1 Make the most of the data you've got: Bayesian models and a surrogate species approach

2 to assessing benefits of upstream migration flows for the endangered Australian grayling

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8 **Abstract:** Environmental water managers must make best use of allocations, and adaptive management is one
9 means of improving effectiveness of environmental water delivery. Adaptive management relies on generation
10 of new knowledge from monitoring and evaluation, but it is often difficult to make clear inferences from
11 available monitoring data. Alternative approaches to assessment of flow benefits may offer an improved
12 pathway to adaptive management. We developed Bayesian statistical models to inform adaptive management
13 of the threatened Australian grayling (*Prototroctes maraena*) in the coastal Thomson River, south-east Victoria
14 Australia. The models assessed the importance of flows in spring and early summer (migration flows) for
15 upstream dispersal and colonisation of juveniles of this diadromous species. However, Australian grayling
16 young-of-year were recorded in low numbers, and models provided no indication of the benefit of migration
17 flows. To overcome this limitation, we applied the same models to young-of-year of a surrogate species
18 (tupong - *Pseudaphritis urvilli*) – a more common diadromous species expected to respond to flow similarly to
19 Australian grayling – and found strong positive responses to migration flows. Our results suggest two
20 complementary approaches to supporting adaptive management of Australian grayling. First, refine
21 monitoring approaches to allow direct measurement of effects of migration flows, a process currently under
22 way. Second, while waiting for improved data, further investigate the use of tupong as a surrogate species.
23 More generally, alternative approaches to assessment can improve knowledge to inform adaptive
24 management, and this can occur while monitoring is being revised to directly target environmental responses
25 of interest.

Keywords: Adaptive management, environmental flows, Australian grayling, Bayesian, surrogate species, cross-taxon response-indicator species

Introduction

Water resource development around the world is placing increasing pressure on aquatic ecosystems (Dudgeon et al. 2006). In response, growing numbers of governments are adopting policies to return water to stressed rivers in the form of environmental flows (Le Quesne et al. 2010), and some programs are well advanced in their implementation (Hart 2015a; Hart 2015b). However, in heavily exploited systems, any water allocated to the environment implies an equal volume of water removed from consumptive purposes, such as irrigated agriculture. Water resource reform is thus a ‘wicked’ problem (sensu Brown et al. 2010), with no solution that can leave all parties satisfied. Amid uncertainty over quantifiable benefits of environmental flows compared to those of consumptive uses, there is pressure from some stakeholders to return water to ‘productive’ uses (Marohasy 2003). It is therefore incumbent upon environmental water managers to make best use of the limited environmental water available. Managers must make decisions regarding environmental water allocation despite uncertainties regarding likely ecological benefits. Monitoring and evaluation within an adaptive management cycle (sensu Walters 2007; Webb et al. in press-b) is one potential means for improving knowledge and therefore decision making in environmental water management, and the concept of adaptive management has been actively embraced by policy makers for environmental flows programs (Papps 2016).

Around the world, fish populations are often the focus of environmental flow programs. Programs are typically focused on single species of commercial importance, particularly various salmonid species in the northern hemisphere (e.g. Jager and Rose 2003). Alternatively, programs may list objectives that target the entire ‘native fish assemblage’ (e.g. SKM 2007). Although environmental flows programs in Australia generally target multiple ecological responses in a ‘system-level’ program, one species often targeted by flow management in south-eastern Australian coastal systems is the Australian grayling (*Prototroctes maraena*). Australian grayling is a nationally threatened diadromous species (Crook et al. 2006). Adults undertake downstream migrations to lower fresh water reaches of rivers to spawn, and the eggs and 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 (Backhouse et al. 2008).

1. Australian grayling are short-lived, and most adults die after their second year (Berra and Cadwallader 1983). Reproduction and recruitment are strongly tied to patterns of flow, and so failure to deliver appropriate flows for several consecutive years can cause localized extinction.
2. Adults respond to flow events in the austral autumn (April – May) by migrating downstream to lower river reaches to spawn (Koster et al. 2013). Eggs and larvae are washed to the sea. If such flow events are not delivered, adults do not migrate, and females resorb eggs (O'Connor and Mahoney 2004).
3. Young-of-year fish migrate from marine waters into freshwater systems in the austral spring and early summer (September – December). The provision of high flow events – hereafter referred to as migration flows – at this time is thought to be important for attracting young-of-year into rivers and facilitating migration to upstream reaches.

The flow components (sensu DEPI 2013) required to induce downstream migration and spawning in adults are now reasonably well understood (Koster et al. 2016; Koster et al. 2013). Acoustic tracking of adults, and egg and larval drift netting surveys, have provided data that give managers in a number of coastal systems a good understanding of the discharge and other conditions required to promote spawning. Less certain are the flow components required in spring and early summer to facilitate upstream migration of young-of-year Australian grayling. Migrating young-of-year fish are too small (about 40-60 mm in length) to be tagged for telemetry tracking, and can be difficult to catch using standard fish sampling techniques such as electrofishing. These factors will add uncertainty to any statistical analysis, potentially preventing strong inferences. Nevertheless, improved knowledge is required to assess the importance of migration flows for Australian 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. If standard approaches to monitoring and assessment cannot provide this knowledge, then alternative approaches must be considered.

More advanced statistical approaches can be used to try to extract the greatest value from the monitoring data available. Hierarchical Bayesian approaches (Gelman and Hill 2007) provide a flexible statistical modelling method that allows models to fit the structure of the data available and the hypotheses being tested (Clark 2005). This flexibility has previously been identified as one reason why Bayesian approaches may be suitable for analyzing data from environmental flows monitoring programs (Webb et al. in press-a; Webb et al. 2010b).

Another 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 flow management in a similar way, but for which more/better data exist (Caro 2010; Murphy et al. 2011). Responses of the surrogate species are assumed to be indicative of real, but unobserved, responses in the target species. While the surrogate species approach has been the subject of considerable debate amidst known weaknesses (Lindenmayer and Likens 2011; Wiens et al. 2008), it is an option when existing data on the species of interest are insufficient to inform management (Favreau et al. 2006; Wiens et al. 2008).

Here, we used both these approaches to assess the importance of migration flows for the upstream dispersal and colonization of juvenile Australian grayling. First, we developed a hierarchical Bayesian model based upon large-scale environmental flows monitoring data and existing knowledge of Australian grayling life history. The model related the movement of Australian grayling young-of-year into the Thomson River system in south-east Victoria, Australia, to several different expressions of migration flows. Mindful of the potential difficulty of fitting primary Australian grayling data to this model, we also applied the same model to a second, more abundant and easily sampled diadromous species (tupong - *Pseudaphritis urvilli*) that exhibits similar life history and migratory behaviour to Australian grayling (Hortle 1978). In particular, both species are short lived; young-of-year of both species migrate upstream into freshwater from the sea during spring and early summer, possibly in response to increased flows; while adults of both species undertake a downstream migration to spawn in autumn-winter (Crook et al. 2010; Koster et al. 2013). For these reasons, tupong may be considered as a surrogate species for Australian grayling responses to environmental water; or more specifically, a *cross-taxon indicator-response* species (Caro 2010) - one that is expected to respond to environmental variation similarly to the species of interest (Australian grayling), but for which inference is simpler because of the presence of larger data sets, or data less affected by unexplained variation.

Methods

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 flows south-east before joining with the Latrobe River, which discharges into the estuarine Gippsland Lakes system and from there to the Southern 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 (capital of the state of Victoria) and also regulates flow for irrigation purposes downstream. From an average annual discharge for the river of 410 GL, the 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 (EarthTech 2003), with Australian grayling being a particular focus. More detailed information on the Thomson River and its catchment is available in Gippel and Stewardson (1995).

The data used in this study were mostly collected under the Victorian Environmental Flows Monitoring and Assessment Program (VEFMAP; Webb et al. 2014; Webb et al. 2010a). 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 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 (Chee et al. 2009). 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 tui were considered to be young-of-year if they were <120 mm and <80 mm in length, respectively (Cadwallader and Backhouse 1983; Hurtle 1978). 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 Australian grayling and tupong young-of-year entering the Thomson system.

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 migration flows delivered during spring/early summer prior to fish sampling (usually ~4-6 months before sampling). We hypothesize that young-of-year will be found further upstream during years with higher migration flows.

This hypothesis was implemented as a hierarchical Bayesian generalized linear model where the response variable (we tested several – see below) is regressed against the distance upstream (from the site nearest the bottom of the Thomson system; T18 in Figure 1) of the sampling site, for each year's sampling data. Year-to-year variation external to the Thomson system may affect young-of-year performance (i.e. the value of the different response variables tested), 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 migration flows, and so for the hierarchical model, this variable is represented as conditional upon those flows.

$$\begin{aligned}
y_{ij} &\sim \text{dist}(\mu_{ij}) \\
\text{link}(\mu_{ij}) &= \alpha + \beta_j \cdot d_i + \delta_j \\
\beta_j &\sim N(\mu_{\beta_j}, \sigma_{\beta}^2) \\
\mu_{\beta_j} &= \pi + \theta \cdot Q_j \\
\delta_j &\sim N(0, \sigma_{\delta}^2)
\end{aligned}$$

In the equation block above, y is the datum collected at site i during year j . This is modelled as one of several different statistical distributions (dist) 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 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 on the intercept value. The β values are assumed to be drawn from a normal distribution with mean μ_{β_j} and variance σ_{β}^2 , where μ_{β_j} is conditional upon the effect (θ) of migration flow (Q), and with intercept π . The hypothesis of a positive effect of the migration flow is assessed through θ ; a positive value for θ indicates a beneficial effect of the flows, and vice-versa for a negative value. δ is assumed to be drawn from a normal distribution with mean 0 and variance σ_{δ}^2 . All mean parameters (α , π , θ) are assigned minimally-informative Normal (0,10) prior distributions, and variances (σ_{β}^2 , σ_{δ}^2) are assigned minimally-informative Uniform (0,10) priors on the standard deviation.

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). The three different expressions of young-of-year each captured slightly different aspects of the data. p(YoY) is the simple detection of young-of-year at a site, with the analysis assessing the reduction in probability of detection moving from downstream to upstream in the system. n.YoY is the simple count of abundances, moving beyond presence/absence to assess the effect of migration flows on abundance. prop(YoY) is the proportion of total young-of-year captures for that year that are found at a single site. This allows us to assess the extent to which young-of-year are balanced among sites; greater balance of upstream sites with downstream indicates a

beneficial effect of migration flows. This expression also standardizes for total number of young-of-year caught in the system that year, as this may be affected by external factors not included in the analysis.

The migration flow (Q_i) was expressed two ways: as the total number of days over the spring/early summer period for which discharge exceeded the environmental flow target (EarthTech 2003) for spring freshes of 800 ML d⁻¹ (9.26 m³ s⁻¹), and of the total discharge from the system over the spring/early summer period. For Australian grayling, this 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) to assess the importance of the quantitative definition of migrations flows. The different parameterizations of the two flow metrics were highly correlated, and so we only proceeded with analyses for the first flow metric described here.

Analyses were performed using OpenBUGS 3.2.1 (Lunn et al. 2009). We employed a standard burn-in among models of 10,000 iterations, using visual assessment of the Markov chains to confirm convergence, and a further 20,000 iterations for parameter estimation. We used the 'step' function in OpenBUGS (which returns a 0 for any input value < 0, and a 1 for a value ≥ 1) to calculate the probability of a positive effect of migration flows upon movement of young-of-year into the Thomson system – i.e. the probability that $\theta > 0$. Specific parameter values returned by the analysis may have little intuitive meaning. To display results graphically, we used posterior predictions from the models for different years versus various distances upstream from 0 km (the bottom site) to 100 km upstream. This upper limit is essentially arbitrary, but it is not far downstream from the uppermost site at which Australian grayling young-of-year were found (T4 at 119 km; Figure 1), and does not affect the interpretation of results.

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, with a total abundance of 136, ranging from 0 (2005, 2007, 2010, 2015) to 58 (2012).

The first analysis using total volume of river discharge over the spring/early summer period, on the probability of young-of-year occurrence – $p(\text{YoY})$, provided absolutely no indication of positive or negative effects for either species (Table 2). With this result in mind, and given that this representation of migration flow does not capture elevated within-channel flows explicitly, we did not perform analyses on the other response variables with this flow metric.

For the alternate expression of migration flows (number of days $> 800 \text{ ML d}^{-1}$), Australian grayling also showed no indication of a positive response to higher flows (Table 2). In contrast, analyses of tupong young-of-year showed strong support for positive effects for two of the analyses: abundance ($n.\text{Yoy}$) and proportion of young-of-year at a site (prop.YoY).

These results can be illustrated graphically by examining how predicted young-of-year performance changes with distance upstream from year-to-year. We used the fitted Bayesian models to predict results for a number of distances, and for each of the years (i.e. with different flows). We present the results for one model ($n.\text{YoY}$) to illustrate the contrast between the results for the two species. Figure 2 shows mean 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 darker lines corresponding to higher migration flows (i.e. because abundances would decrease by less with increasing distance upstream).

This is not the case for Australian grayling. If anything, the opposite pattern seems to occur, with the shallowest slope seen for 2007, when there were 0 days of high flow, and the steepest slope seen for 2013 when there were 51 days (Figure 2a). However, this pattern is not consistent, and the corresponding probability value from Table 2 indicates only very weak support for this hypothesis. In contrast, tupong show strong support for the original hypothesis. The shallowest slopes are seen for years with high migration flows (2012, 2014, 2011), and the steepest slopes are seen for years with low flows (2009, 2007), and in general the steeper slopes are for years with higher migration flows shown by the darker lines (Figure 2b). 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 from the bottom of the system (0 km) to the upstream limit of the predictions (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 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 indicate that we cannot draw any conclusion from the analysis, despite the overall shallow positive slope. 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 migration flows. Uncertainties around these estimates are still considerable, but are generally smaller than those for Australian grayling, and a clear conclusion of positive effect is possible (Table 2).

Discussion

The central tenet of adaptive management is to improve decision making under uncertainty (Walters 2007). 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 downstream migration and spawning are well understood for adult Australian grayling, decisions regarding spring/early summer migration flows to facilitate upstream dispersal and colonization of young-of-year are currently being made using limited information. Given the high conservation priority for this species, and the consequent significant investment being made in environmental water to promote its survival and recovery, improving the information upon which spring/early summer flow decisions are made is a high management priority. Here, we employed two alternate approaches, Bayesian statistical modelling, and surrogate species

analysis, to try to improve the value of existing monitoring information for understanding the importance of migration flows.

VEFMAP employs standard methods for data collection in different rivers (Webb et al. 2010a) 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 (Webb et al. 2015). However, in this case, our results demonstrate that responses of target species may not always be detectable using standard approaches to data collection.

Apart from being a rare species, Australian grayling can be difficult to catch, especially using standard sampling techniques such as electrofishing (W.M. Koster, pers. obs.). Sampling inefficiencies may also be affected by river discharge on the day of sampling (Gwinn et al. 2016). In previous work, we found that Australian smelt (*Retropinna semoni*) sampling efficiency was related to discharge (Webb et al. 2010b). 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 fish in the data set. We also observed that spring/early summer flows are somewhat correlated with discharge on the day of sampling, and so this could be acting to confound analyses of the effect of migration flows for Australian grayling.

If standard monitoring approaches cannot detect changes in Australian grayling, an alternative is to use more targeted monitoring methods – in this case specifically designed to capture young-of-year during their upstream migration phase. This could include, for example, netting during migration flow events, particularly at fish passage structures built into barriers such as weirs. This would 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. The advantages of being able to detect a response in a particular priority species must be weighed against the consequent risk of the loss of ability to detect responses across the wider biota of the system being studied.

The complementary tupong analysis carried out here offers another alternative: using a surrogate species that is expected to respond similarly to flow as the target species to infer the ecological benefits for that target species. Such an approach allows us to exploit existing data, which is an important consideration given that VEFMAP has been a major investment for the Victorian government. Managers and scientists should make best use possible of these data. Furthermore, rare and endangered target species will often 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 a similar way, then the surrogate species approach is appealing.

Surrogate species approaches have been applied relatively widely, and somewhat uncritically, in conservation and restoration planning (Murphy et al. 2011). These approaches have been criticized on both theoretical and empirical grounds, specifically that there is little evidence that surrogate species adequately replicate responses of individual or groups of target species (Favreau et al. 2006; Lindenmayer and Likens 2011). However, this literature also recognizes that surrogate species approaches are acceptable when no alternative is present, and can contribute to 'good enough' management in the face of an otherwise critical lack of knowledge (Wiens et al. 2008).

The expectation that the surrogate species will respond in a similar way as the target species is a major assumption and it should not be applied uncritically. There remains the possibility that we did not see a response to migration flows in Australian grayling young-of-year because there was none to see. More likely, however, is that the target species and surrogate species differ somewhat in their flow requirements. Here, we used slightly different parameterizations (starting month, durations) of the migration 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 inadvertently apply flow management decisions designed to benefit tupong, which may not maximize benefits for Australian grayling. In general, we believe these results provide a good conceptual test of the relationship between migration flows and upstream migration and colonization of diadromous species,

but we must remember that the species are not identical, and that Australian grayling is the primary focus of spring/early summer flow management in the Thomson River.

Direct measurement of the responses of species of conservation interest is always preferable to the use of a surrogate species approach (Lindenmayer and Likens 2011), even when such data are difficult to collect. Above, we have proposed a method that could potentially be used to directly sample grayling young-of-year as they migrate upstream. This approach is speculative, and it could take several years of development before we were confident of the data being generated. In the interim, modelling and measuring the responses of tupong as a surrogate species would provide at least some indication of the likely responses of Australian grayling until our ability to directly measure Australian grayling migration improved. We are thus proposing an adaptive approach to monitoring and evaluation, along with adaptive learning concerning grayling's responses to migration flow events.

The next step is to build these results into the decision-making processes for Australian grayling management in the Thomson River. Otherwise we run the risk that the research reported above contributes further to the knowing-doing gap between environmental management research, and the implementation of that research (Knight et al. 2008). In 2017, VEFMAP is moving into a new phase. At least partly informed by the results of this research, pilot programs have been approved to develop methods to directly assess movement of diadromous species such as Australian grayling and tupong. Once developed, data collected using these new methods are likely to reduce the uncertainty of the Bayesian models presented here, potentially providing strengthened support for decision making regarding migration flows. The surrogate species approach has not, at this stage, been 'tested' with managers in the Thomson River. The next phase of VEFMAP, will provide us with that opportunity while the direct sampling methods continue to be developed.

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. By moving away from standard approaches to monitoring and evaluation, we have improved knowledge of diadromous fish responses to young-of-year migration flow events in the Thomson

River. The analyses have demonstrated the importance of spring/early summer flows for tupong upstream dispersal and colonization, and we can argue (with appropriate caveats) that this also means they are important for Australian grayling. In the absence of better information, this could contribute to ‘good enough’ management of Australian grayling. The models produced are 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, such as varying the magnitude, duration and timing of migration flows. 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 the application of Bayes’ rule. However, we also stress the need to improve our ability over time to directly measure responses of Australian grayling to migration flow events, primarily through improved and more targeted monitoring approaches. Through several iterations of this cycle, environmental flow management decisions to promote Australian grayling recruitment should be improved.

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430

Tables

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

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

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

Table 2. Summary of statistical analyses. The first two columns show the combination of response variable and migration flow parameterization. The numerical columns are the Bayesian probabilities of a positive effect of migration flows on the response variable. 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 relationship (a null result). Probabilities indicating strong support ($p < 0.1$, $p > 0.9$) are in bold.

Response variable	Migration flow metric	Probability of a positive effect of migration flows	
		Australian grayling	Tupong
p(YoY)	Total volume of spring/early summer river discharge	0.47	0.56
p(YoY)	Number of days $> 800 \text{ ML d}^{-1}$	0.30	0.70
prop.YoY	Number of days $> 800 \text{ ML d}^{-1}$	0.36	0.91
n.YoY	Number of days $> 800 \text{ ML d}^{-1}$	0.24	0.94

Figure captions

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. Sites for which Australian grayling and/or Tupong were never found were excluded from the analysis. The location of the discharge gauge for which data were used in analyses is also shown. Modified from (Webb et al. 2010b).

Figure 2. Mean predicted abundance of young-of-year captured for Australian grayling (a) and tupong (b) vs. distance upstream from 0 km to 100 km for both plots, with different lines plotted for each year in the analysis. Line shading denotes the number of days of high flows ($>800 \text{ ML d}^{-1}$) for each year, with darker shading indicating higher number of days. The key presents the exact number of days of high flow for each year and the year this occurred. Specific years mentioned in the main body text are labelled. The y-axis is presented on a logarithmic scale to better separate out results with lower predicted abundances.

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 migration flow threshold of 800 ML d^{-1} . The y axis for both plots 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.

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