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ORIGINAL PAPER

A Bayesian network approach to support environmental flow restoration decisions in the Yarra River, Australia

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Abstract Many rivers in Australia and elsewhere around the world are flow stressed. There is now considerable activity to restore crucial components of the natural flow regime of such rivers—known as environmental flows, but methods underpinning the decision-making often lack rigour and transparency. The restoration of environmental flow regimes is usually determined using historic flow data, available expertise, sometimes ad-hoc compromise between conflicting and spatio-temporally variable water needs, and then implemented through special environmental allocations or water sharing plans. However, ecological flow requirements are poorly integrated into the decision-making process. This paper reports an eco-hydrological Bayesian network model developed to assist in risk assessment and decision-making on improving the flow conditions for Australian Grayling (*Prototroctes maraena*) in the Yarra River in south-eastern Australia. The Yarra environmental flow model was adapted from previous work on Australian Grayling in the Latrobe River system, and contained the same ecological model as for the Latrobe River, but with a new hydrological sub-model developed specifically for the Yarra River. The model was used to assess the relative ecological benefits (to Australian Grayling) of restoring specific components of the natural flow regime, in particular autumn freshes and spring freshes.

Keywords Uncertainty · Evidence-based · Environmental flows · Decision making · Bayesian network · Australian Grayling

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1 Introduction

In Australia, and elsewhere in the world, there is considerable effort going into rehabilitating many of the over-allocated river systems through restoration of a reasonable environmental flow (eFlow) regime (Arthington and Pusey 2003; Qin et al. 2011). The flow regime of a river is recognized as the 'master variable' that drives many riverine ecosystem processes, such as nutrient cycling, fish populations and floodplain dynamics (Sparks 1995; Poff et al. 1997; Chan and Hamilton 2001). The 'natural flow regime' paradigm has thus become a fundamental element of the management of river ecosystems (Richter et al. 1996; Poff et al. 1997).

Within the scientific community there is now broad agreement that prescribed 'minimum' flows are not sufficient to sustain healthy river ecosystems (Arthington et al. 2006). The 'natural flow paradigm' (Richter et al. 1996; Poff et al. 1997; Lytle and Poff 2004) is now seen as 'best practice' in eFlows management because it captures ecologically important temporal variations in the flow regime. Moreover, an eFlow assessment for a river seeks to define how much of the natural flow regime should be preserved or reinstated to maintain specified and valued features of the ecosystem (Tharme 2003).

Obviously, reinstating the full natural flow regime is the preferred option to ensure riverine ecological health.

However, in practice, rehabilitation of flow-stressed rivers invariably involves conflicting social, economic and ecological demands, and therefore consideration of a number of partial flow scenarios is often undertaken with a view of reaching an equitable compromise. Unfortunately, ecological science is not yet adequately integrated into water allocation decision-making (Richter et al. 2006) with the process often being dominated by engineering considerations alone, with little consideration of the needs of freshwater ecosystems. To ensure effective eFlows decision-making, river rehabilitation and restorative actions require the development of scientifically credible estimates of eFlow needs (Richter et al. 2006). The range of available eFlows methods has been well reviewed by Arthington et al. (2006). These methods however often lack transparency on how components of the flow regime are related to ecological outcomes (Hart and Pollino 2009).

As noted above, in severely flow-stressed rivers, physical, social and political constraints often preclude the reinstatement of all components (e.g. low flows, overbank flows, fresh high flows, etc.) of the natural flow regime. But, given certain ecological criteria, assessing the likelihood of success of reinstating alternative partial flow regimes is difficult due to the high degree of uncertainty and complexity of riverine systems. The challenges are determining the relative benefits of reinstating different partial flow regimes. A robust methodology is thus needed that can explicitly link flow component trade-off decisions to the risks to the ecological assets. Bayesian network (BN) models offer such an approach.

The case study addressed in this paper is the Yarra River. This flow-stressed river flows 242 km from the Yarra Valley through to the city of Melbourne, emerging at Port Philip Bay (Fig. 1). Five reaches of the Yarra were considered in the BN model—Millgrove, Yarra Grange, Yarra Glen, Warrandyte and Chandler Highway (Fig. 1: Reaches 2, 3, 4, 5 and 6). Water from the Yarra River is in demand from a number of conflicting environmental, urban, industrial and agricultural needs. In this paper a simple BN model is developed focusing on the key flow components required for the spawning and migration of a key ecological asset, the Australian Grayling (*Prototroctes maraena*). Australian Grayling are also known as 'Yarra Herring' due to the historical abundance of the fish in the Yarra, in sharp contrast to its current scarcity (Koehn and O'Connor 1990). The BN model is used to demonstrate support for evidence-based decision-making on eFlows in the Yarra River.

2 Materials and methods

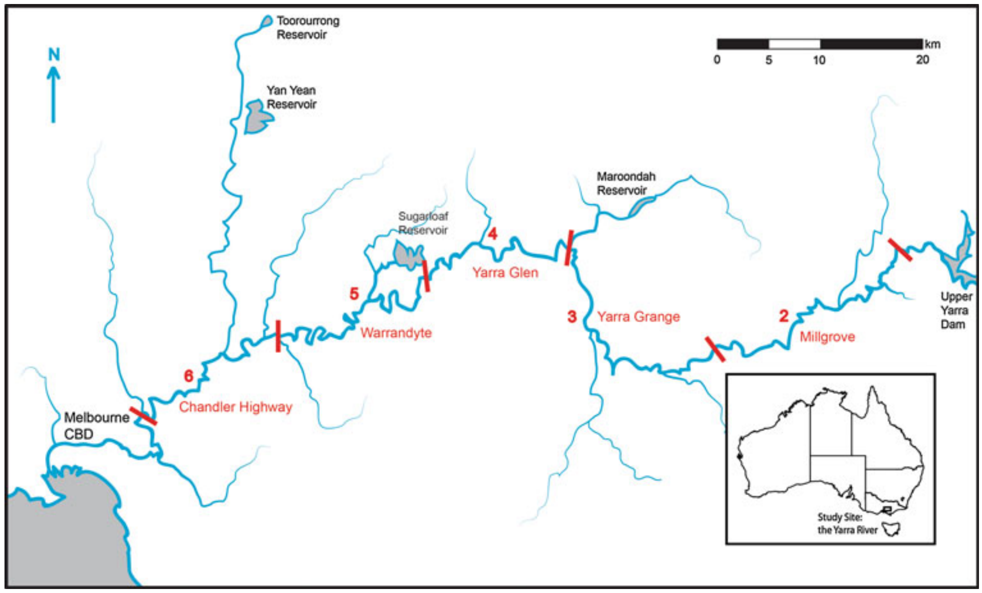
Bayesian networks are composed of an intuitive graphical interface and a formal statistical language that describes the graphically rendered relationships between model variables—they have been well described elsewhere (e.g. Ellison 1996; Borsuk et al. 2004). Briefly, the graphical component can be viewed as a cause-effect diagram composed of linked 'parent' (cause) and 'child' (effect) nodes. For this application, the nodes are additionally decomposed into a low number of discrete states and the linkages between nodes described by a conditional probabilistic relationship dependent on the parent nodes. The discrete states facilitate model use by enabling display of the causal network while also showing the probabilities of the potential states of cause and effect variables for a particular scenario. The conditional probabilities of any relationships within a BN can be cumulatively updated according to additional evidence (e.g. new field monitoring data) based on Bayes' probability theory (e.g. Marcot et al. 2006). A major advantage of the Bayesian approach is its ability to combine diverse sources of knowledge, from stakeholder or expert opinion to simulation model output as well as multiple kinds of field and laboratory data (Bogaert and Fasbender 2007). Additionally, BNs structure uncertainty through consideration of probability distributions, making them well suited to risk analysis and decision-making under uncertainty (Hart et al. 2005). The case study described here was implemented using the software package Netica (Norsys 1997).

The Yarra eFlows BN model (Figs. 2, 3) was adapted from previous work on Australian Grayling in the Latrobe River system (Shenton et al. 2010). A Yarra River specific hydrological BN sub-model was developed and parameterized (by populating the conditional probability tables, or CPTs) with flow scenarios through the different reaches, simulated by a generic water resources model. The relevant nodes of the hydrological BN (low flow, autumn fresh and spring fresh) were then linked to the appropriate ecological BN sub-model nodes (in-stream habitat, transport of larvae and recruitment) to predict recruitment of Australian Grayling (Figs. 2, 3). The conceptual structure, node states and conditional probability tables of the Latrobe Australian Grayling sub-model were originally developed based on general physiology and ecological behavior and adopted without the need for modification to the Yarra River (Shenton et al. 2010). This demonstrates the potential for reuse of ecological modelling 'fragments' (e.g. Bredeweg and Salles 2009) that can easily be linked to the hydrological sub-network of any regulated river system.

2.1 The hydrological BN model

The Yarra BN model employed three flow components known to be important for Australian Grayling spawning and recruitment: Summer (Dec–Feb) low flows, Autumn (Mar–May) fresh flows and Spring (Sept–Nov) fresh flows

Fig. 1 Map showing location of the Yarra River in Victoria, Australia, river reaches represented in the model and major reservoirs



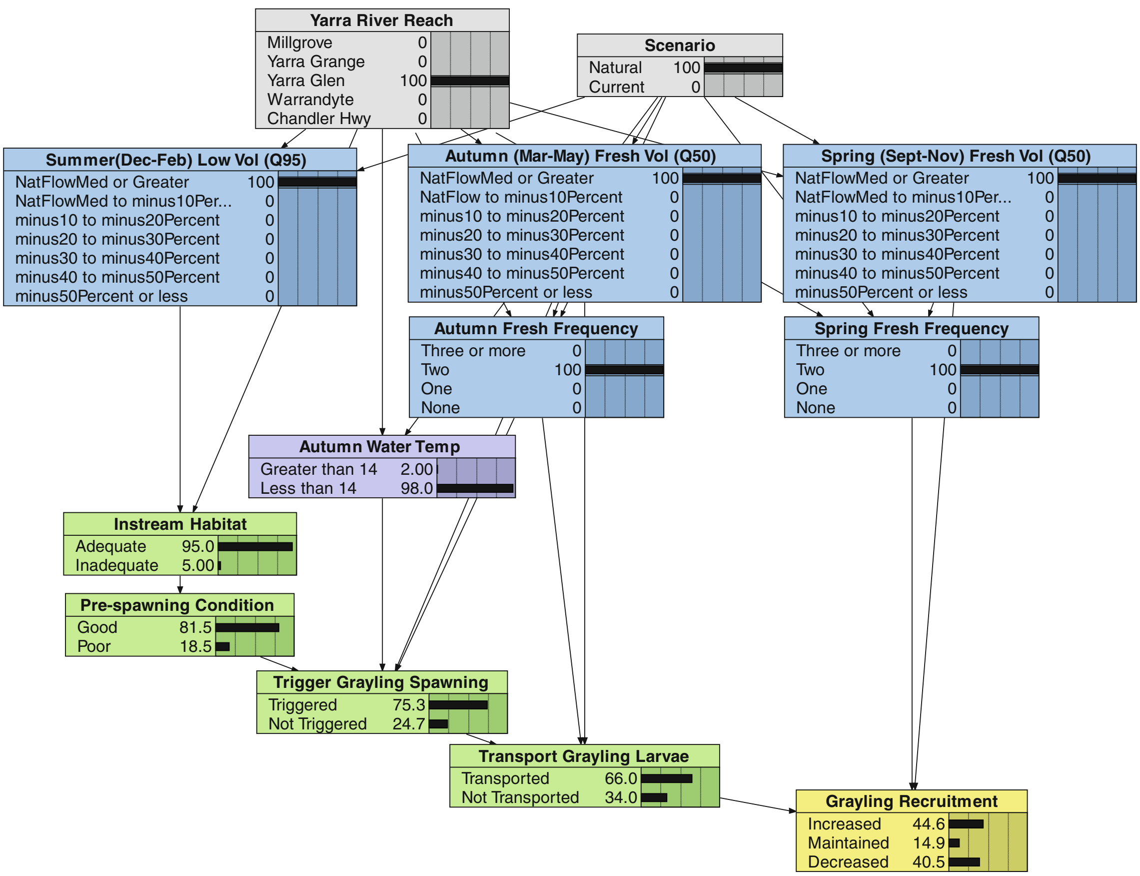


Fig. 2 Complete Bayesian network for flow scenario decision-support for Australian Grayling in the Yarra Glen reach of the Yarra River. A 'natural' flow scenario is defined and an 'ideal' sub-scenario representative of an ideal flow-temperature regime that would have historically resulted in a high probability of Grayling spawning and recruitment

(Shenton et al. 2010). The data to parameterize these components were obtained from simulated daily flow time series using a generalized water resources model called REALM (Perera et al. 2005). The 'Natural' scenario flows are the streamflows that would have occurred over the historical climate sequence without diversions by the

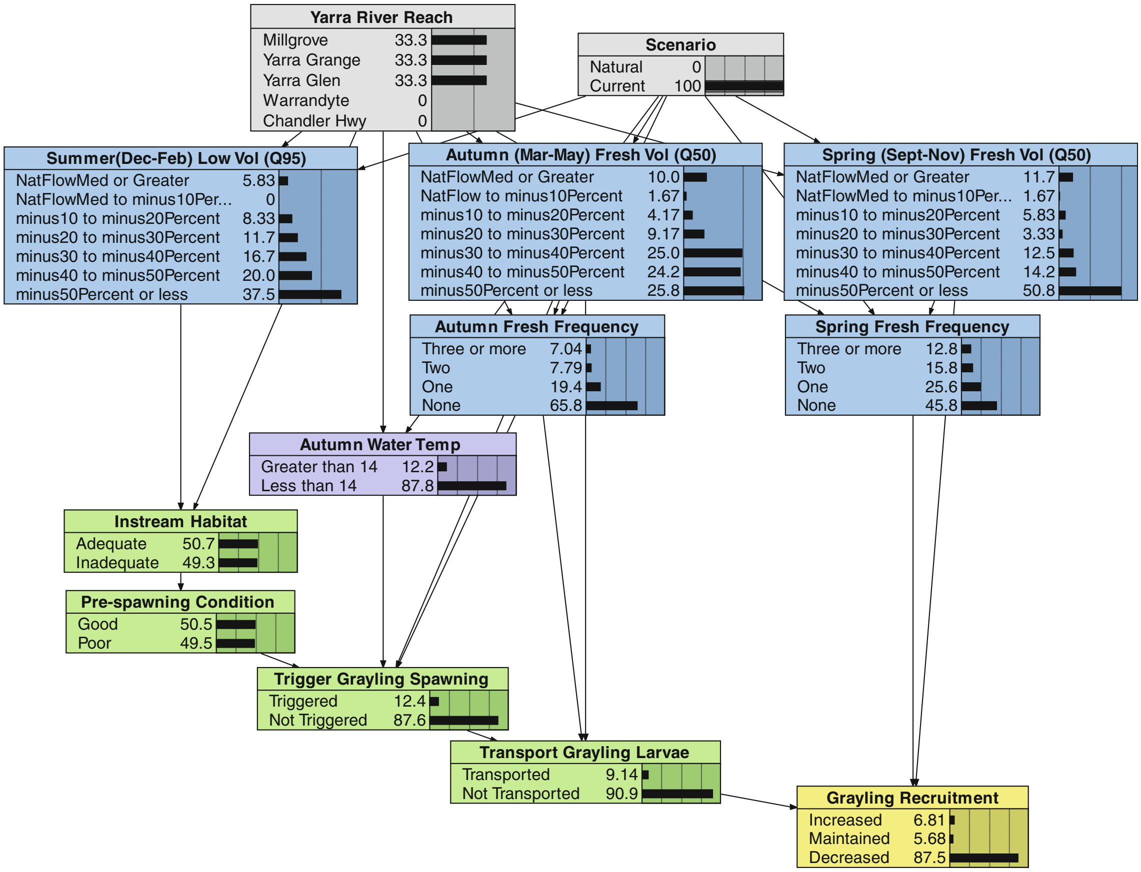


Fig. 3 Bayesian network for flow scenario decision-support for Australian Grayling in the Yarra River. A 'current' flow scenario is defined, and examining the three upper reaches only, showing low spawning and transport despite a favourable temperature regime

metropolitan water supply corporation (Melbourne Water), and by private users, i.e. without the effects of major reservoirs (see Fig. 1) and of farm dams, but they do not include the effects of other land use changes such as urbanization (SKM 2004). The 'Current' scenario simulation includes urban and irrigator diversions and the effects of farm dams and major reservoirs (SKM 2004). 'Yarra River Reach' is thus also a key determinant of the freshes and low flows, given the location of both tributaries and diversions between reaches. The magnitude and frequency of the autumn and spring freshes were obtained from the daily flow data using the 'River Analysis Package' (RAP—www.toolkit.net.au), which is a collection of quantitative tools for eFlow analysis. The autumn and spring fresh volumes were taken as the flows greater than the median (50th percentile) flows of the simulated flow series for that season, and the summer low flow as the median 95th percentile for the summer season (e.g. Boorman and Sefton 1997; Shenton et al. 2010). Durations were treated as constants, due to the additional complexity of handling time in a BN, and the values taken from the flow recommendations (Treadwell 2005). The median flow volumes were used as thresholds in the analysis to determine the distribution of autumn and spring flow events. Additional detailed data showing the hydrological model data appropriately analysed and discretised for the BN are available as electronic supplementary material available from the journal (Online Resource 1). The hydrological BN model (the water 'Vol.' and 'Frequency' nodes in Fig. 2) is structured such that the volume and frequency nodes are linked where changes in the volume result in a concomitant change in flow event frequency determined by the analysis and encoded in the underlying conditional probability tables.

2.2 The ecological BN model

The ecological BN was constructed for a specific ecological endpoint, the Australian Grayling (*P. maraena*). This is an endangered species and protected under State law, being the only extant species of the *Prototroctidae* family in Australia (McDowall 1980). Despite significant gaps in knowledge about the lifecycle of this species, the flow-ecology relationships have been generally characterized. The higher the volume of the summer low flow the better the condition of the reproductive adults, i.e. their

Table 1 Distribution of flow volumes for specific flow components under the 'current' scenario compared with 'natural'

Reach	Flow component	Volume (%)						
		NF or greater	NF to −10 %	−10 to −20 %	−20 to −30 %	−30 to −40 %	−40 to −50 %	−50 % or less
Millgrove	AFV	15	0	3	15	30	18	20
	SFV	10	0	5	3	13	18	53
	SLV	8	0	13	20	20	25	15
Yarra Grange	AFV	8	3	5	5	23	28	30
	SFV	13	3	5	5	10	15	50
	SLV	5	0	5	8	15	18	50
Yarra Glen	AFV	8	3	5	8	23	28	28
	SFV	13	3	8	3	15	10	50
	SLV	5	0	8	8	15	18	48
Warrandyte	AFV	15	8	10	13	20	13	23
	SFV	13	5	3	8	15	10	48
	SLV	8	5	5	23	13	23	25
Chandler Highway	AFV	15	8	10	13	20	13	23
	SFV	13	5	3	13	10	18	40
	SLV	10	0	20	10	13	20	28

NF Natural flow, *AFV* autumn fresh volume, *SFV* spring fresh volume, *SLV* summer low volume

'Pre-spawning Condition' (Chee et al. 2006). The subsequent spawning season occurs in autumn (April–May) (Backhouse et al. 2008), is relatively short (approximately 2 weeks) (Berra 1982), and is triggered by 'Autumn Fresh' flows (Koehn and O'Connor 1990) and a fall in water temperature to below approximately 14 °C (O'Connor and Mahoney 2004). Once spawning has occurred, the larvae drift out to the sea, aided by the autumn high flows. Juveniles return 5–6 months later as part of the whitebait run (i.e. 'Recruitment') in response to 'Spring Fresh' flows (Fulton and Pavuk 1988; McDowall and Fulton 1996). There are generally no populations of Australian Grayling upstream of in-stream barriers, such as dams and weirs, due to constraints on migration (O'Connor, personal communication).

The ecological BN model is shown in the lower half of Figs. 2 and 3 ('Instream Habitat', 'Autumn Water Temp', 'Pre-spawning Condition', 'Grayling Spawning Trigger', 'Transport Grayling Larvae' and 'Grayling Recruitment'). The autumn and spring flow components of the hydrological sub-model are causally linked to the spawning trigger/transport and recruitment nodes respectively. The summer low flow component ensures sufficient quality of habitat with an indirect effect on the pre-spawning condition necessary for efficacious spawning of Australian Grayling. A comprehensive understanding of the flow-ecology relationships in the lifecycle of the Australian Grayling is currently not available. Expert judgement contends that at least one autumn fresh event per season is absolutely necessary to induce Grayling spawning, with marginal increases in spawning probability with successive freshes. A frequency-probability ('knowledge mapping') curve was used to represent and encode this current expert belief in the CPT (Shenton et al. 2010). Such curves can be quickly modified in the BN in light of future evidence gathered from monitoring programs. The underlying CPTs of the model can then be quickly and transparently updated to reflect this learning. This approach also removes the need to elicit individual probabilities, which can be difficult in areas such as this that have significant knowledge gaps and uncertainties.

3 Results

Table 1 summarizes the distribution of flow component volumes for the current scenario in each of the reaches of the Yarra as compared with the natural regime. It is immediately apparent that all three ecologically pivotal flow component volumes are significantly reduced, particularly the spring fresh, which is reduced by up to approximately 50 % in most of the five reaches of the Yarra River.

The complete eFlows BN for Australian Grayling in the Yarra River is shown in Fig. 2. The network is set at the natural flow scenario and the reach 'Yarra Glen'. Given the highly variable nature of the flow regime, as can be seen in the distribution of flow volumes in Table 1, an 'ideal' flow scenario is selected which represents a theoretical ideal flow-temperature regime that would have

Table 2 Modeled probability of Australian Grayling spawning, larval transport and recruitment occurring with the reinstatement of various flow components at Yarra Glen

Flow component(s) reinstated	AF frequency	SF frequency	Probability that spawning is triggered (%)	Probability that larvae transport occurs (%)	Probability that recruitment occurs (%)
AF	1	0	48	36	10
AF + SL	1	0	59	43	14
AF + SF	1	1	48	36	35
AF + SF + SL	1	1	59	43	40

Duration of the freshes is 7 days as stipulated in Treadwell (2005). Units for AF and SF frequency are number per season

AF Autumn fresh flow, *SF* Spring fresh flow, *SL* Summer low flow

historically resulted in a high probability of Grayling spawning and recruitment. This ideal scenario is based on selection of the natural flow volumes of each flow component and a flow event frequency of two. The BN model gives plausible estimates of spawning, transport and recruitment (75, 66 and 60 % respectively). The spatio–temporal interactions and variability in this complex hydro-ecological system are likely responsible for the reduced likelihoods seen in the network and is discussed elsewhere (Shenton et al. 2010).

3.1 Model credibility

Data about populations of Australian Grayling in the Yarra are extremely sparse, and traditional empirical validation of the Grayling ecological model is currently not possible. Validation therefore follows prescriptions of Rykiel (1996) concerning ecological model validation and recognizes that the process can be viewed as a value judgement of model credibility in relation to its utility in decision-making. The experts employed in the building of this eFlows BN assessed model structure and performance using this criterion. The lack of empirical evidence to validate the predictions of the eFlows BN confers caution on application to decision-making. It should be stressed that the context is the driver for these BN models here and as such are designed to support eFlow decision-making through the construction of robust, quantitative models that transparently incorporate the best available science to support reasoning under uncertainty.

3.2 Water allocation scenarios

The upper reaches of the Yarra River were found to have an adequate temperature regime for Australian Grayling spawning, although as shown in Fig. 3, the frequency and volume of the autumn and spring freshes have been significantly reduced. For example, under the 'Current' regime, Yarra Glen has all flow components currently reduced by up to approximately 50 % (see Table 1), which indicates that for the majority of the time there would be no spawning of Australian Grayling in these reaches (likelihood $<$ 10 %). The BN model is structured to allow different flow prioritization strategies to be analysed. Table 2 shows the modeled effects of reinstating each set of flow components to natural flow median volumes. Each set contains the autumn fresh as this flow component is critical to the ecology of Australian Grayling.

The utility in the approach tabulated in Table 2 is that it allows quantification of each flow component reinstatement strategy by giving a measure of ecological risk. Table 2 shows reinstatement of all flow components would confer the greatest ecological benefit, while freshes have the greatest impact on Australian Grayling spawning and recruitment. These results can be used to guide negotiations and support the decision-making process in the allocation of environmental water. As an example, consider the following two flow reinstatement strategies specific for Australian Grayling.

1. Reinstating both the autumn fresh and summer low flow is predicted to result in low recruitment of Australian Grayling (14 %), but provide significantly improved spawning and larval transport when compared to reinstating only the autumn fresh (48–59 % and 36–43 % respectively). This scenario would require approximately 350 ML/day for 7 days (2,450 ML) for the autumn fresh and 300 ML/day for the summer low flow (27,000 ML), or a total of 29,450 ML.
2. Reinstating both the autumn and spring freshes is predicted to result in a large increase in Australian Grayling recruitment (35 %) compared with reinstating either alone ($\sim$17 % for either alone). This scenario would also require a substantial amount of water, with the autumn fresh requiring approximately 350 ML/day for 7 days (2,450 ML) and the spring fresh requiring approximately 1,225 ML/day for 7 days (8,575 ML), or a total of 11,025 ML. However, this volume is significantly lower than for the previous scenario despite providing a larger ecological benefit. This scenario also requires much less water than that required for reinstating all three flow components.

This type of analysis could underpin eFlows decision-making, providing a quantitative rationale to support decisions where the delivery of all flow components is not possible, for example, due to impacts on municipality and irrigation water supply, offering a compromise that balances the reinstatement of partial flow regimes while maximizing ecological benefit. There is potential for complementing the described approach with an explicit multiple criteria decision making system (e.g. Levy 2005), however, this would require further extensive stakeholder participation.

The trade-off decision between the two flow reinstatement strategies outlined above that differentiates between recruitment and spawning is reasonable for Australian Grayling given the nature of its diadromous lifecycle. Crook et al. (2006) have shown a homogenous population of Australian Grayling across adjacent unconnected river systems, suggesting that juveniles from different rivers have a high degree of mixing once in the ocean, and that populations in coastal Victorian rivers share a common marine recruitment source—i.e. Australian Grayling do not necessarily spawn and recruit in the same river. This trade-off is not likely to be applicable for migratory fish such as salmon, which return to the same stream as part of their lifecycle. But a caveat to this lifecycle separation strategy is that such a trade-off fundamentally requires the provision of a well-connected river-ocean system. If a decision is made to focus on the spawning requirement of Australian Grayling in the Yarra then a proviso should be that other rivers in the system have sufficient spring flows to serve as river re-ascension cues for juvenile Grayling. Choosing between the two strategies above is also governed by broader socio-economic considerations of the use of river water. However, this example illustrates a transparent and robust process linking flow volumes to ecological risks, explicitly placing ecological needs for water within an inclusive framework for sustainable eFlows decisions.

4 Discussion

The eFlows BN model developed for the Latrobe River (Shenton et al. 2010) was applied to the Yarra River, focusing specifically on the recruitment of Australian Grayling. One of the objectives of this work was to test the transferability of the Latrobe BN model to the Yarra River. The main difference between the Latrobe BN model and the Yarra BN model was in the hydrological module where the flow characteristics of the Latrobe were replaced with those for the Yarra. The resultant Yarra BN model showed clearly that the Yarra is currently severely flow stressed in most reaches; with the two flow components crucial for Australian Grayling spawning, migration and recruitment (autumn and spring fresh flows) being reduced by up to 50 % over natural flows (Table 1).

This lack of water for each of the critical flow events prevents a complete flow trade-off in this river system, as was available for the Latrobe River (Shenton et al. 2010). For the Latrobe some of the spring higher flows are able to be converted into autumn fresh flows, with potential advantages for Australian Grayling spawning. However, it was possible to use the Yarra eFlows BN model to assess the benefits to Australian Grayling populations in the Upper Yarra from the reinstatement of more flow limited individual and combined flow components. Note that this limited reinstatement scenario, illustrated for Yarra Glen in Table 2, is applicable to all three of the upstream reaches (Millgrove and Yarra Grange also) where the temperature regime is also generally less that 14 °C during autumn, and thus conducive to spawning and transport of Australian Grayling, provided autumn freshes are reinstated.

The Yarra eFlows BN model confirmed that it is unlikely that spawning and recruitment of Australian Grayling would occur under current flow conditions in the upper Yarra, where autumn and spring fresh flow volumes have been reduced by up to half. Despite each of the three reaches of the upper Yarra (Millgrove, Yarra Grange, Yarra Glen) having a temperature profile conducive to Grayling spawning, the BN model predicts only $\sim$10 % probability of such an event happening (Fig. 3). This appears to be due to the absence of requisite autumn high flows. Although some high flows do occur in the Yarra during the critical autumn period, there is a lack of consistency between years. Thus, the upper Yarra now has many periods when there are no autumn freshes for periods of up to three consecutive years, when no recruitment would occur, and a self-sustaining population of Australian Grayling could not exist. A targeted survey of Australian Grayling conducted at the end of 2008 supports this hypothesis, as no Australian Grayling were found in any reach of the Yarra River (O'Connor, personal communication).

One confounding factor in the Yarra River is the presence of a rock weir at the downstream end of Reach 6 (Chandler Highway), which is considered to limit fish migration upstream, despite a specially constructed fish passage, particularly under low flow conditions (Zampatti et al. 2002). Reinstating the ecologically crucial spring flow events may therefore increase the likelihood of future self sustaining populations of the Yarra Herring.

The eFlows BN model described above is well suited to an adaptive management approach (Holling 1978) in that evidence gathered from the monitoring studies can be used to update the network. The best adaptive management programs have been suggested to require rigorous and formalized approaches to planning, collaboration, modelling and evaluation, together with explicit consideration of uncertainty (Schreiber et al. 2004; Eberhard et al. 2009). Simple BN models such as the one described here have the potential to underpin such adaptive management processes for ecologically sensitive flow regime restoration and support scientifically defensible management actions.

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