ADAPTIVE MANAGEMENT OF AUSTRALIAN GRAYLING RECRUITMENT: USING BAYESIAN MODELS AND SURROGATE SPECIES TO ASSESS BENEFITS OF SPRING FLOWS

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Environmental water managers must make best use of scarce water allocations, and adaptive management is one means of improving the effectiveness of environmental water delivery. We developed statistical models designed to inform adaptive management of the threatened Australian grayling (*Prototroctes maraena*) in the Thomson River, Victoria Australia. More specifically, the models assessed the importance of spring flows for facilitating recruitment of this diadromous species. However, grayling young-of-year were recorded in low numbers, which may limit the inferential power of statistical models. To overcome this limitation, we simultaneously applied the same statistical model to young-of-year of a surrogate species (tupong - *Pseudaphritis urvilli*), a more common diadromous species expected to respond to flow similarly to grayling. The grayling models were highly uncertain, providing no strong evidence of responses. Conversely, tupong responded strongly, with young of year migrating further into the Thomson River during years with good spring flows. Our results suggest two, potentially complementary, approaches to supporting the adaptive management of Australian grayling. First, refine monitoring approaches to ensure sufficient young-of-year of this species are captured to allow direct elucidation of effects of spring flows on grayling recruitment. Second, further investigate the use of tupong as a surrogate species, making the assumption that responses seen in this species are equivalent to unobserved, but real, responses in Australian grayling. While this is a far less desirable approach, it is a viable alternative in the absence of better data for the species of interest. The models presented in this paper can be used in an adaptive management cycle to make predictions of environmental responses to management decisions in conjunction with continued monitoring. This could potentially allow managers to fine tune flow events to maximize ecological responses for the water delivered.

1   INTRODUCTION

Water resource development around the world has placed increasing pressure on the aquatic biotas [1]. In response, increasing numbers of governments are adopting policies to return water to stressed rivers in the form of environmental flows [2]. However, in heavily exploited systems, any water allocated to environmental flows implies an equal volume of water removed from consumptive purposes, such as irrigated agriculture. Water resource reform is thus a *wicked problem* [sensu 3], with no possible solution that can leave all parties satisfied. With uncertainty over benefits of environmental flows compared to those of consumptive uses, and with pressure from some stakeholders to return water to 'productive' uses because of this uncertainty [4], it is incumbent upon environmental water managers to make best use of their limited environmental water.

Managers must make decisions regarding environmental water allocation regardless of uncertainties in likely ecological responses. Monitoring and evaluation within an adaptive management cycle [sensu 5] are being used as the means of improving knowledge and therefore management of environmental water in Australia.

Around the world, fish populations are the single greatest focus of environmental flow programs. Programs may be focused on individual species of commercial importance, particularly various salmonid species in Northern Hemisphere environments [e.g. 6]. Alternatively, programs may list objectives that target the entire 'native fish assemblage' [e.g. 7]. Although environmental flows programs in Australia generally target multiple

ecological responses in a 'system-level' program, one species of particular importance in south-east Australian coastal systems is the Australian grayling (*Prototroctes maraena*). Grayling is a nationally threatened species [8], and is vulnerable to flow-related disruptions.

Grayling are diadromous. Adults mature and spawn in fresh water, and the eggs/larvae drift downstream to the sea, with juveniles migrating back into fresh water. Several features of the species' life history makes it vulnerable to flow-related impacts, but manageable through environmental flows [9].

1. They are short-lived. Most adults die after their second year, with a small proportion living to five years.
2. Reproduction and recruitment are strongly tied to flow variation. Because of the short life cycle of the species, failure to deliver appropriate flows for several consecutive years could cause localized extinction.
3. In particular, adults respond to autumn high flow events by migrating downstream to lower river reaches, where they spawn [10]. Eggs are washed into estuarine and marine systems. If such flow events are not delivered, adults do not migrate, and females resorb eggs.
4. Young-of-year fish migrate into freshwater systems in spring. The provision of high flow events at this time is thought to be important for attracting young-of-year into systems and to facilitate their migration to upstream reaches.

The flow *components* [sensu 11] required to induce migration and spawning in adults are now quite well understood [10]. Acoustic tracking of adults and egg/larval drift netting surveys have provided data that gives managers in a number of coastal systems a good understanding of the discharge and other conditions required to induce spawning. Less certain are the flow components required in spring to facilitate upstream migration of young-of-year grayling. These small fish cannot be tagged for tracking, are relatively rare, and also are difficult to catch using standard fish sampling approaches like electrofishing. These factors will add uncertainty to any statistical analysis, potentially preventing strong inferences.

Nevertheless, improved knowledge is required to assess the importance of spring flows for grayling recruitment, and to allow managers to fine-tune the delivery of these flow components as part of an integrated environmental flows program designed to benefit multiple ecological endpoints. One potential approach, in the absence of sufficient (or sufficient quality) data for the species of interest, is to use a surrogate species – one that is expected to react to management the same way, but for which more/better data exist. While this is a far from ideal approach, it is an option when existing data on the species of interest cannot inform management.

Here, we used a two-stage approach to assessing the importance of spring flows for the recruitment of Australian grayling. First, we developed a hierarchical Bayesian model based upon large-scale environmental flows monitoring data and existing knowledge of grayling life history. The model relates the movement of grayling young-of-year into the Thomson River system in south-east Victoria, Australia, to several different expressions of spring flow conditions. Mindful of the potential difficulty of fitting grayling data to this model, we also applied the same model to a second, more abundant and easily sampled species (tupong - *Pseudaphritis urvilli*) that could be considered as a surrogate species for the responses of Australian grayling. Tupong have a similar life history to Australian grayling [12], spawning in autumn, spending early life stages in salt water environments, and then migrating back into the freshwater system as juveniles on high flow events in spring.

2   METHODS

2.1   Study system and data sets

The Thomson River is situated in the east of Victoria, south-eastern Australia (Figure 1). Its headwaters lie on the Baw Baw Plateau and it runs south-east before joining with the Latrobe River, which subsequently discharges into the estuarine Gippsland Lakes system and from there to the ocean (not shown on map detail). The major regulating structure on the river is Thomson Dam, an 1123 GL storage that diverts water from the catchment into the water supply of the city of Melbourne and also regulates flow for irrigation purposes downstream. From an average annual yield for the river of 410 GL, Thomson Dam diverts up to 265 GL into Melbourne's water supply. Maintaining or enhancing native fish communities was identified as one of the objectives of the Thomson River environmental flows study [13], with Australian grayling being a particular focus. More detailed information on the Thomson River and its catchment is available in Gippel and Stewardson [14].
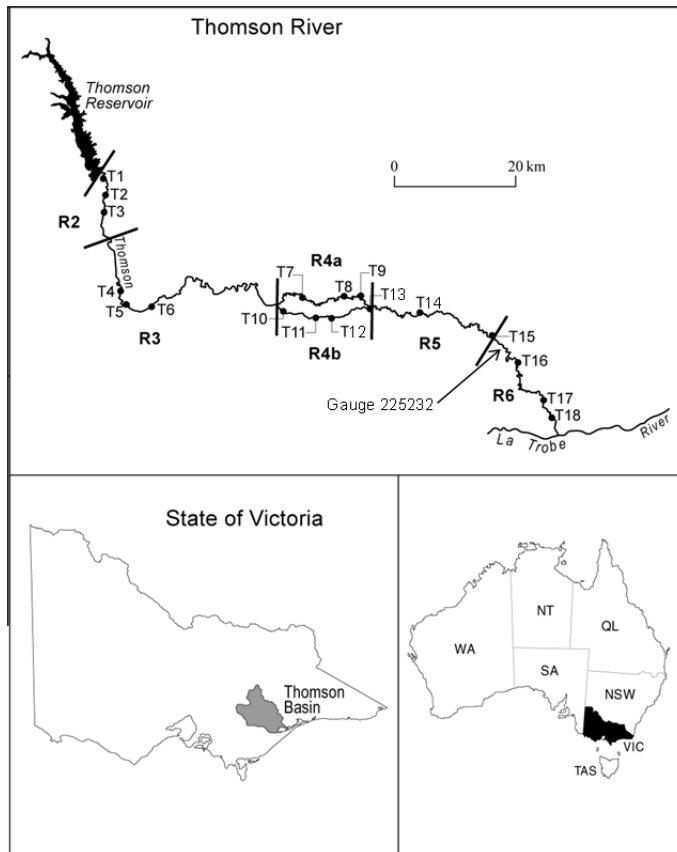
Figure 1. The Thomson River, and its location within the Australian state of Victoria. Rs denote the environmental flow reaches, with Ts showing the sites at which fish sampling is undertaken for VEFMAP. Modified from [15].

The data used in this study were mostly collected under the Victorian Environmental Flows Monitoring and Assessment Program [VEFMAP; 16]. VEFMAP is a large-scale environmental flows monitoring program that uses standard methods to collect data from 10 rivers across Victoria, for endpoints that include geomorphology, water quality, macroinvertebrates, vegetation, and fish.

VEFMAP data collection began in 2009, and for fish sampling in the Thomson River, built upon previous sampling funded by the West Gippsland Catchment Management Authority and mostly undertaken by the Arthur Rylah Institute for Environmental Research. Early years in the data presented below come from those programs.

Fish data had been collected using a combination of boat or bank-mounted electrofishing, fyke nets, and bait traps [17]. Sampling attempted to cover a broad range of habitats to capture all fish species present, and so did not specifically target Australian grayling. Data were collected in late summer-autumn (February – March), with one sample (2009) taken in May. Data were available for 11 years, 2005-2015.

Australian grayling and tupong were considered to be young-of-year if they were <120 mm and <80 mm in length, respectively [12, 18]. For analysis, we excluded sites from which fish (either adults or young-of-year) of the species being analyzed were never found throughout the 11 years of sampling. This was based upon the assumption that fish may be absent from a site (or just not captured) for reasons not included in the statistical model (e.g. a lack of suitable habitat). This resulted in 15 sites being considered for the Australian grayling analysis and 20 sites for the tupong analysis.

Discharge data were sourced from the Victorian Water Measurement Information System (http://data.water.vic.gov.au/monitoring.htm?ppbm=websw&rs&3&rskr_org). We employed data drawn from the most downstream gauging station in the Thomson River (Gauge 225232; Thomson River at Bundalaguah; Figure 1) to characterize the flows that would be experienced by grayling young-of-year entering the Thomson system.

2.2 Statistical model

The conceptual model that lies beneath the statistical model is that young-of-year movement upstream into the Thomson system will be a function of the magnitude of spring flows delivered the spring prior to fish sampling (usually ~4-6 months before sampling). We expect that young-of-year will be found further upstream in the system during years with good spring flows.

This was implemented as a hierarchical Bayesian model where the fish endpoint (we tested several – see below) is regressed against the distance upstream (from the bottom of the Thomson system) of the sampling site, for each year's sampling data. Year to year variation external to the Thomson system may affect overall young-of-year performance, regardless of flow in the Thomson River, and so a random effect was added to account for this. The effect of distance upstream on young-of-year is expected to vary as a function of spring flows, and so for the hierarchical model, this variable is represented as conditional upon spring flows.

In the equation block below, y is the datum collected at site i during year j. This is modelled as one of several different statistical distributions with mean (or probability) μ. μ (transformed by a link function appropriate to the likelihood distribution used) is linearly dependent upon distance upstream (d) of the sampling

$$y_{ij} \sim \text{dist}\left(\mu_{ij}\right)$$

$$\text{link}\left(\mu_{ij}\right) = \alpha + \beta_j \cdot d_i + \delta_j$$

$$\beta_j \sim N\left(\mu_{\beta j}, \sigma^2{}_\beta\right)$$

$$\mu_{\beta j} = \pi + \theta \cdot Q_i$$

$$\delta_j \sim N\left(0, \sigma^2{}_\delta\right)$$

station, with α being the global intercept, β being the effect of distance on young-of-year performance for each year, and δ being the random effect of year. The β values are assumed to be drawn from a normal distribution with mean μ_β and variance $\sigma^2{}_\beta$, where μ_β is conditional upon the effect (θ) of spring flow (Q), and with intercept π. δ is assumed to be drawn from a normal distribution with mean 0 and variance $\sigma^2{}_\delta$. All mean parameters (α, π, θ) are assigned minimally-informative (0,100) prior distributions, and variances ($\sigma^2{}_\beta$, $\sigma^2{}_\delta$) are assigned minimally-informative uniform (0,10) priors on the standard deviation.

2.3 Implementation

The model was implemented with three different expressions of young-of-year data for both Australian grayling and tupong, with different appropriate likelihood distributions and link functions (Table 1).

Table 1. Young-of-year endpoints employed in statistical analyses. A definition of each endpoint is provided, along with the likelihood distribution employed for the model and link function for the linear regression.

Endpoint	Explanation	Likelihood	Link
p(YoY)	The probability of capturing young-of-year at a site	Bernouli (μ)	Logit
prop.YoY	The proportion of total young-of-year captured for the year found at a site	Bionomial (μ, N)	Logit
n.YoY	The abundance of young-of-year captured at a site	Poisson (μ)	Log

N is the number of sites in the model (sites at which any of the target species had been captured).

The spring flow (Q_i) was expressed two ways: as the total number of days over the spring period for which discharge exceeded the environmental flow target for spring freshes of 800 ML d^{-1}, and of the total discharge from the system over the spring period. For grayling, the spring period was deemed to run from September to November, with the corresponding period for tupong starting one month later and running longer (October to January) to match observations of tupong in the field (W.M. Koster, pers. obs.). We also calculated the same statistics for different flow thresholds (1200, 1600 ML d^{-1}) and different durations (3, 4 or 5 months). The different parameterizations of the two flow metrics were found to be highly correlated, and so we only proceeded with analyses for the first flow metric described here.

Analyses were performed using OpenBUGS 3.2.1 [19]. We employed a standard burn-in among models of 10,000 iterations, with a further 20,000 iterations for parameter estimation. We used the *step* function in OpenBUGS to calculate the probability of a positive effect of spring flows upon movement of young-of-year into the Thomson system.

3   RESULTS

A total of 98 Australian grayling young-of-year were captured over the 11 years of surveys, with yearly abundances ranging from 0 (2013) to 34 (2007). Tupong young-of-year were more common, but not dramatically so (n = 136; 0 [several years], 58 [2012]).

Australian grayling showed no indication of a positive response to higher spring flows (Table 2).. In contrast, analyses of tupong young-of-year showed positive effects for the analysis of proportion of young-of-year at a site (prop.YoY) and abundance (n.Yoy).

These results can be illustrated graphically by examining how predicted young-of-year performance changes with distance upstream from year to year, and by looking at differences in young-of-year performance at the bottom of the system (0 km) and far upstream (100 km). We used the fitted Bayesian models to predict results for a number of distance scenarios, and for each of the years (i.e. with different flows). We present the results for one model (n.YoY) to illustrate the contrast between the results for the two species.

Figure 2 shows predicted abundance with distance for each year. The slope of the lines shows the decline in predicted abundance with distance upstream. If the hypothesis were supported we would expect to see shallower slopes for the lines corresponding to higher spring flows (i.e. because abundances would decrease by less with increasing distance upstream).

Table 2. Summary of statistical analyses. The first two columns show the combination of endpoint and spring flow parameterization. The numerical columns are the Bayesian probabilities of a positive effect of spring flows on the endpoint. These probabilities are interpreted differently to null hypothesis significance test p values. A value near 1 indicates support for the hypothesis (positive effect), while a value near zero indicates support for the opposite hypothesis (negative effect). A value near 0.5 indicates no strong relationship (a null result). Probabilities indicating strong support ($p < 0.1$, $p > 0.9$) are in bold.

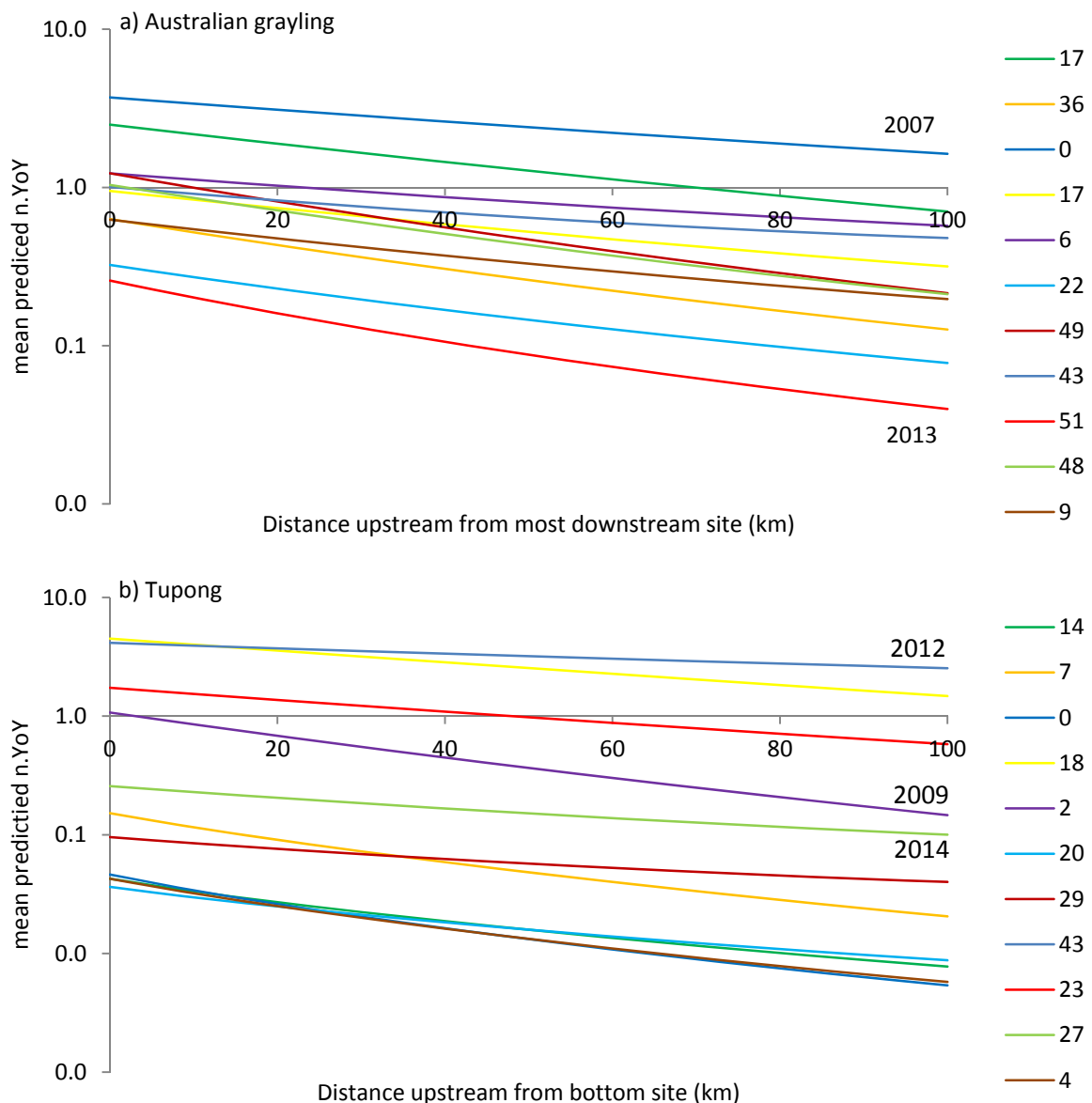| Endpoint	Spring flow metric	Probability of a positive effect of spring flows	
		Australian grayling	Tupong
p(YoY)	Number of days > 800 ML d^{-1}	0.30	0.70
p(YoY)	Total volume of spring discharge	0.47	0.56
prop.YoY	Number of days > 800 ML d^{-1}	0.36	**0.91**
n.YoY	Number of days > 800 ML d^{-1}	0.24	**0.94**

Figure 2. Mean predicted abundance of young-of-year captured for Australian grayling (a) and tupong (b) vs. distance upstream, with difference lines plotted for each year in the analysis. Line colour denotes the different years with the inset key showing the number of days of high flows (>800 ML d^{-1}) for that year (key is presented in year order). The y axis is presented on a logarithmic scale to better separate out results with lower predicted abundances.

This is not the case for Australian grayling (Figure 2a). If anything, the opposite pattern seems to occur, with the shallowest slope seen for 2007 (dark blue), when there were 0 days of high spring flow, and the steepest slope seen for 2013 (red) when there were 51 days. However, this pattern is not consistent, and the corresponding probability value from Table 2 indicates only very weak support for this hypothesis. On average, more grayling young-of-year are expected to be captured during years with lower spring flows. In contrast, tupong show strong support for the original hypothesis (Figure 2b). The shallowest slopes are seen for years with high spring flows (2012, dark blue; 2014, green), and the steepest slopes are seen for years with low spring flows (2009, purple). For these results, there is also an indication that overall predicted abundances of tupong are higher in high flow years.

While Figure 2 illustrates the predicted results in some detail, the large number of coloured lines makes it difficult to interpret. The results can be simplified by looking at the relative difference in young-of-year performance at the bottom of the system (0 km) to upstream (100 km). This summary is illustrated in Figure 3. Using relative change on the y axis of this figure compensates for the fact that overall predicted abundances vary from year to year. Otherwise years with low predicted abundance at 0 km will, by definition have low changes in that predicted abundance as we move upstream. If the original hypothesis is supported, we would see a negative relationship between change in relative predicted abundance and number of days of high spring flows, because the predicted abundance will reduce by less with distance upstream during years with high flows. This pattern is not seen for Australian grayling (Figure 3a), large uncertainty in the estimates indicating we cannot draw any conclusion from the analysis. In contrast, there is a strong and steep negative relationship in median values for tupong (Figure 3b), with predicted drops in abundance of 80-90% with distance upstream during dry years, but dropping to 40% for the year with the highest spring flows. Uncertainties around these estimates are still considerable, but are generally smaller than those for grayling, and a clear conclusion of positive effect is possible.
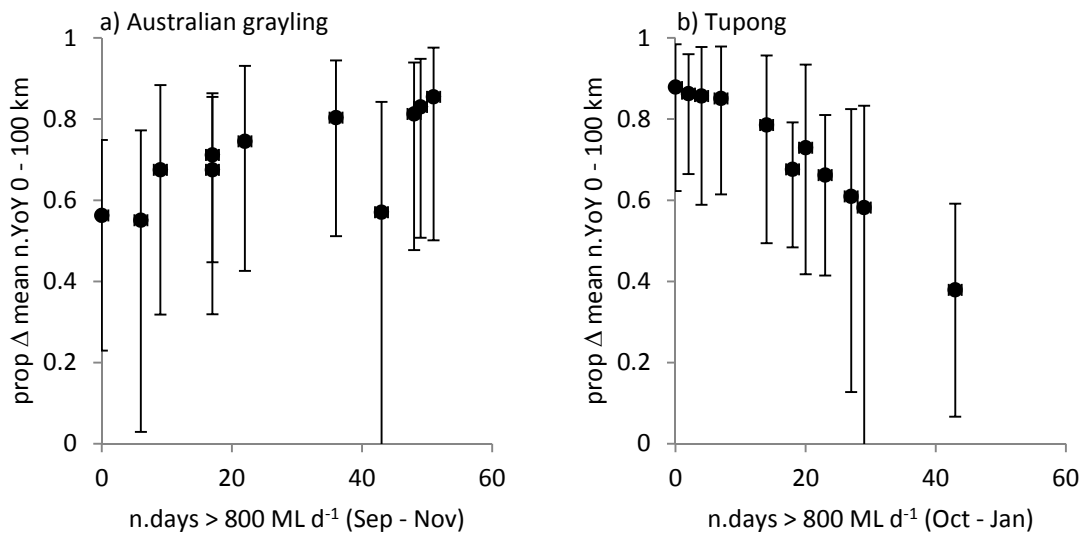

Figure 3. Relative change in predicted abundance of young-of-year captured for Australian grayling (a) and tupong (b) vs. number of days over the spring fresh threshold of 800 ML d^{-1}. The y axis depicts the relative reduction in predicted mean abundance between 0 and 100 km (i.e. (abundance at 0 km – abundance at 100 km) / abundance at 0 km). Dots are the median, with error bars encompassing the 80% credible interval for the estimate.

4 DISCUSSION

The central tenet of adaptive management is to improve decision making under uncertainty [5]. Early stages of an adaptive management cycle involve making decisions with substantial uncertainty. Monitoring and evaluation of those parts of the system that are least understood is designed to reduce uncertainty over time, and therefore improve decision making. While autumn flow requirements for migration and spawning are well understood for Australian grayling, decisions regarding spring flows to facilitate recruitment are currently being made using limited information.

Here, we translated existing conceptual understanding of recruitment requirements of Australian grayling into a statistical model, and used existing monitoring data to assess the importance of spring flows.

VEFMAP employs standard methods for data collection in different rivers to maximize the chances that data can be used in multi-river hierarchical analyses that would strengthen inferences, and allow extrapolation of results to non-monitored systems [20]. However, in this case, our work demonstrates that responses of target species may not always be detectable using standard approaches to data collection.

Apart from being a rare species, grayling can be difficult to catch (W.M. Koster, pers. obs.). Sampling inefficiencies may also be affected by discharge on the day of sampling. In previous work, we found that Australian smelt (*Retropinna semoni*) sampling efficiency is related to discharge [15]. Fish are more likely to be caught under low flows because they are less likely to be swept away after stunning, and also have less chance of avoiding stunning. We did attempt to build similar effects into the models described here but were unable to detect any similar pattern for Australian grayling. However, we attribute this mostly to the low number of young-of-year in the data set. We also observed that spring flows are somewhat correlated with discharge on the day of sampling, and so this could be acting to confound analyses of the effect of spring flows for Australian grayling.

One alternative is to use more targeted monitoring methods – in this case specifically designed to capture Australian grayling young-of-year. This could include, for example, netting during spring flows to directly sample young-of-year as they move upstream. While such an approach is appealing, specialized methods may mean that we lose the ability to detect responses in other species. Moreover, there is no obvious candidate for an improved sampling method at this time.

The complementary tupong analysis carried out here offers another alternative: using a surrogate species, expected to respond similarly to flow variation as the target species to infer the ecological benefits for that target species. There are two main arguments in favour of this approach. First, it allows us to make far better use of existing data. VEFMAP has been a major investment for the Victorian government. Managers and scientists should make best use possible of these data. Second, rare and endangered target species will always be difficult to detect, and observed in low numbers. It is a logical consequence of this rarity that the data will be more affected by unexplained variation than will be the case for a more common species. If we are confident that the two species will respond to flow variation in the same way, then the surrogate species approach is appealing.

The assumption that the surrogate species will respond in the same way as the target species is, however, a major assumption and it should not be applied uncritically. There remains the possibility that we did not see recruitment in Australian grayling because there was none to see. More likely, however, is that the target species and surrogate species differ slightly in their flow requirements. Here, we used slightly different parameterizations (starting month, durations) of the spring high flows for the different species. This was based upon an expectation of slightly different times of recruitment and the duration of the period throughout which young-of-year move into the system. If we lose sight of this difference, it would be possible to slip into flow management decisions specifically designed to benefit tupong recruitment, which may not maximize benefits for Australian grayling. In general, we believe these results provide a good conceptual test of the relationship between spring flows and recruitment of diadromous species, but we must remember that the species are not identical, and that grayling is the primary focus.

5   CONCLUSION

Whilst not losing sight of the limitations of our results, the approach employed in this paper offers a promising method for informing adaptive management of flows for Australian grayling recruitment that makes maximal use of the existing data sets. The analyses have demonstrated the importance of spring flows for tupong recruitment, and we can argue (with appropriate caveats) that this also means they are important for Australian grayling recruitment. The models produced are also of the sort that could be built into a formal adaptive management framework. The Bayesian models can be used to make predictions of responses to different flow management decisions. Implementation of one or more of these decisions with follow up monitoring will test the quality of those predictions, and allow the modelled relationships to be updated with new information as it builds up. Through several iterations of this cycle, decisions for Australian grayling recruitment should be improved.

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