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# Limitations to the feasibility of using hypolimnetic releases to create refuges for riverine species in response to stream warming

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ABSTRACT

Given predicted increases associated with human-induced climate change, stream temperatures are likely to approach upper tolerance limits of aquatic biota within the coming decades. Little information is available regarding thermal tolerance limits of lotic fauna or mechanisms allowing fauna to persist following high temperature events (e.g. use of thermal refuges). Cold-water refuges can facilitate survival of fish in the Northern Hemisphere, but little evidence of similar refuges exists elsewhere.

Planned releases of hypolimnetic, or a mixture of top and bottom, waters from reservoirs have recently been touted as a novel method to potentially ameliorate extreme temperature events. However, the feasibility of this technique has not been fully discussed in the published literature. Therefore, we present a literature review, an analysis of thermal data for some large dams in southern Australia in relation to known thermal tolerances of native fauna, and an assessment of current management practices regarding the technique. We show that hypolimnetic releases have variable impacts on water temperatures downstream of a dam, depending on size, off-take infrastructure and management practices but, even where there is an effect, knowledge gaps are too numerous for this technique to be currently feasible. Furthermore, hypolimnetic releases generally evoke negative connotations among natural resource managers, due to the occurrence of cold-water shock in some species. If knowledge gaps and limitations can be addressed, it is possible that the technique may be considered in future, so we present potential tools for future assessment, capacities and limitations and discuss potential scenarios where environmental managers might consider this technique.



## 1. Introduction

It is widely acknowledged that reduced flows and increasing stream temperatures associated with human-induced climate change pose two of the greatest threats to the ecology and maintenance of biodiversity in lotic ecosystems (e.g. Caissie, 2006; Webb et al., 2008; Chessman, 2009). Integral to ecological function in such systems, temperature has both direct and indirect effects on many aspects of stream ecology (Caissie, 2006; Webb et al., 2008; Olden and Naiman, 2010), affecting the reproductive cues and behaviour of fish and invertebrates, as well as egg, larval and juvenile development (Vannote and Sweeney, 1980; Ward and Stanford, 1982; Preece and Jones, 2002; Todd et al., 2005). Accordingly, altered temperature can cause shifts in plant and animal distributions and assemblages (e.g. Ward and Stanford, 1982; Stewart et al., 2013). These effects are likely to occur globally, but particularly in Australia, where both sea-surface and air temperatures are increasing faster than the global average (Lough and Hobday, 2011).

Predicted increases in both the mean and variability of stream temperatures will place greater stress on lotic biota and test the resilience and resistance of many species. Information about thermal tolerances of lotic fauna is limited, but there is evidence that the limits of some sensitive stream taxa may have already been exceeded in south-western Australia (Davies, 2010). With climate change likely to exacerbate the situation, the availability and distribution of thermal refuges will be increasingly important for the persistence of sensitive taxa in coming decades.

Cold-water refuges can occur at locations where cool and warm waters mix, e.g. groundwater recharges, thermally-stratified pools or tributary inflows (Acuna and Tockner, 2009). These refuges can be important for the persistence of some cold-water fish species, particularly during summer (Olsen and Young, 2009). However, the distribution of thermal refuges is rarely mapped in aquatic

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ecosystems, particularly in the Southern Hemisphere. Also, it is not known whether eurythermal species, such as those native to Australia (Crook and Gillanders, 2013), are utilising thermal refuges to the same extent. Most thermal refuges appear to occur in very large river systems (e.g. stream width > 50 m, Tagliamento River, Acuna and Tockner, 2009), whereas many of the major rivers in semi-arid ecosystems are much smaller. Whether similar refuges exist in such systems remains largely unknown and future investigations are warranted.

With the challenges of climate change, the conservation of stream biodiversity may require innovative human interventions to ameliorate increasing stream temperatures. These novel interventions may involve the manipulation of pre-existing infrastructure, such as man-made water storages, that could be used to create a range of aquatic refuges (Chester and Robson, 2013). The negative ecological impacts associated with large impoundments are well established and include altered flow regimes, cold-water shock (also termed 'cold-water pollution'), and barriers to movement, particularly for migratory fish (see Supplementary Material, Table A1, Branco et al., 2014). However, the potential benefits that such infrastructure may also provide (e.g. greater permance of surface water for fauna to utilise during drought) are rarely considered (e.g. Chester and Robson, 2013). Although some storages are being decommissioned (Branco et al., 2014), this form of infrastructure is likely to remain in the foreseeable future, given that reservoirs provide critical resources for many industries (e.g. electricity, potable water, irrigation). Therefore, attempts to better utilise existing man-made infrastructure to enhance biodiversity, where possible, deserve consideration.

Other than measures designed to avoid cold-water shock, temperature is rarely considered in the planning and implementation of environmental flows (Lake et al., 2007; Olden and Naiman, 2010). Recently, carefully-planned releases mixing top and bottom waters ("shandying") at pre-determined temperatures have been touted as a novel method for ameliorating increased in-stream temperatures (Brown, 2004; Horne et al., 2004; Krause et al., 2005; Null et al., 2013). This type of release is thought to be particularly important during summer, when upper thermal tolerances are most likely to be exceeded, and when releases may benefit sensitive biota and ecosystem functioning as a whole. Few published studies have discussed the feasibility of this technique and it is uncertain whether it is a realistic option for environmental managers.

Holistic studies of the benefit of hypolimnetic releases for freshwater ecosystems are rare. Null et al. (2013) generated comprehensive models of in-stream temperature downstream of dams on the west coast of the USA in relation to different climate-change projections, aiming to preserve cold-water habitat for salmonids. They found that hypolimnetic releases were capable of reducing in-stream temperatures downstream of dams, depending on the scenario, but the models were not assessed against biotic thermal tolerances. A few investigations used thermal regime models to predict how flow management strategies might influence salmonid fisheries (Brown, 2004; Horne et al., 2004; Krause et al., 2005). Two suggested that conditions for trout might be improved without expensive dam retro-fitting, using examples of modelled hypolimnetic release regimes to manipulate in-stream temperatures. While similar cold-water fish species are not endemic in many Mediterranean-climate regions, hypolimnetic releases could be used to sustain other sensitive taxa, such as invertebrates. Introduced salmonid fisheries may benefit from such releases, but we do not advocate altering thermal regimes to suit introduced cold-water species, especially at the expense of native eurythermal species.

This paper uses several approaches to evaluate the feasibility of using hypolimnetic releases to ameliorate elevated stream temperatures. Firstly, it is widely recognised that the annual thermal regime in streams can influence important life-cycle stages for a range of biota (Olden and Naiman, 2010). We have overlayed life-history information for two Australian native fish, Murray cod (*Maccullochella peelii peelii*) and river blackfish (*Gadopsis marmoratus*), with annual thermal regimes from both regulated and unregulated rivers where they occur. These visual representations (*sensu* Olden and Naiman, 2010) provide an example of a potentially useful tool for guiding environmental management.

Secondly, it is likely that the upper thermal tolerances of sensitive invertebrate taxa are being exceeded in parts of southern Australia (Davies, 2010). While similar tolerance data are not often available, such thresholds may be relevant in other Mediterranean climatic zones. Therefore, we compared a series of metrics for stream temperatures from regulated and unregulated rivers to determine the likely frequency of high stream temperature events that exceed published thresholds.

Finally, we examined whether hypolimnetic releases are being incorporated into existing management plans in southern Australia and whether targeted releases could be realistic to ameliorate high temperatures. We discuss knowledge gaps that should be addressed before managers might consider carefully-planned hypolimnetic releases under a range of possible future scenarios. We also provide recommendations regarding the monitoring that should accompany any such future trials.

Therefore, the main study aims are to: (1) provide an overlay of thermal regimes and life-history information for fish as examples that could be used to guide environmental managers; (2) present thermal regimes above and below large reservoirs compared with unregulated systems; and (3) discuss potential benefits of controlled hypolimnetic releases and possible scenarios where this technique might be feasible in the future, together with relevant limitations and knowledge gaps. While much of this paper uses examples of Australian conditions, many of the limitations and knowledge gaps are likely relevant to rivers and reservoirs worldwide where thermal tolerances are poorly understood and stream temperature data are sparse.

## 2. Methods

### 2.1. Overlaying stream temperature with thermal tolerance ranges of fish

Stream thermal regimes can be plotted using a series of metrics similar to flow metrics (Olden and Naiman, 2010; Null et al., 2013). These metrics can then be related to ecological communities (e.g. individual species or functional groups) by overlaying corresponding life-history stages (Olden and Naiman, 2010). For Australia, some data exist regarding thermal tolerances for a range of species (Supplementary Material, Table A2) and the ecologically-relevant metrics are likely to vary among taxa. For this example, we selected three that were likely to be ecologically-relevant, including temperature preference, optimal growth range and breeding season range. Temperature preference represents the temperature at which fish spent the most time when provided with a gradient. Optimal growth range represents the temperatures that led to highest growth rates, and breeding season range indicates the time interval when eggs are observed in natural environment (typically compiled from multiple studies) and the onset of upstream migration prior to spawning, which appear to correspond with temperature ranges which correlate with greatest hatching success and larval survivorship in the laboratory (Koehn et al., 2009).

We provide two examples of the approach for Murray cod (*M. peelii peelii*) and river blackfish (*G. marmoratus*), two large