10.1071/MF23023

Marine and Freshwater Research

Supplementary Material

Cold-water pollution impacts on two 'warm-water' riverine fish: interactions of dam size and life-history requirements

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Input data generation, stocking and angling, population model development process, model parametrisation and rules

Flow and temperature data

The available water temperature datasets for both rivers were temporally limited, and available data were repeated in order to generate the temporal extent needed to detect population responses under the population modelling approach. A complete dataset for the downstream reach of Pindari Dam on the Severn River was only available for a 7-year sequence 2014 to 2020. These data were repeated 5 times to represent the span of years 2014–2049 for Murray cod and golden perch modelling in this reach. A complete dataset for the Gwydir River at downstream of Copeton dam was only available for a nine-year sequence (2011–2020). Data sequences were repeated 5 times to obtain a 45-year flow-temperature sequence for Murray cod (2011–2056), and also for golden perch (2011–2038) but with less repetition as the golden perch metapopulation model is more sensitive to changes in flow-temperature data inputs. Data from the Bronte gauge on the Mehi River were also repeated to match to this temporal extent (2011-2038) and used to inform golden perch population responses for population 2 (see Fig. 1). Within each dataset, some records were missing and had to be estimated using running averages to ensure completeness for this modelling. For example, complete daily records of temperature and flow were needed to estimate spawning conditions for each species within each year.

Spawning opportunity analysis gauge locations

Table S1. Gauge sites (see Fig. 1) used for flow and temperature input data used in the 'spawning opportunity analysis'.

River	Gauge ID	Location description
Severn	416039	Strathbogie gauge - 46.8 km upstream of Pindari Dam
Severn	416067	Ducca Marrin gauge - 5.3km downstream of Pindari Dam
Macintyre	416012	Holdfast gauge - 154.7km downstream of Pindari Dam
Gwydir	418008	Bundarra gauge - 68.2 km upstream of Copeton Dam
Gwydir	418026	Copeton Dam gauge - 2.9 km downstream of Copeton Dam
Gwydir	418004	Yarraman Bridge gauge - 239.3 km downstream of Copeton Dam
Mehi	418058	Bronte gauge - Adjacent to the Gwydir River population

Stocking and angler harvest

Stocking data for the Gwydir River were obtained from NSW DPI Fisheries (https://www.dpi.nsw.gov.au/fishing/recreational/resources/stocking) for Murray cod and golden perch. Murray cod were also stocked in the Macintyre River downstream of the Severn River, but these were considered unlikely to have moved upstream to influence the populations in the Severn River. Additional stocking of golden perch occurred in the Severn upstream of Pindari Dam, but these were considered unlikely to have moved over the Pindari Dam wall and influenced populations downstream. Similarly, golden perch stocked in the Macintyre River were considered not to influence this population.

Model development and structure

Detailed ecological information for Murray cod and golden perch had previously been collated and documented (Koehn *et al*. 2020) and forms the basis of the population models used. In addition to the information provided below, further details (structure, fecundities, etc.) of these models can be found in Todd *et al*. (2005), Todd and Koehn (2007), Koehn and Todd (2012) and Todd *et al.* (2022). These workshops also provided real-life expertise and operational knowledge so that the appropriate scenarios for modelling could be developed, appropriate model framework established, data accessed (especially river flows and temperatures) and ecological rules within the models determined.

Murray cod model construct

The Murray cod population model used is a stage/age matrix construct previously developed for the MDB (Todd and Koehn 2007; Koehn and Todd, 2012) and was modified to reflect the species' ecology in the northern MDB. Murray cod was modelled as a single population in both rivers where geographic population boundaries were chosen based upon the extent of cold-water pollution effects and the ecology of the species. For the Gwydir River, population boundaries were from Copeton Dam to the Mehi River junction (~240 km). The Severn River population was modelled from Pindari Dam to Severn River Falls (~83 km). Modifications were made to the spawning season and the period of presence of eggs and larvae (a reduction to 900 mm in the average maximum length, which also reduced fecundity at age), and to the minimum required spawning temperature for Murray cod, setting it at two consecutive days at 18°C. The model summarises the life history of Murray cod by explicitly representing 50 age classes (Koehn and Todd 2012). Murray cod were assumed to become sexually mature at five years of age, with fecundity increasing depending on the maximum size of fish in the population (see the Murray cod fecundity relationships derived for this study; Rowland 1998a, 1998b). A 1:1 sex ratio was assumed, and spawning seasons were modelled as 1 October to end of December in each year, with eggs and larvae present from when spawning temperature conditions are met.

Murray cod egg and larval survival

Murray cod egg and larval proportional survival was estimated as a product of the daily temperature during the egg and larval period in each year applied to an experimentally derived mortality relationship (Ryan *et al.* 2003) which was converted into survival relationship (Todd *et al.* 2005: Fig. S1).

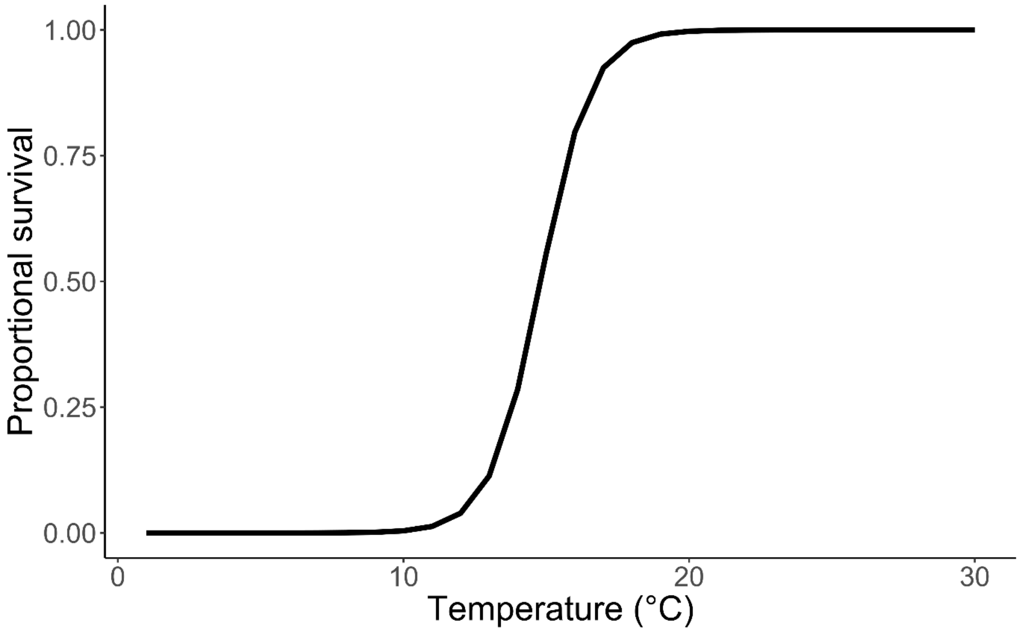

Fig. S1. Proportional Murray cod egg and larval survival with increasing temperature. Relationship derived from Ryan *et al.* (2003) and Todd *et al*. (2005).

Egg and larval survival were also affected by flow for Murray cod, where maximum flow in the critical 10-day period dictated egg survival according to a linear relationship (Fig. S2).

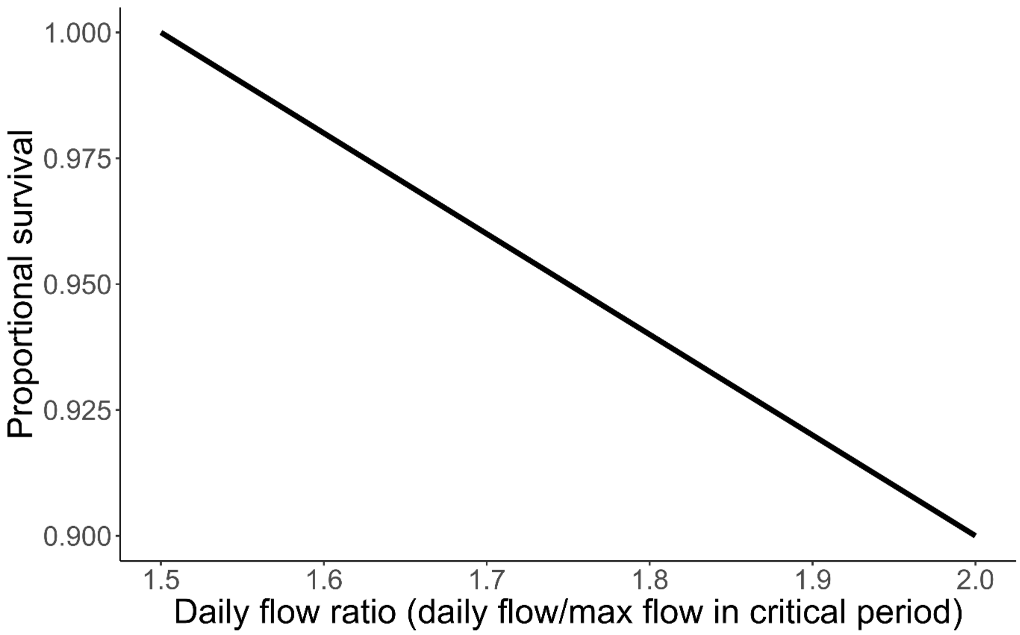

Fig. S2. Proportional Murray cod egg survival against the daily flow ratio. Note this detects an increase in flow and reduced survival if an increase occurs.

The highest flow in the 10-day critical period after spawning also dictated larval survival. Here, survival was 5% when this highest flow was >50,000 ML day^{-1} and 100% if flows were <10,000 ML day^{-1} (but could still be affected by temperature). Survival was dictated by a flow relationship (Fig. S3) when ≥10 000 or ≤50 000 ML day^{-1}.

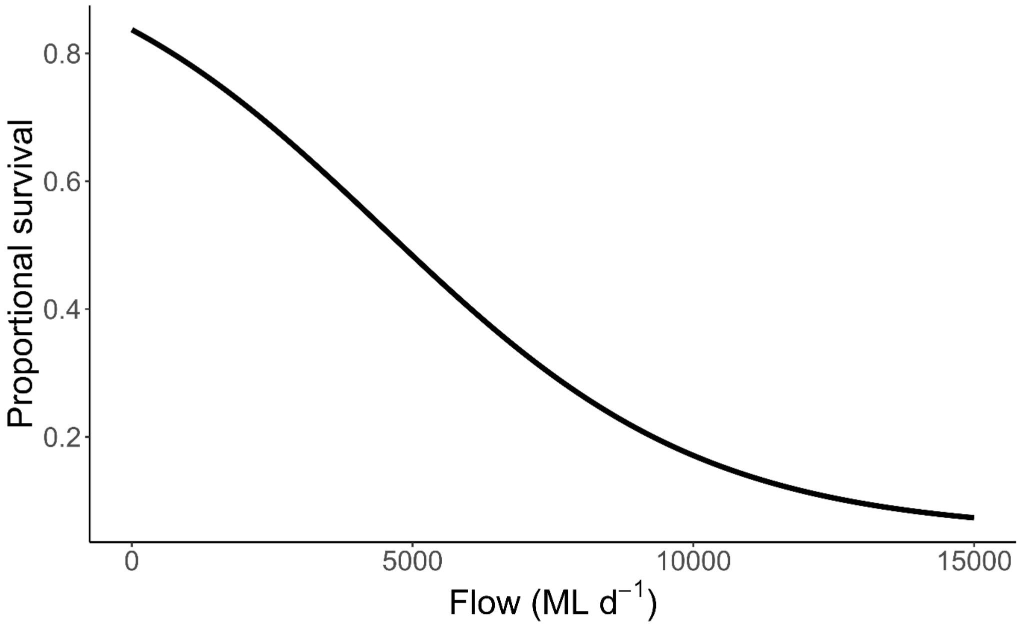

Fig. S3. Proportional Murray cod larval survival with increasing flow.

Murray cod hypoxic blackwater

Hypoxic blackwater events were applied to Murray cod model runs in years where daily flows of 35 000 ML day^{-1} were observed. In these instances, the 20th highest flow in that year was used to predict proportional survival of adult Murray cod in the respective population by a sigmoidal relationship (Fig. S4.).

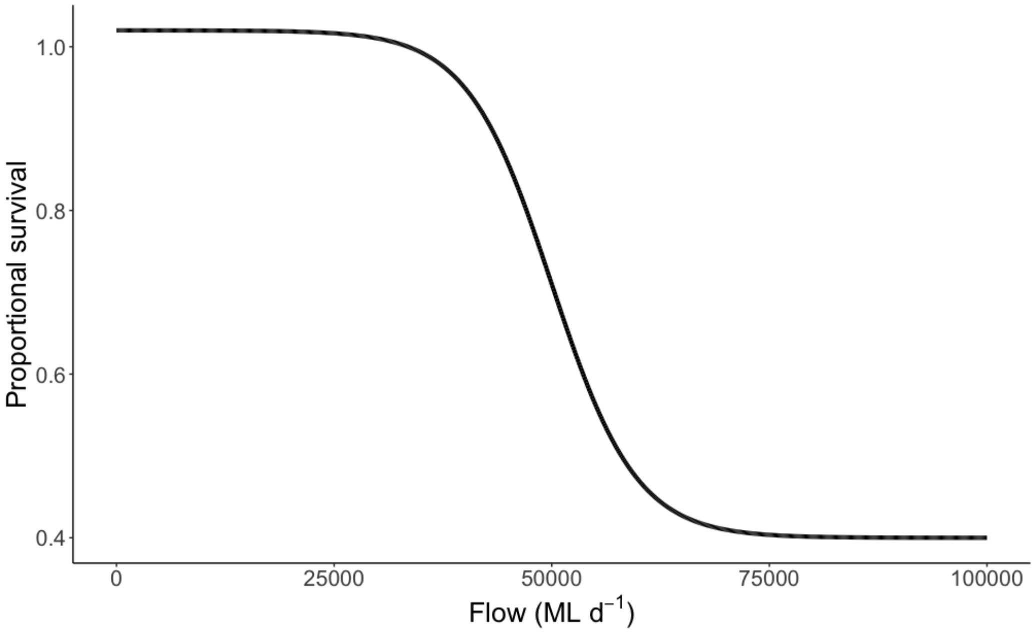

Figure S4. Proportional Murray cod survival as a function of flow in a year where hypoxic blackwater is predicted. Note that hypoxic blackwater events are triggered in the model when flows of ≥35 000 ML day^{-1} occur.

Golden perch model construct

The golden perch population models were also modified from a previously developed model for the MDB (NSW Department of Planning, Industry and Environment 2021) based on their ecology (Table 2; Koehn *et al.* 2020a). The golden perch model is similar to the Murray cod model but includes the flow-dependent movements of the life-stages of this highly mobile species (Koehn and Nicol 2016; Zampatti *et al*. 2018) and is constructed as a metapopulation that includes immigration and emigration between adjoining populations on the Gwydir River. Here, golden perch responses were modelled by two separate populations on the Gwydir River: population 1 which was bounded by Copeton Dam and Tareelaroi Weir (~240 km downstream), and a downstream population 2 on the Mehi River bounded by Tareelaroi Weir and the town of Collarenabri (~270 km downstream). Golden perch was modelled as a single population on the Severn River as the Severn River Falls (~83 km downstream) (i.e. the downstream population extent) acts as a natural barrier to upstream movement from the Macintyre River, such that a metapopulation model is unsuitable.

In the model, flow and temperature data regulate effects on the early life history survival (eggs and larvae) and movement (larval drift, fingerlings, and flow-cued movements of juvenile and adult golden perch) and productivity regulates larval and young-of-the-year (also referred to as fingerlings) survival. Hypoxic blackwater effects were not included for golden perch as this species is thought to be less susceptible to hypoxia (Thiem *et al*. 2017), with a suspected ability to move away from blackwater events. Golden perch model rules are detailed below.

Golden perch spawning

Spawning was triggered in each spawning season (August–February) for golden perch in this study when 2 consecutive days of ≥20 °C were observed. For the Gwydir and Mehi populations, and a flow increase of ≥200% over a 7-day period is also needed to initiate a spawning event. Spawning in the Severn River was triggered when flows are ≥100 ML day^{-1}. The proportion of individuals spawning for both rivers as a function of flow on a given day is given in Fig. S5.

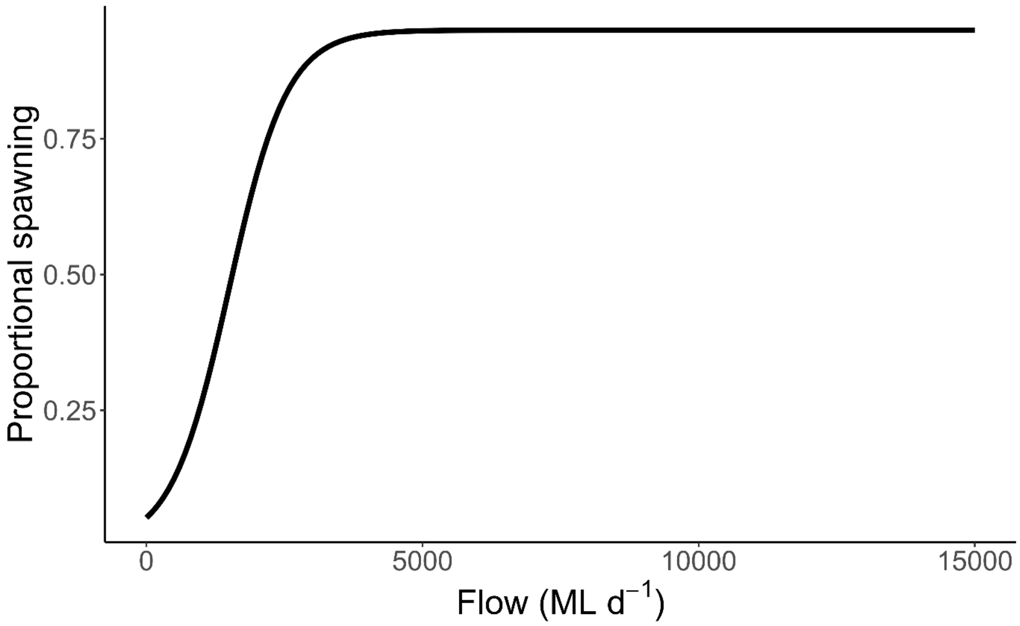

Figure S5. Proportion of golden perch females spawning on a given day as a function of increasing flow.

Survival of eggs and larvae as a function of temperature was calculated in the same way as for Murray cod, except the egg and larval periods were modified for golden perch.

Golden perch larval drift

Larval drift was estimated as a function of the flow of each day where larvae were present as defined by the specified spawning rules, and daily drift values were then summed across the spawning season of each year. Larval drift into the adjacent downstream reach for golden perch in both rivers was estimated as a function of daily flow which was tailored to the length and size of each river reach in this study (Fig. S6). Here, a daily drift value is calculated as a function of flow on a given day, where the drift value is multiplied by the number of larvae present (to give a proportional drift value) on that given day (as estimated by the spawning rules detailed above). This daily proportional drift value is summed over the spawning period of each model time-step (year) which gives the yearly proportion of larval drift out of each population. Note that larval drift is always downstream, and drifting individuals are added to the downstream population where appropriate, or ‘lost’ to the population model when no downstream population is modelled (i.e. the model assumes these individuals are lost and does not track their fate).

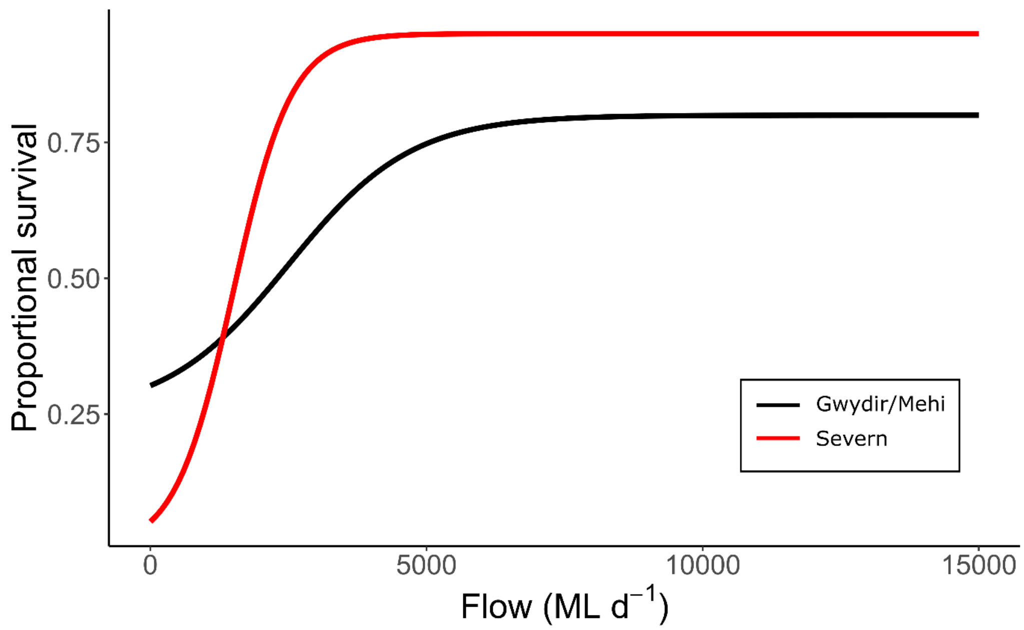

Figure S6. Larval drift for golden perch as a function of flow on a given day. These values are applied to the number of larvae spawned on a given day and summed over each spawning season. Note that all larvae spawned on a given day are assumed to drift to the downstream reach if flow is ≥15 000 ML day^{-1}.

Golden perch juvenile movement (Gwydir River model only)

Movement between upstream and downstream populations in the Gwydir River metapopulation model (Fig. S7) was estimated as a function of daily flow at the nearest gauge location to the relevant population border. Here, movement rates for juveniles and adults in each year were estimated as a function of the maximum daily flow within that year, which followed a sigmoidal relationship, where higher flows generated higher movement values (movement was estimated as a proportion of each population within that year: Fig. S7). The movement function was adapted from earlier versions of the model (Todd *et al.* 2022), where movement rates were modified to reflect the relatively small size of the population reaches. Note that the model assumes that movement occurs at the end of each time-step. A reset flow of 4 000 ML day^{-1} (based on 3300 ML day^{-1} overtop flow at the Tareelaroi Weir) is set, where flows above this value drive large movements, including:

- Movement from an upstream population to a downstream population (downstream movement) is included by the following rules;
- Movement is dictated by daily flows (Fig. S7) unless the reset flow value is reached, where movement is 50% of the population;
- Movement downstream population to Barwon River (individuals are lost);
- Movement is dictated by flows (Fig. S7) unless the reset flow value is reached, where movement is 10%;
- Movement downstream population to an upstream population (upstream movement);
- Only occurs on a reset flow due to the Tareelaroi Weir barrier, where movement is 40%.

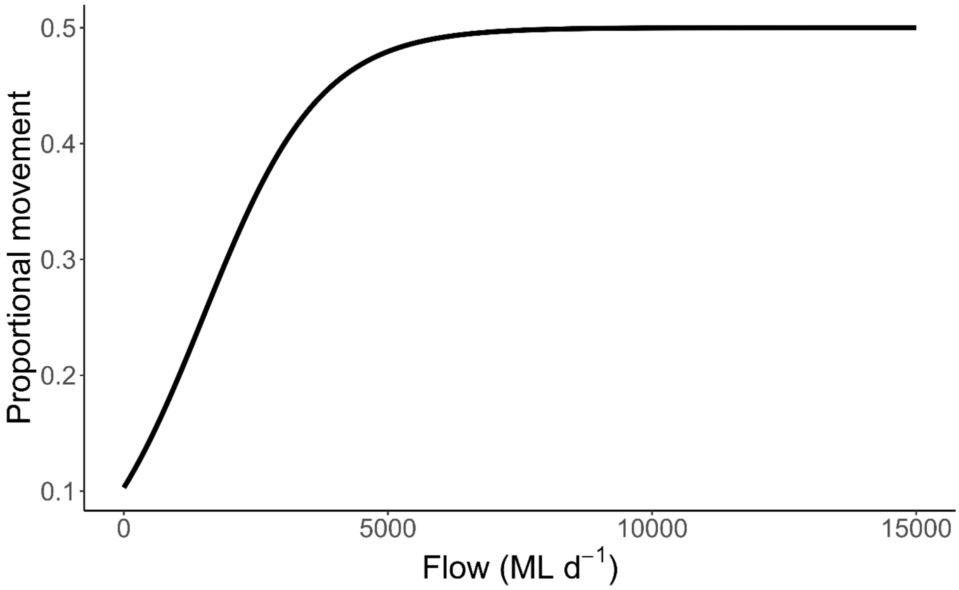

Figure S7. Golden perch juvenile yearly movement proportion as a function of the maximum daily flow (ML day^{-1}) within a year for golden perch in the Gwydir River.

Golden perch adult movement (Gwydir River model only)

Adult movement follows the same rules as juvenile movement (upstream and downstream), except that the rate of movement is slightly lower (Fig. S8). Note that a spawning run is also estimated for each year, which is 20% of adult movement.

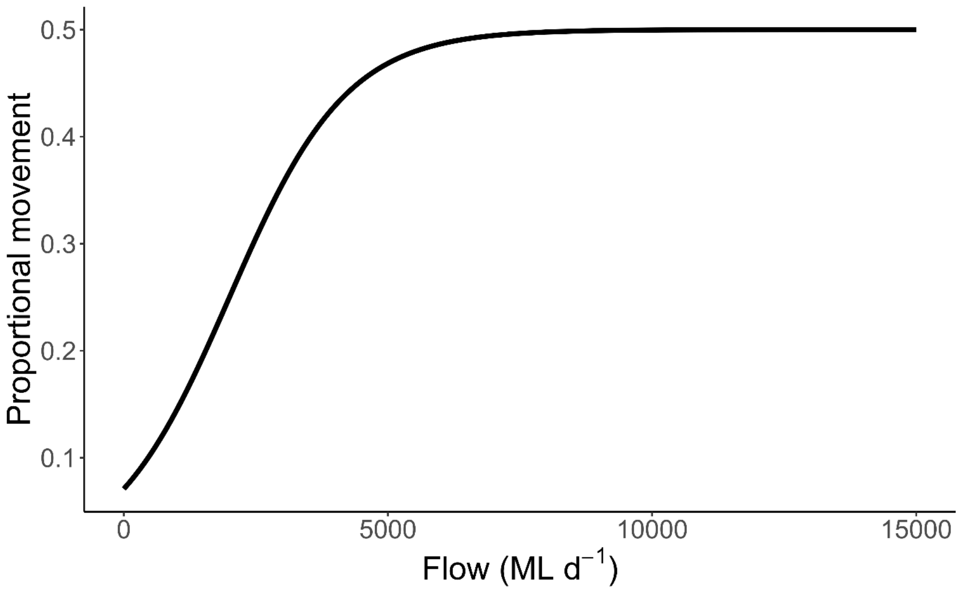

Figure S8. Adult yearly movement proportion as a function of the maximum daily flow (ML day^{-1}) within a year for golden perch in the Gwydir River.

Downstream movement and larval drift from population 2 into the unmodelled downstream reach (Barwon River) was also estimated by the same function of flow, where individuals that moved downstream were assumed to be 'lost' to the population model. The fate of these 'lost' individuals was not tracked further by the population model. Movement and larval drift out of the Severn River population were estimated in the same way as estimated for the downstream population in the Gwydir River model (i.e. individuals were 'lost' from the population in the model). All other life history variants were estimated in the same way as in the Gwydir River model.

Productivity construct

A riverine productivity value was also generated for each reach across all modelling in this study. The productivity value determines the survival rate of early life history stages in both the Murray cod and golden perch population models and is designed to incorporate variation in population responses by linking survival rates to river flows. A 'Z-score' was generated to estimate productivity in each year. A 'Z-value' was first calculated for each day across the dataset:

$$Z\ value = \frac{F - \bar{F}}{\sigma}$$

where F is daily flow, $\bar{F}$ is mean daily flow of the whole dataset and σ is the standard deviation of daily flow across the whole dataset. The average of the highest twenty Z-values in each year was taken as the productivity value (or Z-score) in each year. This Z-score represents the extent of the highest flows within each year relative to the long-term flow average. The Z-score was used to inform yearly variation around an average survival rate for young-of-the-year for both Murray cod and golden perch in this study.

References

NSW Department of Planning, Industry and Environment (2021) Fish for the Future: Native fish population modelling final report. NSW DPIE.

Koehn JD, Todd CR (2012) Balancing conservation and recreational fishery objectives for a threatened species, the Murray Cod, *Maccullochella peelii*. *Fisheries Management and Ecology* **19,** 410-425.

Koehn JD, Raymond SA, Stuart I, Todd CR, Balcombe SR, Zampatti BP, Bamford H, Ingram BA, Bice C, Burndred K, Butler G, Baumgartner L, Clunie P, Ellis I, Forbes J, Hutchison M, Koster W, Lintermans D, Lyon JP, Mallen-Cooper M, McLellan M, Pearce L, Ryall J, Sharpe C, Stoessel DJ, Thiem JD, Tonkin Z, Townsend A, Ye Q (2020) A compendium of ecological knowledge for restoration of freshwater fishes in Australia's Murray–Darling Basin. *Marine and Freshwater Research* **71,** 1391-1463.

Rowland SJ (1998*a*) Age and growth of the Australian freshwater fish Murray cod, *Maccullochella peelii peelii*. *Proceedings of the Linnean Society of New South Wales* **120**, 163–180.

Rowland SJ (1998*b*) Aspects of the reproductive biology of Murray cod *Maccullochella peelii peelii*. *Proceedings of the Linnean Society of New South Wales.* **120**, 147–162. doi:10.1080/18324460.1912.10439228

Ryan T, Lennie R., Lyon J., and O'Brien T. (2003) Thermal rehabilitation of the Southern Murray–Darling Basin. Final Report to Agriculture, Forestry, Fisheries Australia, MD 2001 FishRehab Program, Arthur Rylah Institute for Environmental Research, Department of Sustainability and Environment, Melbourne, Vic., Australia

Thiem JD, Wooden IJ, Baumgartner LJ, Butler GL, Forbes JP, Conallin J (2017) Recovery from a fish kill in a semi-arid Australian river: can stocking augment natural recruitment processes? *Austral Ecology* **42**, 218–226. doi:10.1111/aec.12424

Todd C, Koehn J (2007) Modelling management scenarios for Murray cod populations in the Mullaroo Creek. Report for the Mallee Catchment Management Authority, Victoria. Arthur Rylah Institute for Environmental Research, Melbourne, Vic., Australia.

Todd CR, Ryan T, Nicol SJ, Bearlin AR (2005) The impact of cold water releases on the critical period of post-spawning survival and its implications for Murray cod (*Maccullochella peelii peelii*): a case study of the Mitta Mitta River, southeastern Australia. *River Research and Applications* **21**, 1035–1052. doi:10.1002/rra.873

Todd C, Wootton H, Koehn J, Stuart I, Hale R, Fanson B, Sharpe C, Thiem J (2022) Population modelling of native fish outcomes for the Reconnecting River Country Program: Golden Perch and Murray Cod. Final report for the NSW Department of Planning and Environment, Reconnecting River Country Program. Arthur Rylah Institute for Environmental Research, Technical Report Series No. 341. Department of Environment, Land, Water and Planning, Melbourne, Vic., Australia.

Zampatti BP, Strawbridge A, Thiem J, Tonkin Z, Mass R, Woodhead J, Fredberg J (2018) Golden perch (*Macquaria ambigua*) and silver perch (*Bidyanus bidyanus*) age demographics, natal origin and migration history in the River Murray, Australia. SARDI Publication No. F2018/000116-1, SARDI Research Report Series number 993. South Australian Research and Development Institute (Aquatic Sciences), Adelaide, SA, Australia.