

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**

3 J. Angus Webb^{1,*}, Wayne M. Koster², Ivor G. Stuart², Paul Reich², Michael J. Stewardson¹

4 ¹ Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia

5 ² Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water and Planning,
6 Heidelberg, Victoria 3084, Australia

7 * angus.webb@unimelb.edu.au, +61 3 8344 9347, +61 3 8344 6215

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.

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

28 **Introduction**

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

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

51 juveniles migrating back into fresh water. Several features of the species' life history makes it vulnerable to
52 flow-related impacts, but manageable through environmental flows (Backhouse et al. 2008).

53 1. Australian grayling are short-lived, and most adults die after their second year (Berra and
54 Cadwallader 1983). Reproduction and recruitment are strongly tied to patterns of flow, and so
55 failure to deliver appropriate flows for several consecutive years can cause localized extinction.

56 2. Adults respond to flow events in the austral autumn (April – May) by migrating downstream to
57 lower river reaches to spawn (Koster et al. 2013). Eggs and larvae are washed to the sea. If such
58 flow events are not delivered, adults do not migrate, and females resorb eggs (O'Connor and
59 Mahoney 2004).

60 3. Young-of-year fish migrate from marine waters into freshwater systems in the austral spring and
61 early summer (September – December). The provision of high flow events – hereafter referred to
62 as migration flows – at this time is thought to be important for attracting young-of-year into
63 rivers and facilitating migration to upstream reaches.

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

77 More advanced statistical approaches can be used to try to extract the greatest value from the monitoring
78 data available. Hierarchical Bayesian approaches (Gelman and Hill 2007) provide a flexible statistical modelling
79 method that allows models to fit the structure of the data available and the hypotheses being tested (Clark
80 2005). This flexibility has previously been identified as one reason why Bayesian approaches may be suitable
81 for analyzing data from environmental flows monitoring programs (Webb et al. in press-a; Webb et al. 2010b).

82 Another potential approach, in the absence of sufficient (or sufficient quality) data for the species of interest,
83 is to use a surrogate species – one that is expected to react to flow management in a similar way, but for
84 which more/better data exist (Caro 2010; Murphy et al. 2011). Responses of the surrogate species are
85 assumed to be indicative of real, but unobserved, responses in the target species. While the surrogate species
86 approach has been the subject of considerable debate amidst known weaknesses (Lindenmayer and Likens
87 2011; Wiens et al. 2008), it is an option when existing data on the species of interest are insufficient to inform
88 management (Favreau et al. 2006; Wiens et al. 2008).

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

104 **Methods**

105 ***Study system and data sets***

106 The Thomson River is situated in the east of Victoria, south-eastern Australia (Figure 1). Its headwaters lie on
107 the Baw Baw Plateau and it flows south-east before joining with the Latrobe River, which discharges into the
108 estuarine Gippsland Lakes system and from there to the Southern Ocean (not shown on map detail). The major
109 regulating structure on the river is Thomson Dam, an 1123 GL storage that diverts water from the catchment
110 into the water supply of the city of Melbourne (capital of the state of Victoria) and also regulates flow for
111 irrigation purposes downstream. From an average annual discharge for the river of 410 GL, the Thomson Dam
112 diverts up to 265 GL into Melbourne's water supply. Maintaining or enhancing native fish communities was
113 identified as one of the objectives of the Thomson River environmental flows study (EarthTech 2003), with
114 Australian grayling being a particular focus. More detailed information on the Thomson River and its
115 catchment is available in Gippel and Stewardson (1995).

116 The data used in this study were mostly collected under the Victorian Environmental Flows Monitoring and
117 Assessment Program (VEFMAP; Webb et al. 2014; Webb et al. 2010a). VEFMAP is a large-scale environmental
118 flows monitoring program that uses standard methods to collect data from 10 rivers across Victoria, for
119 endpoints that include geomorphology, water quality, macroinvertebrates, vegetation, and fish. VEFMAP data
120 collection began in 2009, and fish sampling in the Thomson River built upon previous sampling funded by the
121 West Gippsland Catchment Management Authority and mostly undertaken by the Arthur Rylah Institute for
122 Environmental Research. Early years in the data presented below come from those programs.

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

127 Australian grayling and tui were considered to be young-of-year if they were <120 mm and <80 mm in
128 length, respectively (Cadwallader and Backhouse 1983; Hurtle 1978). For analysis, we excluded sites from

129 which fish (either adults or young-of-year) of the species being analyzed were never found throughout the 11
130 years of sampling. This was based upon the assumption that fish may be absent from a site (or just not
131 captured) for reasons not included in the statistical model (e.g. a lack of suitable habitat). This resulted in 15
132 sites being considered for the Australian grayling analysis and 20 sites for the tupong analysis.

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

138 ***Statistical model***

139 The conceptual model that lies beneath the statistical model is that young-of-year movement upstream into
140 the Thomson system will be a function of the magnitude of migration flows delivered during spring/early
141 summer prior to fish sampling (usually ~4-6 months before sampling). We hypothesize that young-of-year will
142 be found further upstream during years with higher migration flows.

143 This hypothesis was implemented as a hierarchical Bayesian generalized linear model where the response
144 variable (we tested several – see below) is regressed against the distance upstream (from the site nearest the
145 bottom of the Thomson system; T18 in Figure 1) of the sampling site, for each year's sampling data. Year-to-
146 year variation external to the Thomson system may affect young-of-year performance (i.e. the value of the
147 different response variables tested), regardless of flow in the Thomson River, and so a random effect was
148 added to account for this. The effect of distance upstream on young-of-year is expected to vary as a function
149 of migration flows, and so for the hierarchical model, this variable is represented as conditional upon those
150 flows.

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

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

$$\beta_j \sim N(\mu_{\beta_j}, \sigma_{\beta}^2)$$

$$\mu_{\beta_j} = \pi + \theta \cdot Q_j$$

$$\delta_j \sim N(0, \sigma_{\delta}^2)$$

151

152

153

154

155

156

157

158

159

160

161

162

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.

163

Implementation

164

165

166

167

168

169

170

171

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

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

174 The migration flow (Q_i) was expressed two ways: as the total number of days over the spring/early summer
175 period for which discharge exceeded the environmental flow target (EarthTech 2003) for spring freshes of 800
176 ML d^{-1} ($9.26 \text{ m}^3 \text{ s}^{-1}$), and of the total discharge from the system over the spring/early summer period. For
177 Australian grayling, this period was deemed to run from September to November, with the corresponding
178 period for tupong starting one month later and running longer (October to January) to match observations of
179 tupong in the field (W.M. Koster, pers. obs.). We also calculated the same statistics for different flow
180 thresholds ($1200, 1600 \text{ ML d}^{-1}$) and different durations (3, 4 or 5 months) to assess the importance of the
181 quantitative definition of migrations flows. The different parameterizations of the two flow metrics were
182 highly correlated, and so we only proceeded with analyses for the first flow metric described here.

183 Analyses were performed using OpenBUGS 3.2.1 (Lunn et al. 2009). We employed a standard burn-in among
184 models of 10,000 iterations, using visual assessment of the Markov chains to confirm convergence, and a
185 further 20,000 iterations for parameter estimation. We used the 'step' function in OpenBUGS (which returns a
186 0 for any input value < 0 , and a 1 for a value ≥ 1) to calculate the probability of a positive effect of migration
187 flows upon movement of young-of-year into the Thomson system – i.e. the probability that $\theta > 0$. Specific
188 parameter values returned by the analysis may have little intuitive meaning. To display results graphically, we
189 used posterior predictions from the models for different years versus various distances upstream from 0 km
190 (the bottom site) to 100 km upstream. This upper limit is essentially arbitrary, but it is not far downstream
191 from the uppermost site at which Australian grayling young-of-year were found (T4 at 119 km; Figure 1), and
192 does not affect the interpretation of results.

193 **Results**

194 A total of 98 Australian grayling young-of-year were captured over the 11 years of surveys, with yearly
195 abundances ranging from 0 (2013) to 34 (2007). Tupong young-of-year were more common, but not
196 dramatically so, with a total abundance of 136, ranging from 0 (2005, 2007, 2010, 2015) to 58 (2012).

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

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

206 These results can be illustrated graphically by examining how predicted young-of-year performance changes
207 with distance upstream from year-to-year. We used the fitted Bayesian models to predict results for a number
208 of distances, and for each of the years (i.e. with different flows). We present the results for one model (n.YoY)
209 to illustrate the contrast between the results for the two species. Figure 2 shows mean predicted abundance
210 with distance for each year. The slope of the lines shows the decline in predicted abundance with distance
211 upstream. If the hypothesis were supported we would expect to see shallower slopes for the darker lines
212 corresponding to higher migration flows (i.e. because abundances would decrease by less with increasing
213 distance upstream).

214 This is not the case for Australian grayling. If anything, the opposite pattern seems to occur, with the
215 shallowest slope seen for 2007, when there were 0 days of high flow, and the steepest slope seen for 2013
216 when there were 51 days (Figure 2a). However, this pattern is not consistent, and the corresponding
217 probability value from Table 2 indicates only very weak support for this hypothesis. In contrast, tupong show
218 strong support for the original hypothesis. The shallowest slopes are seen for years with high migration flows
219 (2012, 2014, 2011), and the steepest slopes are seen for years with low flows (2009, 2007), and in general the
220 steeper slopes are for years with higher migration flows shown by the darker lines (Figure 2b). For these
221 results, there is also an indication that overall predicted abundances of tupong are higher in high-flow years.

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

237 **Discussion**

238 The central tenet of adaptive management is to improve decision making under uncertainty (Walters 2007).
239 Early stages of an adaptive management cycle involve making decisions with substantial uncertainty.
240 Monitoring and evaluation of those parts of the system that are least understood is designed to reduce
241 uncertainty over time, and therefore improve decision making. While autumn flow requirements for
242 downstream migration and spawning are well understood for adult Australian grayling, decisions regarding
243 spring/early summer migration flows to facilitate upstream dispersal and colonization of young-of-year are
244 currently being made using limited information. Given the high conservation priority for this species, and the
245 consequent significant investment being made in environmental water to promote its survival and recovery,
246 improving the information upon which spring/early summer flow decisions are made is a high management
247 priority. Here, we employed two alternate approaches, Bayesian statistical modelling, and surrogate species

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

250 VEFMAP employs standard methods for data collection in different rivers (Webb et al. 2010a) to maximize the
251 chances that data can be used in multi-river hierarchical analyses that would strengthen inferences, and allow
252 extrapolation of results to non-monitored systems (Webb et al. 2015). However, in this case, our results
253 demonstrate that responses of target species may not always be detectable using standard approaches to data
254 collection.

255 Apart from being a rare species, Australian grayling can be difficult to catch, especially using standard sampling
256 techniques such as electrofishing (W.M. Koster, pers. obs.). Sampling inefficiencies may also be affected by
257 river discharge on the day of sampling (Gwinn et al. 2016). In previous work, we found that Australian smelt
258 (*Retropinna semoni*) sampling efficiency was related to discharge (Webb et al. 2010b). Fish are more likely to
259 be caught under low flows because they are less likely to be swept away after stunning, and also have less
260 chance of avoiding stunning. We did attempt to build similar effects into the models described here but were
261 unable to detect any similar pattern for Australian grayling. However, we attribute this mostly to the low
262 number of young-of-year fish in the data set. We also observed that spring/early summer flows are somewhat
263 correlated with discharge on the day of sampling, and so this could be acting to confound analyses of the
264 effect of migration flows for Australian grayling.

265 If standard monitoring approaches cannot detect changes in Australian grayling, an alternative is to use more
266 targeted monitoring methods – in this case specifically designed to capture young-of-year during their
267 upstream migration phase. This could include, for example, netting during migration flow events, particularly
268 at fish passage structures built into barriers such as weirs. This would directly sample young-of-year as they
269 move upstream. While such an approach is appealing, specialized methods may mean that we lose the ability
270 to detect responses in other species. The advantages of being able to detect a response in a particular priority
271 species must be weighed against the consequent risk of the loss of ability to detect responses across the wider
272 biota of the system being studied.

273 The complementary tupong analysis carried out here offers another alternative: using a surrogate species that
274 is expected to respond similarly to flow as the target species to infer the ecological benefits for that target
275 species. Such an approach allows us to exploit existing data, which is an important consideration given that
276 VEFMAP has been a major investment for the Victorian government. Managers and scientists should make
277 best use possible of these data. Furthermore, rare and endangered target species will often be difficult to
278 detect, and observed in low numbers. It is a logical consequence of this rarity that the data will be more
279 affected by unexplained variation than will be the case for a more common species. If we are confident that
280 the two species will respond to flow variation in a similar way, then the surrogate species approach is
281 appealing.

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

289 The expectation that the surrogate species will respond in a similar way as the target species is a major
290 assumption and it should not be applied uncritically. There remains the possibility that we did not see a
291 response to migration flows in Australian grayling young-of-year because there was none to see. More likely,
292 however, is that the target species and surrogate species differ somewhat in their flow requirements. Here, we
293 used slightly different parameterizations (starting month, durations) of the migration flows for the different
294 species. This was based upon an expectation of slightly different times of recruitment and the duration of the
295 period throughout which young-of-year move into the system. If we lose sight of this difference, it would be
296 possible to inadvertently apply flow management decisions designed to benefit tupong, which may not
297 maximize benefits for Australian grayling. In general, we believe these results provide a good conceptual test
298 of the relationship between migration flows and upstream migration and colonization of diadromous species,

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

301 Direct measurement of the responses of species of conservation interest is always preferable to the use of a
302 surrogate species approach (Lindenmayer and Likens 2011), even when such data are difficult to collect.

303 Above, we have proposed a method that could potentially be used to directly sample grayling young-of-year as
304 they migrate upstream. This approach is speculative, and it could take several years of development before we
305 were confident of the data being generated. In the interim, modelling and measuring the responses of tupong
306 as a surrogate species would provide at least some indication of the likely responses of Australian grayling until
307 our ability to directly measure Australian grayling migration improved. We are thus proposing an adaptive
308 approach to monitoring and evaluation, along with adaptive learning concerning grayling's responses to
309 migration flow events.

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

320 **Conclusion**

321 Whilst not losing sight of the limitations of our results, the approach employed in this paper offers a promising
322 method for informing adaptive management of flows for Australian grayling recruitment that makes maximal
323 use of the existing data. By moving away from standard approaches to monitoring and evaluation, we have
324 improved knowledge of diadromous fish responses to young-of-year migration flow events in the Thomson

325 River. The analyses have demonstrated the importance of spring/early summer flows for tupong upstream
326 dispersal and colonization, and we can argue (with appropriate caveats) that this also means they are
327 important for Australian grayling. In the absence of better information, this could contribute to 'good enough'
328 management of Australian grayling. The models produced are of the sort that could be built into a formal
329 adaptive management framework. The Bayesian models can be used to make predictions of responses to
330 different flow management decisions, such as varying the magnitude, duration and timing of migration flows.
331 Implementation of one or more of these decisions with follow up monitoring will test the quality of those
332 predictions, and allow the modelled relationships to be updated with new information as it builds up through
333 the application of Bayes' rule. However, we also stress the need to improve our ability over time to directly
334 measure responses of Australian grayling to migration flow events, primarily through improved and more
335 targeted monitoring approaches. Through several iterations of this cycle, environmental flow management
336 decisions to promote Australian grayling recruitment should be improved.

337 **Acknowledgments**

338 This work was funded through DELWP Research Contract, "VEFMAP Stage V: Further analysis of VEFMAP
339 data". We thank Fiona Spruzen, Paulo Lay, and the project Technical Reference Group for their guidance. We
340 also acknowledge the long-term data collection efforts of the staff from the Arthur Rylah Institute and other
341 providers, as well as the management of VEFMAP by the West Gippsland Catchment Management Authority.

342 **References**

- 343 Backhouse G, O'Connor J, Jackson J (2008) National Recovery Plan for the Australian Grayling *Prototroctes*
344 *maraena*. Department of Sustainability and Environment, Melbourne
- 345 Berra TM, Cadwallader PL (1983) Age and growth of Australian grayling, *Prototroctes maraena* Gunther
346 (Salmoniformes : Prototroctidae), in the Tambo River, Victoria Mar Freshw Res 34:451-460
347 doi:<http://dx.doi.org/10.1071/MF9830451>
- 348 Brown VA, Harris JA, Russell YR (2010) Tackling Wicked Problems Through the Transdisciplinary Imagination.
349 CSIRO publishing, Melbourne
- 350 Cadwallader PL, Backhouse GN (1983) Guide to the Freshwater Fish of Victoria. Victorian Government Printing
351 Office, Melbourne
- 352 Caro T (2010) Conservation by Proxy. Island Press, Washington, D.C.
- 353 Chee Y, Webb A, Stewardson M, Cottingham P (2009) Victorian Environmental Flows Monitoring and
354 Assessment Program: Monitoring and assessing environmental flow releases in the Thompson River.
355 eWater Cooperative Research Centre, Melbourne
- 356 Clark JS (2005) Why environmental scientists are becoming Bayesians Ecol Lett 8:2-14

357 Crook DA et al. (2010) Catadromous migrations by female tui (*Pseudaphritis urvillii*) in coastal streams in
358 Victoria, Australia Mar Freshw Res 61:474-483

359 Crook DA, Macdonald JJ, O'Connor JP, Barry B (2006) Use of otolith chemistry to examine patterns of diadromy
360 in the threatened Australian grayling *Prototroctes maraena* J Fish Biol 69:1330-1344

361 DEPI (2013) FLOWS - a method for determining environmental water requirements in Victoria: Edition 2.
362 Department of Environment and Primary Industries, Melbourne

363 Dudgeon D et al. (2006) Freshwater biodiversity: importance, threats, status and conservation challenges Biol
364 Rev 81:163-182

365 EarthTech (2003) Thomson River environmental flow requirements & options to manage flow stress. Earth
366 Tech Engineering Pty Ltd, Melbourne, Australia

367 Favreau JM, Drew CA, Hess GR, Rubino MJ, Koch FH, Eschelbach KA (2006) Recommendations for assessing the
368 effectiveness of surrogate species approaches Biodivers Conserv 15:3949-3969

369 Gelman A, Hill J (2007) Data Analysis Using Regression and Multilevel/Hierarchical Models. Analytical methods
370 for social research. Cambridge University Press, Cambridge; New York

371 Gippel CJ, Stewardson MJ (1995) Development of an environmental flow management strategy for the
372 Thomson River, Victoria, Australia Regul Rivers-Res Manage 10:121-135

373 Gwinn DC, Beesley LS, Close P, Gawne B, Davies PM (2016) Imperfect detection and the determination of
374 environmental flows for fish: challenges, implications and solutions Freshw Biol 61:172-180

375 Hart BT (2015a) The Australian Murray-Darling Basin Plan: challenges in its implementation (part 1) Int J Water
376 Resour Dev 32:819-834 doi:10.1080/07900627.2015.1083847

377 Hart BT (2015b) The Australian Murray-Darling Basin Plan: challenges in its implementation (part 1) Int J Water
378 Resour Dev 32:835-852 doi:10.1080/07900627.2015.1084494

379 Hurtle ME (1978) The ecology of the sandy, *Pseudaphritis urvillii*, in south-east Tasmania. University of
380 Tasmania

381 Jager HI, Rose KA (2003) Designing optimal flow patterns for fall Chinook salmon in a central valley, California,
382 river North Am J Fish Manage 23:1-21

383 Knight AT, Cowling RM, Rouget M, Balmford A, Lombard AT, Campbell BM (2008) Knowing but not doing:
384 Selecting priority conservation areas and the research-implementation gap Conserv Biol 22:610-617
385 doi:10.1111/j.1523-1739.2008.00914.x

386 Koster WM, Amtstaetter F, Dawson DR, Reich P, Morrongiello JR (2016) Provision of environmental flows
387 promotes spawning of a nationally threatened diadromous fish Mar Freshw Res:doi:
388 10.1071/MF15398 doi:10.1071/MF15398

389 Koster WM, Dawson DR, Crook DA (2013) Downstream spawning migration by the amphidromous Australian
390 grayling (*Prototroctes maraena*) in a coastal river in south-eastern Australia Mar Freshw Res 64:31-41
391 doi:Doi 10.1071/Mf12196

392 Le Quesne T, Kendy E, Weston D (2010) The Implementation Challenge: taking stock of government policies to
393 protect and restore environmental flows. The Nature Conservancy & WWF,

394 Lindenmayer DB, Likens GE (2011) Direct measurement versus surrogate indicator species for evaluating
395 environmental change and biodiversity loss Ecosystems 14:47-59

396 Lunn D, Spiegelhalter D, Thomas A, Best N (2009) The BUGS project: Evolution, critique and future directions
397 (with discussion) Statistics in Medicine 28:3049-3082

398 Marohasy J (2003) Myth and the Murray: measuring the real state of the river environment IPA Backgrounder
399 15(5)

400 Murphy DD, Weiland PS, Cummins KW (2011) Critical Assessment of the use of surrogate species in
401 conservation planning in the Sacramento-San Joaquin Delta, California (U.S.A.) Conserv Biol 25:873-
402 878

403 O'Connor JP, Mahoney JC (2004) Observations of ovarian involution in the Australian grayling (*Prototroctes*
404 *maraena*) Ecology of Freshwater Fish 13:70-73

405 Papps D (2016) Adaptive Management of Commonwealth Environmental Water in the Murray-Darling Basin.
406 Paper presented at the ABARES Outlook, Canberra,

407 SKM (2007) Environmental flows monitoring for the Goulburn and Broken rivers: monitoring design report.
408 Sinclair Knight Merz, Melbourne

409 Walters CJ (2007) Is adaptive management helping to solve fisheries problems? Ambio 36:304-307

410 Webb JA, Arthington AH, Olden JD, Davis JA (in press-a) Models of ecological responses to flow regime change
411 to inform environmental flow assessments. In: Horne AC, Webb JA, Stewardson MJ, Richter BD,
412 Acreman M (eds) Water for the Environment: policy, practice, implementation and management.
413 Elsevier,

- 414 Webb JA, de Little SC, Miller KA, Stewardson MJ, Rutherford ID, Sharpe AK, Poff NL (2015) A general approach
415 to predicting ecological responses to environmental flows: making best use of the literature, expert
416 knowledge, and monitoring data *River Res Appl* 31:505-514 doi: 10.1002/rra.2832
- 417 Webb JA, Miller KA, de Little SC, Stewardson MJ (2014) Overcoming the challenges of monitoring and
418 evaluating environmental flows through science-management partnerships *Int J River Basin Manage*
419 12:111-121 doi:10.1080/15715124.2014.901332
- 420 Webb JA, Stewardson MJ, Chee YE, Schreiber ESG, Sharpe AK, Jenz MC (2010a) Negotiating the turbulent
421 boundary: the challenges of building a science-management collaboration for landscape-scale
422 monitoring of environmental flows *Mar Freshw Res* 61:798-807
- 423 Webb JA, Stewardson MJ, Koster WM (2010b) Detecting ecological responses to flow variation using Bayesian
424 hierarchical models *Freshw Biol* 55:108-126 doi:10.1111/j.1365-2427.2009.02205.x
- 425 Webb JA, Watts RJ, Allan C, Warner AT (in press-b) Principles for monitoring, evaluation and adaptive
426 management of environmental flows. In: Horne AC, Webb JA, Stewardson MJ, Richter BD, Acreman M
427 (eds) *Water for the Environment: policy, science, implementation and management*. Elsevier,
- 428 Wiens JA, Hayward GD, Holthausen RS, Wisdom MJ (2008) Using surrogate species and groups for
429 conservation planning and management *BioScience* 58:241-252

430

431 **Tables**

432 Table 1. Young-of-year response variables employed in statistical analyses. A definition of each response
 433 variable is provided, along with the likelihood distribution employed for the model, and link function for the
 434 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

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

436 Table 2. Summary of statistical analyses. The first two columns show the combination of response variable and
 437 migration flow parameterization. The numerical columns are the Bayesian probabilities of a positive effect of
 438 migration flows on the response variable. These probabilities are interpreted differently to null hypothesis
 439 significance test p values. A value near 1 indicates support for the hypothesis (positive effect), while a value
 440 near zero indicates support for the opposite hypothesis (negative effect). A value near 0.5 indicates no
 441 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

442

443 **Figure captions**

444 Figure 1. The Thomson River, and its location within the Australian state of Victoria. Rs denote the
445 environmental flow reaches, with Ts showing the sites at which fish sampling is undertaken for VEFMAP. Sites
446 for which Australian grayling and/or Tupong were never found were excluded from the analysis. The location
447 of the discharge gauge for which data were used in analyses is also shown. Modified from (Webb et al. 2010b).

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

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

459

460

461

462

463

464

465 <?xml version="1.0" encoding="UTF-8" ?>
466 <funding-group>
467 <award-group id="IDOETYAE1925">
468 <funding-source funder-id="http://dx.doi.org/10.13039/100009675">Department
469 of Environment, Land, Water and Planning, State Government of
470 Victoria</funding-source>
471 </award-group>
472 </funding-group>
473





