Active Management of Environmental Water to Improve Ecological Outcomes

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Abstract: Environmental water is being embraced by governments around the world as a means to partly restore rivers impacted by excessive river regulation and to protect those that are not yet overregulated. In cases where environmental water is provided as a water right, managers can make ongoing active management decisions regarding the timing and magnitude of environmental flows in response to changing conditions and understanding of environmental demands. Such active management should lead to improved environmental outcomes but also comes with a significant ongoing management cost when compared to rules-based environmental water releases. This study uses an optimization tool to examine the environmental gain achievable with the active management of environmental water compared to rules-based releases. A case study of the Yarra River, Victoria, Australia, demonstrates the potential for substantial environmental gains achieved through active management of environmental water. **DOI: 10.1061/(ASCE)WR.1943-5452.0000991.** *© 2018 American Society of Civil Engineers.*

Author keywords: Active management; Environmental flow; Environmental water release; Flow regime; Optimization; Water resources management.

Introduction

Water managers are grappling with the challenge of providing water to meet increasing human demand (Vorosmarty et al. 2010) while sustaining diverse river ecosystems (Dudgeon et al. 2006). Governments in many countries have responded to this challenge by providing environmental flows (Le Quesne et al. 2010). Environmental flows are "the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems, and the human livelihoods and well-being that depend on these ecosystems" (Arthington et al. 2018). A significant challenge remains in designing release strategies for major infrastructure to meet environmental flow requirements (Acreman et al. 2014; Arthington et al. 2006; Harman and Stewardson 2005; Horne et al. 2017a). Releases from storage to meet environmental water requirements are often guided by a series of release rules (Harman and Stewardson 2005). However, there are now a number of places where the water allocation system allows for adaptive and ongoing decisions on how to release water from storage to best meet downstream environmental needs (Horne et al. 2017a, b)—a process termed *active management* (O'Donnell and Garrick 2017).

Several strategies for implementing environmental flows are used around the world. This includes a variety of legal mechanisms used to allocate environmental water, each placing different demands on the institutions responsible for implementing these mechanisms (Horne et al. 2017b; Le Quesne et al. 2010; O'Donnell 2014; O'Donnell and Garrick 2017; Speed et al. 2013). Broadly speaking, allocation mechanisms for environmental water can be categorized as (Horne et al. 2017b):

1. Those that impose conditions on other water users (such as conditions on licenses to abstract water, conditions on storage operators to release flow, and the implementation of a cap or limit on total abstraction volume); and
2. Those that provide a legal right to water for the environment [such as the Ecological Water Reserve in South Africa (Republic of South Africa 1998) or Environmental Water Entitlements in Australia (Commonwealth of Australia 2007)].

The first mechanism (here referred to as *rules-based*) is more common. These mechanisms can be set through long-term planning instruments and implemented consistently between years, in some cases with varying rules depending, for example, on catchment inflows (i.e., wet, dry, or average). While it is possible to use a rules-based approach with the second mechanism, it is also possible to actively manage environmental water delivery decisions in response to changing opportunities and risks rather than rules. If an environmental water right is to be actively managed, an environmental water manager is required to hold this water in storage and make decisions about how to achieve the best environmental outcomes. In doing so, the manager is not required to achieve any prespecified flow regime but can make release decisions according to changing conditions related to environmental conditions, system storage state, decisions of other water users, and flows both current and anticipated. This is similar to the way in which irrigators would make decisions to call on their licensed water from storage, though

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Note. This manuscript was submitted on November 20, 2016; approved on May 15, 2018; published online on October 11, 2018. Discussion period open until March 11, 2019; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496.

of course any release decisions are subject to operational capacity constraints and factors such as ensuring that downstream properties are not flooded (Docker and Johnson 2017).

Environmental water rights are held in high regard for their legal security and flexibility to adapt to changing conditions and environmental needs (Godden 2005; Neave et al. 2015). It makes intuitive sense that making release decisions according to changing conditions would lead to better environmental outcomes in the long term. However, active management has a significant ongoing management cost compared to rules-based environmental water releases (Docker and Johnson 2017; Garrick 2015; O'Donnell and Garrick 2017; Pollard and Toit 2011). The question thus arises: To what extent can ecological outcomes be improved through active management of environmental water?

This paper uses the Yarra River in Victoria, Australia, as a case study to explore the difference in environmental outcomes achieved when using a rules-based or active management approach to environmental flow releases. Optimization is used as a tool to compare the two approaches. The modeling outcomes using an active release approach are then compared to various rules-based release strategies to better understand the manner in which ecological outcomes vary with management practice.

Optimization for Environmental Flows

Models that optimize environmental water releases can be used to simulate active management decisions to maximize environmental outcomes. Such optimization models, developed to support environmental flow decisions, commonly include a representation of the physical water resource system and operational constraints, a representation of ecological outcome for each of a number of species, and an objective function that accumulates these species outcomes together considering spatial and temporal information (Horne et al. 2016). While a wide range of existing studies use optimization to determine environmental flow releases (see Horne et al. 2016 for a review), these have focused on environmental flows provided through rules-based allocation mechanisms. Further, previous optimization methods often used similarity to the natural flow regime as a measure of ecological outcome (Chang et al. 2010; Han et al. 2012; Ringler and Cai 2006; Shiau and Wu 2013) or ecological response curves combined through least squares or averaging (Higgins et al. 2011; Szemis et al. 2013).

This paper uses an optimization model, with a 1-year planning horizon, to design a flow regime that meets multiple environmental objectives. To improve the level of realism in the modeling of an active management approach, two key developments to existing optimization methods were required for environmental water release strategies: first, the direct representation of ecological outcomes (rather than hydrological changes) including consideration of interdependencies between species and individual aspects of the flow regime (flow components) (Horne et al. 2017c), and second, consideration of environmental dynamics and changing ecosystem priorities among years. These two considerations are essential for active management where releases of environmental water can vary from year to year.

Methodology

The main objective of this article is to explore the differences in environmental outcomes possible using an active management approach compared to a rules-based approach. The Yarra River (described next) is used as a case study. An optimization model for the Yarra system was used to develop a release strategy representing (1) active management by allowing release decisions to vary at each time step and (2) rules-based management using the same release decisions for multiple years.

Case Study: The Yarra River in Victoria, Australia

The Yarra River originates in a steep forested region and flows 120 km downstream to enter Port Phillip Bay at the city of Melbourne, Victoria, Australia (Fig. 1). The river is highly regulated by large reservoirs from which water is diverted to supply Melbourne and several irrigation diversions along the river. The regulation of flows and volume of abstraction has altered the instream flow regime significantly, with the annual flow at some locations reduced to half the predevelopment flow (SKM 2012).

Currently, storage release rules provide a minimum base flow throughout the year. The Victorian state government also holds an environmental water right in the basin totaling 17 million m^3, which is allocated each year as a priority. Water rights in the system are based on the riparian doctrine (Productivity Commission 2003). Melbourne Water, the environmental water manager, is responsible for actively managing the environmental water right in the Yarra River. Flow delivery constraints apply to different parts of the system, including capacity constraints on storage release valves and flooding constraints (Melbourne Water 2014). Subject to these constraints, Melbourne Water decides when to release environmental water from the various reservoirs to achieve the best environmental outcomes. Environmental water releases target management objectives at three key reaches: Upper Yarra (Reach 1), Yering Gorge (Reach 2), and Millgrove (Reach 5) (Fig. 1) (Melbourne Water 2014).

The Yarra River supports a range of important environmental values. Table 1 lists the objectives identified by the environmental water manager as critical for environmental water management decisions (H. Clarke, Melbourne Water, personal communication, 2015) that have been included in the optimization model. These objectives were identified as part of a detailed environmental flow assessment study (SKM 2012).

Modeling Approach

The analysis in this paper uses the Seasonal Environmental Watering Decision Support (SEWDS) model (Horne et al. 2017a). This model optimizes the source and volume of environmental water releases to achieve the maximum environmental benefit, subject to a series of water availability and physical system constraints (Fig. 2). The SEWDS tool includes a representation of the river network, data on catchment inflows, and nonenvironmental flow releases (i.e., all water in the system that is not within an environmental manager's control, including irrigation releases on catchment inflows downstream of storage) for a given planning year and ecological models for the key environmental management objectives of the river. The SEWDS model schedules the environmental flow releases into a river (the decision) such that the total-weighted sum of the ecological outcomes for all management objectives over a planning horizon of 1 year is maximized (the objective). The model uses mixed integer linear programming (MILP) and runs using a daily time step. The form of the core constraints representing the water resource model in SEWDS is given in what follows.

The Yarra River system is represented as a network of nodes and directed arcs in the SEWDS model. The nodes represent reservoirs and the start/end locations of a river reach. The directed arcs represent (1) river reaches and (2) link reservoirs to the river at specific nodes.

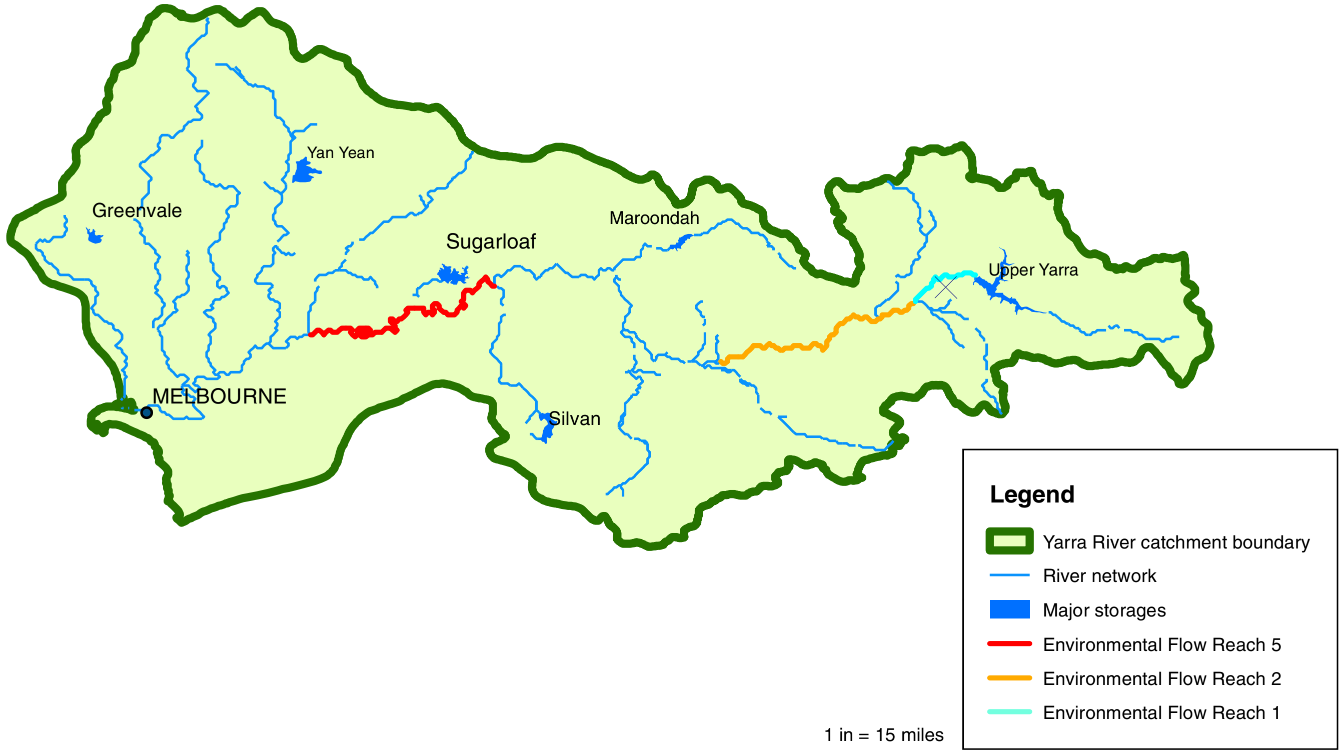

Fig. 1. Yarra River Basin.

Table 1. Environmental water management objectives

Environmental water management objective	Required process	Relevant flow component	Size of flow component (best case) for Reaches 1, 2, and 5 (Fig. 4)
Preserve Australian grayling (endangered diadromous fish species)	Maintain water quality Ensure longitudinal connectivity for fish passage	Summer low flow	Reach 1: N/A Reach 2: Weekly minimum flows >300 mL Reach 5: Weekly minimum flows >300 mL
	Provide access to suitable habitat	Autumn fresh event	Reach 1: N/A Reach 2: 640 ML/day for 21 days Reach 5: 1,900 ML/day for 21 days
	Assist spawning and migration	Spring fresh event	Reach 1: N/A Reach 2: N/A Reach 5: 2,000 ML/day for 7 days
Preserve blackfish and Macquarie perch	Maintain water quality Ensure longitudinal connectivity for fish passage	Summer low flow	Reach 1: N/A Reach 2: Weekly minimum flows >300 ML Reach 5: Weekly minimum flows >300 ML
	Provide access to suitable habitat Protect eggs and larvae from high flow disturbances	Limit October to November high flows	Reach 1: N/A Reach 2: Avoid pulses >300 ML/day for 1 day (blackfish only) Reach 5: Avoid pulses >500 ML/day for 1 day (Macquarie perch only)
Protect Macroinvertebrates	Provide access to suitable habitat by scouring sediments and algae from pool and benthic surfaces in riffles	Summer low flow	Reach 1: N/A Reach 2: Greater than 80 ML/day Reach 5: Greater than 200 ML/day
		Autumn fresh events	Reach 1: N/A Reach 2: Three events at 820 ML/day for 2 days Reach 5: Three events at 3,500 ML/day for 2 days
		Spring fresh events	Reach 1: N/A Reach 2: 820 ML/day for 2 days Reach 5: 3,500 ML/day for 2 days
Maintain channel geometry	Scour and remove sediment	High flow	Reach 1: 1,000 ML/day for 1 day Reach 2: N/A Reach 5: N/A

Sources: Adapted from Melbourne Water (2014) and SKM (2012).
Note: 1 ML = 1,000 m^3.

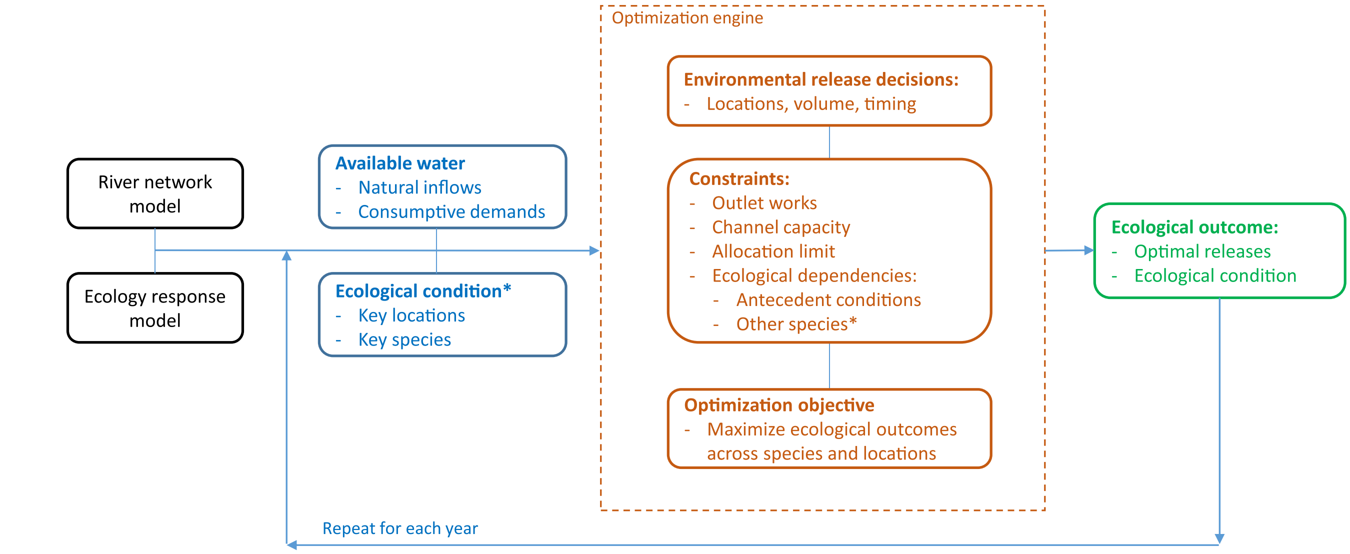

Fig. 2. Overview of SEWDS optimization model structure to support environmental flow release decisions [developments that build upon functionality developed by Horne et al. (2017a) are marked with an asterisk].

Variables

x_{ad}: total flow on arc a on day d;
γ_{ad}: binary variable that equals 1 if environmental flow is released from arc a representing a link from a reservoir to the river on day d.

Constraints:

$$\sum_{d\in D}\sum_{a\in A_{res}\cup A_{har}} x_{ad} \le EnvTotal \qquad (1)$$

$$\sum_{a\in A_n^-} x_{a(d-t_a)} + e_{nd}^- = \sum_{a\in A_n^+} x_{ad} + e_{ad}^+ \quad \forall\ n\in N_{riv},\quad d\in D \qquad (2)$$

$$\sum_{a\in A_n^+} x_{ad} \le ResCap_n \quad \forall\ n\in N_{res},\quad d\in D \qquad (3)$$

$$x_{ad} \le ReachCap_a \quad \forall\ a\in A_{reach},\quad d\in D \qquad (4)$$

$$x_{ad} \le e_{ad} \quad \forall\ a\in A_{reach},\quad d\in D \qquad (5)$$

$$x_{ad} \le H_{ad} \quad \forall\ a\in A_{har},\quad d\in D \qquad (6)$$

$$x_{ad} \le Cap_a \gamma_{ad} \quad \forall\ a\in A_{res},\quad d\in D \qquad (7)$$

$$x_{ad} \le Rise_b x_{b(d-1)} + M(1-\gamma_{ad}) \quad \forall\ a\in A_{reach},\quad b = downReach(a),\quad d\in D \qquad (8)$$

$$x_{ad} \ge Fall_b x_{b(d+1)} - M(1-\gamma_{ad}) \quad \forall\ a\in A_{reach},\quad b = downReach(a),\quad d\in D \qquad (9)$$

$$a_{ad} \ge 0 \quad \forall\ a\in A_{reach}\cup A_{res}\cup A_{har},\quad d\in D \qquad (10)$$

$$\gamma_{ad} \in \{0,1\} \quad \forall\ a\in A_{res},\quad d\in D \qquad (11)$$

Constraint (1) guarantees that no more than the allocated volume of environmental water (EnvTotal) is released on arcs from reservoirs (A_{res}) or harvested from a river (on arcs A_{har}) for environmental purposes. Constraint (2) maintains the water balance in the river reaches, ensuring that the total flow coming into each node in the river (N_{riv}) equals the total flow going out of the node on each day of the planning period while respecting the travel time (t_a) for flow on each incoming arc. Note that A_n^- and A_n^+ constitute the set of arcs coming into and going out of node $n\in N_{riv}$. Constraint (3) ensures that the total releases made from a reservoir node in N_{res} on any day will not exceed the daily release capacity of the reservoir. Constraints (4) and (5) model the channel capacity constraints on the total flow in the river reaches, ensuring that no environmental releases arrive at the reach on any day when the river is overflowing due to a natural event [the nonenvironmental flow in the river on the day (e_{ad}) is greater than the reach capacity] and that the total flow in the reach remains within the channel capacity on days when the nonenvironmental flows are within the channel capacity. Constraint (6) guarantees that the total flow that stops being harvested on a day at a particular location along an arc in A_{har} is not greater than the flow being harvested at that location on that day. If an environmental water release is made from a reservoir, then Constraints (8) and (9) model the rate of rise and fall requirements for the reach immediately downstream of the reservoir. Constraints (10) and (11) define the scope of the variables.

The SEWDS model was extended in this study to include interdependencies between species, temporal sequencing of environmental conditions, and changing environmental priorities between years. These aspects provide additional information to inform active management.

Representing ecological outcomes within an optimization model is a significant challenge (Barbour et al. 2016; Horne et al. 2016). Active management has the added complication of requiring information on the temporal sequencing of environmental conditions through time. Priorities for environmental flow releases may then vary between years in response to the condition of different ecological assets at different locations. Conditional probability networks (CPNs) are adopted here because they allow for the representation of species interdependencies, temporal sequencing of conditions, and the marginal value of different flow conditions (Horne et al. 2017c). CPNs accommodate dynamic behavior in which ecological outcomes vary with antecedent conditions and differences in flow sequencing. This is a critical consideration in active management because the release decisions are heavily dependent on the health of the various ecological assets at the end of the previous season. Environmental outcomes are represented through a series of influence diagrams (Watthayu and Peng 2004), which are then translated to CPNs. These CPNs link flow release decisions (decision nodes) for a given season to an outcome (utility node) for an individual species, with important intermediate processes linking the decisions to the outcome (chance nodes) (Fig. 3). For example, the decision to provide a fresh or pulse event (decision nodes) may impact the probability that fish spawning will occur (chance node), which in turn impacts the likelihood of a particular fish species being in good, average, or poor condition (utility node). Each chance and utility node in the CPN is governed by probabilities that define how a given environmental state will lead to a certain outcome in nodes further down the influence diagram.

In SEWDS, a linear objective is optimized (e.g., maximize benefit to key identified species) subject to a set of linear constraints (e.g., capacity constraints of river reaches, operational constraints on releasing water from storages, dependencies in CPN models). However, the conditional dependencies in the CPN may not be straightforward, for example when the condition of one species depends on the condition of another species (see example CPN in Fig. 3). Binary variables are added in SEWDS to model such relations linearly. We demonstrate this for the CPN in Fig. 3.

Let L be the set of states for the summer low flow (e.g., good, average, or poor). Let M and U be the sets of magnitudes and durations at which a fresh event can be delivered for the species. Let C be the set of states for the antecedent condition for the species, H the set of states for habitat provision, S the set of states for spawning and recruitment, O the states for the overall objective for the species, and R the set of states for the related species condition.

If the summer low flow is in condition $\ell^* \in L$, and the fresh event is delivered at magnitude $m^* \in M$ with duration $u^* \in U$, then the probability that the considered species will be in condition $o \in O$ can be determined using Bayes' theorem as follows:

$$P(o) = \sum_{c\in C}\sum_{h\in H}\sum_{s\in S}\sum_{r\in R} P(o|c,h,s,r)P(c)P(h|\ell^*)P(s|m^*,u^*)P(r)$$

where P(.) is the probability function. To model this in SEWDS, we include two types of binary variables:

y_ℓ, which equals 1 only if the summer low flow is in state ℓ, and z_{mu}, which equals 1 if the fresh event is delivered at magnitude m and duration u. The following constraints are added to the model for each $\ell \in L$, $m \in M$, and $u \in U$:

$$P(o) \leq \sum_{c\in C}\sum_{h\in H}\sum_{s\in S}\sum_{r\in R} P(o|c,h,s,r)P(c)P(h|\ell)P(s|m,u)P(r) + (1-y_\ell) + (1-z_{mu})$$

For brevity, we are omitting here the details of additional binary variables and constraints to capture the definitions of y_ℓ and z_{mu}.

The CPNs for each environmental objective were developed through an expert elicitation process. For further details on the Yarra system CPNs, readers are referred to the Supplemental Data. The example in Fig. 3 is structured around outcomes for fish; however, CPNs can similarly be produced for other types of environmental management objectives (such as vegetation, macroinvertebrates, and channel form).

A major challenge in accommodating ecological models in decision-making is to develop a comparable scale of conditions or outcomes across management objectives. In this article the common approach of defining states or severity ratings (good, average, and poor condition) associated with a scale of zero to one is used (King et al. 2003; Sale et al. 1982; Young et al. 2003).

Temporal sequencing is included in the SEWDS model by providing the ecological outcomes at the end of the previous year as the starting ecological conditions at the start of the current year (Fig. 2). To include the ecological priorities in SEWDS, the condition of the environmental assets of management interest at the start of a year are used to inform the relative weights (w_{sr}) of different environmental assets in the objective function. This approach gives more importance to species that are in poorer condition at the start of the planning year compared to other species. To achieve

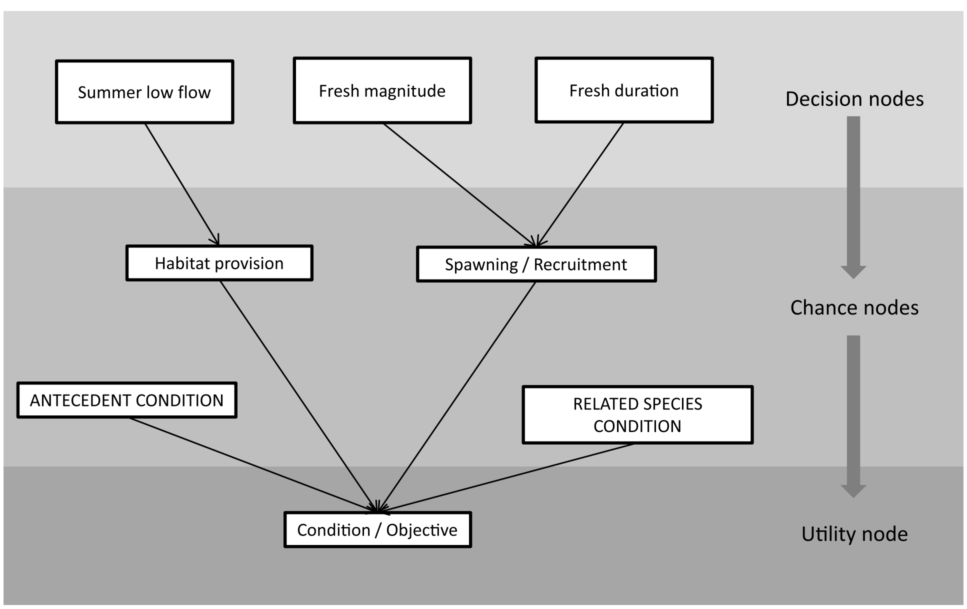

Fig. 3. Example structure of an influence diagram (which would be backed by a CPN) to develop an environmental water regime. The decision nodes relate to the decision to provide particular flow components through environmental releases combined with exogenous flow (all nonenvironmental flow releases), with the aim of improving a specific ecological outcome (given by the utility node), with the causal relationship mapped through chance nodes. [Developments that build upon functionality developed by Horne et al. (2017a) are shown in small capital letters.]

this, a higher weight is included in the objective function for species with a high probability of being in poor condition at the start of the year. More precisely, the weight of an ecological species s in reach r is given by the following equation:

$$w_{sr} = \alpha P^s_{good} + \beta P^s_{average} + \gamma P^s_{poor}$$

where P^s_{good}, $P^s_{average}$, and P^s_{poor} = probabilities that species s is in a good, average, and poor state at the start of the planning year, respectively; and α, β, and γ = fixed parameters, with $\alpha < \beta < \gamma$. The initial conditions for each asset at the start of each year can be defined by the user or else obtained from the outputs of the optimization model at the end of the previous year. In this article there is no attempt to model the different priorities that might arise from societal value judgments (e.g., whether a species is iconic or endangered). However, it is recognized that these exist and they could easily be represented in the objective function in adjusting relative weighting among environmental assets.

Analysis Conducted

An active management scenario was modeled for a period of 49 years (with a water year in this region defined as July to June) spanning from 1963 to 2011. The current environmental water right in the Yarra is 17 million m^3; however, the model was also run with higher and lower limits on environmental water releases to consider how the benefits of active and rules-based management might change under these different scenarios.

Because there are no current environmental release rules in the Yarra system for direct comparison, the outcomes from the active management scenario were first used to develop appropriate release rules. Current environmental water planning (and relevant decision support tools) is generally based on assessments for specific climate-based scenarios or representative years (Basdekas et al. 2014; Cardwell et al. 1996; Chen 2011; Melbourne Water 2014; Ringler and Cai 2006; Yang and Yang 2012). In this study, the water releases suggested by the SEWDS model were analyzed to examine the basis for developing rules-based releases for different climate types. Similarly, the SEWDS model was used to determine whether there was consistency in the timing of environmental water releases and the size of other catchment stream flows and storage releases.

Two different environmental release rules were developed. The rules define a recurring monthly release pattern for wet, average, and dry years. The two approaches used to develop these rules were based on the following factors:

1. Optimization of active management, where the release rules were defined as the median monthly release determined by the SEWDS model for each individual year ("median of individual optimized releases"); and
2. Rules defined by optimizing a set of rules across dry, wet, and average years so that the environmental outcomes are maximized while ensuring that the monthly releases are the same across years. Separate sets of rules were derived for three different climatic conditions, where each set of rules were based on the analysis of 10 years of streamflows representative of wet, dry, and average conditions selected from the 49 years of available records ("release rules optimized across years").

Importantly, these patterns were used only to define the monthly release volume, and the daily releases were allowed to vary within each month. Antecedent conditions and capacity constraints on flow releases in the Yarra River were the same for both scenarios.

Results

A common approach to managing environmental flows using rules is to formulate release strategies based on annual inflows (dry, average, or wet conditions). To assess the potential for developing rules that vary with climatic conditions, the outputs from the SEWDS model were analyzed to determine whether there was any consistency in the patterns of optimum release made during dry, wet, and average years. The statistical similarity in release strategies under different inflow conditions for a range of different water right volumes is presented in Table 2. In the Yarra River system, for allocations up to 35 million m^3 a year, the differences in the outcomes between average and dry years are statistically significant; however, there is not enough evidence to suggest that the environmental outcomes from wet years are different than those from average years (Table 2). For high allocations (e.g., 100 million m^3) differences between all year types become nonsignificant. This suggests that when using a rules-based approach, there may be merit in developing a different strategy for dry years, but there is probably no benefit in having different rules for average and wet years.

In the majority of years, a large amount of environmental water is used to enable the Australian grayling to spawn (a key fish species included in the management objectives) (Table 1). This individual flow component was therefore examined in more detail to look for common release triggers that could inform the development of rules regarding release volumes. Fig. 4 shows that while there is considerable variation in the volume of water required to meet spawning flow requirements, there is little systematic variation between wet, average, and dry years. This indicates that

Table 2. Probability from one-way analysis of variance (ANOVA) to test differences in total environmental outcomes between wet, average, and dry years (defined by Reach 5 annual flows)

	Environmental allocation (GL)					
Year types tested	5	10	17	25	35	100
Wet, average, dry	**0.0003**	**0.0000**	**0.0001**	**0.0020**	0.0116	0.0692
Wet, average	0.8556	0.4661	0.3824	0.2834	0.2280	0.3311
Average, dry	**0.0005**	**0.0001**	**0.0008**	**0.0134**	0.0682	0.1776

Note: Statistically significant results (probability <0.05) are in bold.

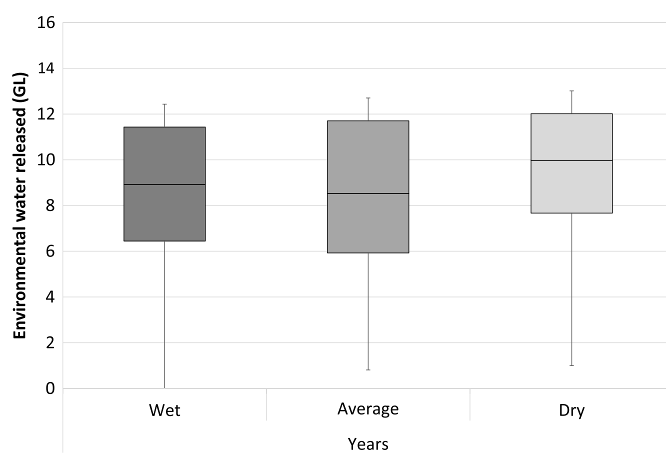

Fig. 4. Magnitude and variability in water used for Australian grayling spawning event separated based on wet, average, and dry years. There is no clear difference in release volumes targeting Australian grayling based on year type.

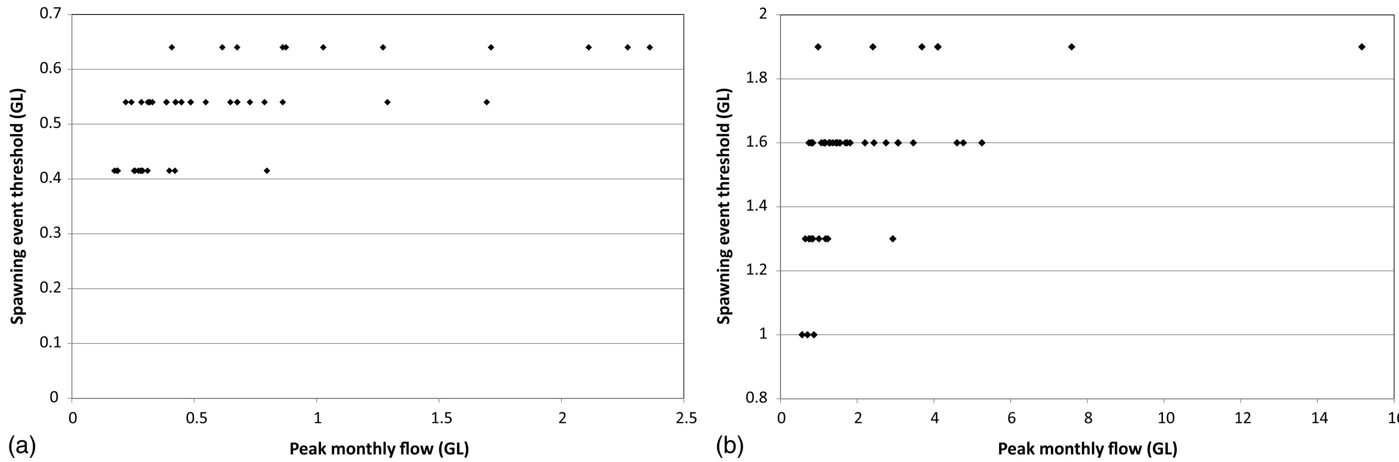

Fig. 5. Relationship between thresholds of spawning event provided in each year and peak flow in month in which event starts in (a) Reach 2; and (b) Reach 5.

different annual climatic conditions have little impact on the optimum environmental water release volumes for spawning (Fig. 4).

The environmental flow assessment defines a spawning fresh event by both the magnitude and the duration of the flow event (SKM 2012). In some instances, it may be more beneficial to use water to extend the duration of an event and, in others, to increase the magnitude of the event. The best approach will be influenced by the existing river flows (i.e., catchment inflows and releases made from storage to satisfy the demands from other water users) and the capacity constraints of both the channel and release infrastructure. Fig. 5 indicates little dependence between the magnitude of the spawning event and the peak monthly flows when no environmental releases occur. It can be seen from the scatter of points in Fig. 5(a) that it would be difficult to develop a release rule that would ensure successful spawning events in Reach 2 when peak monthly flows are less than 1 million m^3/day. Fig. 5(b) shows that a similar situation exists in Reach 5, though here the corresponding threshold is 5 million m^3/day. These results suggest that there is little potential for developing rules based on the analysis of peak monthly flows. Further analysis to support this is provided in the Supplemental Data.

The lack of consistency in the patterns when optimized in individual years made it difficult to develop event-based release rules. Instead, release rules were developed based on monthly release patterns, with different recommendations for wet, dry, and average years (Fig. 6).

Fig. 7 shows a comparison of the environmental outcomes obtained when environmental water is actively managed (shown in black), and where it is managed using rules based on (1) the median of individual optimized releases (light gray) and (2) release rules optimized across years (dark gray). In the Yarra system, the figure shows that active management significantly outperforms rules-based releases, providing an improved outcome for the Australian grayling population for the same volume of environmental water. Results are similar for other environmental management objectives (such as macroinvertebrates). As expected, the optimized release rules perform better than rules based on median monthly releases. Fig. 6(b) shows that over the past 10 years, the optimized release rules have performed as well as active management in terms of recruitment of Australian grayling. This is due to the specific years of data used in developing the optimized release rules. The past 10 years of record have been predominantly dry, and this sequence was thus used to define the rules-based strategy for dry years. When looking further back in the historical sequence, the rules do not perform as well.

With active management, on average 14.5 million m^3, 13.2 million m^3, and 12.8 million m^3 of environmental water is released for dry, average, and wet years, respectively, whereas

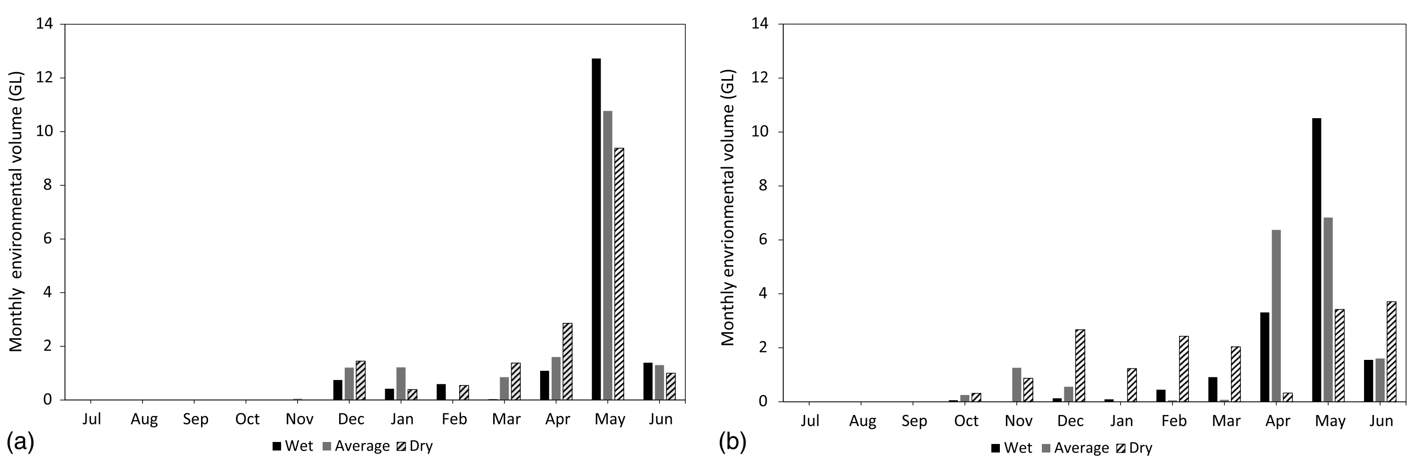

Fig. 6. Monthly environmental water volumes available for wet, average, and dry years under (a) median monthly release rule; and (b) optimized release rule.

J. Water Resour. Plann. Manage., 2018, 144(12): 04018079

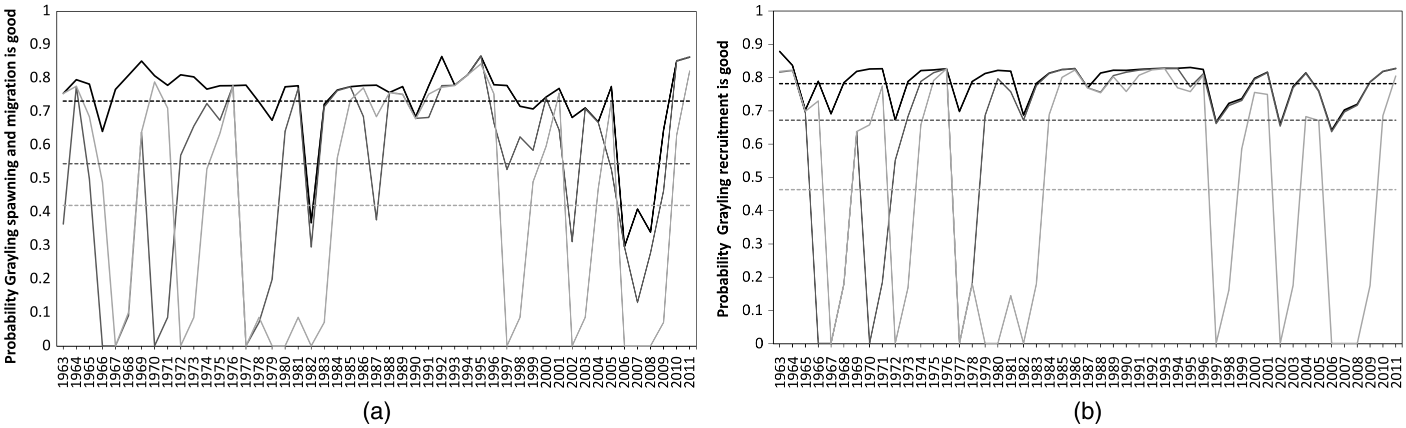

Fig. 7. Comparison of (a) Australian grayling spawning and migration outcomes; and (b) Australian grayling recruitment outcomes based on active management releases (black), median of individual optimized releases (light gray), and release rules optimized across years (dark gray). Dotted lines: average outcome across each scenario.

under the rules-based approach, all 17 million m^3 of environmental water is released for each year type. Thus, the active management approach leads to a total savings of approximately 14%, 22%, and 25% of environmental water for dry, average, and wet years, respectively.

Discussion and Conclusion

While environmental water downstream from storage has traditionally been provided through rules-based releases, there are now allocation mechanisms that also allow for the possibility of active management. A question arises as to how much additional benefit is gained when decisions for environmental releases can be made on an ongoing and adaptive basis about the timing and magnitude of releases from storage. Where active management is possible, it is useful to understand whether additional benefits from managing water in this manner outweigh the additional costs and resources required. This article provides a first step toward answering this question by demonstrating that it is possible to systematically compare the environmental outcomes achieved through active management compared to a rules-based approach. An optimization tool was used to simulate the active management of an environmental water regime in a highly regulated river. The Yarra River case study demonstrates that the outcomes achievable through active management are appreciably better than those achievable through rules-based delivery of environmental water. This suggests that there would be merit in further exploring the use of legal rights to manage environmental water and in investigating how such approaches may improve environmental outcomes without additional water.

However, it is important to consider two issues in more detail. First, the analysis undertaken in this article assumes perfect foresight; that is, at the time watering decisions are made, the optimization model "knows" how the streamflow for the year will unfold. It is expected under these circumstances that the greater the degree of freedom in the model, the better the outcome. The modeling exercise serves to examine the extent or size of the difference in outcomes. However, in reality, an environmental manager or storage operator works under uncertainty concerning future climate conditions, and accordingly, future work should investigate the outcomes once climatic uncertainty is incorporated into the modeling framework. One approach currently being investigated is the use of a stochastic modeling framework that considers uncertainty via the use of a so-called scenario tree using forecast data. In this approach, different future conditions are given a probability of occurrence, with each time step having options that branch from the suite of conditions possible to the previous time step (Powell 2014). This modeling approach produces solutions that hedge over the range of possible future conditions, enabling environmental water managers to make decisions that put them in the best position to be able to manage outcomes no matter what climate scenario unfolds. This may result in a very different release pattern from that with perfect foresight about future climate. This remains an area for further research, both from a technical perspective and considering how a model that acknowledges uncertainty in this way would be used by mangers in their institutional setting.

The second consideration is that active management of environmental water requires an institutional framework and resources to enable these ongoing decisions (O'Donnell and Garrick 2017). There are costs associated with these additional resources (Garrick 2015), and this must be compared to the potential improvements in ecological outcomes.

An optimization model that determines how to use environmental water with active management and perfect foresight is effectively modeling the best possible outcome for a volume of environmental water (as it provides the model with the most information and the fewest possible constraints). If the outcome from this model run shows highly variable release patterns between years, it is likely that a rules-based approach would be inadequate. Where release patterns are more consistent between years, it may be possible to achieve similar outcomes through a rules-based approach.

Environmental water is usually allocated using a mechanism that is the most cost-effective or politically expedient. This article demonstrates that it is also relevant to consider the ability of different allocation approaches to achieve environmental outcomes during implementation. Active management has the potential to improve efficiency of use, which is going to be increasingly important for all environmental water managers under growing human populations and climate change.

Acknowledgments

This study was funded by the Australian Research Council (ARC Linkage Project LP130100174) and a number of partner agencies. We are also grateful for the interactions and discussions held with the Melbourne Water environmental flows team and scientific

advisors. The water resource model data used for the study were generously provided by Melbourne Water.

Supplemental Data

Fig. S1 is available online in the ASCE library (www.ascelibrary.org).

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