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Review of cold water pollution in the Murray–Darling Basin and the impacts on fish communities

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Allan Lugg *is Senior Fisheries Conservation Manager, Fisheries NSW (4 Woollamia Road, Huskisson, NSW 2540, Australia; Tel: +62 2 4428 3401; Email: Allan.Lugg@dpi.nsw.gov.au).* ***Craig Copeland*** *Manager Conservation Action Unit, Fisheries NSW (1243 Bruxner Highway, Wollongbar, NSW 2477, Australia; Tel: +61 2 6626 1353; Email: Craig.Copeland@dpi.nsw.gov.au). This paper arose from the realisation that relatively few people appreciated the significance of Cold Water Pollution in the Murray Darling Basin and its likely role in the decline of native fish communities.*

Summary The release of water from deep below the surface of large dams causes significant disturbance to water temperature regimes in downstream river channels with consequent impacts upon aquatic biota and river health. The Murray–Darling Basin (MDB) has a large number of dams, which are known to cause cold water pollution (CWP) in the downstream reaches of the impounded rivers. This study reviews the situation with regard to CWP in the MDB including the location, magnitude and extent of temperature suppression, the impacts upon fish, constraints and progress towards ameliorating the problem.

Key words: *cold water pollution, dams, impoundments, Murray–Darling Basin, thermal pollution, water temperature.*

Background

The Murray–Darling Basin (MDB) in south-eastern Australia contains hundreds of impoundments including 103 that are classified as 'large dams' (ANCOLD 2012). The fact that water stored within large dams stratifies into discrete temperature layers throughout the warmer months of the year with warm water near the surface (the epilimnion) and substantially cooler waters near the bottom (the hypolimnion) has been known for a long time (e.g. Neel 1963). Release of hypolimnetic water affects the thermal regime of rivers in a variety of ways including suppressed summer temperatures, increased winter temperatures, reduced annual amplitude, reduced diel variation and delayed seasonal peaks (e.g. Acaba *et al.* 2000; Ryan *et al.* 2001). During the warmer months, water withdrawn from near the base of the dam and released downstream is generally much colder than the natural temperatures that prevailed in the river prior to dam construction and this effect has been termed both cold water pollution (CWP) and thermal pollution.

The importance of water temperature for fish breeding and the potential for CWP to affect aquatic organisms and river health in the MDB has been recognised for at least 45 years. For example, Lake (1967) attributed the absence of Freshwater Catfish from parts of the Murray and Murrumbidgee Rivers to releases of cold water from Hume and Burrinjuck Dams, respectively. In 1987, the Murray–Darling Basin Ministerial Council (MDBMC 1987) recognised that the problem existed more generally in MDB rivers including the Upper Murray, Kiewa, Goulburn, Murrumbidgee, Lachlan, Macquarie, Gwydir and Border Rivers. Subsequently, the issue attracted increased attention from fisheries biologists and river ecologists in the late 1990s (Harris 1997; Lugg 1999; Acaba *et al.* 2000; Rish *et al.* 2000).

While the adverse consequences of CWP for river health were widely recognised, little was done to rectify the problem. Several dams constructed or enlarged in the 1980s and early 1990s (e.g. Windamere, Pindari) included multi-level outlet structures, and destratification had been trialled at several others (e.g. Windamere, Carcoar, Chaffey) (Rish *et al.* 2000) but most dams were constructed before the problem was widely recognised or accepted. The lack of action to address the problem more generally was possibly influenced by overseas experience, which suggested that CWP was relatively insignificant in terms of downstream extent. For example, Ward (1974) had noted that the Chessman Dam on the North Platte River (USA) affected stream temperature for just 8.5 km. The belief that released waters warmed to ambient temperatures within relatively short distances of the dam wall prevailed until the mid 1990s. For example, MDBMC (1987) suggested distances of less than 100 km as representative of the extent of CWP downstream of four major dams in the MDB.

Even at those dams where selective withdrawal infrastructure was present, issues related to inadequate capacity of high level outlets, the depth of water relative to the position of openings, the need to avoid entrainment of blue-green algae in surface waters, lack of clear operating protocols and physical challenges associated with changing the position of baulks and trash racks has meant that CWP issues still exist downstream of these dams (e.g. Acaba *et al.* 2000; Rish *et al.* 2000).

The general view that released water returned to ambient temperatures within a short distance of the dam wall was questioned by Harris (1997) who compiled a longitudinal profile of the Macquarie River indicating that water temperature 300 km downstream of Burrendong Dam was still about 3°C cooler than the observed surface temperature of the impounded waters and was nearly 5°C lower than the predicted temperature for that site.

The other main factor that has contributed to the lack of action was the perceived high cost of rectification. For example, Department of Public Works and Services (1996) estimated the 'ball park' costs for retrofitting multilevel outlets on 6 NSW dams at $5–$30M each. In response, Sherman (2000) reviewed alternative approaches that could be more cost effective. He suggested that 'draft tube mixers' (electrically driven impellors forcing surface water towards the bottom outlets) and submerged fabric curtains surrounding the outlet tower held the most promise for large impoundments.

In 2001, the Inland Rivers Network and the World Wide Fund for Nature collaborated to convene a workshop on CWP (Phillips 2001). Concerns about costs persisted. For example, Jeffery (2001) reported on destratification trials at Dartmouth Dam and noted that 'destratification may be possible but will be extremely expensive' and that modifying the existing outlet tower to provide a multilevel offtake capability would cost $15–20 million.

Between 1997 and 2009, the MDB suffered a period of extreme drought ('The Millennium Drought') and the impetus to act on CWP generated by the 2001 workshop waned. The drought was the most extreme in living memory, and CWP was ameliorated to a substantial extent due to extended periods of low to very low water levels in most impoundments. As a result, there was little priority given to addressing the issue either at individual dams or at a basin scale. Since, the breaking of the drought, storage levels have increased substantially and CWP is again likely to be a significant driver of river health in the MDB.

Review of Water Temperature Impacts on Biological Processes of Aquatic Organisms

'Hands on' experience with hatchery production of native fish species for restocking waterways for recreational angling and aquaculture has highlighted the importance of temperature as a cue for spawning and larval development (e.g. Llewellyn 1971; Rowland 1992). But temperature has a substantial effect on a wider range of physiological and biological processes of aquatic organisms (ANZECC 2000), and it is likely that fish and other aquatic organisms in CWP-affected rivers are affected in a wide variety of ways.

Gehrke (1988a,b) and Gehrke and Fielder (1988) demonstrated pronounced decreases in heart rate, ventilation rate and metabolic rate occurred in Spangled Perch (native to the MDB) as the temperature was reduced over a 5°C range (from 20°C to 15°C). This species ceased to feed at temperatures below 16°C, and between 13°C and 14°C, the amount of energy required for metabolism exceeded dietary energy intake, and the fish relied heavily on fat reserves to survive.

Both Koehn and O'Connor (1990) and Ryan *et al.* (2003) provide comprehensive data for the relationship between egg hatching times and temperature for a wide range of MDB species. Todd *et al.* (2005) reported that Murray Cod eggs suffer close to 100% mortality at temperatures below 13°C and close to 100% survival at temperatures just 3°C higher.

In relation to growth Ryan *et al.* (2002, 2003) found that Freshwater Catfish held at 28°C grew at three times the rate as those held at 12°C while juvenile Murray Cod held at 15.5°C and lower temperatures had significantly restricted growth and failed to grow following the reintroduction of warmer water. Growth rates for both Murray Cod and Freshwater Catfish were significantly greater at temperatures above 18.5°C and 22.5°C, respectively. Fish held at temperatures less than 15.5°C demonstrated minimal growth over a 3-month trial and fish held at 12.5°C lost body weight.

Both Ryan *et al.* (2003) and Astles *et al.* (2003) conducted temperature preference trials on Golden Perch and Murray Cod. When presented with a thermal gradient, both species selected the warmer water with a median range of 24–31°C and 24–33°C, respectively.

While much of the experimental work on water temperature has demonstrated chronic impacts upon fish, the work conducted by Astles *et al.* (2003) at Burrendong Dam (Macquarie River) demonstrated that CWP can have an acute impact upon juvenile fish in a relatively short period of time. They introduced fish to warm (23–28°C) and cool (13–16°C) channels representative of the natural and the suppressed summer temperatures in the river. Juvenile Silver Perch started dying within 2 days of being exposed to cold water and more than 30% died within 10 days. Over the full 30-day experiment, Silver Perch in the cool channels suffered significantly greater mortality in contrast to those in the warm channels.

Given the potential for direct mortality and the demonstrated impacts upon a wide range of biological processes, it is not surprising that species of native warm-water fish have become extinct in CWP-affected rivers. Koehn *et al.* (1997), documented the loss of three species of native fish (Trout Cod, Murray Cod and Macquarie Perch) and their replacement by the introduced fish, Brown Trout from the Mitta Mitta River downstream of Dartmouth Dam after it had been operating for 12 years. Subsequently, Ryan *et al.* (2002) and Todd *et al.* (2005) modelled the response of the Murray Cod population in the Mitta Mitta River and concluded that the impact of CWP on postspawning survival was the main factor explaining the loss of the population, due to the loss of successive recruitment events having a compounding effect over time. An increase of 8°C was required to reduce the risk posed by CWP to be indistinguishable from the natural unaffected condition.

Fish spawning is recognised to be both thermally and temporally limited with defined seasonal spawning periods as well as minimum temperature thresholds (e.g. McDowall 1996, Lintermans 2007). Lugg (1999) developed 'spawning envelopes' defined by the beginning and end of the spawning season and the minimum spawning temperature thresholds to highlight the disconnect between spawning preferences of native fish and water temperatures in the Murrumbidgee River at Gundagai, which is affected by cold water discharges from both Blowering and Burrinjuck Dams. Subsequently, Burton (2000, 2001a,b) and Preece and Jones (2002) conducted similar analyses for the Lachlan, Macquarie, Cudgegong and Namoi Rivers and showed that four native fish species had multiple spawning opportunities upstream of the dams but no or substantially reduced opportunities immediately downstream of the dams.

Research into the nature of the impacts of temperature upon fish has continued to provide new insights. Lyon *et al.* (2007) showed that the 'fast start' swimming performance of Golden Perch was considerably reduced at temperatures less than 15.5°C, which was likely to affect both prey capture and predator avoidance capabilities. Whiterod (2013) has also shown an exponential relationship between temperature and the swimming ability of Murray Cod. Rutherford *et al.* (2009) provide a comprehensive compilation of thermal response of upland MDB fish and invertebrate species in relation to Bendora Reservoir on the Cotter River.

Locations Exhibiting CWP in the MDB

Various reports have highlighted the existence of altered thermal regimes in MDB rivers although many are anecdotal and/or speculative rather than proven (e.g. MDBMC 1987; Lugg 1999; Whittington & Hillman 1999 and Harris 2001). In response, Ryan *et al.* (2001) completed a desk top assessment of dams in Victoria identifying 24 dams in the Victorian section of the MDB causing CWP. Preece (2004) undertook a similar assessment of 93 NSW dams identifying nine MDB dams with 'large and pervasive' CWP impacts and a further two in the moderate category and four in the minor category. Both authors recognised that height of the dam (as a proxy for water depth) was an important determinant of temperature stratification but other significant factors such as the position of the outlets and size of the outlet also determined the magnitude and significance of the CWP release to the downstream river channel.

There appears to be no similar assessment of potential for CWP in South Australia, the ACT or Queensland. South Australia has no large dams (in the MDB) so significant CWP is unlikely. There are four major dams in the ACT (Cotter, Bendora, Scrivener and Corin) and four major dams in Queensland MDB rivers (Glenlyon, Beardmore, Coolmunda and Leslie) where CWP is possible (ANCOLD 2012). The potential for CWP impacts below Bendora Dam in the ACT has been comprehensively studied by Rutherford *et al.* (2009).

Temperature Variation Within MDB Dams

A prerequisite for CWP is the establishment of a substantial temperature difference between surface and deeper waters. Analysis of the temperature profiles for 11 priority impoundments in the NSW MDB (summarised in Appendix I) indicates that all 11 dams consistently develop substantial temperature differences between surface and bottom waters in the spring, summer and autumn. The maximum temperature difference from surface to bottom was within the range of 11.1–16.7°C for 10 of the dams highlighting the potential magnitude of the impact upon the river. Only Keepit Dam was outside this range with a maximum difference of 8.8°C reflecting its relative shallowness in comparison with the others. Extreme differences typically occurred during the months of December, January and February.

Examination of plots of the temperature profile data indicates that even when there is a marked temperature difference between the surface and the bottom, an abrupt thermocline is not always present. In some instances, the change in temperature takes place relatively slowly over a considerable depth (e.g. see Fig. 1).

Magnitude of Temperature Suppression in Rivers Downstream of Dams

Estimates of the magnitude of the temperature suppression effect for various rivers have been obtained by several authors

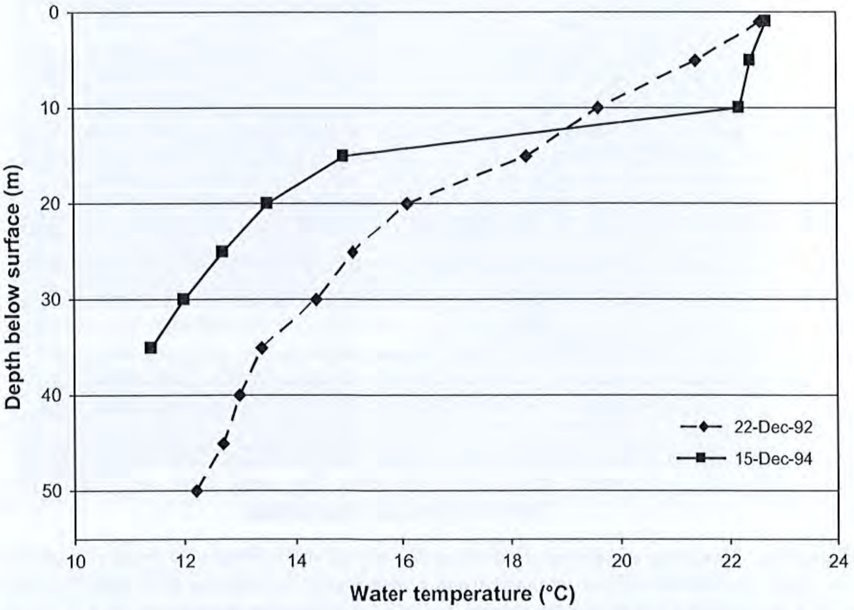

Figure 1. Comparison of two temperature profiles from Burrinjuck Dam (Murrumbidgee River) indicating a distinct thermocline (15 December 1994) and a more progressive change in temperature with depth (22 December 1992). Drawn from data supplied by NSW Office of Water.

(16 locations are identified in Appendix S1). The upper limit of these estimates is 16°C (on the Tumut River downstream of Blowering Dam) but it is more usually up to 12°C. Sinclair Knight Merz (2005) noted that low storage levels due to drought accounted for the lack of apparent CWP impacts downstream of Victorian dams where discharges were monitored during 2002–2004.

It is clear that the magnitude of temperature suppression varies between and within years and even on a day to day basis. Estimates of temperature suppression also vary according to the baseline used for comparison and the way that the data are analysed. Comparisons made at a 'single-point-in-time' can produce estimates that are much larger than comparisons made from monthly averages. This is especially the case if 'single-point-in-time' estimates are targeted at periods when the impacts are likely to be peaking. For example, data collected by one of the authors and used to produce longitudinal profiles of the Lachlan River indicate temperature suppression by Wyangala Dam in the range of 12–14°C immediately downstream of the dam (Fig. 2). Both profiles are likely to represent close to the 'worst case scenario' since the data were collected when four factors coincided – (i) the impoundment was nearly full, (ii) the water column was strongly thermally stratified (mid-summer), (iii) low level outlets were being used and (iv) large discharges were being released. By contrast, Burton (2000) estimated the impact of Wyangala Dam on the Lachlan river to be 'up to 7°C' on the basis of monthly averages.

Such estimates of 'single-point-in-time' or instantaneous impact are likely to be more biologically relevant because the biota has to respond to, and cope with the extreme conditions as they occur on a daily basis.

Seasonal Displacement Aspects

Relatively few studies have examined how CWP might offset normal river temperature rises from the natural seasonal signature. Preece and Jones (2002) stated that, for the Namoi River, the maximum annual temperature immediately downstream of Keepit Dam occurred in February, several weeks later than that expected to occur naturally. At Gunnedah (46 km downstream), the peak was less than one week later (4 days later on average). Burton (2000) could find no evidence for a seasonal lag in the Lachlan River, although the graphs presented seem to indicate that the peak occurs in January for the site upstream of the dam, whereas it occurs in February/March for the sites downstream of the dam. In work carried out in the Murray River, Ryan *et al.* (2001) state that Hume Dam causes a delay in peak temperatures in the Murray River from January to March while Eildon Dam delays the peak on the Goulburn River from January/February to March.

Analysis of data from the Tumut River downstream of Blowering Dam for the years 1992–1999 indicates that the temperature in nearby unregulated tributaries peaked in January, but the peak temperature of dam releases did not occur until late March to mid-April, indicating a very substantial delay of 9–13 weeks. Rising water temperature coinciding with increasing day length is believed to be an important breeding cue for many fish (e.g. McDowall 1996). In the unregulated tributaries of the Tumut River, temperatures rose at a rate around 2.6°C per month commencing in early July, whereas in the Tumut River, there was no comparable rise until early December.

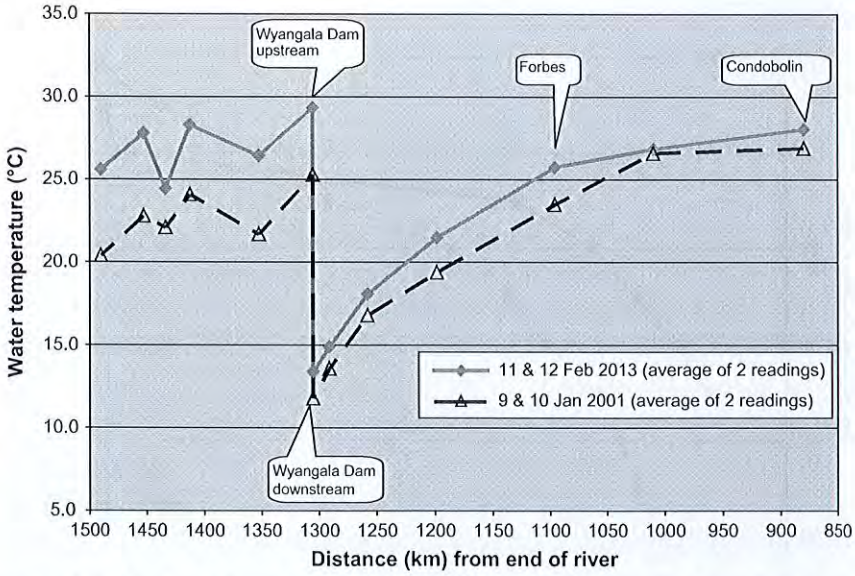

Figure 2. Longitudinal water temperature profiles of the Lachlan River on 9 January to 10 January 2001 (dashed line with open triangles) and 11 February to 12 February 2013 (solid line with closed diamonds) indicating both the magnitude and extent of the temperature suppression downstream of Wyangala Dam under close to 'worst case' conditions (mid-summer, high dam levels, low level outlets being used, large discharges being made). Drawn from data collected by Allan Lugg. River distances calculated from Google Earth.

Geographical Extent of Temperature Suppression

As previously mentioned, a general belief that CWP was relatively insignificant in terms of downstream extent prevailed until the mid-1990s, and this general view was questioned by Harris (1997) who compiled a longitudinal profile of the Macquarie River downstream of Burrendong Dam. Subsequently, Whittington and Hillman (1999) produced a small-scale map of the MDB indicating 16 river reaches where CWP was evident. The distances shown range up to about 300 km. Similarly, Lugg (1999) extrapolated the Harris' result to 11 sites in the MDB suggesting around 2700 km of river in the NSW MDB was affected.

These studies catalysed more detailed investigations. Acaba *et al.* (2000)

reviewed data for the Macquarie River and Burrendong Dam and concluded that temperature suppression persisted downstream for between 150 and 250 km. Similarly, Burton (2000) examined 11 months of data from the Lachlan River and concluded that temperature recovered to be within 1–2°C of natural within 170 km of Wyangala Dam. Burton (2001a) subsequently deployed new temperature sensors in the Macquarie River and concluded that it recovered to within 1–2°C of natural within 100–150 km of Burrendong Dam (however, the graphs presented indicate that during February 1999, temperatures downstream of the dam were lower than those upstream of the dam for nearly 300 km). Buchan and Keenan (undated) examined the Murrumbidgee/Tumut system and concluded that the combined impact of the releases from Burrinjuck Dam (on the Murrumbidgee River) and Blowering Dam (on the Tumut River) extended 300 km downstream of the confluence of the two rivers (affecting a combined total of 440 km of river).

As for estimates of the magnitude of CWP, estimates of the geographical extent of CWP are likely to vary depending on the timing of data collection and the method of analysis. The longitudinal profiles of the Lachlan River (Fig. 2) indicate that the extent of CWP can be in the order of 250–350 km under worst case scenario conditions.

Management of CWP in the MDB

Management of CWP in the MDB remains the responsibility of the states although the new MDB Plan recognises 'water temperature outside the natural range' as a type of water quality degradation and further recognises that 'release of stored water from below the thermocline of dams' is a 'key cause of water quality degradation' (Australian Government 2013). The Plan sets target values for water temperature being the monthly median between 20th percentile and 80th percentile of natural monthly water temperature for all catchments.

In New South Wales, the Government adopted a CWP Strategy in 2004. This is a 25-year strategy, which aims to progressively mitigate CWP in 5-year stages. The strategy involves changes to dam licensing arrangements (to promote investigation of remediation options), improved dam management arrangements where CWP infrastructure is already in place and a cooperative approach to investigating and undertaking works at high-priority dams (Department of Primary Industries Office of Water 2013).

As part of Stage 1 of the strategy, an interagency group was formed to promote collaboration between biologists, water managers and dam owner/operators in mitigating CWP in NSW. Works Approvals issued under the *Water Management Act 2000* now require options for the mitigation of CWP to be investigated and undertaken where possible (NSW Office of Water 2012). The group developed *Guidelines for Managing Cold Water Releases from High-Priority Dams* (NSW Office of Water 2011) to assist dam owner/operators when undertaking investigations, designing new or upgraded infrastructure and assessing performance.

Five NSW MDB dams (Googong, Chaffey, Pindari, Split Rock and Windamere) have existing variable or multilevel outlets that command most of the water column and have a theoretical capacity to effectively mitigate CWP. In the past, most of these have not been actively managed to mitigate CWP due to a variety of constraining factors including lack of documented operating protocols and clear temperature objectives and targets, infrastructure limitations resulting in difficult and laborious changing of the withdrawal level and conflict with requirements to minimise the risk of releasing toxic blue-green algae to the downstream river channel. Operating protocols for these dams have now been developed and requirements to operate the infrastructure to achieve temperature outcomes have been included in works approvals (NSW Cold Water Pollution Inter Agency Group 2012). However, operation of these outlets in accordance with these protocols is still in its infancy.

In discussing the operation of the multilevel offtake on Windamere Dam, Burton (2001b) highlighted the constraints imposed by the presence of blue-green algae in the impounded waters. Blue-green algae remain a serious constraint in managing CWP. In NSW, algal management protocols require that water be withdrawn from levels greater than 10 m below the surface when blue-green algae blooms are present within the impounded waters (Martin Prendergast, pers. comm., 2013; Lorraine Hardwick, pers. comm., 2013). This is to minimise the risk of entraining potentially toxic algae and releasing it into rivers that are used to supply water to town, domestic and stock users.

Postconstruction or postenlargement modification of infrastructure has been completed at Tantangara Dam (upper Murrumbidgee River). However, this dam was not a major source of CWP as it only makes minimal discharges to the downstream river channel (although this may change in the future in response to increasing demand from Canberra).

The cost of dam modifications and new infrastructure is a continuing constraint. For example, works to install a louvre shutter system on Keepit Dam as part of the dam upgrade have been planned but not commenced due to financial restrictions (Martin Prendergast, pers. comm., 2013). For this reason, alternative low-cost options are being pursued. State Water Corporation (NSW) has initiated works to mitigate CWP at Burrendong Dam on the Macquarie River by the installation of a suspended geotextile curtain around the existing outlet tower (State Water 2013). The curtain will block the withdrawal of cold water from the deep outlets while drawing surface water downwards towards the outlets. AMOG Consulting (2010) has costed this option at around $2 million. However, the completed cost is more likely to be around $5 million (Martin Prendergast, pers. comm., 2013).

There are no current plans for remediation action to address CWP in the Victorian (J Koehn, pers. comm.) or Queensland (Charles Elway, pers. comm.) sections of the Basin.

Discussion

There is substantial evidence indicating that CWP is widespread within the MDB, occurring at many major dams and affecting most of the major rivers (see Appendix S1). The impact of cold water releases is greatest immediately downstream of the dam and diminishes with distance downstream. It seems clear that measurable impacts of CWP can extend for several hundred kilometres downstream of large dams particularly when four factors coincide: (i) the dam is full or near full, (ii) there is a large difference between surface and bottom water temperatures (which typically occurs during summer), (iii) low level outlets are in use and (iv) large discharges are being made to the downstream river channel. Peak temperature suppression in the range of 10–12°C appears to occur frequently at many sites. By contrast, temperature suppression when storage levels are low or very low such as occurs during periods of drought can be negligible (e.g. Sinclair Knight Merz 2005).

It is apparent that studies of the magnitude and geographical extent of CWP have produced results that are somewhat ambiguous. Longitudinal river temperature profiles generated from data gathered over the space of 1 or 2 days (e.g. Harris 1997; Fig. 2) has produced results indicating impacts extending for several hundred kilometres. By contrast, analysis of longer duration data sets has suggested that impacts are less extensive. The difference can be explained by the fact that the former approach is quantifying an instantaneous impact, whereas the latter approach is quantifying an average impact. Averaging may mask transient and short-lived events, which could have significant ramifications from a biological perspective. As previously discussed, Astles *et al.* (2003) demonstrated that juvenile Silver Perch started dying within two days of being exposed to cold water and more than 30% died within 10 days. Assessment and interpretation of CWP impacts on the basis of data averaged over a monthly or other arbitrary timestep is likely to mask extreme but short duration events and give a misleading impression as to the biological significance of CWP.

CWP has been shown to affect aquatic biota at numerous levels reducing their metabolic functioning, survival, growth and opportunity to spawn and recruit. Results of population modelling (e.g. Todd *et al.* 2005) suggest that CWP is a major contributing factor in the observed decline and local extinction of many native fish species in the MDB. CWP has been noted as a contributing factor in 10 nominations by the Fisheries Scientific Committee (in NSW) of threatened species and ecological communities (Fisheries Scientific Committee 2013).

Introduced fish species (e.g. European Carp, Redfin, trout) have lower breeding temperature thresholds than native species (e.g. McDowall 1996), and it appears likely that CWP has enabled these species to enjoy greater recruitment success and proliferate, placing additional pressure upon native species.

The most recent assessment of fish communities in the Murray–Darling Basin (MDBA 2012a) presents a bleak picture of river health generally and native fish communities more particularly. Of the 23 valleys assessed, only one (the Paroo) had a rating of 'good' for the Fish Condition Index. Twenty of the 23 were rated as 'poor', 'very poor' or 'extremely poor'. CWP is likely to be one of the main factors contributing to the poor condition of fish communities across the basin.

Progress in addressing CWP has been slow for a variety of reasons. The prolonged 'millennium drought', which began when initial concerns about CWP were being more widely acknowledged, resulted in dams being drawn down to low or very low levels for years at a time. This meant that the volume of hypolimnetic water at low temperature was much less than when the dams are full or near full, and the outlets were more frequently withdrawing from the surface layer, and CWP was substantially mitigated as a result. In addition, water managers were focussed on managing dwindling water supplies, while fisheries managers were focussed upon ensuring fish communities survived the immediate challenge of diminishing habitat availability and quality.

Withdrawing water from near the surface of impoundments rather than near the bottom has the potential to dramatically improve the temperature regime of downstream rivers. Figure 3 indicates the practical limits to the temperature regime in the Macquarie River downstream of Burrendong Dam during 2012–2013 as dictated by the temperature limits of the water stored within the dam. It highlights

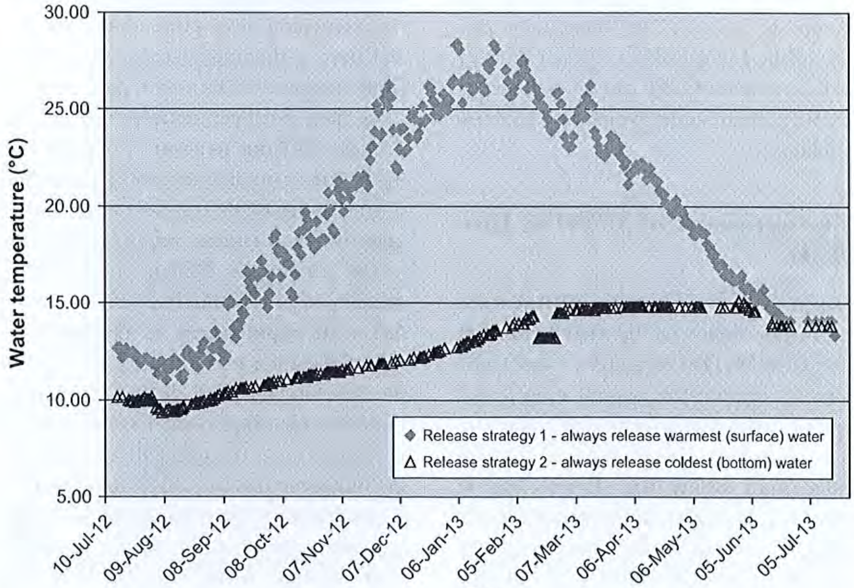

Figure 3. Representation of the limits to water temperature that could have been achieved in the Macquarie River downstream of Burrendong Dam during 2012–2013 under two contrasting release strategies. Assumes no limitations as to which part of the water column the water was drawn from or other constraints exist. Developed from in-dam thermistor chain data supplied by NSW State Water Corporation.

the improvements that could theoretically be achieved by adopting two different release strategies – 'always release the warmest surface water' versus 'always release the coldest bottom water'. At the height of summer, the released water could potentially be more than 10°C warmer than would be achieved by releasing the cold bottom water and a much more natural seasonal signature could be achieved. In reality, operational constraints and/or management objectives may mean that less dramatic improvements are achieved. Sherman (2003) investigated these issues in relation to Hume Dam and found that warm surface water was sufficiently abundant and surface layer residence time was sufficiently long to ensure an adequate supply of warm water for CWP mitigation. Of course, such improvements are dependent upon appropriate infrastructure being in place.

Sherman *et al.* (2007) modelled the potential improvements to temperature that could be achieved in the Murray River downstream of Hume Dam and concluded that the resulting 4–6°C increase during the critical spring-early summer spawning period would result in a 30–300% increase in the population abundance of female Murray Cod. Similarly, Todd *et al.* 2005 consider that a minimum 5–6°C is required in the Mitta Mitta River downstream of Dartmouth Dam to eliminate the threat to Murray Cod.

The substantial costs associated with ameliorating CWP at large dams remain a significant constraint with dam managers and Governments reluctant to commit to programmes where the costs of rectification are substantial. The effectiveness and operability of a suspended geotextile curtain at Burrendong Dam as an example of an innovative, low-cost solution should be of benefit in progressing action on CWP at other sites.

The ability to achieve CWP outcomes is also challenged by the presence of blue-green algae in many impoundments (Martin Prendergast, pers. comm., 2013). The risk associated with releasing toxic blue-green algae to downstream river channels that are used for town, domestic and stock watering is real. The risk varies from year to year and even week to week depending on the severity of the bloom, its proximity to the outlet works, the mix of species including the presence of potentially toxic species and even the nature of the downstream river channel. Achievement of CWP outcomes can be heavily constrained at times when potentially toxic algae are present within a storage.

Rolls *et al.* (2013) have recently highlighted the importance of integrating thermal regimes with flow regimes following a study of the responses of fish communities to environmental flows in the rivers of the northern MDB. Both Federal and State governments have invested heavily in water planning, water reallocation, water entitlement buyback and environmental flow management over the last 20 years in an attempt to restore environmental health to the MDB rivers and wetlands. Considerable efforts have been focussed on restoring flow regimes particularly large flows to restore wetland habitats. In contrast, there has been much less focus on river channel habitats. Paradoxically, the release of environmental water from large impoundments to restore floodplain wetlands may prove to be a hindrance to the recovery of native fish communities in river channels if CWP is not addressed and fish survival, growth, spawning and recruitment continues to be adversely impacted by unnaturally low water temperatures.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Summary of sites in the Murray Darling Basin where authors have indicated the existence of Cold Water Pollution (CWP) impacts.

Appendix I

Summary of key temperature characteristics for 11 large dams in the Murray Darling Basin catchments of NSW. Raw data supplied by NSW Office of Water and State Water Corporation. Analysis conducted by the authors.

Dam	Number of profiles examined	Period (month/year)	Temperature (°C) range of deep layer (observed minimum – observed maximum)	Temperature (°C) range of surface layer (observed minimum – observed maximum)	Maximum observed difference between surface and deep layer (°C)
Glenlyon	21	7/98–6/00	7.2 (12.3–19.50)	15.2 (14.8–30.0)	16.3
Pindari	24	7/97–5/99	2.9 (11.2–14.1)	14.0 (13.5–27.5)	14.2
Copeton	21	10/97–6/99	3.8 (10.1–13.9)	14.3 (12.6–26.9)	14.0
		07/12–07/13	1.1 (12.4–13.5)	16.0 (12.8–28.6)	
	367				15.6
Split Rock	24	7/97–5/99	1.8 (12.1–13.9)	13.2 (13.7–26.9)	14.0
Keepit	19	10/97–4/99	13.0 (11.0–24.0)	14.9 (11.7–26.6)	8.8
		07/12–07/13	21.4 (3.2–24.6)	19.0 (10.0–29.0)	
	368				11.1
Chaffey	49	7/97–6/99	4.1 (9.3–13.4)	16.5 (11.2–27.7)	14.8
Burrendong	17	11/98–11/99	2.8 (11.1–13.9)	13.1 (12.0–25.1)	13.6
		7/12–7/13	5.8 (9.3–15.1)	17.4 (11.0–28.4)	
	365				15.6
Windamere	98	11/97–11/99	9.5 (10.0–19.5)	17.9 (10.1–28.0)	15.9
Wyangala	30	2/96–5/97	10.3 (10.8–21.1)	15.2 (12.5–27.7)	16.1
		07/12–07/13	1.6 (10.0–11.6)	16.7 (10.9–27.6)	
	219				16.2
Burrinjuck	43	11/90–3/99	11.0 (8.1–19.1)	20.0 (9.9–29.9)	16.2
Blowering	44	2/92–4/99	5.5 (8.5–14.0)	15.9 (11.2–27.1)	16.7