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BAYESIAN NETWORK MODELS FOR ENVIRONMENTAL FLOW DECISION-MAKING: 1. LATROBE RIVER AUSTRALIA

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ABSTRACT

Current methods underpinning environmental flow (eFlow) decisions often lack transparency, do not adequately consider uncertainties and rarely include adaptive management principles. We report the development and application of an eFlow Bayesian Network (BN) model that links four flow components with an ecological model to predict the spawning and recruitment of two important native fish species, the Australian Grayling and River Blackfish, in the highly regulated and flow-stressed lower Latrobe River in Victoria, Australia. Autumn high flows, in conjunction with low stream temperature, are critical for Grayling spawning. The BN model was used to predict the probability of spawning and recruitment of these two native fish species for four flow scenarios. Quantitative data, flow simulation models and expert judgement were used to parameterize the BN model. The model results showed clearly that currently, and into the future, there is a very low likelihood of spawning and recruitment of Australian Grayling in the lower Latrobe. River Blackfish are minimally affected by the predicted reductions in flow and increased stream temperatures. Management scenarios aimed at modifying flows and stream temperatures to increase the likelihood of successful spawning and recruitment of Australian Grayling were assessed. Self-sustaining populations of Australian Grayling could conceivably be achieved in the upper reaches of this river if fish passage was provided through an on-stream reservoir. A major benefit in building and applying an eFlow BN model is that it can facilitate meaningful analysis and discussion of the ecological effects of particular eFlow regimes.

KEY WORDS: environmental flows; evidence-based; decision-support; Australian Grayling; River Blackfish

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INTRODUCTION

Many of the world's rivers and wetlands are significantly degraded, with much of this degradation due to an increase in irrigated agriculture over the past 100 years. This increased irrigation has resulted in excessive amounts of water being abstracted from these systems leaving many flow-stressed (Poff *et al*., 2003). In Australia, and elsewhere in the developed world, there is now considerable effort going into rehabilitating these over-allocated river systems by restoring a reasonable environmental flow (eFlow) regime (Arthington and Pusey, 2003). Such restoration of eFlows is well suited to an adaptive management approach, where a flow regime is determined using the best available knowledge, legal entitlements are negotiated and a flow regime then implemented through allocation or water sharing (Richter *et al*., 2006). The results need to be carefully monitored and evaluated, and then on the basis of this scientific information, the eFlow regime may be refined over time (Dyson *et al*., 2008).

A number of methods are now available for assessing the optimum eFlow regime for a particular river system—one that will ensure that a healthy aquatic ecosystem is sustained. These methods generally attempt to achieve a flow regime similar to that which would have occurred naturally, in particular by considering the magnitude, frequency, timing, duration and rate of change of flow for the various flow components (Poff *et al*., 1997; Hillman *et al*., 2003). The range of available methods has been well reviewed by Arthington *et al*. (2007). What is clear from this review is that the available methods rely heavily on expert opinion, often lack the required hydrological data (simulated daily natural flows) and generally lack transparency on how various flow components are related to ecological outcomes (Hart and Pollino, 2009).

Bayesian Network (BN) models are being increasingly used in natural resources management (McCann *et al*., 2006; Nyberg *et al*., 2006; Pollino *et al*., 2007; Uusitalo, 2007) and a recent review examined the potential of using BNs specifically for eFlows (Hart and Pollino, 2009). BN models have a number of properties that make them particularly useful for ecological data analysis. In particular, they show cause–effect relationships directly through a simple causal graphical structure, but are also easily constructed, extended and modified; they are able to handle missing data; they incorporate uncertainty in relationships; they are an accessible and intuitive modelling approach; they can show good predictive accuracy even with rather small sample

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sizes; and they allow the conditional probabilities between variables to be constructed using either observed data, other models or expert knowledge. BN models can be used to integrate flow information and other biophysical factors to produce measurable ecological outcomes. Cain (2001) provides an excellent guide on the properties and application of BNs.

The objective of the work reported here was to develop a BN model that link important flow components with an ecological model to predict the spawning and recruitment of two important fish species—Australian Grayling and River Blackfish—in the highly regulated and flow-stressed Latrobe River in Victoria, Australia (WGCMA, 2005). The model showed clearly that spawning of Australian Grayling is now limited in this system for two reasons—a lack of high flows (freshes) during autumn and a modified steam temperature regime. River Blackfish spawning and recruitment appears largely unaffected by the current regulation of this river. We used this BN model to investigate what changes to the current management of this river would be required to increase the likelihood of successful spawning and recruitment of Australian Grayling.

This first paper describes an eFlows BN model developed specifically for regulated river systems in poor ecological condition where incremental improvements to river health are sought. By contrast, the second paper in the series (Chan *et al*., 2009) reports an eFlows BN model for the unregulated Daly River in the Northern Territory, Australia, which is under emerging pressure from further agricultural development. Both these eFlows BN models should assist decision makers in deciding upon the flow regimes that ensure riverine ecological health.

STUDY AREA

The Latrobe River is located in Gippsland in the state of Victoria, Australia (Figure 1, 38.1°S 146-147°E). The Latrobe is integral to Victoria's major coal-fired power generation system located in the Latrobe valley. The river is highly regulated with two reservoirs on major tributaries (Blue Rock Reservoir on the Tangil River; Moondarra Reservoir on the Tyers River), and Lake Narracan located on the Latrobe River. Lake Narracan is an on-stream reservoir built specifically to supply water for power generation. The lower Latrobe River is one of the most ecologically disturbed river systems in Australia due to desnagging, extensive clearing of riparian vegetation, artificial cut-offs and channel widening (Reinfelds *et al*., 1995). Large-scale changes to the catchment have also occurred as a result of industrialization, urban growth and widespread clearing for agriculture. The lower reaches of the Latrobe River are fringed by extensive, high value Ramsar wetlands.

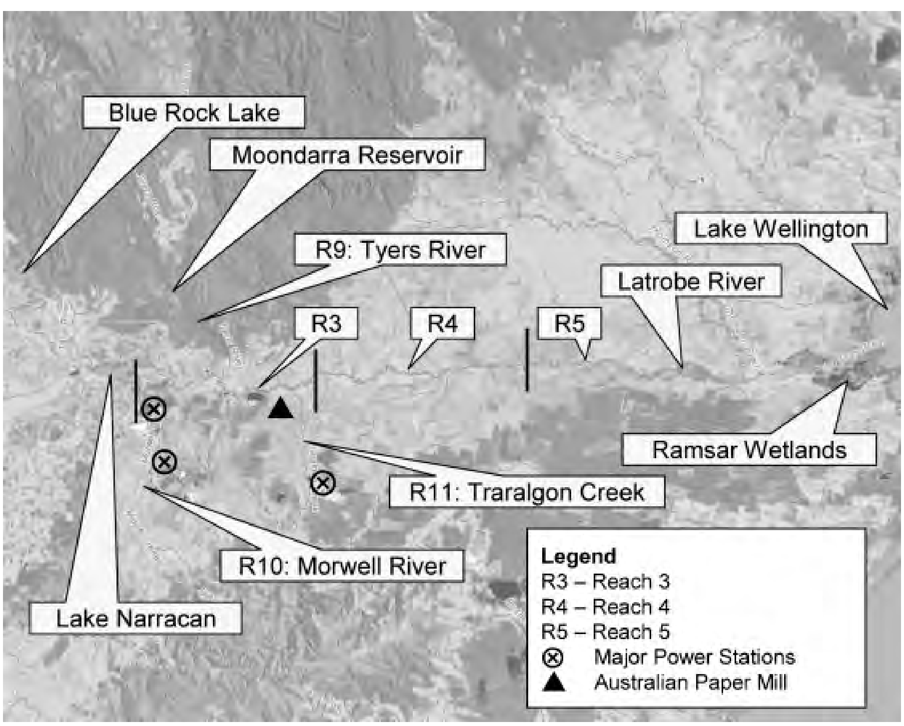

Figure 1. Map showing the location of the reaches modelled in the lower Latrobe River (R3, R4, R5), Tyers River (R7), Morwell River (R8) and Traralgon Creek (R9). Also shown are the major reservoirs and the major industries (Map obtained from www.vicwaterdata.net)

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Our study focused on the lower Latrobe River (Figure 1—Reaches 3, 4 and 5), which extends below Lake Narracan to Lake Wellington. The tributaries covered are the Tyers River (Reach 9), Morwell River (Reach 10) and Traralgon Creek (Reach 11). Flows in the Tyers River are regulated by the operation of the upstream Moondarra Reservoir. Much of this river is forested and in excellent condition (EarthTech, 2006). The Morwell River is extensively modified with significantly degraded riparian vegetation, although some natural and reconstructed wetlands exist in the lower section. Traralgon Creek was naturally an ephemeral stream, but currently receives significant industrial discharge and urban stormwater. River Blackfish have been found in all three of these tributaries, but Australian Grayling are rare (EarthTech, 2006).

METHODS

The FLOWS method and REALM

An eFlow regime for the Latrobe River (EarthTech, 2006) has been developed using the 'FLOWS method' (DNRE, 2002b), a process that incorporates the key components of the natural flow regime necessary to maintain the biological, geomorphological and physicochemical processes implicit in sustained river health. Flow components defined in the method are used to describe the timing, magnitude, frequency and duration of the different parts of the natural flow regime and associated with key ecological functions (Table I). The FLOWS method was used as a framework to build the eFlows BN described here.

The FLOWS method also requires that a simulated flow time series is available to assess different water allocation scenarios. In this study, we used REALM (REsource ALlocation Model) for this purpose (Perera *et al*., 2005). REALM is a generalized computer simulation package that models harvesting and bulk distribution of water resources. Perera *et al*. (2005) have previously illustrated the use of REALM in water supply planning, management and modelling of eFlows. REALM was used here to simulate daily flow time series (1957–2004) for 'natural' and 'current' scenarios in the Latrobe. These were analysed using the freeware 'River Assessment Package' (RAP—www.toolkit.net.au) which is a collection of quantitative techniques for eFlow analysis.

Bayesian Network models

BNs are statistical tools that have been used in ecology to predict the influence of environmental variables on ecological response variables (Marcot *et al*., 2006). BN models consist of three elements: (a) a set of nodes representing the management systems key variables; (b) a set of links that represent the cause–effect relationship ('conditional dependence') between the 'parent' and 'child' nodes and (c) a set of probabilities representing the belief that a node will be in a certain state given the states of the connecting nodes. Underlying each of the nodes in the network is a probability table, which is either a marginal (MPT) or conditional probability table (CPT). The MPTs can be seen as input nodes and are frequently based on quantitative data or data from simulation models. The CPT defines the probabilities of each of the discretized states of the child node conditional on the parent node. BNs can be effectively incorporated in a traditional risk management framework through explicitly displaying the causal web of interacting factors and the probabilities of multiple states of predictor and response variables (Hart *et al*., 2005; Marcot *et al*., 2006)

Limitations of BNs include (Uusitalo, 2007; Hart and Pollino, 2009): (a) they do not permit feedback functions

Table I. The flow components and their functions as used in the FLOWS method (DNRE, 2002b)

Flow component	Flow characteristic	Key functions
Cease to flow	No surface flow	Dried habitats and substrates Facilitates organic matter and carbon processing
Low flow	Minimum flow	System maintenance Connect instream habitats
Freshes	Flow greater than median flow	Biological triggers Physico-chemical changes
High flows (in Channels)	Connect most in channel habitats	Channel connectivity Allows migration Sediment movement
Bankfull flows	High flow within channel capacity	Channel and habitat forming Sediment transport
Overbank flows	Flow extending to floodplain	Floodplain connectivity Organic matter inputs

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either within a node or from output variable back to input variables; (b) they handle time functions poorly, although the BN model structure can be replicated, with specific time-dependant nodes linked between the replicates; (c) most BN software requires that continuous probability distributions be discretized, which can result in the state variable being over-simplified and (d) poor handling of spatial detail. However, these limitations contribute to the role of any model, which is to simplify the system, but further, they force explicit consideration about these simplifications and underlying assumptions.

Model ecological endpoints

The ecological endpoints chosen for the BN were the recruitment of two native fish species—Australian Grayling (*Prototroctes maraena*) and River Blackfish (*Gadopsis marmoratus*). These two species have very different life cycles and flow-ecology responses, with Australian Grayling being diadromous and River Blackfish being non-diadromous (Koehn and O'Connor, 1990). Our hypothesis is that if conditions for these two fish species can be improved this would then represent a broad spectrum of conditions that could benefit other species.

Australian Grayling—is an endangered species (Lake, 1971), protected under State law, and the only extant species of the *Prototroctidae* family. Detailed knowledge of the life cycle of this species is lacking and much of the current thinking remains speculative. Spawning occurs in autumn (April–May) (Backhouse *et al*., 2008), triggered by high flows (Koehn and O'Connor, 1990) and a fall in water temperature to ca. 13–14°C (O'Connor and Mahoney, 2004). The spawning season is relatively short (ca. 2 weeks) (Berra, 1982, 1984) and spawning habitat still largely unknown. Once spawning has occurred, the larvae drift out to the sea, and juveniles return around 5–6 months later as part of the whitebait run in response to a spring fresh (Fulton and Pavuk, 1988; McDowall and Fulton, 1996).

River Blackfish—differ from Grayling in that they are not migratory, spending their entire life in freshwater (Koster and Crook, 2008). River Blackfish spawning occurs in spring to early summer, when water temperatures are greater than 16°C (Jackson, 1978), with spawning generally occurring in woody debris (snags) in deep pool habitats (Jackson, 1978; Davies, 1989). Evidence suggests that River Blackfish spawning is triggered by temperature and habitat type, and not any specific flow event (Koehn *et al*., 1994). Koehn *et al*. (1994) also suggest that Blackfish use the same habitats for both spawning and rearing young.

Conceptual model

The conceptual model for the Latrobe eFlows BN model, shown in Figure 2, consists of linked hydrological and ecological sub-models. The hydrological sub-model was based around key flow components identified through expert consultation (see Acknowledgments), with the REALM model providing daily flow time series for the scenario. The 'knowledge engineering' process described in Pollino *et al*. (2007) was used to structure and inform this consultation and elicitation process. The ecological sub model was based on the native fish conceptual model produced by the Victorian eFlows and Monitoring Assessment Program (VEFMAP) (Cottingham *et al*., 2005; Chee *et al*., 2006) which is for a hypothetical regulated lowland river that contains both diadromous and non-diadromous fish. The Latrobe River conforms to this description.

The hydrological sub-model

The complete hydrological sub-model can be seen in the top half of Figure 3. After extensive consultation with

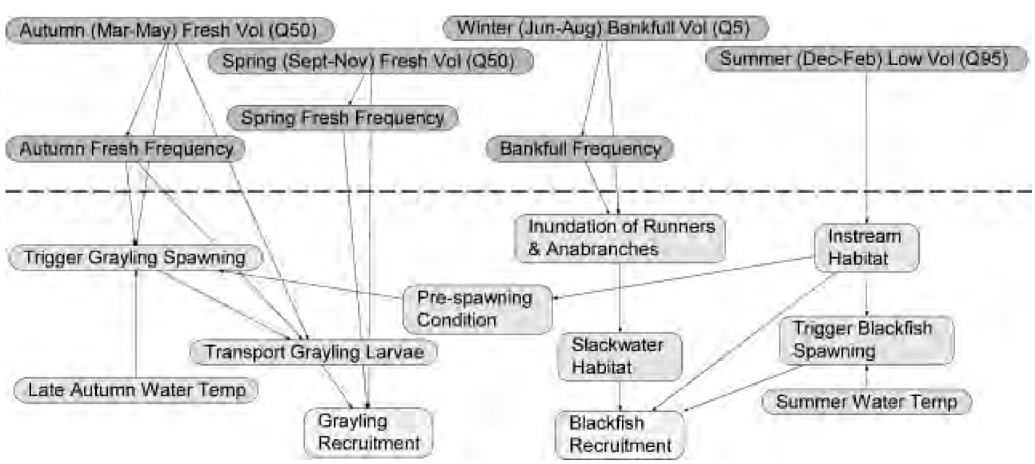

Figure 2. eFlow conceptual model for the Latrobe River showing the linked hydrological and ecological models. The 'reach' and 'scenario nodes have been removed for clarity

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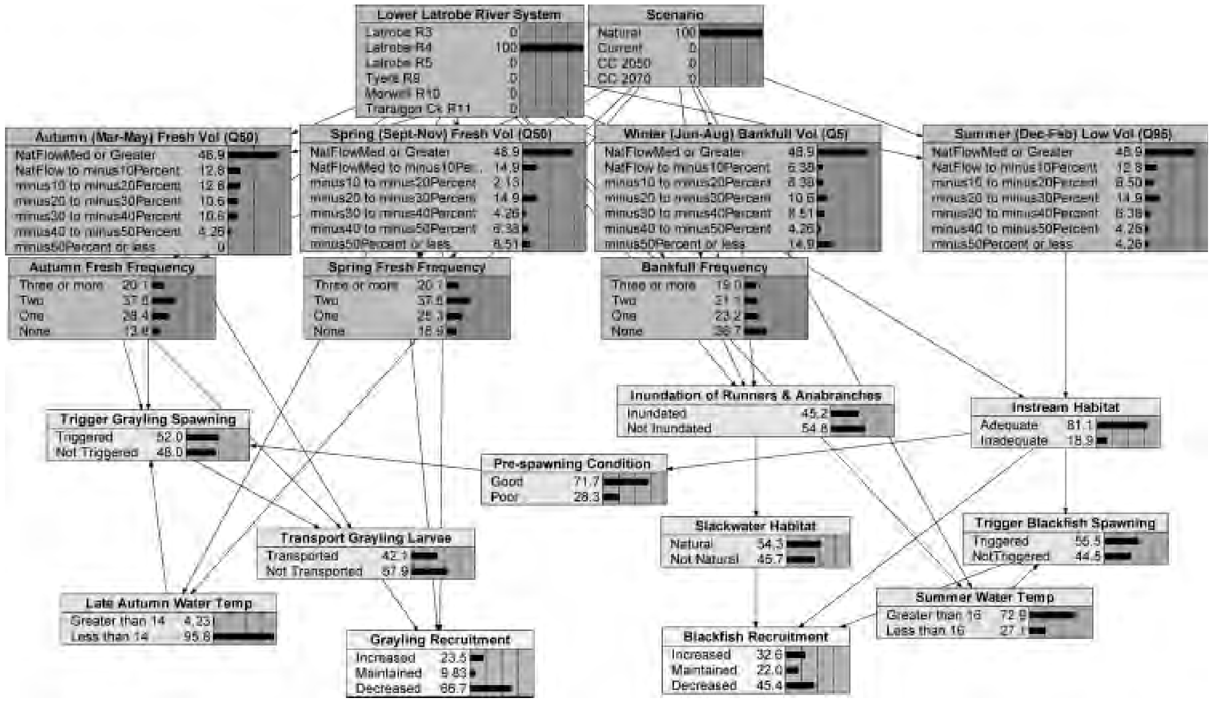

Figure 3. Complete Latrobe eFlow BN model showing the predicted outcomes for Grayling and Blackfish recruitment in Reach 4 under the 'natural' flow scenario

relevant fish experts, four ecologically crucial flow components were chosen:

- Summer low flows—provide suitable pool habitat of adequate depth for both Australian Grayling and Blackfish.
- Autumn fresh flows—provide the cue for Grayling spawning and downstream transport of larvae.
- Spring fresh flows—provide the cue for re-ascension of adult Grayling from the ocean to reach upstream spawning grounds.
- Bankfull flows—provide adequate slack water habitat for River Blackfish larvae.

Each of the four flow components were characterized by three attributes—magnitude (or volume), frequency and duration. The magnitude describes a trigger flow volume necessary to achieve hydraulic and ecological objectives. Surrogate flow percentile metrics were used to create natural flow-derived flow baselines from which to compare the relative change of the 'current' time series data and climate change scenarios. The choice of each flow metric was:

- Summer low flow—this was taken as the 95th percentile flow (Q95), which is the flow exceeded by 95% of all flows in the river (Boorman and Sefton, 1997).
- Spring and autumn freshes—were taken as the 50th percentile flow (Q50) for the respective seasonal period (SKM, 2003).
- Bankfull flow—was taken as the 5th percentile flow (Q5), a subjective choice, but one that performs well when compared to the flow recommendations (EarthTech, 2006).

The node states used in the hydrological sub-model are listed and justified in the Supplementary Material. In the model, the nodes were populated with quantitative data obtained from the simulated flow time series. The volume analysis was specific for each reach and scenario. For each flow component data set, the median flow volume was calculated and used as the representative flow volume. For example, for the summer low flow, the 'natural' daily time series summer Q95 flow data set was produced and the median value of these data was chosen as the flow volume threshold. The distribution of flow volumes in relation to this threshold was analysed and the distributions used to populate the seven discretized states of the summer low node. Analysis of the current flow and climate change data sets was then performed using these threshold flow volumes as benchmarks. As an example, the complete set of flow components and derived median flow volumes for Reach 4 can be seen in Table II. The hydrological sub-model was also structured such that the volume and frequency nodes are causally linked (Figure 3). Thus, spell frequency distributions derived from a 'spells' analysis, using the volume thresholds for each flow component, were encoded in the CPTs. Thus, changes in the volume result in a concomitant

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Table II. Comparison of the magnitude (and frequency) of the four flow components for Reach 4 in the Latrobe River for the natural and current flow regimes. Also shown are the recommended values derived using the FLOWS method (EarthTech, 2006). The percentile metric used to derive the natural and current flows from the simulated natural flow daily time series are also shown (e.g. Summer low (Q95)—is the flow exceeded 95% of the time over the summer period)

Flow component	Scenario	Magnitude (ML d^{-1})	Frequency (per year)
Summer low (Q95)	Natural	>675	—
	Current	>540	—
	Recommended	>520	—
Spring fresh (Q50)	Natural	>2920	2
	Current	>2920	2
	Recommended	>6900[a]	3
Autumn fresh (Q50)	Natural	>908	2
	Current	>454	0
	Recommended	>1470[a]	3
Winter bankfull (Q5)	Natural	>7500	1
	Current	>7500	1
	Recommended	>8640	2

[a]The EarthTech (2006) flow recommendation use only two seasons—December–May and June–November—with no specific recommendation for spring or autumn flow events. We have assumed the Autumn fresh is covered by the recommendations for December–May, and the Spring fresh by the recommendations for June–November.

change in the frequency node spell distribution. The hydrological sub-model therefore represents a dynamic probabilistic model of a flow-time series.

One of the main limitations of BN modelling is the difficulty in handling temporal difference and so modelling the volume, frequency and duration as independent variables proved difficult. For this reason, only volume and frequency were explicitly analysed, with the value for duration taken from the flow recommendations (EarthTech, 2006) and implicitly used in the analysis to determine volume and frequency distributions. A drawback in this methodology is evident when analysing smaller tributary streams (e.g. Reaches 9, 10 and 11). The flow events in these streams are relatively small and so the relationship between the volume and spell distribution is often not linear so the proportional decrease in spell frequency with decreasing flow threshold is therefore not evident.

The ‘Instream Habitat’ node was assumed to depend upon the ‘Summer (Dec-Mar) Low Vol’ node. The CPT linking these two nodes was populated using the hydraulics software package HECRAS (http://www.hec.usace.army.mil/) to estimate the water surface profile for each summer low flow volume. Then, using cross-sectional plots of the Latrobe River, these water heights were related to the amount of habitat inundated, and an expert judgement employed to determine whether this was ‘Adequate’ or ‘Inadequate’. A similar method was used to produce the CPT relating ‘Inundation of Runners & Anabranches’ with the ‘Winter (Jun-Aug) Bankfull Vol’ and ‘Bankfull Frequency’. All CPTs are documented in the Supplementary Material.

The nodes for ‘Reach’ and ‘Scenario’ were added to make the BN model more flexible and useful, allowing collation of data from all sites for generic, system-wide scenario analysis, but also allowing reach-specific predictions. The ‘Reach’ node allows the selection of individual river reaches. The ‘Scenario’ node allows the user to select one of four different flow scenarios—‘natural’, ‘current’, ‘cc2050’ and ‘cc2070’. The last two are climate change scenarios, where ‘current’ scenario volumes in each reach were reduced by 20 and 50% respectively to give the climate change estimates for the years 2050 and 2070. The basis for these percent changes is provided in DSE (2008).

The ecological sub-model

The complete ecological sub-model can be seen in the bottom half of Figure 3. The states for each node in the ecological model are listed in the Supplementary Material, together with the data sets, analysis and relevant sources of knowledge used to define them. Given the paucity of quantitative data relating fish spawning to the flow components, expert opinion was used to derive estimates for the relevant CPTs.

The parameter elicitation process involved individual fish experts (see Acknowledgements) estimating probability distributions for ‘Pre-spawning Condition’, ‘Trigger Grayling Spawning’, ‘Trigger Blackfish spawning’, ‘Grayling Recruitment’ and ‘Black Recruitment’ nodes. The final probabilities were obtained by averaging the responses of the experts. *In situ* stream temperature data were obtained from the Victorian Data Warehouse (www.vicwaterdata.net) for each reach, with each data set containing monthly sampling over a 30-year time period. Estimates of climate change were derived by adjusting the current stream

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temperature data set by a 'worst case scenario' estimate, which in this case is a 2°C increase by the year 2050 and a 6°C increase by the year 2070 (CSIRO, 2007). A 'natural' temperature data set was obtained using air temperature records from the Bureau of Meteorology (www.bom.gov.au/) for the Latrobe Valley. Given that stream temperatures in this range tend to change linearly with air temperatures (Mohseni and Stefan, 1999), a 1:1 relationship was assumed between the recorded air temperature in the region and modelled stream temperature. Lovett and Price (1999) report a 3–5°C lower mean daily temperature fluctuation for Australian forested streams compared to cleared streams. An average of 4°C was therefore used to adjust the data set to give an estimate of the historical stream temperature.

The relationship between ecological response and flow event frequency is currently not well understood. Expert knowledge 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 knowledge in the CPT (Figure 4). This novel evidence-based approach to linking flow and ecology is designed to fit within

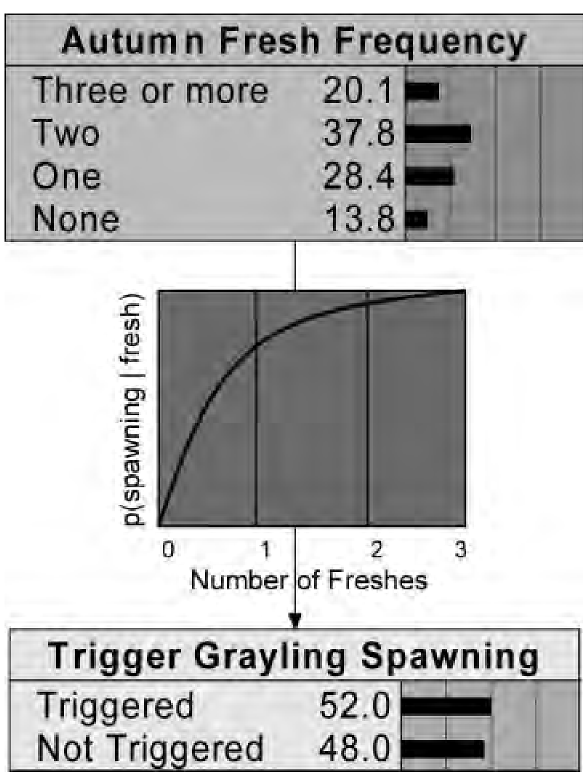

Figure 4. A knowledge mapping curve showing the effect of autumn fresh frequency on the probability of successful Australian Grayling spawning. The same curve was used for each of the three reaches in the lower Latrobe River. The distribution of 'Autumn Fresh Frequency' shown in the top box is for Reach 5

an adaptive management framework where, upon garnered evidence, the equation for the curve can be easily replaced by a closer fitting curve. The underlying CPTs of the model are then transparently updated to reflect this learning. This approach also removes the need to elicit individual probabilities, which can be difficult in areas with significant knowledge gaps and uncertainties.

Sensitivity analysis

Sensitivity analysis (Figure 5) was performed on the network to identify which nodes have the greatest influence on the endpoint predictions (shown as Probability(Grayling Recruitment) = Maintained). The probability of each parent node can be changed and changes in the endpoint node observed (Pollino *et al*., 2007). The most influential nodes are closest to the *x*-axis. The sensitivity analysis used here calculates reductions in Shannon's entropy to rank the nodes according to their influence on the endpoint in relation to added evidence (Pearl, 2000). Entropy is commonly used to evaluate the uncertainty of a variable characterized by a probability distribution (Pearl, 2000). Ranking nodes according to entropy reduction indicate the linkages in need of further research to reduce uncertainty and maximize confidence in decision-making.

Sensitivity analysis of the Latrobe BN showed an expected polarity between the two ecological objectives of Grayling and Blackfish recruitment (Figure 5). The dominating influences on Grayling recruitment are 'Trigger Grayling Spawning', 'Transport Grayling Larvae', 'Autumn Fresh Frequency' and 'Spring Fresh Frequency'. This suggests that these nodes should be the targets of further research to reduce the uncertainty regarding the response of Australian Grayling to flow alteration. By contrast, Blackfish recruitment appears to be dominated by 'Blackfish Spawning', 'In-stream Habitat' and 'Summer Water Temperature'.

Validation

The paucity of data on current populations of Australian Grayling and River Blackfish in the Latrobe River precluded a thorough empirical validation of the BN model. However, the closeness of model predictions to any observed data is acknowledged as an important aspect of validation and results were in fact found to concur with the recent fish survey in the Latrobe (EarthTech, 2006). Given this lack ecological data, we therefore employed a 'reasonableness' criterion. This 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 therefore assessed model structure and performance using this criterion. The lack of data on the Latrobe suggests a

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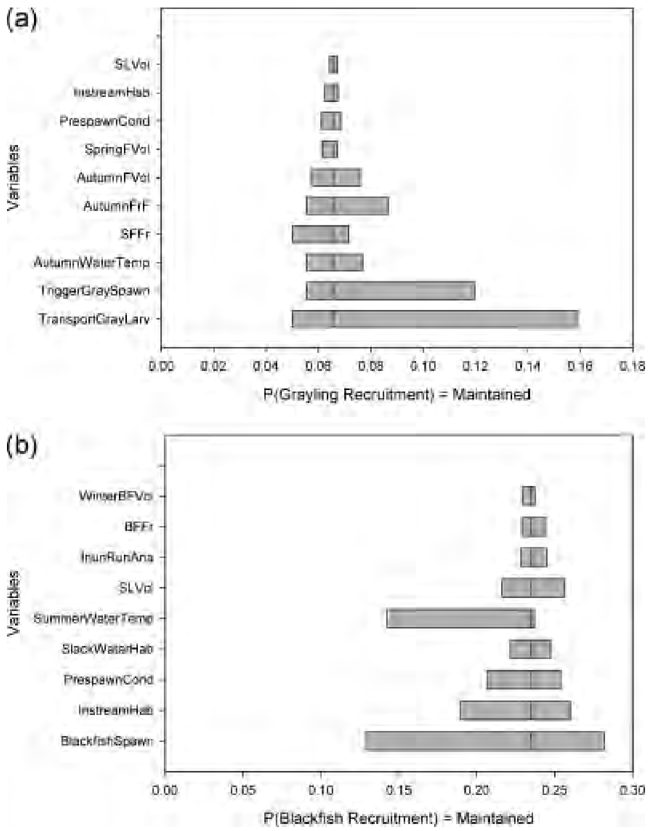

Figure 5. Sensitivity analysis results for (a) Grayling and (b) Blackfish. The bars represent the range of variation in the endpoint when values or parent nodes are varied

degree of caution should be exercised in the interpretation of these results, but it should be noted that the modelling framework was intentionally structured to incorporate future monitoring data in order to further validate the model.

RESULTS

The eFlows BN is used to assess ecological impacts under 'natural', 'current' and two climate change scenarios. The results show clearly that currently, and into the future, there is a very low likelihood of Australian Grayling populations in the lower Latrobe River. This is primarily due to two effects—firstly, autumn freshes that trigger spawning are, and will be, significantly reduced in frequency and secondly, the autumn stream temperatures are inadequate (i.e. >14°C). Blackfish will be minimally affected by the predicted reductions in flow and increased stream temperatures.

Natural flow regime

Figure 3 shows the results for Australian Grayling and River Blackfish recruitment under 'natural' flows for Reach 4. The results for the other reaches of the Latrobe River are similar. The model predicts only a 33% probability that Australian Grayling recruitment will be increased or maintained under natural flow conditions over this time period. For Blackfish, the model predicts a probability of around 55% that recruitment of this species will be increased or maintained. The low probability of Grayling recruitment probably arises because the BN model uses the complete 47-year hydrological data set, which would tend to average out inter-annual variability in the system. Inspection of the natural flow record does in fact show periods of up to five consecutive years when sufficient autumn flow freshes are absent. Given the average lifespan of 4 years for Grayling (Crook *et al*., 2006), this suggests possible historic periods of localized extinction.

Figure 6 shows the ability of the BN model to predict recruitment under expert defined 'ideal' natural flow conditions. Here it was assumed that the probability of the 'Autumn Fresh Vol' being the natural flow or greater was 100%, that these flows occurred twice per season and that the stream temperature during this period was less than 14°C. Under these 'ideal' natural conditions, the model predictions are more reasonable. Thus, for Australian Grayling there is a 74% probability that spawning would be triggered, and a 58% probability that recruitment would be increased or maintained. For River Blackfish the corresponding predictions are 60% probability for spawning and 62% probability that recruitment would be increased or maintained.

Current flow regime

The current flow regime shows the effects of river regulation on the recruitment of the two native fish species (Figure 7). These data show that the probability of both the spawning and recruitment of Australian Grayling is low under current flow conditions in all reaches. In contrast, the model predicts that the probability of spawning and recruitment of River Blackfish under current flows is quite favourable (generally >70% for spawning and >60% for recruitment)

While the summer, winter and spring flows are adequate for both Australian Grayling and River Blackfish, the volume and frequency of the autumn fresh flows are significantly decreased, and this has a detrimental effect on both spawning and larval transport of the Australian Grayling. Additionally, the current less than favourable autumn stream temperatures (42% probability that less than 14°C compared with 96% probability under natural conditions) would severely impact the ecology of Australian Grayling.

Climate change scenarios

The climate change scenarios modelled for the lower Latrobe River indicate that by either 2050 or 2070, self-sustaining

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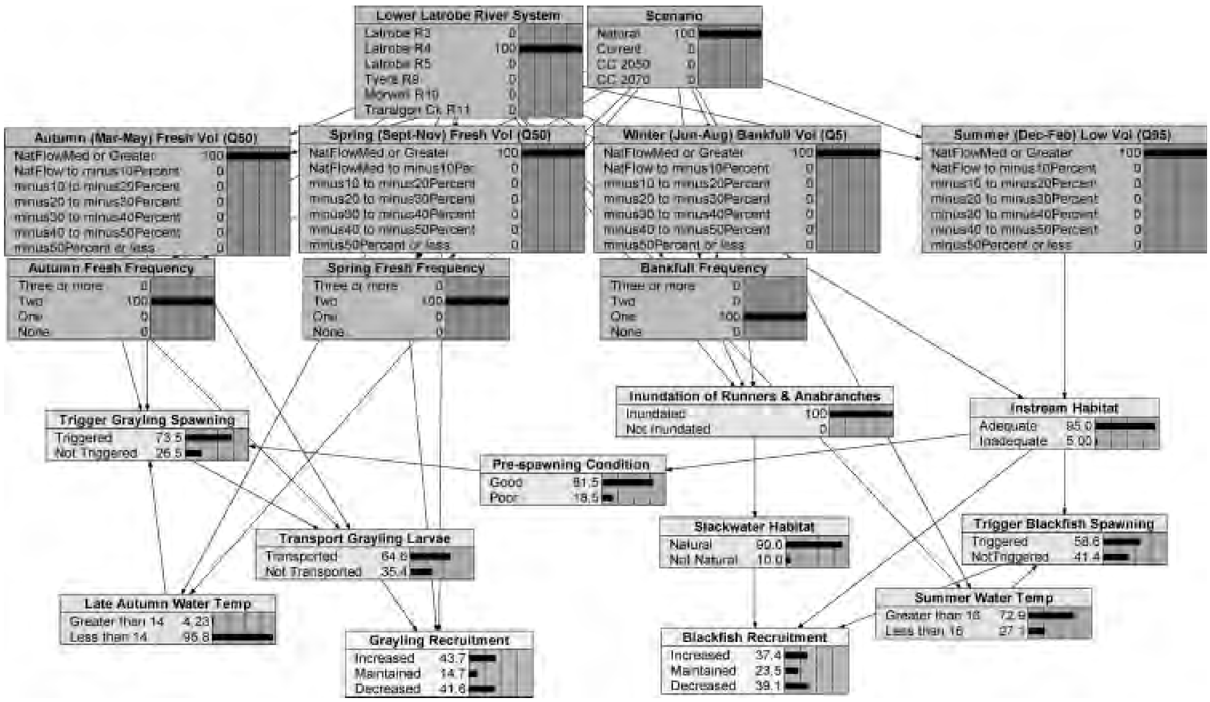

Figure 6. Latrobe eFlow BN model showing the predicted outcomes for Grayling and Blackfish recruitment in Reach 4 under an 'ideal' natural flow regime. This scenario assumes 100% probability that the 'Autumn Fresh Vol' is the natural flow or greater, and that these freshes occurred twice per year (i.e. 100% probability that 'Autumn Fresh Frequency' = 2)

populations of Australian Grayling are very unlikely to exist. The main constraint will be temperature where the late autumn stream temperature will be generally too high for spawning to be triggered. Additionally, the autumn freshes will be further reduced. In contrast, the model predicts minimal impacts on the spawning and recruitment of River Blackfish despite a predicted 50% reduction in low flows in the lower Latrobe River by 2070.

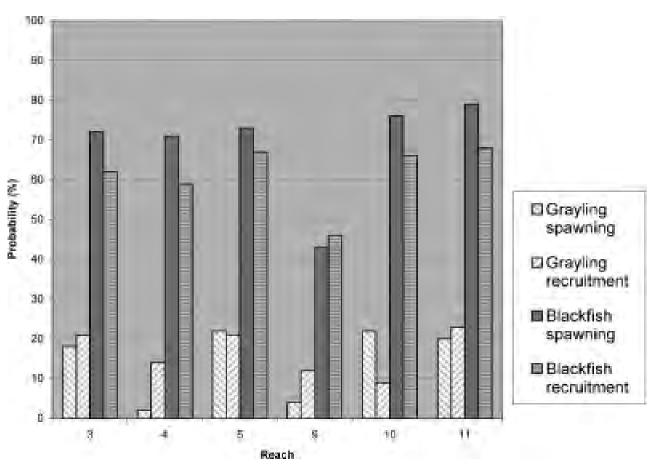

Figure 7. Predictions of the probability (%) of Australian Grayling and River Blackfish spawning and recruitment under the current flow regime in the lower Latrobe River. Data show the probability (%) that spawning will be triggered, and that recruitment will be increased or maintained. Reach 4 is extremely degraded and additionally experiences the greatest reduction of autumn fresh flows

Management scenarios

The eFlows BN model was used to assess two management scenarios, which were aimed at modifying flows and stream temperatures to identify conditions for improved recruitment of Australian Grayling.

Scenario 1—involved trading off the autumn fresh and spring fresh flow components of the current flow regime. This scenario was chosen because regulation of this river has significantly reduced both volume and frequency of autumn fresh flows, while the spring fresh flow is minimally impacted. For Reach 4, we modelled a reduction of 40% in the spring fresh volume (2920–1750 ML d^{-1}), and an increase in the autumn fresh volume up to the natural flow median volume (454–908 ML d^{-1}). The results (Figure 8a) showed significant increases in the probability of spawning (2–24%) and larval transport (5–21%) but little change in the probability that recruitment of Australian Grayling would be increased or maintained (14–21%). Almost certainly, this poor result regarding Australian Grayling recruitment was due to the less than optimal temperature regime.

Scenario 2—involved the Scenario 1 flow trade off in combination with a management strategy to reduce the autumn stream temperature to below 14°C (Figure 8b). This

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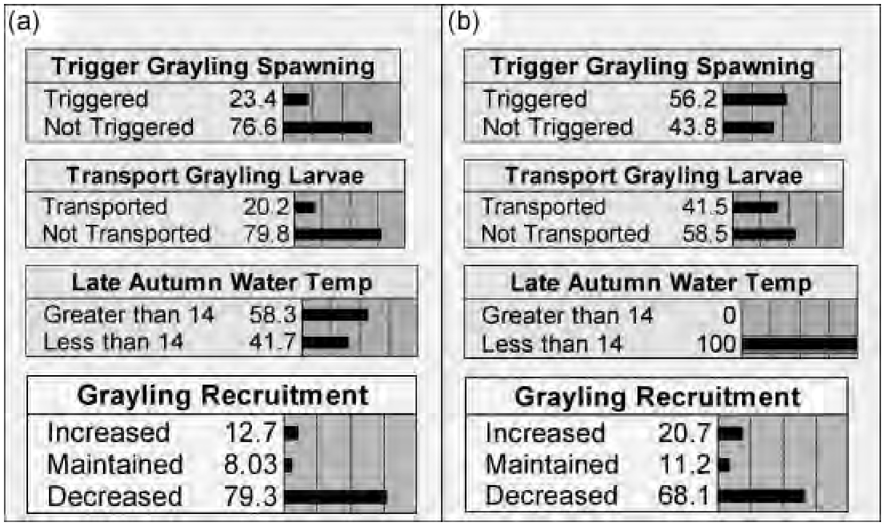

Figure 8. Management scenarios for the Australian Grayling: (a) reduction of 40% in the spring fresh and an increase in the autumn fresh volume up to the natural flow median volume. (b) As for scenario A, but with the implementation of a strategy to reduce the late autumn water temperature to less than 14°

scenario increased the probability that spawning would be triggered from 24–50%, doubled the probability that Grayling larval transport (21–43%) and also increased the probability of recruitment being increased or maintained (21–33%).

DISCUSSION

The Latrobe eFlows BN model for Australian Grayling performed well under 'ideal' natural flow conditions predicting a 74% probability that spawning would be triggered, and a 58% probability that recruitment would be increased or maintained in Reach 4. For the other reaches, the BN model predicts equally high probabilities (roughly 60%) of spawning and recruitment for both fish species. For the current flow regime, the model predicts an inadequate flow-temperature regime for Australian Grayling in all six reaches, which results in a very low probability of spawning and recruitment in the lower Latrobe River and its tributaries. As discussed above, a late autumn stream temperature of less than 14°C is necessary for Grayling spawning, but currently this is only achieved roughly 50% of the time in all but one of the reaches, namely the Tyers River. Presumably, this latter finding is due to cold water releases from Moondarra Reservoir.

In contrast, the model predicts that River Blackfish populations should be present in all reaches of the lower Latrobe and the three tributaries under both natural and current flow conditions. Under natural flows, the model predicts a 60% probability of River Blackfish spawning and a 62% probability that recruitment would be increased or maintained. Under current flow conditions the corresponding predictions are 71% probability of spawning and 66% probability that recruitment would be increased or maintained. These predictions are supported by recent fish population surveys in the Latrobe (EarthTech, 2006) where River Blackfish were found in all six reaches addressed in this work, albeit in reduced numbers, whereas Australian Grayling were exceedingly rare.

The lifecycle of the Australian Grayling is dependant on high flow events in autumn for spawning and larval transport, together with the provision of cool late autumn river temperatures. Currently, neither of these critical factors exists in the lower Latrobe River. Table III provides a summary of the autumn fresh volume and frequency distributions in each of the reaches under investigation and the effect on spawning. What is immediately apparent from these data is a significant reduction in the volume and frequency of autumn freshes in the Lower Latrobe, with Reaches 4 and 9 significantly reduced.

The Latrobe eFlows BN model was also used to explore management scenarios involving the possible trading off of the spring fresh flows for autumn fresh flows. The results suggest that it would be possible to provide adequate autumn freshes through a reduction of the spring fresh volume without any change in the overall annual volume discharged. This change, coupled with adequate stream temperature, would create conditions that could support spawning, but not recruitment. This trade-off would not necessarily impact the Australian Grayling population as a whole since recent studies by Crook *et al.* (2006) suggest a common marine recruitment source. This is a further reason to consider the whole river system in any eFlows decision-making processes concerning Australian Grayling.

The autumn fresh/spring fresh trade-off showed only modest gains in recruitment due to the inadequate autumn

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Table III. Autumn fresh comparisons for each reach in relation to the impact on Grayling spawning

Reach	Volume	Frequency	Current Trigger Grayling Spawning
3	Autumn (Mar-May) Fresh Vol (Q50) NatFlowMed or Greater 12.8 NatFlow to minus10Percent 6.38 minus10 to minus20Percent 21.3 minus20 to minus30Percent 8.50 minus30 to minus40Percent 17.0 minus40 to minus50Percent 12.8 minus50Percent or less 21.3	Autumn Fresh Frequency Three or more 7.30 Two 18.1 One 39.3 None 35.3	Trigger Grayling Spawning Triggered 17.3 Not Triggered 82.7
4	Autumn (Mar-May) Fresh Vol (Q50) NatFlowMed or Greater 21.3 NatFlow to minus10Percent 17.0 minus10 to minus20Percent 8.51 minus20 to minus30Percent 12.8 minus30 to minus40Percent 10.6 minus40 to minus50Percent 25.5 minus50Percent or less 4.26	Autumn Fresh Frequency Three or more 6.29 Two 13.6 One 43.4 None 36.7	Trigger Grayling Spawning Triggered 2.08 Not Triggered 97.9
5	Autumn (Mar-May) Fresh Vol (Q50) NatFlowMed or Greater 19.1 NatFlow to minus10Percent 10.6 minus10 to minus20Percent 17.0 minus20 to minus30Percent 12.8 minus30 to minus40Percent 10.6 minus40 to minus50Percent 14.9 minus50Percent or less 14.9	Autumn Fresh Frequency Three or more 6.33 Two 15.7 One 43.2 None 34.7	Trigger Grayling Spawning Triggered 26.2 Not Triggered 73.8
9	Autumn (Mar-May) Fresh Vol (Q50) NatFlowMed or Greater 2.13 NatFlow to minus10Percent 2.13 minus10 to minus20Percent 2.13 minus20 to minus30Percent 0 minus30 to minus40Percent 0 minus40 to minus50Percent 4.26 minus50Percent or less 89.4	Autumn Fresh Frequency Three or more 0.43 Two 1.28 One 20.4 None 77.9	Trigger Grayling Spawning Triggered 3.46 Not Triggered 96.5
10	Autumn (Mar-May) Fresh Vol (Q50) NatFlowMed or Greater 97.9 NatFlow to minus10Percent 2.13 minus10 to minus20Percent 0 minus20 to minus30Percent 0 minus30 to minus40Percent 0 minus40 to minus50Percent 0 minus50Percent or less 0	Autumn Fresh Frequency Three or more 2.13 Two 15.0 One 82.8 None 0	Trigger Grayling Spawning Triggered 20.5 Not Triggered 79.5
11	Autumn (Mar-May) Fresh Vol (Q50) NatFlowMed or Greater 100 NatFlow to minus10Percent 0 minus10 to minus20Percent 0 minus20 to minus30Percent 0 minus30 to minus40Percent 0 minus40 to minus50Percent 0 minus50Percent or less 0	Autumn Fresh Frequency Three or more 0 Two 2.13 One 97.9 None 0	Trigger Grayling Spawning Triggered 19.5 Not Triggered 80.5

stream temperatures. Upstream of Lake Narracan, the median autumn stream temperatures of the unregulated reaches are ca. 12°C (LVWSB, 1986) due to virtually intact riparian vegetation and cooler alpine water. In contrast, the current inadequate autumn stream temperature in the lower Latrobe gives a significantly smaller window of opportunity for spawning and, given the stochastic nature of the fresh, results in a very low likelihood of the requisite spawning conditions occurring. Reinstating riparian shade may offer a solution as the modulating effects of riparian vegetation on stream temperature are well documented (Lovett and Price, 1999; DeWalle, 2008; Ghermandi *et al*., 2009).

These insights into the current situation in the lower Latrobe River point to two potential changes in this river system that would increase the probability of self-sustaining populations of Australian Grayling—access to the unregulated upper reaches of the Latrobe River and the provision of autumn high flows in the Tyers River. The obvious problem with the first proposal is the presence of Lake Narracan acting as a barrier to Grayling migration. A solution could be to provide fish passage (Clay, 1995). However, this would need to be thoroughly investigated since Mallen-Cooper and Brand (2007) have suggested that successful fishway design needs to be context specific. For example, a relatively small fish like Grayling would have trouble negotiating a fishway where the turbulence was greater that around 92 watts per cubic metre (Mallen-Cooper, 1999). Even if Grayling could gain access to the upper reaches of the Latrobe River, the

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question still remains as to whether the fish could migrate through the lower reaches of this river, given the poor water quality and ecological condition. Evidence of Grayling migrating though the comparably poor reaches of the Barwon River in Victoria (Koehn, 1986; Hall and Harrington, 1989), which flows through extensive agricultural, industrial and urban areas before reaching the ocean, suggests they could.

The second possibility involves the Tyers River below Moondarra Reservoir. The Tyers River has relatively pristine riparian vegetation and the cooler autumn stream temperature necessary for Grayling spawning. However, the BN model indicates that the flow regime is currently inadequate. There does exist some scope for autumn release from Moondarra Reservoir (B. Hansen, personal comm.); however, such a strategy would have to be done in conjunction with improvements in the water quality of the lower reaches of the Latrobe. To conclude, a major benefit in building and applying an eFlows BN model such as that reported here is that it can facilitate meaningful analysis and discussion of the ecological effects of particular eFlow regimes.

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