considered with the rate of change of flow restricted to 25%, i.e., exogenous flows on a day will not be topped with environmental releases if the rate of change in flow to the following day is greater than 25% of the exogenous flow on the first day.

Forecast Ensembles

In this study, we obtain the forecast the ensemble for possible flow pulses using the Poor Man's Ensemble (PME) 9-day rainfall forecast data (Ebert 2001) available from the Australian Bureau of Meteorology and applied bias-correction factors based on corresponding historical rainfall data for the period July 2010–June 2012. The forecast and historical rainfalls were converted to streamflows via application of the SIMHYD rainfall-runoff model (Chiew et al. 2002). Based on the normalized residual error between forecast and historical streamflow, Matalas' residual approach was used to generate sets of 100 time-and space-correlated error residuals. This produces 100 9-day forecast ensembles for each forecast date, representing a range of streamflow forecast uncertainty. These uncertainty-adjusted forecasts were used as inputs to the Yarra optimization models to assess Australian grayling spawning and migration outcome and flooding risk under considered piggybacking rules (Fig. 4). Fig. 6 shows the streamflow forecasts obtained for an event in April 2011 and an event in March 2011 in Reach 2 of the Yarra River.

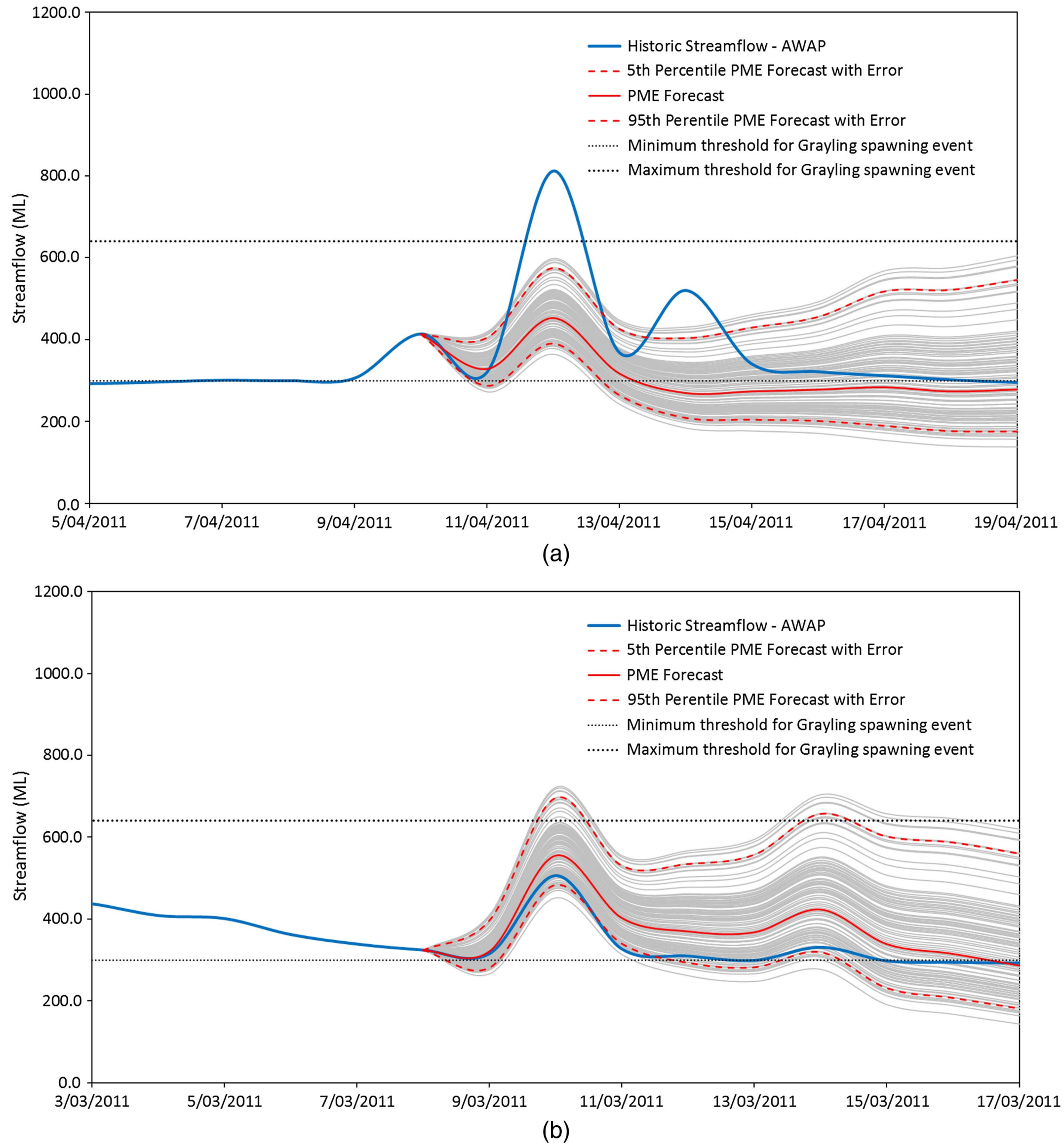

Fig. 6. Streamflow forecasts for two pulse events in (a) April 2011; and (b) March 2011 in Reach 2 of Yarra River. 1 ML = 1000 cubic meters.

Results and Discussion

The ability to piggyback or not can have a substantial impact on provisioning the spawning conditions for Australian grayling in the Yarra River. To compare the impact of the piggybacking rules on Australian grayling spawning conditions, we analyzed the relevant flow pulses between July 2010 and June 2012 (the duration when the PME 9-day rainfall forecast data was available for the Yarra River from the Australian Bureau of Meteorology). The results showed that, on average across all flow pulses, the unrestricted piggybacking rule leads to a greater increase in the probability of a spawning event compared to the restricted rules. More importantly, none of the piggybacking rules increased flooding risks in the river significantly. This is because the overall channel capacity of the river is large compared to the environmental water releases needed to achieve the fresh event targeting Australian grayling spawning. We demonstrate these results using the two forecast events in Fig. 6.

Fig. 7 shows the results for the pulse event in April 2011 [Fig. 6(a)]. As stated previously, the choice of thresholds (both for x and y axes) defining the four quadrants of the framework needs to be negotiated among stakeholders. For this demonstration, we have used the halfway marks for both maximum flow and increase in spawning. For each piggybacking rule, Fig. 7 shows the impact on the spawning outcomes (measured as the percentage increase in the probability that a spawning event for Australian grayling will occur) and the flooding outcome (measured through the maximum flow in Reach 2 of the Yarra River) under the streamflow forecast. Figs. 7(a and b) show the results when we assume that the target species (Australian grayling) is in good condition and poor condition at the start of the year, respectively. We see that in both cases and for all piggybacking rules, the data points span quadrants A and D of the risk framework. All piggybacking rules have low flooding risks as none of the environmental releases cause flooding in the reach. This happens because the environmental water releases are not significant compared to the overall channel capacity of the river. With a good starting condition of the species, the majority of data points for all piggybacking rules are contained in quadrant A (conditional release), with a few data points for the unrestricted piggybacking rule (Rule 1) lying in quadrant D (make release) also. On the other hand, with poor starting conditions of the species, for all piggybacking rules, most data points

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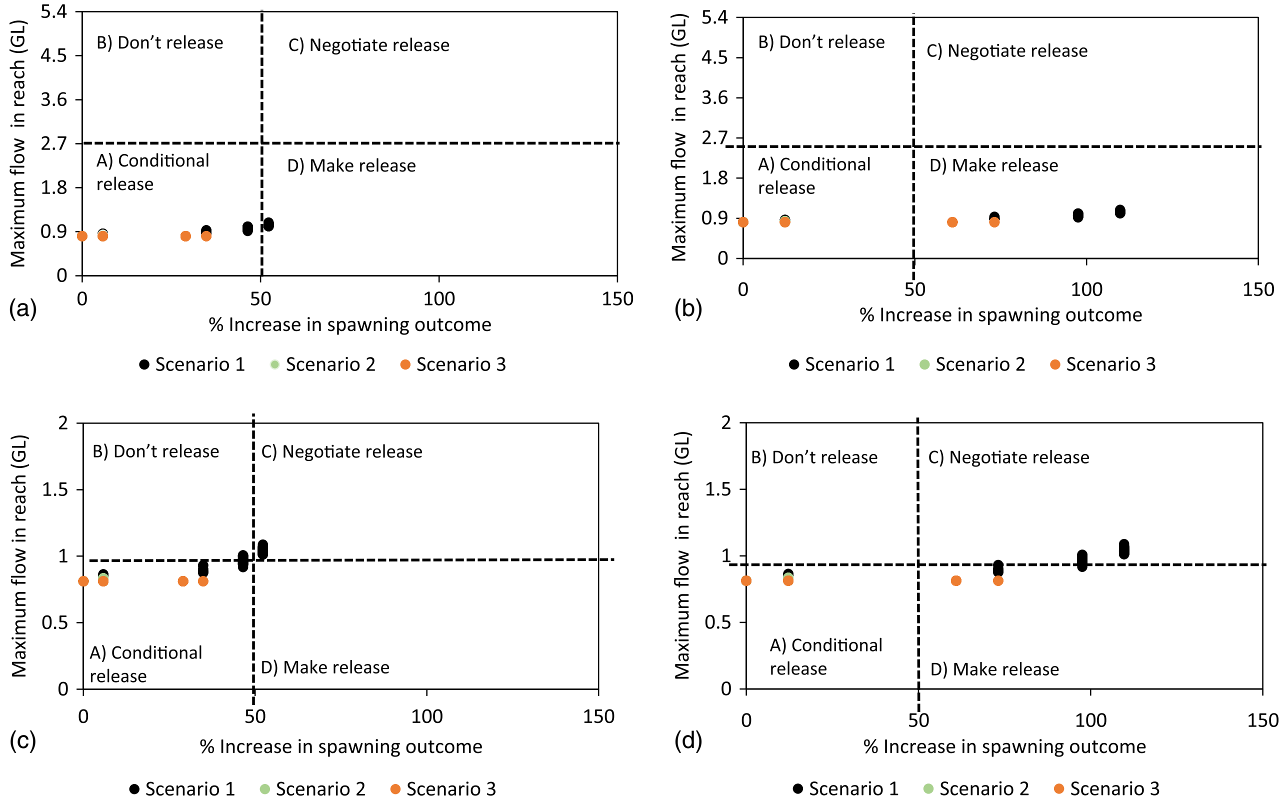

Fig. 7. Maximum flow and percentage increase Australian grayling spawning outcome that will occur for each piggybacking rule for a pulse event in April 2011, with Australian grayling in (a and c) good condition at start of year; and (b and d) poor condition at start of year. Dashed horizontal line represents (a and b) actual and (c and d) reduced bankfull threshold for Reach 2 of Yarra 2. Data points for Rule 2 are superimposed by data points for Rule 3. 1GL = 1000000 cubic meters.

lie in quadrant D of the risk framework. Therefore, for this flow event, irrespective of the starting conditions of the species, the unrestricted piggybacking rule provides a greater chance of achieving the environmental target, but does not increase flooding risks.

Unrestricted piggybacking releases can be made in the preceding example as the bankfull flow threshold for the reach (2.7 gallons) is significantly higher than the flow forecast ensemble and the target threshold (0.64 gallons). If we undertake the same analysis but with a lower bankfull flow, say 1 gallons, then under Rule 1 the chances of flooding increase significantly [Figs. 7(c and d)], with the maximum flow in the reach exceeding 1 gallon for a number of environmental flow release schedules. In this case, under Rule 1, we get low impact on the flooding risks and low to moderate impact in the spawning outcome, with data points sitting across quadrants A and C when the starting species' conditions are assumed to be good [Fig. 7(c)], and in quadrants D and C when the when the starting species' conditions are assumed to be poor [Fig. 7(d)]. In this case, the environmental water releases according to the unrestricted rule can be made in view of the risk tolerance of the environmental water manager, after weighing out the negative impacts of flooding against the positive impact of the spawning event. On the other hand, piggybacking releases under Rules 2 and 3 do not increase flooding risks, but this is achieved at the cost of a reduced impact of the spawning event.

Fig. 8 shows the results when the risk framework is applied to the flow pulse in March 2011 in Reach 2 of the Yarra River [Fig. 6(b)]. None of the piggybacking rules pose any risk of flooding in the reach (even with reduced bankfull flow). However, the unrestricted rule (Rule 1) can potentially give twice the increase in Australian grayling spawning in comparison to the two restricted piggybacking rules, highlighting that the way in which piggybacking is implemented can have a significant impact on the potential environmental outcomes.

Conclusions and Future Work

To date, the risk assessment for piggybacking flows has been defined by the consequences of flooding that may occur. However, failing to piggyback flows also constitutes a risk to the environment. In this paper we highlight the need to consider both flooding and environmental impacts of piggybacking flows when assessing the associated risk. We have shown that for the particular flow events considered in the Yarra River, the increased risk of flooding by piggybacking environmental flows is negligible, while the potential ecological benefits are large. This approach would allow an environmental manager to assess the risks of piggybacking for an individual environmental flow release as forecast data becomes available. An analysis of this type could also be used to involve stakeholders in an understanding of trade-offs and risks.

The approach presented in this paper can be used to assess the relative environmental and flood risk from piggybacking environmental flow releases to meet other ecological endpoints. The level of flood risk is likely to be influenced by the size of the selected flow component relative to the capacity constraints of the river system, along with the certainty in forecast estimates. The level of risk to the environment will largely be driven by the antecedent conditions and the likelihood of future opportunities to provide the required flow event.

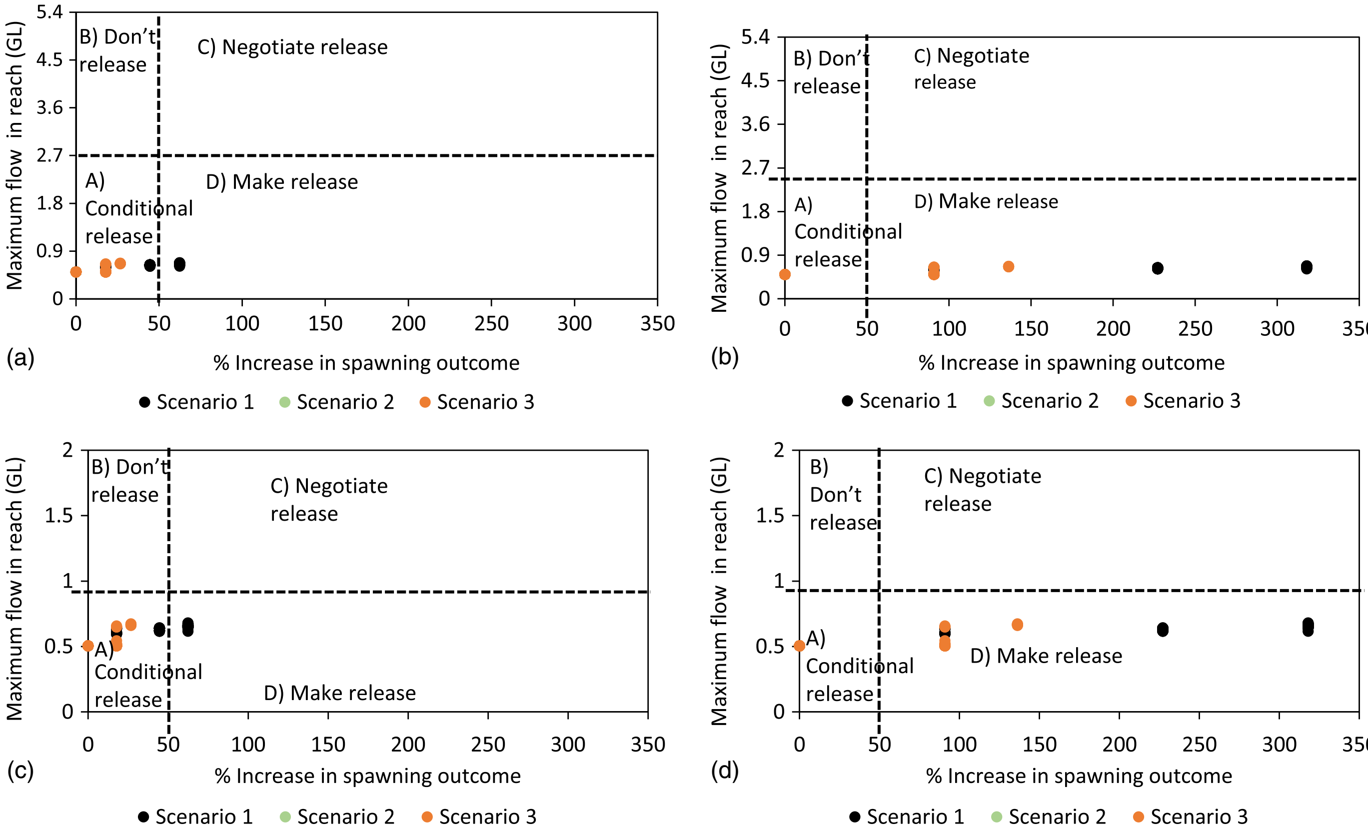

Fig. 8. Maximum flow and percentage increase Australian grayling spawning outcome that will occur for each piggybacking rule for a flow pulse in March 2011, with Australian grayling in (a and c) good condition at start of year; and (b and d) poor condition at start of year. Dashed horizontal line represents (a and b) actual and (c and d) reduced bankfull threshold for Reach 2 of Yarra 2. Data points for Rule 2 are superimposed by data points for Rule 3.

Despite the presence of forecast uncertainty, the results show that for a fresh event targeting Australian grayling spawning (the largest recommended annual flow event in the Yarra River), there are negligible chances of increasing flooding risks even when unrestricted piggybacking of environmental releases is allowed. This suggests that in the Yarra River, the current policy that restricts piggybacking for Australian grayling spawning events is preventing the maximally efficient use of environmental water, and should be replaced by a more flexible approach that allows piggybacking of natural events when deciding upon environmental flow releases.

A key challenge will be in systems that operate in quadrant C (both a high change to flood risk and environmental risk hinging on the piggybacking release). Where piggybacking is required at regular intervals with regular flooding risk, or there are significant economic and social impacts (e.g., bridges or other infrastructures), then works may be required to improve the delivery capacity for environmental water while limiting the increase in flood risk. Importantly, stakeholders must be involved in developing the management approach and understanding the environmental release decision process. Individuals are more likely to adopt a skeptical attitude toward risks that are imposed by a societal (or government) decision than if they are a part of the decision process. Where flood risks due to environmental flow events occur at irregular intervals, there may be a role for options contracts or other negotiated options for flooding of private property (Vrijling et al. 1995).

The change in risk can be reduced through improvements in forecast skill and the treatment of uncertainty. Improved forecast abilities will lead to reduced risks for piggybacking events. It is however also possible to use more sophisticated approaches to include forecast uncertainties in piggybacking decisions to make best use of the whole range of currently available ensemble predictions. Tools can be developed that allow active management of piggybacking decisions, i.e., making release decisions for the event at the current time step while hedging against the possibilities of future opportunities and the related costs (environmental as well as flooding). As part of future work, we are investigating a stochastic approach that allows assessment of flooding risks in conjunction with environmental risks when making piggybacking decisions under forecast uncertainty. Another useful direction of future work is development of methods that optimize piggybacking rules, i.e., methods that design piggybacking rules that balance the environmental benefits against flood risks over time.

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