SNOWY RIVER RECOVERY

SNOWY RIVER FLOW RESPONSE MONITORING
WATER QUALITY IN THE SNOWY RIVER BEFORE AND AFTER THE FIRST ENVIRONMENTAL FLOW REGIME

APRIL 2008

NSW Government
Department of Water & Energy

Publisher

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April 2008

ISBN 978 0 7347 5182 9

ISSN 1449 8022

Acknowledgements

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Data from the NSW sites were collected and recorded in the Department of Water and Energy (DWE) HYDSYS database by Paul Corbett and Adam Wiggins. Andrew Nolan of Snowy Hydro provided the data for the Thredbo River and Jindabyne Dam releases. Data for the Victorian sites were obtained from the Department of Sustainability and Environment and analysed with the permission of Stephen Salathiel. Drafts of this report were reviewed by Simon Williams, Andrew Brooks, Teresa Rose, Lee Bowling, and Dr. Tony Church (SKM).

This publication may be cited as:

Bevitt, R. and Jones, H. (2008) *Water quality in the Snowy River before and after the first environmental flow regime.* Snowy River Recovery: Snowy River Flow Response Monitoring. Department of Water and Energy, Sydney

DWE 08_045

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Summary

The Snowy Mountains Scheme (SMS) was completed in 1967 in the Australian alpine region of south eastern New South Wales to provide water for irrigation to the Murray and Murrumbidgee rivers and for power generation. Until 2002, the SMS captured and diverted 98% of the Snowy Rivers mean annual natural flow (MANF) from four dams and an aqueduct on the Mowamba River just below Jindabyne Dam. The SMS has affected all components of the flow regime in the Snowy River below Jindabyne Dam, with reduced baseflows, flow variability, spring snowmelt flows and floods. The hydrological impacts of the SMS lessen further downstream with increasing flows to the river from tributaries.

The Australian, NSW and Victorian governments agreed in October 2000 to release environmental water to the Snowy River, with up to 28% MANF planned to be released in stages over 10 years. These environmental water releases are dependant on water savings in the Murray-Darling Basin. The first environmental flow release (EFR) on 28 August 2002 increased flows in the Snowy River below Jindabyne Dam from 1.9% MANF to 3.4% MANF as measured at Dalgety. Median daily discharge in the Snowy River at Dalgety increased from 42 Mld^{-1} before EFR to 84 Mld^{-1} with the EFR. However, a prolonged drought in the period coincident with EFR meant that flows at all other Snowy River sites below Jindabyne Dam and several tributaries have actually decreased, by as much as 31% of pre-EFR flows. River discharge would presumably be even lower in the upper Snowy River during the drought without the EFR.

Since the construction of Jindabyne Dam, the reduced flows have resulted in a smaller and shallower water body, where water temperature may be more influenced by ambient air temperatures and salinity is likely to be more influenced by local conditions and catchment inputs. The water temperature and electrical conductivity of the Snowy River below Jindabyne Dam was compared before and after the EFR, to determine any response to the first three years of EFR.

Water temperature and electrical conductivity were measured by continuous probe at two Snowy River and one reference site in NSW, and by hand-held probes at seven other Snowy River and reference sites in NSW and Victoria. Sufficient data for seasonal water temperature analyses was only available for the continuous station at Dalgety, whilst daily variability was able to be analysed for Dalgety and the Mowamba River. Linear statistical models were developed to model the continuous water temperature data based on predictors for seasonality, mean daily flow and air temperatures. Changes in electrical conductivity were analysed for all sites using non-parametric Mann-Whitney U test.

Two hypotheses associated with water temperature (H*o* 1 and H*o* 2) and one hypothesis associated with salinity (Ho 3) were examined:

H*o* 1 Following an increase in baseflow in the Snowy River after the 21% MANF release, there will be a significant reduction in the mean daily water temperatures in summer and a slight increase in mean daily water temperature in winter at sites 4 and 6 compared to the pre- flow release period and compared to reference condition measured at sites 12 and 13 (Figure 1);

H*o*2 Following an increase in baseflow in the Snowy River after the 21% MANF release, there will be a significant reduction in daily and seasonal variability in water

temperature at sites 4 and 6 compared to the pre- flow release period and compared to reference condition measured at sites 12 and 13; and

H*o* 3 There will be a decrease in mean EC at all Snowy River sites (particularly in the Dalgety area) compared to the pre- flow release period and compared to reference condition measured at sites 11-13, 31-33.

Although there was no significant change in mean, maximum or minimum water temperature at Dalgety associated with the environmental flow release, there was a very highly significant negative relationship between mean daily flow and water temperature which suggests that larger EFR would reduce stream water temperatures. The averaged summer maximum water temperature was 23.7 °C and 23.5 °C before and after EFR. There was no significant difference in mean daily winter water temperature, but there was a small, significant decrease in minimum winter water temperature at Dalgety from 5.1 °C to 4.5 °C associated with EFR, which is below the 5 °C temperature tolerance of some native fish species in the catchment. Environmental flow releases were associated with a statistically significant increase in the diurnal water temperature range at Dalgety by 0.8 °C and an increased variability of daily fluctuations in the range of water temperatures, however the small changes are unlikely to be of ecological significance and were detected as significant because of the large data set. It is unclear whether the significant difference in diurnal variation at the Mowamba River reference site between the periods coincident with before and after EFR was due to climatic variability among years, or because with only nine months of water temperature records in the period coincident with before EFR there is no replication among years. The diurnal variation in water temperature was consistently higher in the Mowamba River than for the Snowy River at Dalgety because of the higher variability in natural discharge and the smaller stream size of the Mowamba River.

The hypotheses have been based on the river receiving 21% MANF flow releases, rather than the small 3.4% MANF flows that were released. Additionally, whilst flows have increased slightly from 1.9% MANF to 3.4% MANF at Dalgety, discharge at all sites except Dalgety have actually decreased after the first flow release, therefore changes in water quality at most sites cannot be attributed to environmental flows and are probably due to other environmental factors such as the drought. In particular, there were large and statistically significant decreases in electrical conductivity at all Snowy River sites and two of the reference sites which, at Dalgety, is likely to be an effect of the increased flows from the Mowamba River, but at all other Snowy River and reference sites with decreased flows, the decreased electrical conductivity may be due to reduced catchment runoff during the drought. With increasing time with environmental flow releases, climatic factors such as drought should average out.

The analyses in this report were constrained by limitations of the data, which included inconsistent periods of record and gaps in the Mowamba and Willis temperature time series, as well as low sampling frequency at the discretely monitored sites. The design is spatially and temporally unbalanced, so interpretations are largely limited to comparisons within each site and the hypotheses relating to water temperature cannot be adequately tested. Very small changes that are not ecologically significant have been detected as statistically significant in the analyses because of the large continuous data sets. Recommendations include continuous water quality monitoring of Jindabyne Dam and releases, depth profiles of water quality in Lake Jindabyne, additional continuous water quality stations in NSW and Victoria to improve the temporal and spatial design, *in situ* air temperature data and recommendations for future data analysis.

1. Introduction

The Snowy Mountains Scheme (SMS) was completed in 1967 in the Australian alpine region of south eastern New South Wales to provide water for irrigation to the Murrumbidgee and Murray Rivers, and also for power generation. The SMS captures and diverts the headwaters of 12 rivers and 71 creeks (Bevitt *et al*., 1998) with the main capture of water from the Snowy River being from the Guthega, Island Bend, Eucumbene and Jindabyne Dams and the Mowamba River aqueduct. Approximately 98% of mean annual natural flow (MANF) was diverted from the Snowy River at Jindabyne Dam from 1967 to 2002 (Morton and Green, in prep.). The construction of the SMS has affected all components of the flow regime in the Snowy River below Jindabyne Dam, with reduced baseflows, flow variability, spring snowmelt flows and floods (Pendlebury *et al*., 1996; Rose and Bevitt, 2003). The hydrological impacts of the SMS lessen further downstream with increasing flows to the river from tributaries, so in the lower Snowy River flows are reduced by approximately 65% of MANF (Morton and Green, in prep.).

Community concern about the severe flow reduction in the Snowy River and the ecological impacts on the river led to an Expert Panel environmental flow assessment of the Snowy below Jindabyne Dam (Pendlebury *et al*., 1996). As recommended in that report, the Snowy River Flow Response Monitoring Project was implemented in 1997, and upgraded in 1999, as a long term project to measure the ecological condition of the Snowy River before environmental flows and monitor ecological response after environmental flow releases (Bevitt, 1999; Rose and Bevitt, 2003). It is a multidisciplinary project monitoring hydrology, water quality, geomorphology, sediments, vegetation, macro-algae, macroinvertebrates and fish.

Based on the findings of the Snowy Water Inquiry, the Australian, NSW and Victorian governments agreed in October 2000 to release environmental flows to the Snowy River (SWI Heads of Agreement, 2002). Dependent on water savings in the Murray-Darling Basin, flows were planned to be released in four stages over 10 years, up to 28% MANF, as follows:

- Stage 1: August 2002: Flows of 6% MANF to be released to the Snowy River from the Mowamba River downstream of Jindabyne Dam, by decommissioning the Mowamba Weir
- Stage 2: 2004 to 2009; Release flows of 15% MANF from Jindabyne Dam (requiring new outlet works to be constructed)
- Stage 3: 2010 to 2012: Release flows of 21% MANF
- Stage 4: After 2012: Release flows of 28% MANF (dependent upon additional water savings) (SWI Heads of Agreement, 2002: SWI Outcomes Implementation Deed, 2002; Snowy Water Licence, 2002).

The first stage of the environmental flow releases (EFR) to the Snowy River from the Mowamba River occurred on 28 August 2002 when the Mowamba Weir was decommissioned. To date, the second stage of EFR has not occurred given the drought and limited water savings in the Murray-Darling Basin. The initial EFR increased flows in the Snowy River below Jindabyne Dam from 1.9% MANF to 3.4% MANF (Morton and Green, in prep.). When the new Jindabyne Dam outlets works were completed in 2007 the Mowamba Weir was recommissioned, which is likely to have hydrological and ecological impacts. This progress report assesses water quality changes attributable to the first stage of environmental water allocations up to 2005.

Water quality has been identified as an important attribute to measure for flow response monitoring in the Snowy River (Pendlebury *et al*, 1996; Davies, 1999; Chessman, 1999a; Snowy Water Inquiry, 1998). Impoundments such as Jindabyne Dam can have major effects on the water quality of a river, particularly water temperature. Changes in water temperature downstream may include loss of diurnal and seasonal variability, increased winter water temperature, decreased or increased summer temperatures depending on the release depth, changes in the annual temperature cycle, and reduced daily variability (Ward and Stanford, 1979; Webb and Walling, 1993). Deep-release dams release water from the hypolimnion (Ward and Stanford, 1979) and cause thermal pollution in summer by releasing cold water which can persist for long distances downstream of the dam (eg. Harris, 1997; Lugg, 1999), and impact on macroinvertebrate distribution and the spawning cues of fish (Chessman, 1999b; Preece and Jones, 2002; Todd *et al*., 2005).

At full storage capacity the depth of Jindabyne Dam is approximately 50m. The data analysed in this report is from 1998 to 2005, prior to the construction of a new multi-level off take on the dam completed in 2007. Therefore, during the reporting period, releases were from a fixed outlet at 18m below the surface (Snowy Hydro, unpubl. data). Based on depth profile data from surveys by the NSW Government (Bowling *et al*., 1993; Maini *et al*., 1997; Acaba *et al*., 1998) and Snowy Hydro (unpublished data, 2000) the release level in the reporting period was usually from the bottom of the metalimnion or the very top of the hypolimnion, depending on storage level. Although this is not strictly consistent with Ward and Stanfords' (1979) definition of a deep release dam, thermal profiles of Jindabyne Dam in 1997 showed that water temperatures at the 18m level were between 9 to 12^{o}C all year round (Acaba *et al*., 1998).

The Snowy River has been reduced to a relatively small water body below Jindabyne Dam particularly in the Jindabyne Gorge and Dalgety Uplands reaches, so it is probable that water temperatures in the Snowy River have greater diurnal and seasonal variability than temperatures that occurred under the naturally higher baseflows pre- Jindabyne Dam, because of the lack of thermal buffering in small water bodies. Environmental flows of greater than 21% MANF, in particular the increased baseflows, are expected to decrease diurnal and seasonal variability in water temperature. Lower summer water temperatures are expected, along with higher winter minimum temperatures. The increased discharge in winter from Jindabyne Dam should prevent the freezing of pool edges that has been observed in late autumn and winter in the Jindabyne Gorge and Dalgety Uplands reaches.

The impact of reduced flows below Jindabyne Dam may cause associated changes in dissolved oxygen in the Snowy River. Temperature and dissolved oxygen are crucial in the physiology and distribution of aquatic biota. Changes to temperature and dissolved oxygen are likely to impact on algae, macrophytes, macroinvertebrates and fish (Wehr, 1981; Entwisle, 1990; Brown, 1996; Lake, 1996; Bevitt *et al*., 1998; Boulton and Brock, 1999; Chessman, 1999b). Stratification of temperature and dissolved oxygen was considered a likely impact of Jindabyne Dam on pools in the Snowy River, particularly in the Jindabyne Gorge (Wayne Erskine, *pers. comm,* 1998*;* Turner and Erskine, 2005) where there are several deep pools experiencing reduced mixing of the water column with the reduced flows below the dam. Bevitt (2003) conducted a pilot study in the summer of 2000 and found temperature stratification occurred on occasion in pools deeper than 2.5 metres between Jindabyne Dam and Dalgety. Similarly, Turner and Erskine (2005) found that strong thermoclines occurred during summers from 1997 to 1999, with oxygen stratification well developed in pools deeper than 4 metres at sites between Jindabyne Dam and Dalgety. Dissolved oxygen is not included in the water quality monitoring program because of resource constraints, however temperature stratification is being investigated (Bevitt, in prep.).

Salinity can limit the distribution of river biota when it is beyond the tolerance range of these organisms, resulting in stress or death, and affects the availability of nutrients to plants (Boulton and Brock, 1999). Electrical conductivity (EC), as an estimate of salinity, is generally lowest during high flows, and highest during low flows in Australian rivers (WASC, 2002). EC may have increased in the Snowy River because of reduced flows, and is likely to be dominated by local processes such as localised ground water discharge. It is expected that electrical conductivity will decrease with increased baseflows from Jindabyne Dam.

This report examines the water quality data for five years before the first flow release (1998 to 2002) and three years after (2002 to 2005) the first environmental water release to the Snowy River. This report is only intended as a progress report on response to the 3.4% MANF flows as the project was designed in 1999 to detect a response to 21% MANF before it was announced that EFR would be staged over ten years, and the project hypotheses cannot be fully tested until 21% flows are released. Significant responses are not expected to the small increase in flows to 3.4% MANF.

The water quality monitoring program aims to assess the effects of the 21% MANF environmental flow release regime by testing the following hypotheses. Two hypotheses associated with water temperature (H*o* 1 and H*o* 2) and one hypothesis associated with salinity (Ho 3) were examined. Some hypotheses are site specific because of data availability, see sections 2 and 3 for details and site location:

H*o* 1 Following an increase in baseflow in the Snowy River after the 21% MANF release, there will be a significant reduction in the mean daily water temperatures in summer and a slight increase in mean daily water temperature in winter at sites 4 and 6 compared to the pre- flow release period and compared to reference condition measured at sites 12 and 13 (Figure 1);

H*o*2 Following an increase in baseflow in the Snowy River after the 21% MANF release, there will be a significant reduction in daily and seasonal variability in water temperature at sites 4 and 6 compared to the pre- flow release period and compared to reference condition measured at sites 12 and 13; and

H*o* 3 There will be a decrease in mean EC at all Snowy River sites (particularly in the Dalgety area) compared to the pre- flow release period and compared to reference condition measured at sites 11-13, 31-33.

2. Study design

The Snowy River below Jindabyne Dam flows for 352 km to Marlo on the Victorian Coast (Figure 1). The river was divided into three macro-reaches for analyses based on hydrological and geographic differences. The three macro-reaches are termed upland, midland and lowland and within each one or more sites are monitored for water quality (Table 1). One or more reference sites are sampled on nearby unregulated rivers for each macro-reach (Table 1). Reference sites were chosen to represent the water quality conditions that the Snowy River is expected to become more similar to with EFR, and to assess whether any trends observed with EFR are unique to the Snowy River (and therefore attributable to EFR) or if the trends occur elsewhere in the catchment. There are no control sites for water quality.

Table 1. Spatial stratification of water quality design.

Macroreach	Snowy River site	Reference site
Upland	4 Dalgety	12 Mowamba River
		13 Thredbo River
Midland	5 Burnt Hut	11 Delegate River
Lowland	6 Willis	31 Roger River
	7 McKillops Bridge	32 Buchan River
	30 Jarrahmond	33 Brodribb River

Water temperature and electrical conductivity (EC) are measured, along with river discharge at most sites (Table 2). The sampling frequency for water quality varies between sites. The sampling frequency, period of record of historical data available for the study sites are also shown in Table 2, and agencies holding data within NSW and Victoria are shown in Table 2. The only sites with continuous water quality monitoring are the Snowy River at Dalgety and Willis, and the Mowamba River. The upland water quality sites operated by Snowy Hydro at the Jindabyne Dam release and the Thredbo River are monitored monthly for water quality, while the midland sites at Burnt Hut and the Delegate River are measured discretely 2 to 6 times per year, and the lowland Victorian sites are measured monthly (Table 2).

There are two separate sites on the Mowamba River (Table 2), with water quality monitored by the Department of Water and Energy (DWE) at Lynwood above the weir, and discharge measured by Snowy Hydro at Pats Patch below the weir. The water quality results presented in this report refer to the site above the weir, and all references to discharge in the Mowamba River are for Pats Patch below the weir.

Figure 1. Snowy River catchment below Jindabyne Dam showing Snowy River and reference sites.

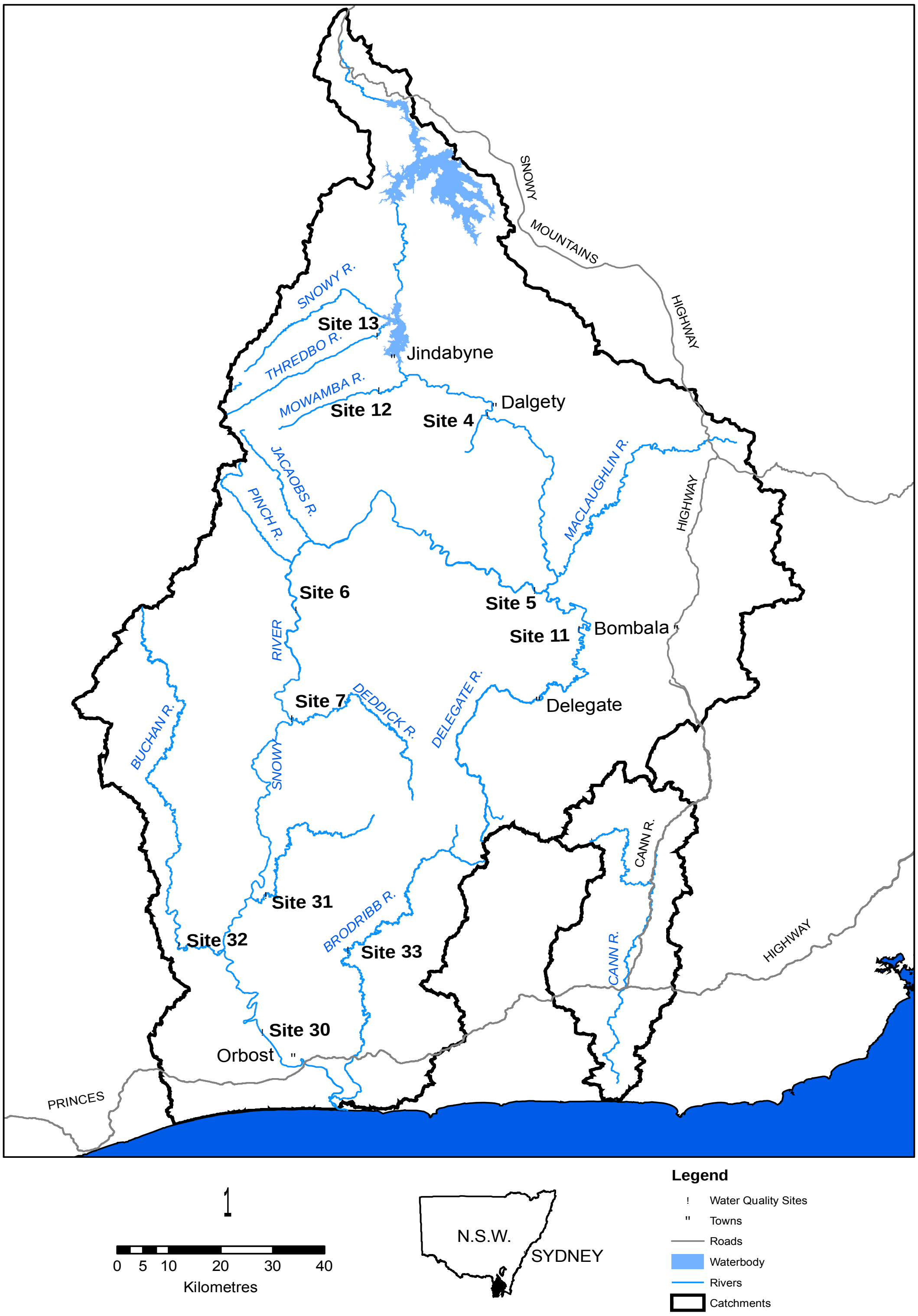


Table 2. Water quality sites on the Snowy River and reference rivers.

Site No.	Site name and gauge number	Variables measured	Period of record	Sampling frequency	Agency holding the data	Data analysed for
Snowy River sites						
	Jindabyne Dam releases Gauge 222020	Discharge Temperature, EC	From 1999 to 2006 From 2006	Continuous[1] Monthly	Snowy Hydro	Discharge Thermal pollution Longitudinal temperature
4	Snowy River at Dalgety weir, Gauge 222026	Discharge, Temperature, EC	From 1997	Continuous[1] + 6 per year	DWE	As above Ho 1-3
5	Snowy River at Burnt Hut Crossing, Gauge 222013	Discharge, Temperature, EC	From 1975	6 per year	DWE	Ho 3 Longitudinal temperature
6	Snowy River at Willis Gauge 222023	Discharge, Temperature, EC	From 1997	Continuous[1] + 6 per year	DWE	Ho 3 Longitudinal temperature
7	Snowy River at McKillops Bridge, Gauge 222209	Discharge, Temperature, EC	From 1975	Monthly	DSE	Ho 3 Longitudinal temperature
30	Snowy River at Jarrahmond Gauge 222200	Discharge, Temperature, EC	from 1975	Monthly	DSE	Ho 3 Longitudinal temperature
Reference sites						
11	Delegate River at Quidong, Gauge 222008	Discharge, Temperature, EC	From 1975	Continuous[1] 6 per year	DWE	Discharge Ho 3
12	Mowamba River at Lynwood, Gauge 222027	Temperature, EC	From Dec 2001	Continuous[1]	DWE	Ho 1-3
	Mowamba River at Pats Patch, Gauge 222546	Discharge	From Jan 2002	Continuous	Snowy Hydro	Discharge
13	Thredbo River at Paddy's Corner[3] Gauge 222541	Discharge Temperature, EC	From 2002	Continuous[1] Monthly	Snowy Hydro	Discharge Thermal pollution Longitudinal temperature
31	Rodger River near Jackson's Crossing Gauge 222217	Temperature, EC	from 1976	Monthly	DSE	Ho 3 Longitudinal temperature
32	Buchan River at Buchan Gauge 222206	Discharge, Temperature, EC	from 1975	Continuous[1] Monthly	DSE	Ho 3 Longitudinal temperature
33	Brodribb River at Sardine Creek . Gauge 222202	Temperature, EC	from 1975	Monthly	DSE	Ho 3 Longitudinal temperature

[1] Measurements are recorded at a very high frequency (every 15 minutes) and are typically referred to as "continuous"

Dalgety and Mowamba River were the only sites used for statistical analyses of seasonal water temperature for H*o* 1 and H*o* 2, because of several large data gaps spanning whole seasons at Willis. There was insufficient sampling frequency of water temperature records at some discretely monitored sites to conduct seasonal water temperature comparisons for H*o* 1 and H*o* 2, but these data were included in the longitudinal water temperature profile. Continuous and discrete EC data were analysed for all sites for H*o* 3. The last column of Table 2 shows how the data for each site were used.

3. Methods

3.1 DATA COLLECTION AND EXTRACTION

Measurements of water temperature and electrical conductivity are taken by *in situ* probes at the three continuously monitored stations (Table 2), and with hand-held probes at sites where discrete monthly or two-monthly sampling is undertaken. Time of day is recorded for spot samples.

Victorian data were supplied by the Department of Sustainability and Environment. Data for the Thredbo River and Jindabyne Dam release were provided by Snowy Hydro. Climatic data were provided by the Bureau of Meteorology from the SILO database.

Mean daily discharge (Mld^{-}1), daily mean, minimum and maximum water temperature (^{o}C) and mean daily EC (µscm^{-1}) were extracted from the DWE's HYDSYS database for the continuous stations at Dalgety, Willis and Mowamba, using a standard 24 hour period from midnight to midnight. Discrete data for NSW were also extracted from the HYDSYS database for water temperature and EC.

3.2 DATA ANALYSES

The statistical design for analysing the effect of the 21% MANF EFR on water quality in the Snowy River would ideally be a BARI design (Cottingham *et al*., 2005), a modification of the BACI design (Underwood, 1991 and 1992), with comparisons made between "before" and "after" periods and between the reference sites and Snowy River sites, however data limitations meant that the analyses was constrained to intervention style comparisons for individual sites.

Water temperature time series for the Snowy River at Dalgety and Willis, and the Mowamba River Reference site were obtained from the continuous data loggers. Temperatures recorded at 15 minute intervals were summarised to obtain daily summary statistics of water temperatures for these locations. These summaries were the daily mean, maximum and minimum water temperatures.

Exploratory data analysis revealed that the daily water temperatures constitute a regular time series exhibiting strong seasonal cycles, inter-annual variability in water temperature patterns and serial correlation. Linear statistical models are extremely suitable for modelling data with these characteristics (Searle, 1971).

The daily water temperature data for Willis was not analysed because there were several large data gaps. There were insufficient sampling occasions in the three years following the first flow release at the discretely monitored sites ($n < 10$) to undertake seasonal comparisons of water temperature (ie, there were insufficient sampling events during each summer and winter period to conduct analyses). Seasonal comparisons may be possible in later years with a larger dataset after the first flow release.

For testing the seasonal temperature variation between seasons (hypotheses 1 and 2), the Dalgety data were separated into calendar months for summer (December to February) and for winter the data were from mid June to mid-July to reduce the variability in temperature within the winter calendar month because of the great range of temperatures within the winter season.

Variables used as predictors of daily water temperature for the Snowy River at Dalgety were the mean daily flow (MDF) (log-transformed) and mean daily air temperatures for Thredbo, Bombala and Orbost. Lags were taken of these air temperatures for several days prior to water temperature measurement. MDF for the Mowamba River was of limited usefulness as a predictor because measurements were only available from 2002 onwards. Sinusoidal dummy variables, consisting of cosine and sine components, often provide a good description of seasonal cycles (Bliss, 1970). Harmonic terms were preferred to air temperature because the former allows for forecasting of seasonality and enables the derivation of annual minima and maxima from estimates of the model parameters. The sinusoidal dummy variables used to model seasonality were cosine {0.0172 x (*yearday – 0.5*)} , sine {0.0172 x (*yearday – 0.5*)}, cos {0.03443 x (*yearday – 0.5*)} and sin {0.03443 x (*yearday – 0.5*)}.

When the assumptions of independence between observations and homogeneity of errors are no longer valid, generalised least squares (GLS) allows a range of correlation and variance structures to be incorporated into the variance-covariance matrix (Davidian and Giltinan, 1995). High levels of autocorrelation existed between daily water temperatures and autoregressive error models of order 1 (Chatfield, 2003) resulted in a vast improvement to all linear models of water temperature. An AR1 model has the form:

$$\varepsilon_t = \phi\, \varepsilon_{t-1} + a_t \qquad \ldots(1)$$

Where ε_t and ε_{t-1} are residuals from the fitted model at times `t` and `t-1`, ϕ is the autoregressive parameter for lag 1 (a measure of the strength of the serial correlation between observations), and a_t is a homoscedastic noise term that is independently and normally distributed.

The assumption of homogeneity of variance was violated in several instances. The variance often varies with the magnitude of the mean response, in which case a power variance function of the fitted values will often model the heteroscedasticity. In other situations, the variance may vary as a function of a covariate such as the mean daily flow (MDF) and covariates can be incorporated in the variance function. Variance functions may take several forms (Davidian and Giltinan, 1995). These include the power and exponential variance functions. The power variance function is described by:

$$Var(\varepsilon_{ij}) = \sigma^2 |\upsilon_{ij}|^{2\delta} \qquad \ldots(2)$$

where the variance of the residuals ε_{ij} (ith observation in the jth group) are a function of the power δ of the variance covariate υ_{ij}. σ^2 is the estimated residual variance. The exponential variance function is:

$$Var(\varepsilon_{ij}) = \sigma^2 \exp(2\delta\upsilon_{ij}). \qquad \ldots(3)$$

Plots of the data revealed inter-annual variation among water temperatures. Each year was considered a random effect in the linear model because estimating the effect of specific years was not of interest, and inter-annual variability would be expected to be a consequence of climatic variability. The class of statistical models known as linear mixed effects models (Laird and Ware, 1982) were used to incorporate random effects into linear models. Linear mixed models are highly flexible and allow the modelling of within-group errors by correlation and variance structures. Linear mixed effects models estimate variance components by restricted maximum likelihood (REML) estimation. The 'before' and 'after' periods (pre-EFR and post-EFR) following the implementation of an environmental flow regime in August 2002 was considered a fixed effect in the linear model.

The sequence in which the linear predictors are added to the model is important when these are not independent. Interpretation of the F statistic obtained from ANOVA summaries should be assessed as the significance of the variable after accounting for the variation explained by the variables preceding it. Hence, harmonic terms for air temperature variables were always added to the linear models before MDF and EFR and the variation explained by MDF or EFR should be interpreted as 'variation after accounting for the variation due to atmospheric conditions'. The order in which the variables EFR and log(MDF) were introduced into models was interchanged because of their potential influence on each other. The significance of EFR was based on fitting this factor before MDF.

The approach to modelling followed the strategy described by Pinheiro and Bates (2000) using S-Plus (Insightful, 2003). Linear models were fitted using an hierarchical approach and competing models were compared using the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC) and the likelihood ratio (Pinheiro and Bates, 2000). The AIC and BIC are functions of the log-likelihood obtained from a fitted model that penalise the likelihood for the number of parameters included in the model. Hence, if two models are to be compared and there is little difference between the log-likelihoods of the two models but a difference in the number of parameters used to fit the models, then the more parsimonious model (i.e., the model with fewer parameters) will be preferred. It will have smaller values of the AIC and BIC.

A nested set of GLS and linear mixed models, fitted by maximum likelihood, can be compared by likelihood ratio (LR) tests (Pinheiro and Bates, 2000) in addition to comparisons using AIC and BIC criteria. The LR statistic for two competing models has a χ^2_{n-m} distribution where *n-m* is the difference in the degrees of freedom between the two models. The LR test is particularly useful for assessing significance of random effects terms and different variance-covariance structures.

The adequacy of a model was assessed by examining residual diagnostic plots (Draper and Smith, 1998). These provided an assessment of the assumptions of normality, homogeneity and linearity. Autocorrelation in water temperatures was investigated by examining autocorrelation functions (ACF) of the residuals from linear models, after adjusting for seasonal variation and streamflow effects on water temperature. More complex models incorporating autocorrelation and variance functions for modelling heteroscedasticity were fitted when indicated by residual diagnostic plots. The LR test was used to compare these models with simpler models (Pinheiro and Bates, 2000).

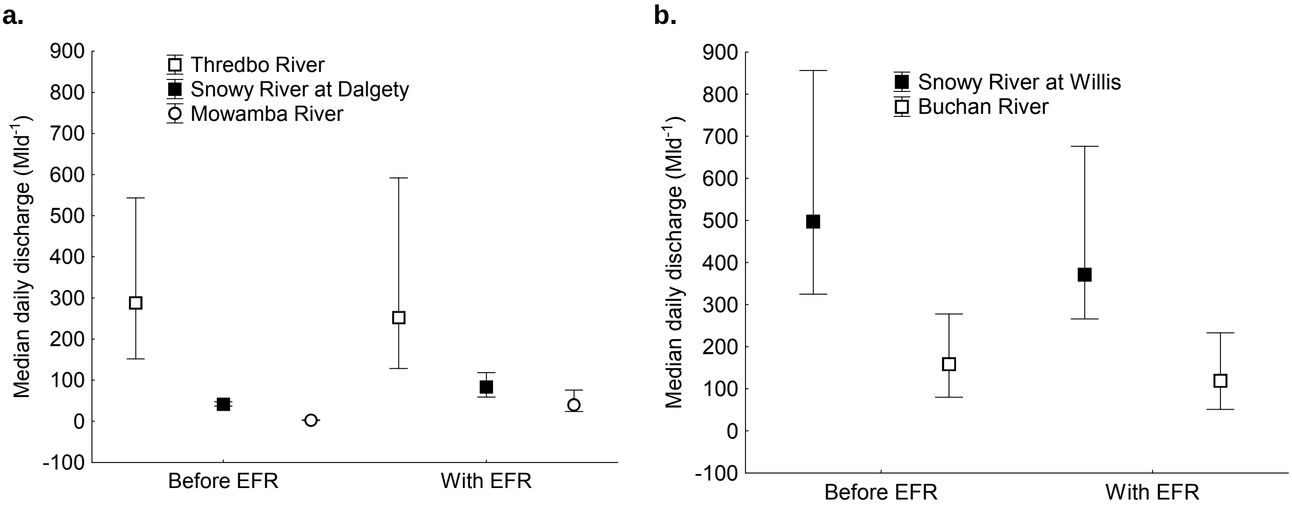
4 RESULTS

4.1 HYDROLOGY

The decommissioning of the Mowamba River aqueduct on 28 August 2002 increased median daily discharge in the Mowamba River below the weir from 3 Mld^{-1} before EFR to 40 Mld^{-1} with EFR (Figure 2a). Median daily discharge in the Snowy River at Dalgety increased from 42 Mld^{-1} before EFR to 84 Mld^{-1} with EFR (Figure 2a). Discharge in both the Mowamba and Snowy Rivers were significantly lower than median daily discharge in the Thredbo River reference site (Figure 3a), which decreased from 287 Mld^{-1} to 252 Mld^{-1} in the periods coincident with before and after EFR (Figure 2a).

An increase in daily discharge variability occurred at Dalgety with EFR, along with increased seasonality from higher spring discharge very similar to the Mowamba River (Figure 3a), although summer baseflows were higher in the Snowy River at Dalgety than in the Mowamba River with EFR.

Figure 2. Median daily discharge at a) Snowy River at Dalgety and the Thredbo River reference site, and b) Snowy River at Willis and the Buchan River reference site (error bars are 25th-75th percentiles).

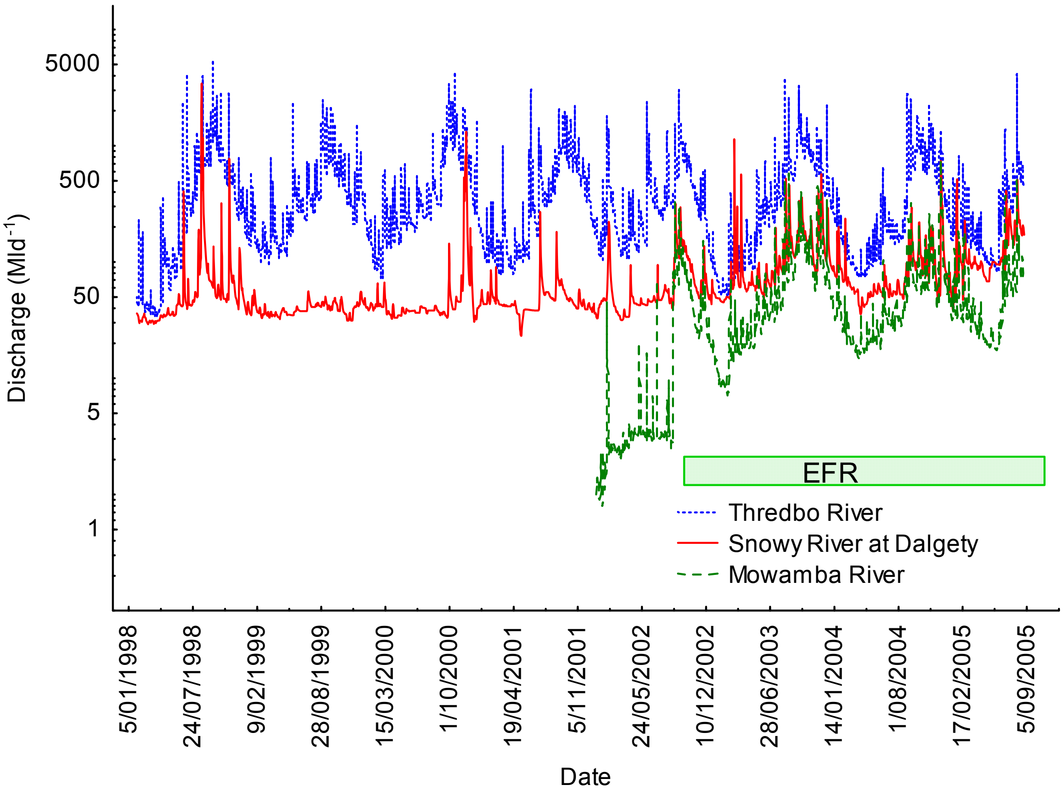


Median daily discharge decreased at Willis from 498 Mld^{-1} before EFR to 371 Mld^{-1} after EFR. Discharge in the Buchan River also decreased from 159 Mld-1 to 119 Mld-1 in the periods coincident with before and after EFR, with a reduction in high flows at both sites coincident with EFR and the drought (Figure 2b). Flows were lower in the Buchan River than the Snowy River at Willis because of the much smaller catchment area of the Buchan River. The reduced flows in the lower Snowy River and the Thredbo and Buchan River reference sites coincident with EFR reflect the drought conditions in the region that corresponded with the EFR.

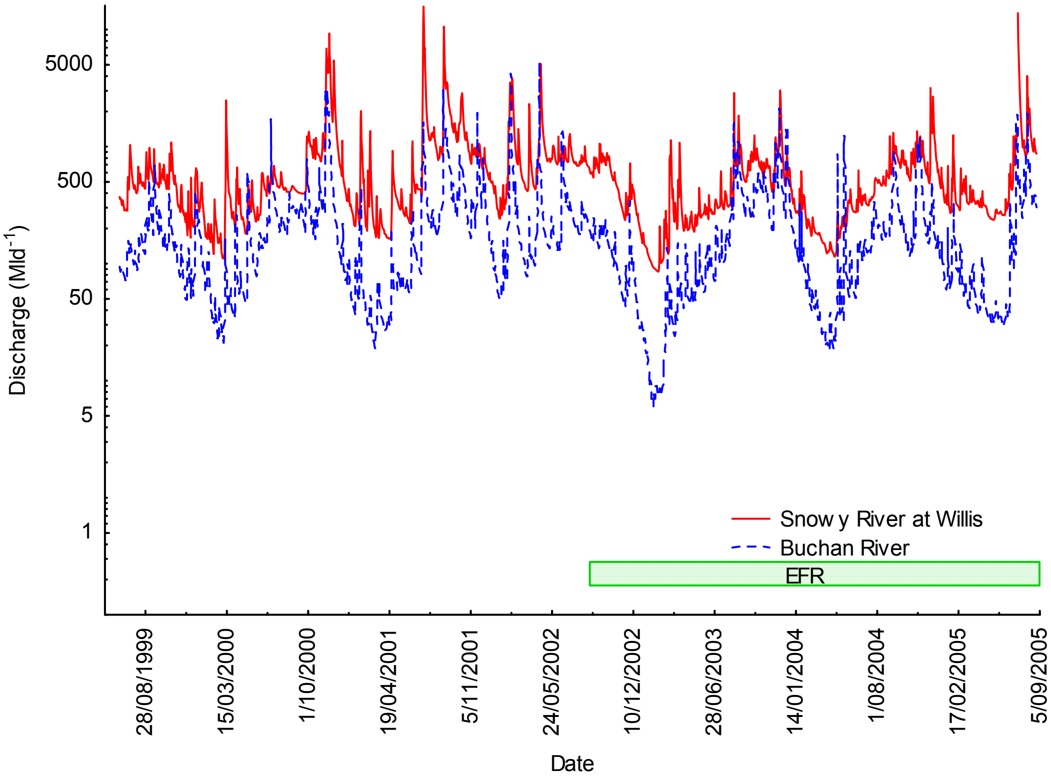
Daily flows in the Snowy River at Willis were much higher and more variable than the Snowy River at Dalgety throughout the study period (Figure 2 and Figure 3), as Willis has a much larger catchment area and there are a number of additional tributaries which increase both the volume and the natural variability of flows at Willis.

Figure 3. Mean daily discharge from January 1998 to August 2005 at a) Snowy River at Dalgety and the Thredbo River reference site, and b) Snowy River at Willis and the Buchan River reference site (logarithmic scale).

a.



b.



4.2 AIR TEMPERATURES

Thredbo and Bombala air temperatures both showed strong seasonality, with consistently cooler temperatures at Thredbo (Figure 4a) and high serial correlation between daily mean temperatures (Table 3 and Table 4). Mean daily air temperatures were around 14°C in summer and 2°C in winter at Thredbo, and 18°C and 6°C respectively at Bombala. Air temperatures at Orbost showed much less seasonal variation (Figure 4b), with mean daily air temperatures of 11°C in summer and 10°C in winter (annually = 10.8). There was some indication of inter-annual variation in air temperatures at Thredbo, particularly in 2002 (Figure 5), but this was not significant when autocorrelation was taken into account. There were no significant differences in air temperatures for the periods coincident with before and after EFR, and no evidence of temporal trends in air temperature (Table 4).

Table 3. Parameter estimates and associated standard errors for daily mean air temperature models for Thredbo and Bombala.

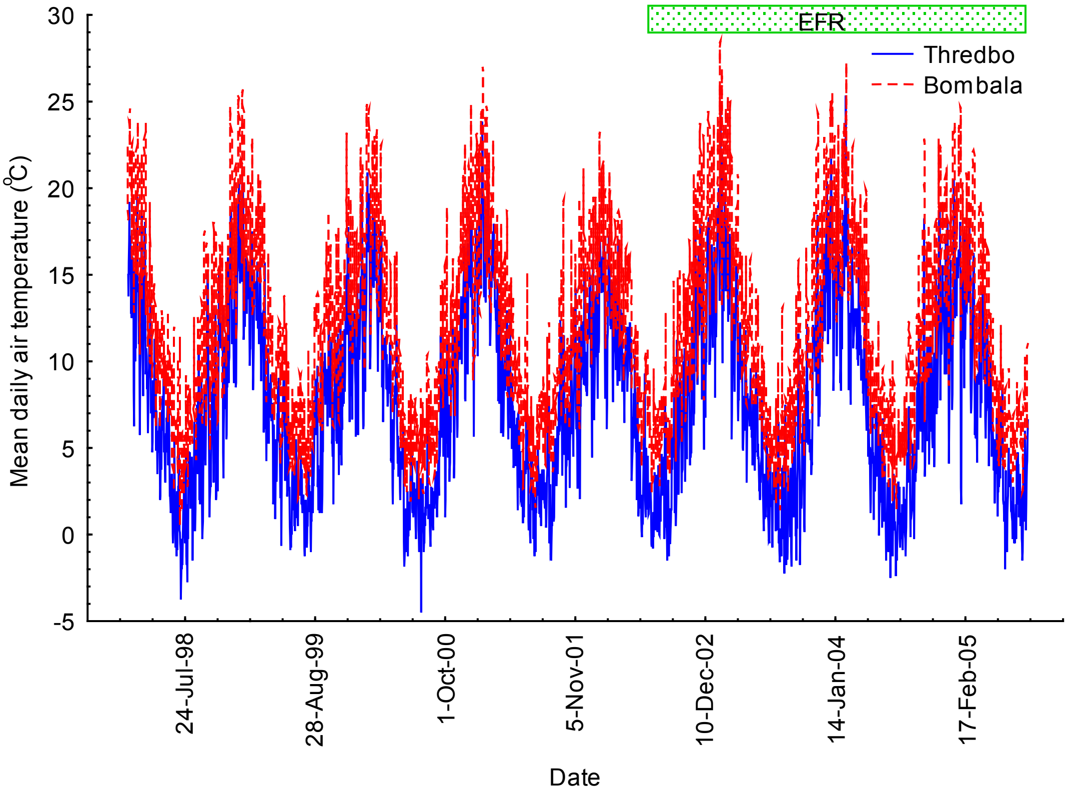
Parameter	**Thredbo**	**Bombala**
intercept	7.86 (0.120)	12.1 (0.111)
cos(ωt)	6.10 (0.166)	6.06 (0.154)
sin(ωt)	2.09 (0.167)	1.91 (0.155)
EFT	0.018 (0.120)	0.132 (0.111)
serial correlation	0.66	0.59

Table 4. ANOVA summary table for a linear model with serially correlated errors (correlation = 0.66) of Thredbo air temperatures incorporating seasonal effects, a nonlinear temporal trend and an intervention for the introduction of environmental flows on the Snowy River. Denominator degrees of freedom = 2761.

Source of variation	Numerator DF	F-value	p-value
Seasonality	2	730.4	< 0.0001
Nonlinear trend	4	0.160	0.96
Environmental flow	1	1.131	0.29

Figure 4. Mean daily air temperature from January 1998 to August 2005 at a) Thredbo and Bombala, and b) Orbost.

a.



b.

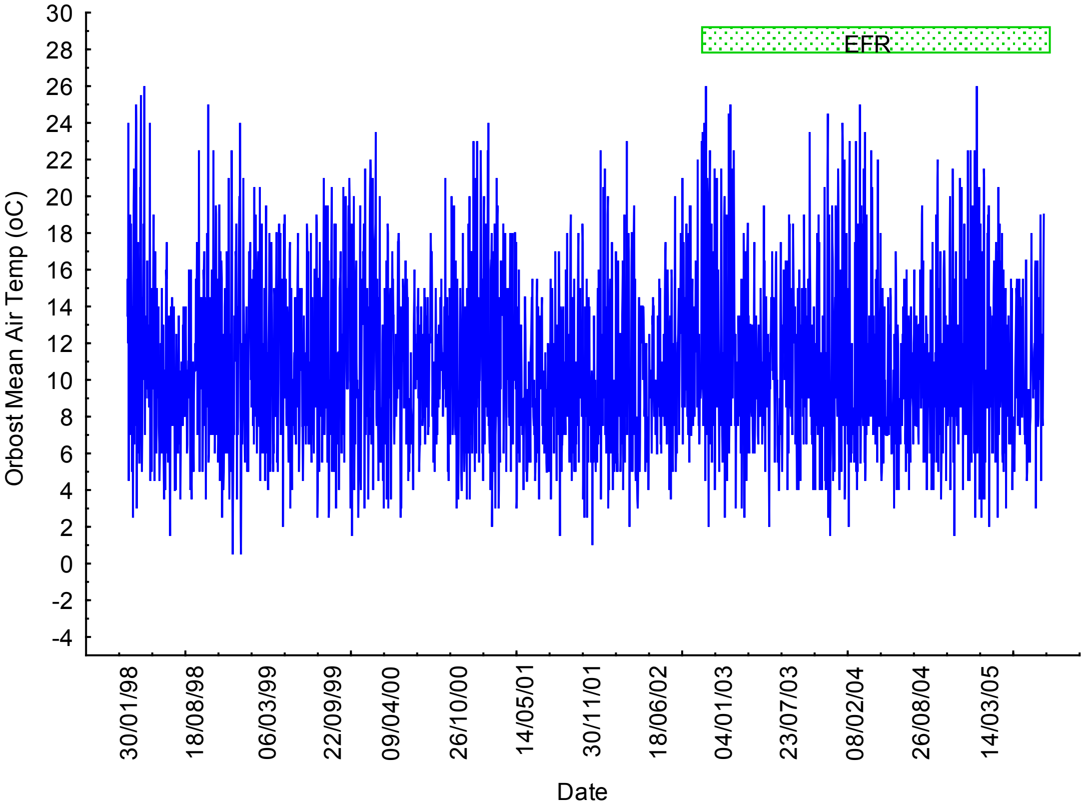
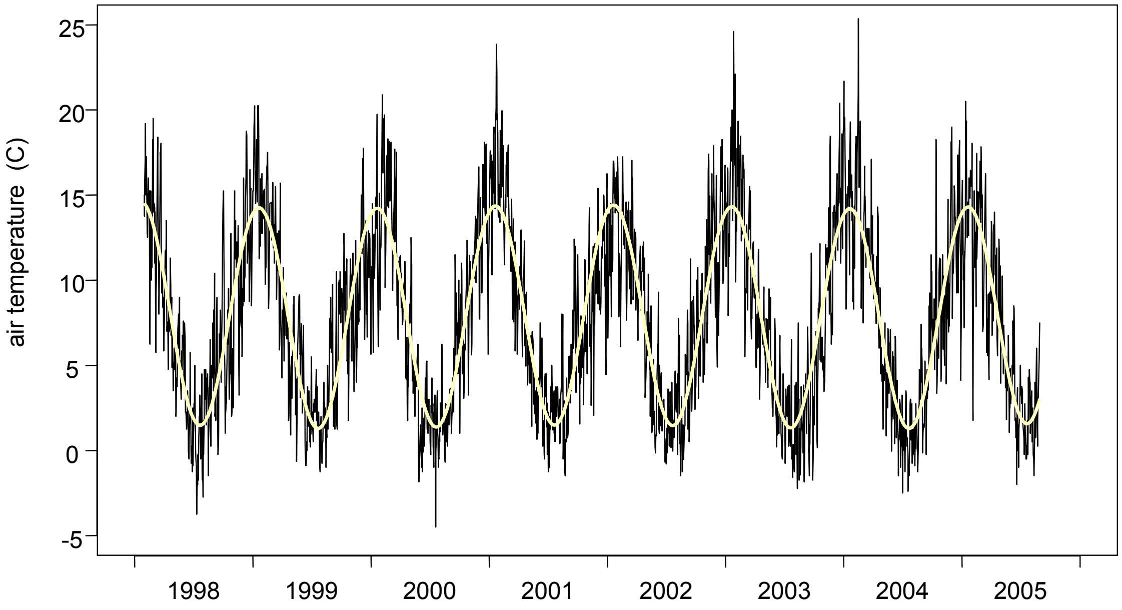


Figure 5. Mean daily air temperatures (^{o}C) at Thredbo from 1998–2005. The fitted yellow line represents the model adjusted for serial correlation but ignoring possible inter-annual variation in air temperatures.



4.3 ANNUAL TRENDS IN MEAN WATER TEMPERATURE FOR THE SNOWY RIVER AT DALGETY

The mean daily water temperatures in the Snowy River at Dalgety were represented by a linear mixed model with covariates for MDF (logarithms) and harmonic seasonal terms, and a random component consisting of two parts: inter-annual variability and random (residual) error among days. The residual errors were serially correlated (LR = 4213.6, $p < 0.0001$) with heterogeneous errors (LR = 402.2, $p < 0.0001$). Serial correlation was described by a first-order autoregressive (AR1) model and a variance power function adequately modelled heteroscedasticity (Figure 6). The parameter estimates are summarised in Table 5. The model revealed a negative effect of stream flow on daily mean water temperatures but no significant impact of environmental flows on average water temperatures (LR = 2.73, $p = 0.10$; Table 5). The plots of standardised residuals to fitted values for the error models are shown in Figure 7.

Figure 6. Time series of the daily mean water temperatures for the Snowy River at Dalgety. The fitted line is the prediction from the linear mixed model.

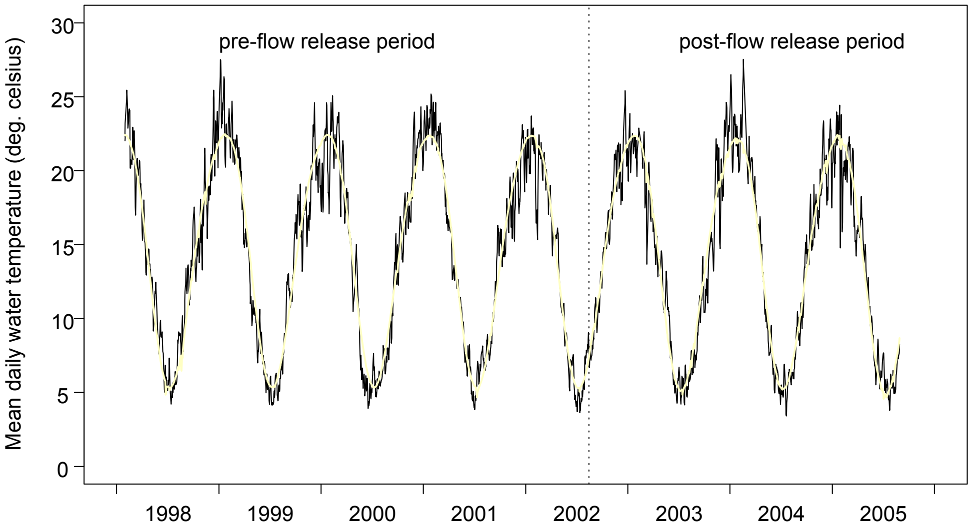
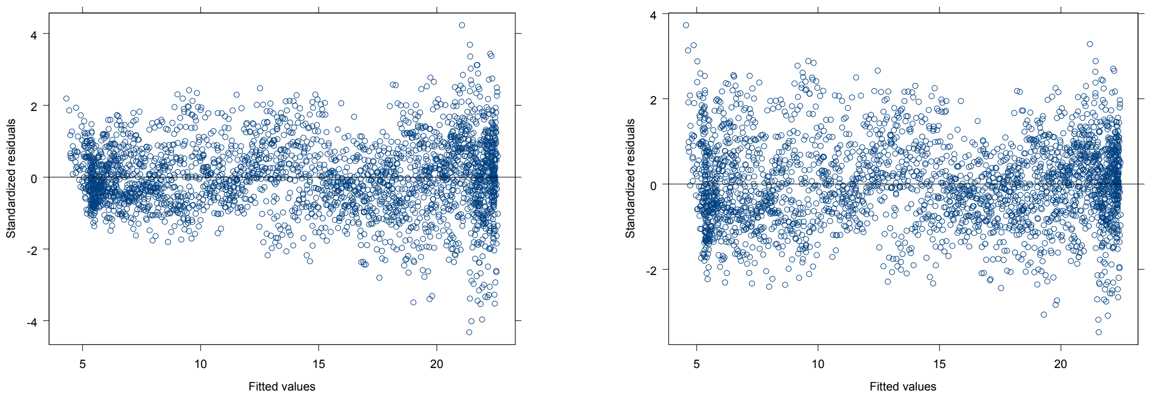


Table 5. Parameter estimates for a linear mixed model of mean daily water temperatures for the Snowy River at Dalgety. * indicates a 0.001 level of significance.**

Parameter estimate	Coefficient	Standard error	
intercept	15.9	0.274	***
cos (0.0172*day)	8.26	0.178	***
sin (0.0172*day)	1.80	0.177	***
cos (0.0344*day)	-0.92	0.157	***
sin (0.0344*day)	0.20	0.161	ns
$\log_e$ (MDF)	-0.36	0.057	***
years (variance)	0.0002		

residual error variance	0.130		
Environmental flow release	-0.06	0.102	ns
ϕ, AR1 correlation	0.90	0.061	
δ, variance power function	0.55	0.026	

Figure 7. Plots of standardised residuals vs. fitted values for the a) homogeneous error model, and b) heterogenous error model.



a. **b.**

4.4 HYPOTHESIS 1

> *"…There will be a reduction in the mean daily water temperatures in summer and a slight increase in mean daily water temperature in winter at sites 4 and 6 compared to the pre- flow release period and reference sites 12 and 13, following an increase in baseflow in the Snowy River. Response should be detected after the 21% MANF release…"*

4.4.1 Daily mean summer water temperatures

The best predictors of summer mean daily water temperatures at Dalgety included mean daily flow (log-transformed), the air temperature at Thredbo, and the air temperatures for the previous three days. The parameter estimates for this regression model are summarised in Table 6. The model indicates that an increase in streamflow depresses water temperature by approximately 2 ºC for each ten-fold increase in stream flow (i.e. from 10 Mld^{-1}, 100 Mld^{-1}, 1000 Mld^{-1}, etc.).

Random variation among years in summer water temperatures was not significant (LR = 3.24, p = 0.07). The residual variance in water temperatures was not constant and a regression model with heterogeneous AR1 correlated errors was a highly significant improvement over a homogeneous error model (LR = 52.5, p < 0.0001). The variance was an exponential function of log(MDF).

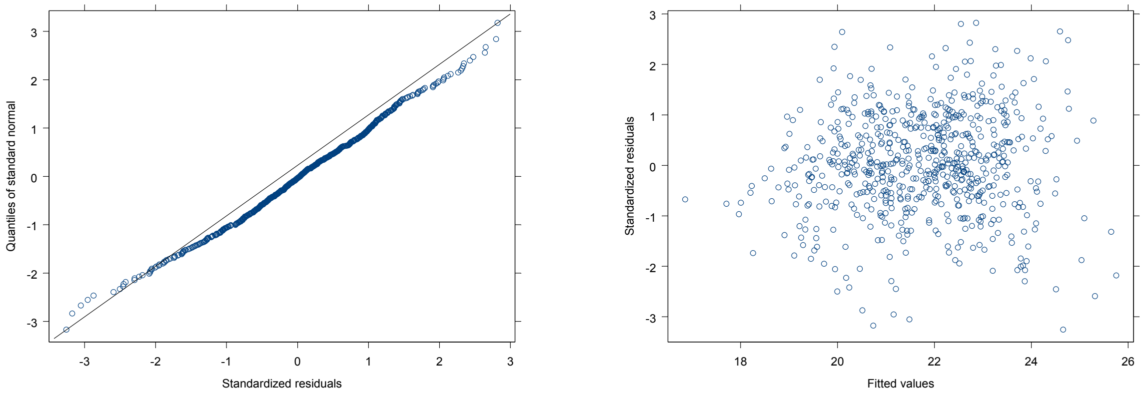
There was no significant difference in daily mean water temperatures between the before and after EFR periods, after adjusting for the effects of air temperature ($F_{1,6} = 0.09$, $p = 0.77$).

Table 6. Parameter estimates (with standard errors) for the regression model of summer daily mean water temperatures. 'MDF' is mean daily flow and 'Air' is the air temperature at Thredbo; the subscripts refer to number of lagged days. All predictors were highly significant.

Intercept	**$\log_e$(MDF)**	**Air_t**	**Air_{t-1}**	**Air_{t-2}**	**Air_{t-3}**	ϕ	δ
19.05	-0.883	0.108	0.182	0.122	0.040	0.83	0.28
(0.701)	(0.139)	(0.012)	(0.012)	(0.012)	(0.012)	(0.14)	(0.04)

The residual diagnostic plots are satisfactory, but indicate some lack of fit for the extreme values (Figure 8).

Figure 8. Residual diagnostic plots for the regression model with heterogeneous AR1 correlated errors.



a. **b.**

4.4.2 Daily maximum summer water temperatures

Daily maximum water temperatures during the summers were closely predicted by the air temperatures at both Thredbo and Bombala, and the logarithm of MDF at Dalgety (Table 7). A slightly better model of summer water temperatures was produced using the air temperatures at Bombala rather than Thredbo. There was also significant inter-annual variability among summer maximum water temperatures which was included as a random effect in the linear mixed model ($LR = 5.48$, $p = 0.02$). Daily water temperatures were strongly autocorrelated (AR1 autoregressive errors; $LR = 362.5$, $p < 0.0001$) and there was evidence of non-constant (heteroscedastic) variance ($LR = 32.0$, $p < 0.0001$). Several models of heteroscedasticity were examined but the best model was an exponential variance function that was dependent on mean daily flow at Dalgety. That is, as stream flow increased so too did the variability in daily maximum water temperature.

There was no direct evidence of an impact of environmental flows on maximum water temperatures ($F_{1,6} = 0.003$, $p = 0.96$) of 23.7 ºC before EFR to 23.5 ºC with EFR, although daily maximum water temperatures were negatively correlated with MDF (Table 7).

Table 7. Parameter estimates (with standard errors) for the regression model of summer daily maximum water temperatures. 'MDF' is mean daily flow and 'Bombala Air' is the air temperature at Bombala; the subscripts refer to number of lagged days. All predictors were highly significant.

Intercept	log$_e$(MDF)	Bombala Air$_t$	Bombala Air$_{t-1}$	Bombala Air$_{t-2}$	Bombala Air$_{t-3}$	ϕ	δ
17.9	-0.71	0.12	0.17	0.12	0.03	0.68	0.24
(1.12)	(0.24)	(0.013)	(0.013)	(0.013)	(0.013)	(0.08)	(0.05)

The LME model of daily maximum water temperatures provided a reasonable fit to the data (Figure 9). There was no evidence for an impact of environmental flow releases on daily maximum water temperatures after adjusting for the effects of air temperature ($F_{1, 5} = 0.004$, p = 0.95). The comparison of the before EFR and with EFR periods was made without adjusting for the effects of mean daily flow for obvious reasons.

Figure 9. The model for the daily maximum water temperatures at Dalgety (circles) provided a reasonable fit of the data (red line). The green line shows the predicted water temperatures after adjusting for the effect of air temperature. The dotted line is the overall mean of the adjusted water temperatures and deviations around this line indicate whether the water temperatures for a particular summer were higher or lower than average.

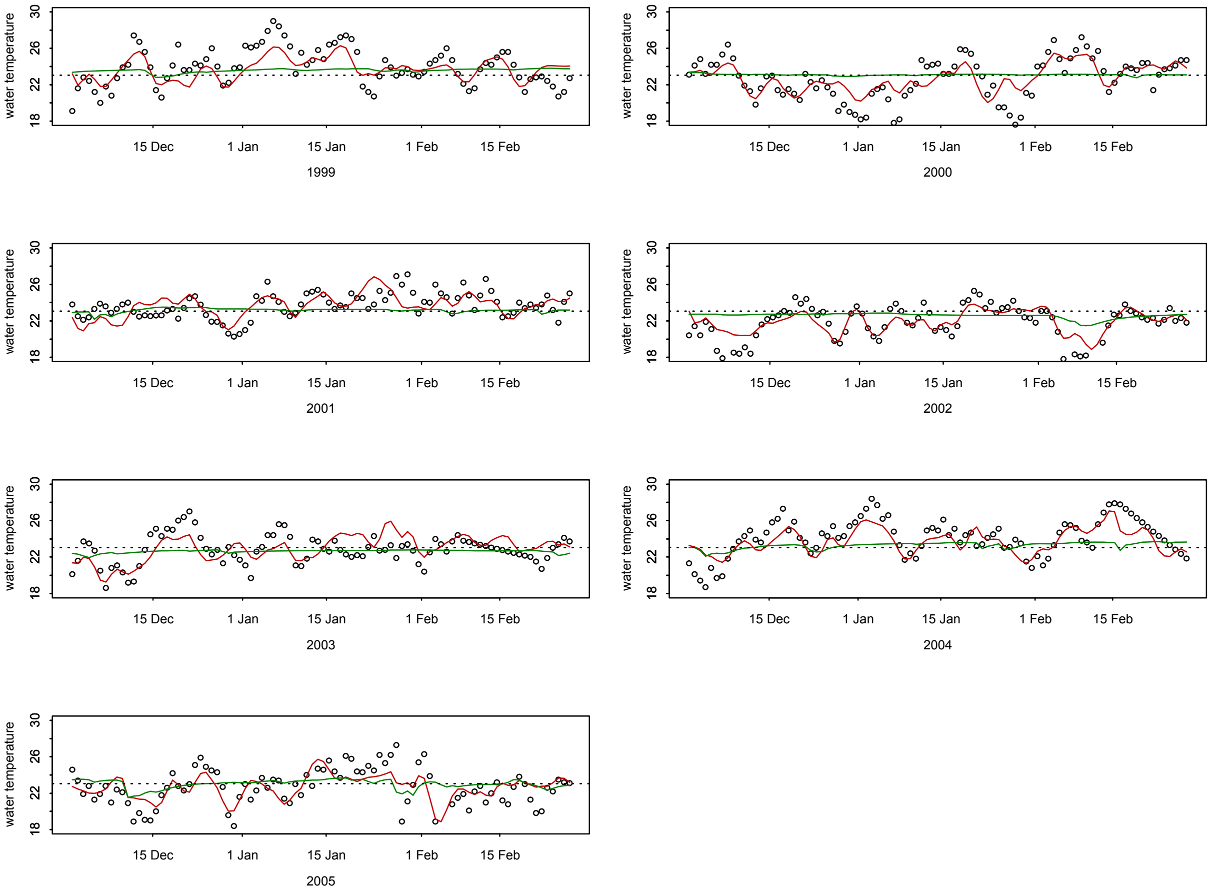
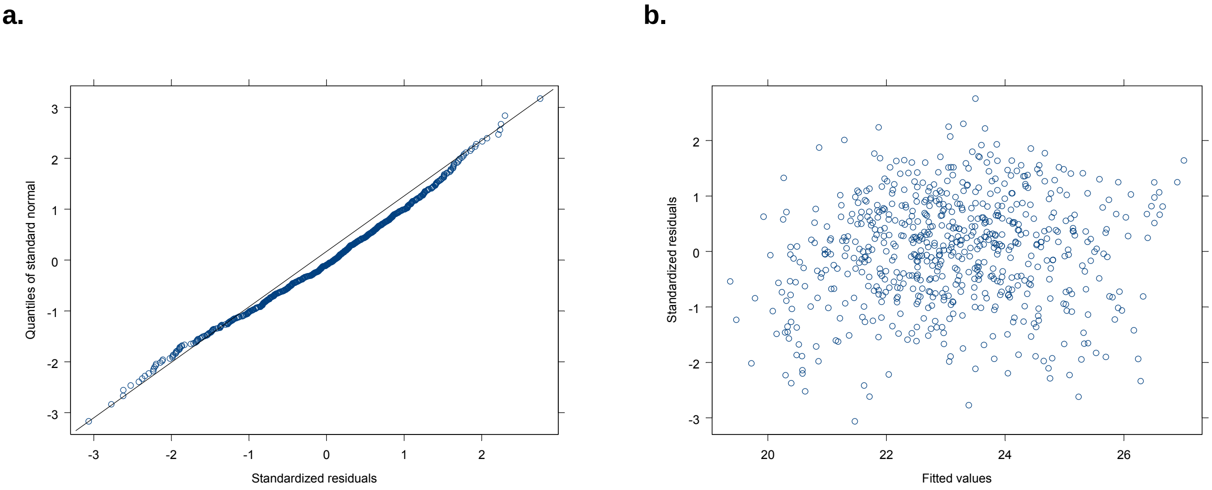


Figure 10. Residual diagnostic plots of the linear mixed model of daily maximum summer water temperatures for the Snowy River at Dalgety.



4.4.3 Daily minimum winter water temperatures

The daily minimum water temperatures for the winter of each year were positively correlated with lagged air temperatures at Bombala and negatively correlated with the mean daily flow at Dalgety (Table 8).

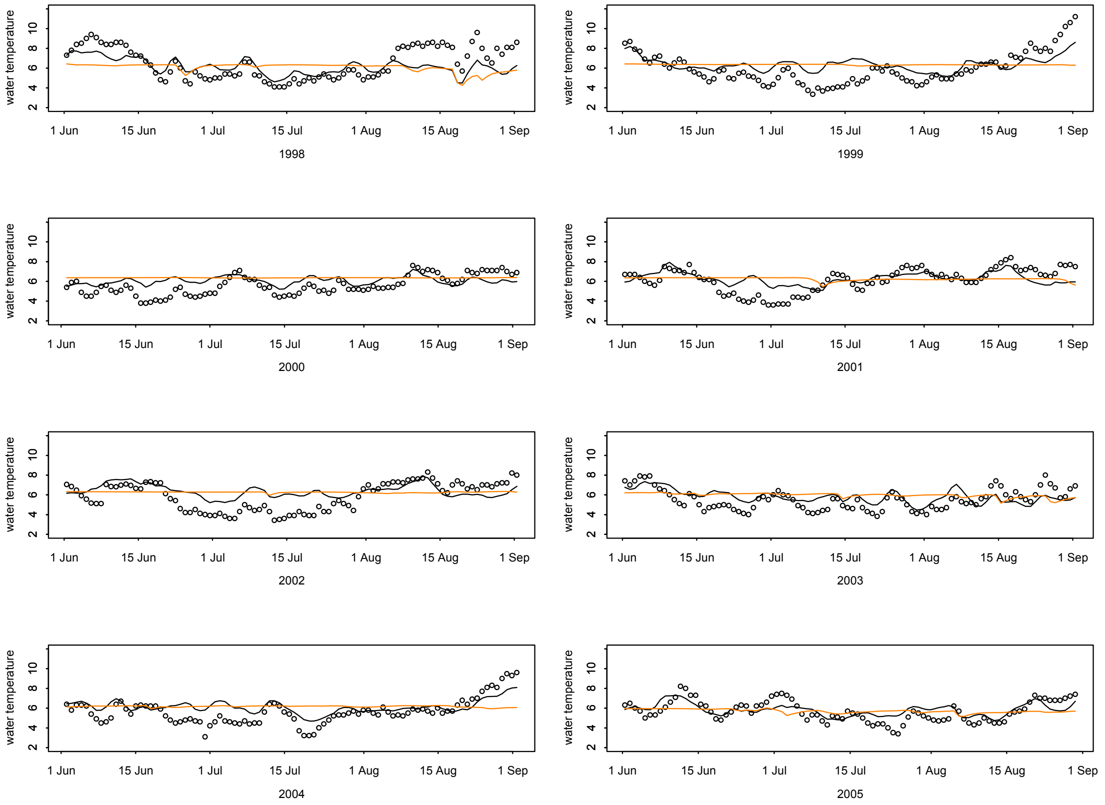
Table 8. Estimates of regression parameters for a linear model with correlated errors (AR1 model, ϕ = 0.93), of daily minimum water temperatures for the Snowy River at Dalgety.

Parameter	Estimate (s.e.)	
Intercept	5.57 (0.39)	***
Bombala air temperature, previous day (lag 1)	0.10 (0.01)	***
Bombala air temperature, lag 2	0.13 (0.01)	***
Bombala air temperature, lag 3	0.09 (0.01)	***
Bombala air temperature, lag 4	0.06 (0.01)	***
Bombala air temperature, lag 5	0.03 (0.01)	**
Environmental Flow Releases	0.01 (0.05)	ns
$\log_e$ (mean daily flow at Dalgety)	-0.47 (0.07)	***

No effect of environmental flow releases on minimum winter water temperature of 5.1 ºC before EFR to 4.5 ºC with EFR was detected after adjusting for the effects of air temperature ($F_{1,6}$ = 1.01, p = 0.35). The fitted values from the model showed some lack of fit to the observed data (Figure 11) but the fit was improved by including the stream flow for the Mowamba River (lagged by 1 day). Inflows from the Mowamba River had a positive impact on daily minimum stream temperatures (0.213 ± 0.054 ºC for every megalitre of streamflow).

Data for Mowamba stream flows were only available from 2002 onwards, hence, could not be incorporated in a test of before EFR and with EFR impact on minimum winter water temperature.

Figure 11. Daily minimum water temperatures for winter at Dalgety with modelled temperatures (black) and predicted temperatures, adjusted to the mean Bombala air temperature (orange) superimposed on the plot.



4.5 HYPOTHESIS 2

> *"…There will be a reduction in daily and seasonal variability in water temperature at sites 4 and 6 compared to the pre- flow release period and reference sites 12 and 13, following an increase in baseflow. Response should be detected after the 21% MANF release…"*

4.5.1 Diurnal temperature variation

The diurnal variations in water temperature at Dalgety were dominated by a strong seasonal cycle ($F_{4, 2754}$ = 296.2, p < 0.0001) (Figure 12) but were also positively correlated with the logarithm of mean daily streamflow ($F_{1,2754}$ = 101.8, p < 0.0001). Air temperature and lags in air temperature were not significantly related to the diurnal variation in water temperatures (Table 9). Autocorrelation between daily variations was highly significant (LR = 393.9, p < 0.0001).

In addition to significant inter-annual variability in diurnal variation (LR = 11.3, p = 0.0008) there was a statistically significant effect of EFR (t_{2754} = 9.58, p < 0.01) (Figure 12). The diurnal variation was estimated to have increased by 0.08 ± 0.025 ºC (±1 standard error) since August 2002.

Figure 12. Diurnal variation of daily water temperatures for the Snowy River at Dalgety. The fitted yellow line is the prediction from the statistical model.

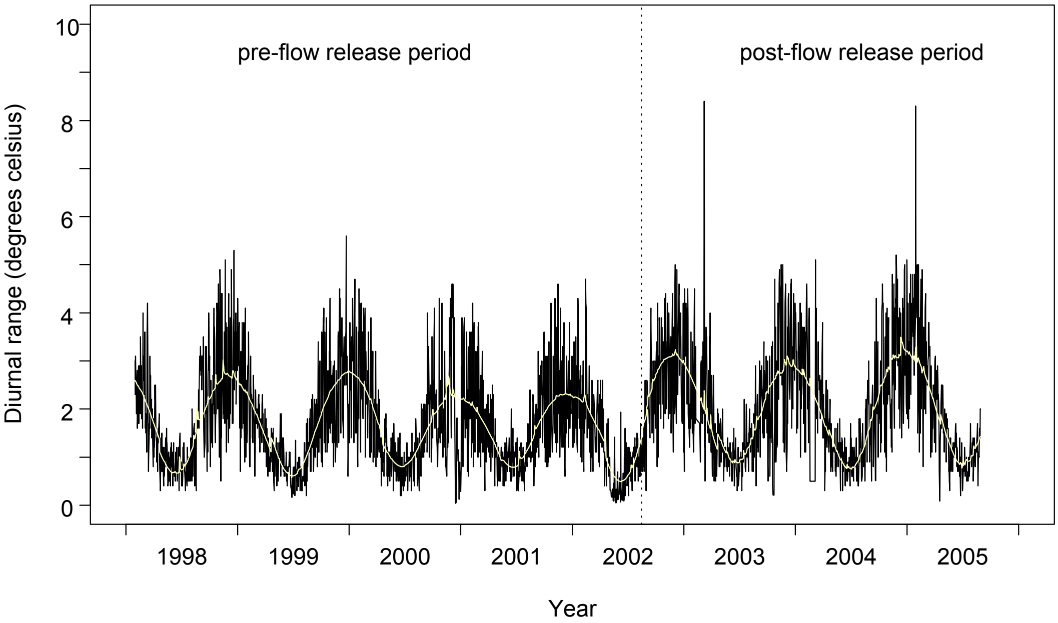
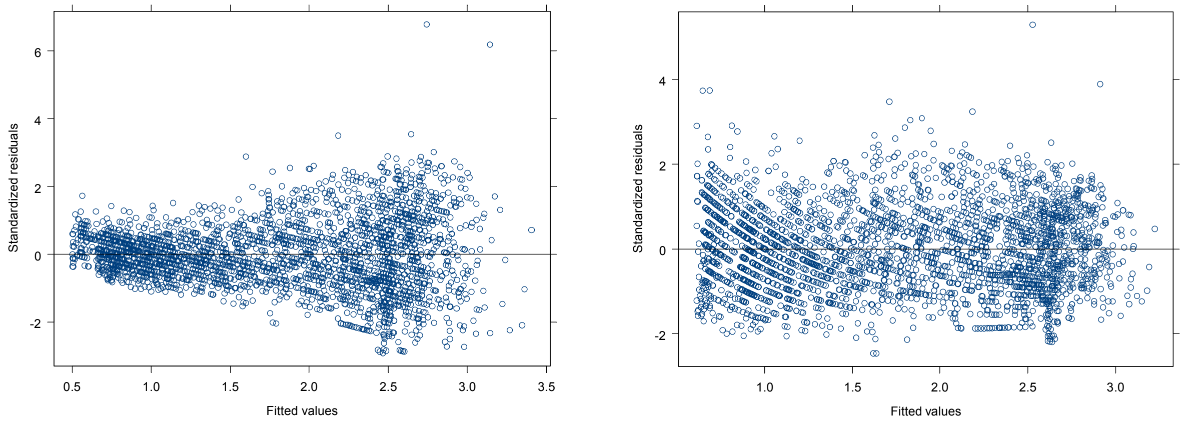


Table 9. Summary of the model fitting process for the diurnal variation in water temperature at Dalgety.

Model description	df	AIC	BIC	Log likelihood	Test	Likelihood ratio	p-value
1. log(MDFlow) + seasonality	7	6909.9	6951.4	-3447.9			
2. Model 1 + AR1 correlated errors	8	6518.0	6565.4	-3251.0	1 vs. 2	393.9	< 0.0001
3. log(MDFlow) + Air_t + corr. errors	5	6649.0	6678.7	-3319.5	2 vs. 3	137.0	< 0.0001
4. Model 2 + random year effects	14	6508.7	6562.0	-3245.4	2 vs. 4	11.3	0.0008
5. Model 4 + heteroscedastic var.	16	5531.4	5596.6	-2754.7	4 vs. 5	981.3	< 0.0001
6. Model 5 + Envir. Flows	17	5528.3	5599.5	-2752.2	5 vs. 6	9.49	0.002

Plots of standardised residuals against fitted values indicated non-constant variance (Figure 13a). Several models of variance heteroscedasticity were fitted to the data but the best was the power variance function that allowed the variance to vary as a function of the diurnal range (Figure 13b).

Figure 13. Plots of standardised residuals for the model of diurnal range a.) unadjusted for heterogeneous errors, and b.) after adjustment for heterogeneous errors via a variance power model.

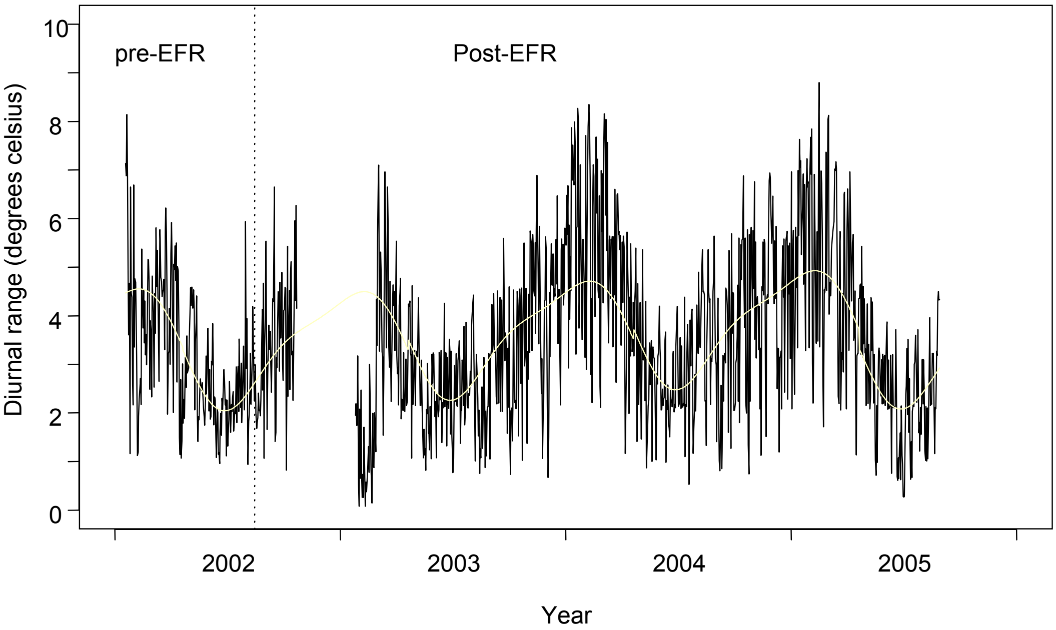


a. **b.**

4.5.2 Diurnal variation for the Mowamba River

The diurnal variations for the Mowamba River followed a similar pattern to the Snowy River at Dalgety except that streamflow was not significant (F1, 1220 = 1.01, p = 0.32). The linear part of the model consisted only of seasonal, harmonic terms (F1, 4 = 115.8, p < 0.0001). Significant inter-annual variation was present (LR = 11.6, p = 0.006). Errors were serially correlated and an AR1 error model (ϕ = 0.45) produced a highly significant improvement (LR = 334.8, p < 0.0001). Variances were heterogeneous (LR = 177.6, p < 0.0001) and were modelled by a power variance function.

Figure 14. Diurnal water temperature variation for the Mowamba River. The fitted yellow line is the prediction from the statistical model.



There was a significant difference in diurnal variation between the periods coincident with before EFR and after EFR ($F_{1,\,1216}$ = 4.57, p = 0.03) indicating a slight increase in the diurnal variation in the period coincident with after EFR. As this cannot be attributed to EFR, being a reference site above the weir, this result is due to either climatic variability between years or is an artefact of the unbalanced data set, as there was less than a year of water temperature records in the period coincident with before EFR so no replication in that period.

4.5.3 Comparison of water temperatures between Dalgety and the Mowamba River

An analysis of the impact of an intervention at a single site, as undertaken above, while providing insights to temporal patterns in water temperature, does not have the logical strength of a comparison between a test location (i.e. the Snowy River at Dalgety) and a reference location (i.e. Mowamba River).

Diurnal range

A linear mixed model with heterogeneous, correlated errors was fitted to the diurnal temperature ranges from Dalgety and Mowamba. There were very highly significant differences between sites, season, and EFR. There was a significant interaction between site and EFR at the 5% level (Table 10). The significant interaction is important as it suggests there was an effect of EFR on the Snowy River at Dalgety. The diurnal range was smaller at Dalgety than for the Mowamba River. The diurnal range at Dalgety increased after EFR was introduced but only increased slightly for the Mowamba River in the period coincident with EFR.

Table 10. ANOVA summary for the comparison of Dalgety and Mowamba River

Source of variation	numDF	denDF	F-value	p-value
Site	1	2436	910.3	< 0.0001
season	4	2436	131.3	< 0.0001
Site:season	4	2436	5.84	0.0001
EFR	1	2436	84.7	< 0.0001
Site:EFR	2	2436	4.56	0.03

Daily Mean Water Temperatures

A linear mixed model with heterogeneous, correlated errors was fitted to the daily mean water temperatures from Dalgety and Mowamba. There were very highly significant differences between sites and season and a significant interaction between these (Table 11). EFR was not significant and there was no significant interaction between sites and EFR (Table 11).

Table 11. ANOVA summary for the comparison of daily mean water temperatures for Dalgety and Mowamba River

Source of variation	numDF	denDF	F-value	p-value
Site	1	2436	284.1	< 0.0001
season	4	2436	407.8	< 0.0001
Site:season	4	2436	4.17	0.002
EFR	1	2436	0.30	0.58
Site:EFR	2	2436	0.26	0.61

4.6 HYPOTHESIS 3

> *"…There will be a decrease in mean EC at all Snowy River sites (particularly in the Dalgety area) compared to the pre- flow release period and the reference sites (11-13, 31-33) following an increase in baseflow. Response should be detected after the 21% MANF release..."*

4.6.1 Continuously gauged sites

Electrical conductivity of the Snowy River at Dalgety and Willis and the Mowamba River reference for the reporting period of January 1998 to August 2005 is shown in Figure 15. A general decline in electrical conductivity is evident at Dalgety after the 3.4% MANF flow release. The decrease in median electrical conductivity at Dalgety from 108 µscm^{-1} to 64µscm^{-1} was significant (Mann-Whitney U Test, $p < 0.05$) (Figure 16). A significant decrease also occurred at Willis from 104.7 µscm^{-1} to 84.2 µscm^{-1} with EFR (Mann-Whitney U Test, $p < 0.05$) (Figure 16). There was no significant change in electrical conductivity in the Mowamba River in the periods coincident with before and after the environmental water releases to the Snowy River (Mann-Whitney U Test, $p<0.05$) (Figure 16).

Figure 15. Electrical conductivity of the Snowy River at Dalgety and Willis and the Mowamba River for the reporting period of January 1998 to August 2005.

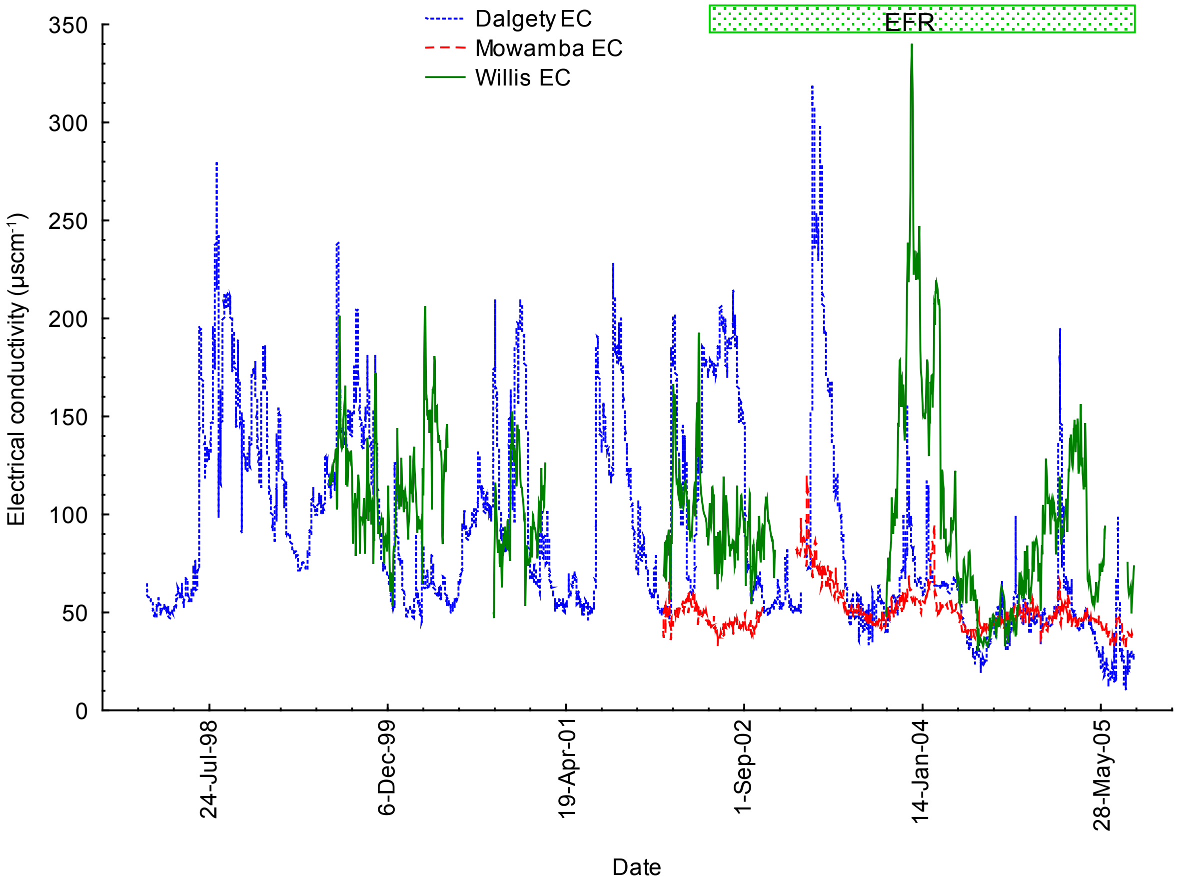
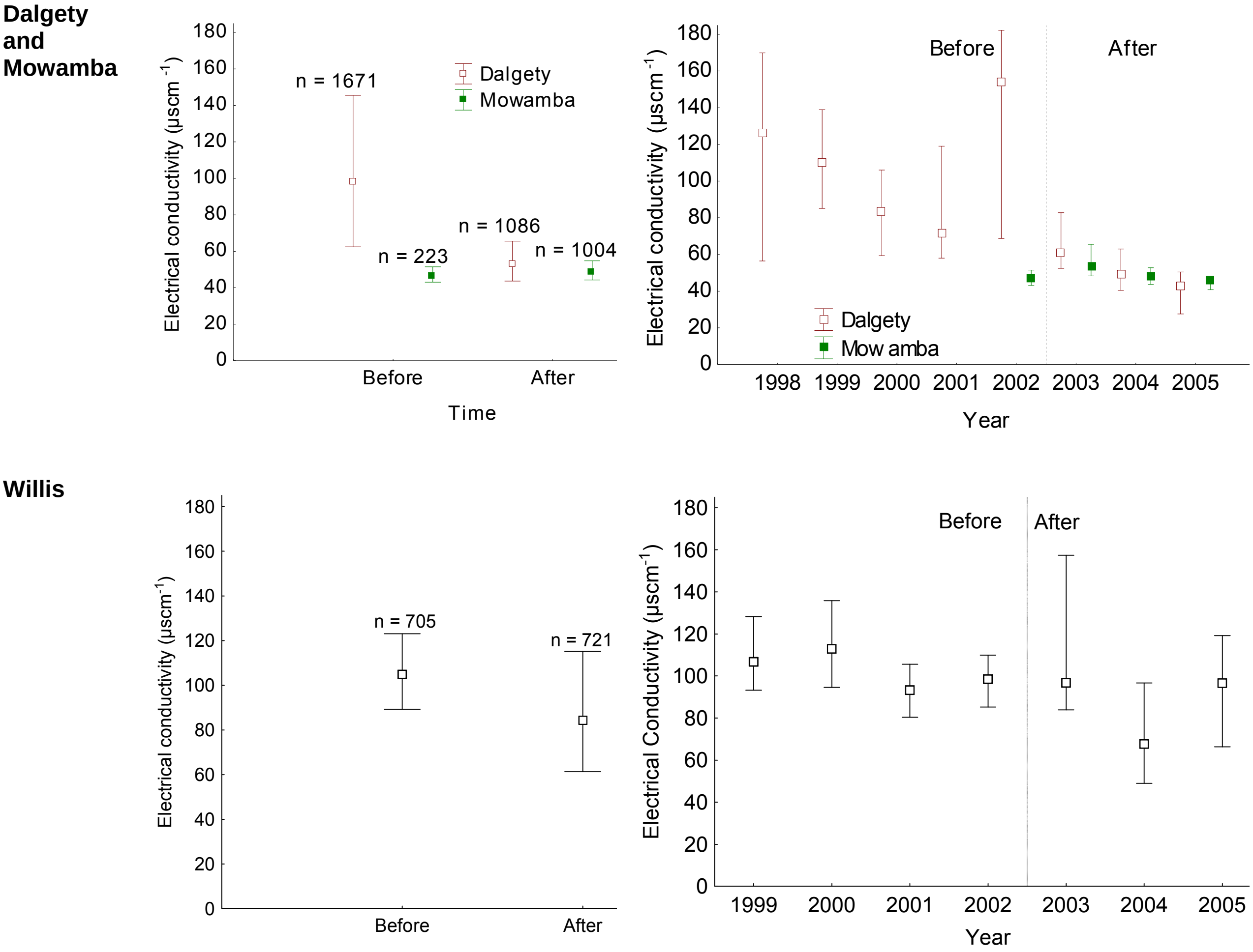


Figure 16. Median electrical conductivity at Dalgety, Willis and the Mowamba River reference site, a) before and after environmental flow releases in the Snowy River, and b) each year. Error bars around the median represent 25th to 75th inter quartile range.



a) **b)**

Electrical conductivity at Dalgety appears to respond to flow events (Figure 17) by increasing with high flow events, but there is an overall decrease in electrical conductivity evident with the higher baseflows. There was a great increase in electrical conductivity at Dalgety in response to a flood that immediately followed extensive bushfires in the catchment in March 2003 (Figure 17). Electrical conductivity at Willis does not appear to respond to flow events (Figure 18). Electrical conductivity is fairly consistent and low at the Mowamba River reference site although there is a slight pattern of increases in summer, and a strong seasonal pattern in discharge due to spring snowmelt (Figure 19). There is some similarity in the pattern of electrical conductivity at Dalgety and the Mowamba River in the period coincident with EFR, suggesting that electrical conductivity at Dalgety is influenced both by the return of a seasonal pattern in discharge from the Mowamba River and also by the lower electrical conductivity of the Mowamba River (Figure 17 and Figure 19).

Figure 17. Electrical conductivity and discharge at Dalgety from January 1998 to August 2005.

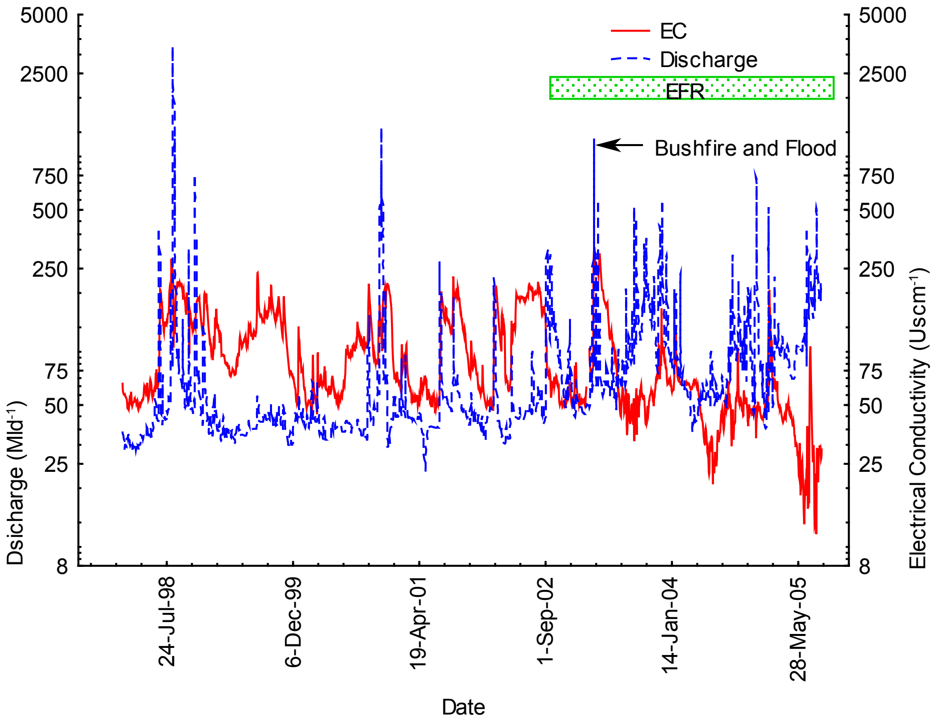


Figure 18. Electrical conductivity and discharge at Willis from June 1999 to August 2005.

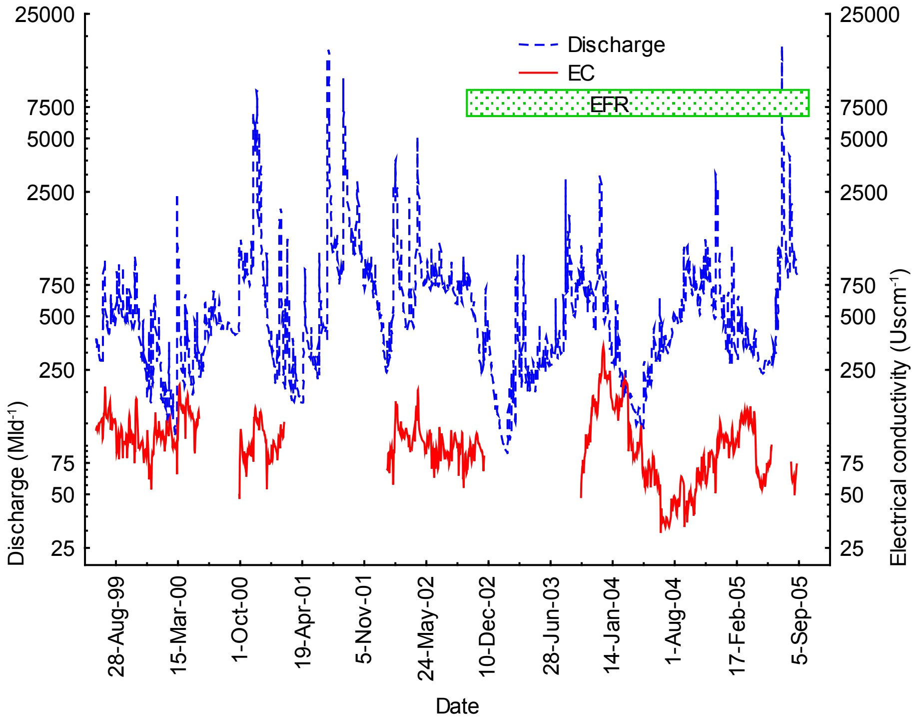
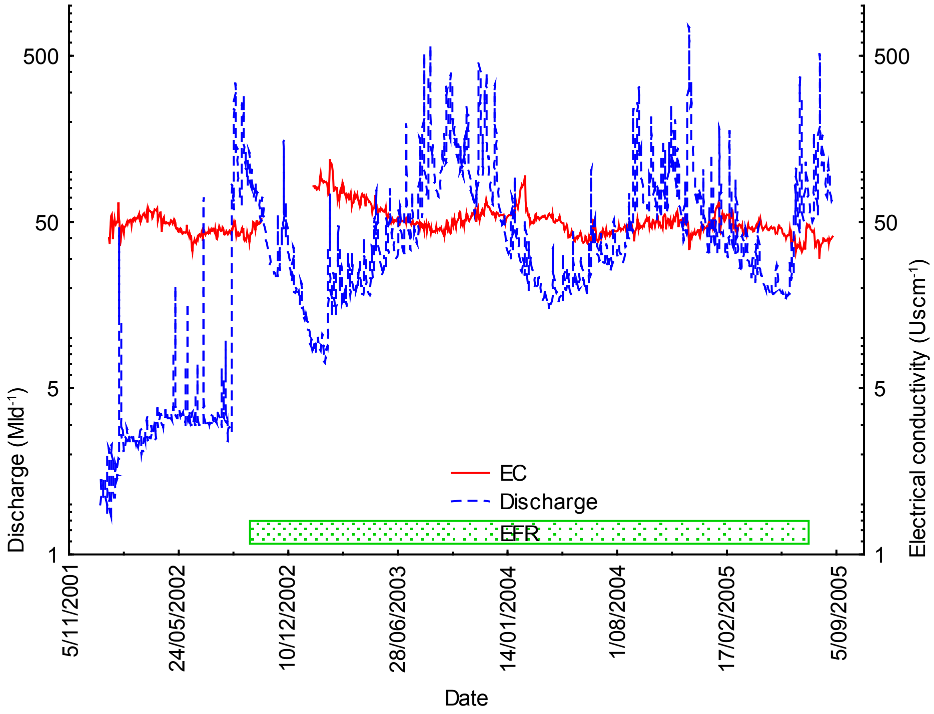


Figure 19. Electrical conductivity and discharge at Mowamba River from January 2002 to August 2005.

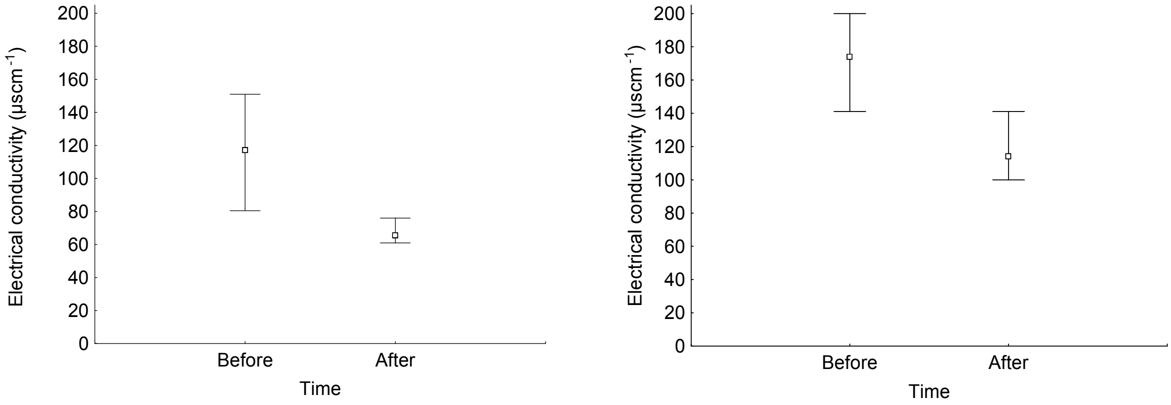


4.6.2 Discretely sampled sites

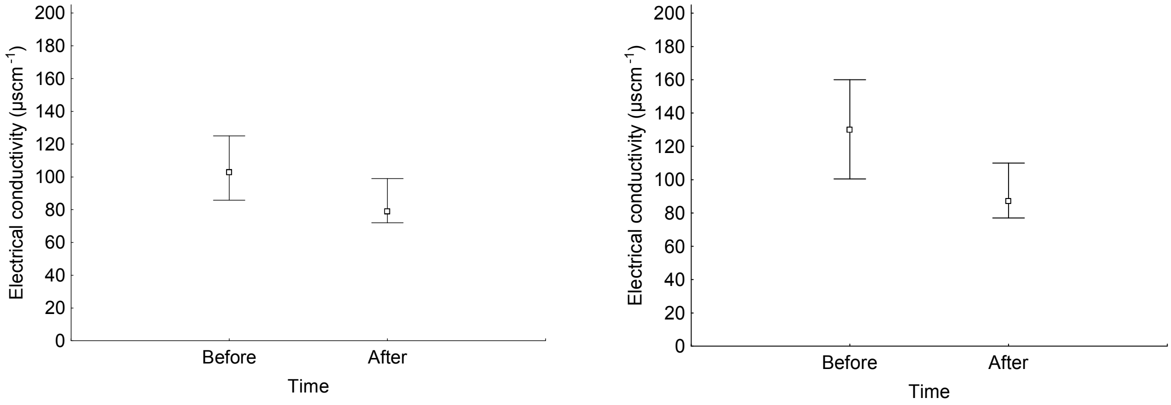
Significant decreases in electrical conductivity at all Snowy River sites with discrete data were detected after environmental flow releases (Mann-Whitney U Tests, $P < 0.05$) (Figure 20). Decreases in median electrical conductivity were as follows: Dalgety from 117µscm^{-1} to 65.5 µscm^{-1}, Burnt Hut from 173.5 µscm^{-1} to 114 µscm^{-1}, Willis from 102.8 µscm^{-1} to 79 µscm^{-1}, McKillops from 130 µscm^{-1} to 87 µscm^{-1} and Jarrahmond 143.3 µscm^{-1} to 109.5 µscm^{-1} (Figure 20). The results for the discretely measured data at Dalgety and Willis were very similar to the continuous data (Figure 16 and Figure 20).

Significant decreases in median electrical conductivity were also found in two of the reference rivers in the period coincident with after environmental flows to the Snowy River, indicating that other (untested) factors are involved in the results for both the Snowy River and reference rivers, most likely the drought that was coincident with EFR. Median electrical conductivity in the Buchan River decreased from 85 µscm^{-1} to 63 µscm^{-1} and in the Brodribb River from 90 µscm^{-1} to 84 µscm^{-1} (Mann-Whitney U tests, $p< 0.05$) (Figure 21). Median electrical conductivity in the Delegate River decreased from 94 µscm^{-1} to 79 µscm^{-1} (Figure 21), although this was not statistically significant (Mann-Whitney U test, $p > 0.05$). There was no change at the Roger River reference site in the period coincident with EFR in the Snowy River (Figure 21).

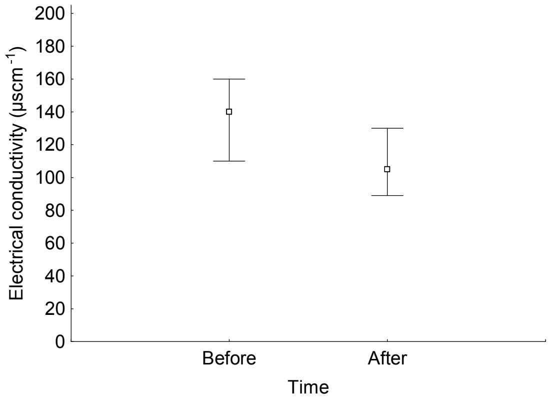
Figure 20. Median electrical conductivity before and after the 3.4% MANF flow release at Snowy River sites with discrete data.



a) Dalgety **b) Burnt Hut**

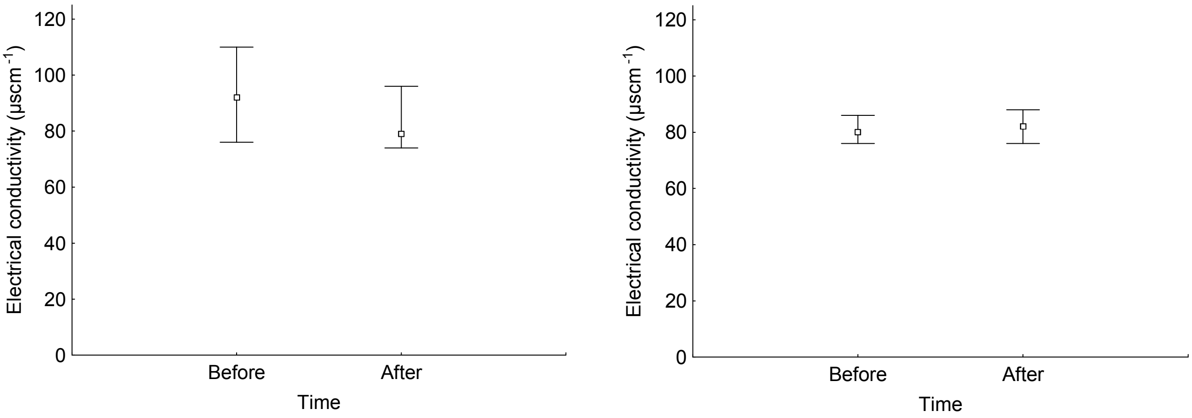


c) Willis **d) McKillops**

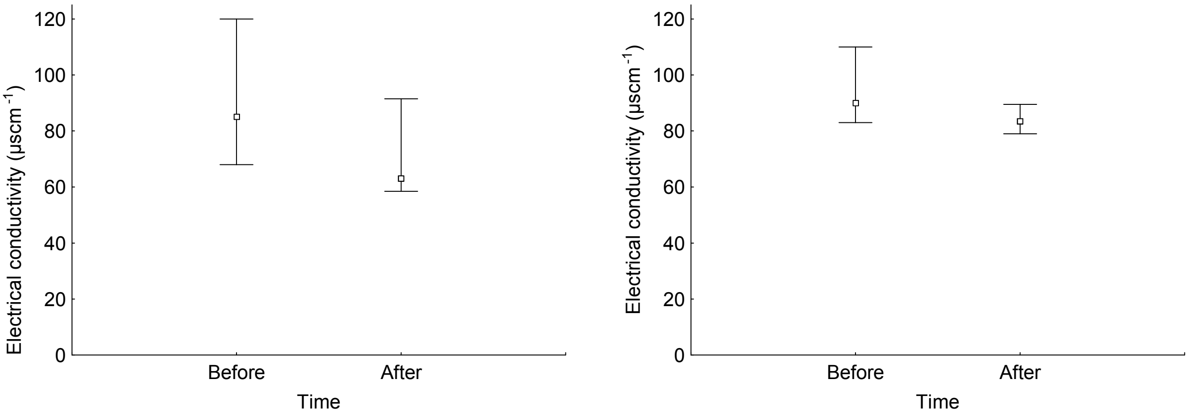


e) Jarrahmond

Figure 21. Median electrical conductivity before and after the 3.4% MANF flow release at reference sites with discrete data.



a) Delegate River **b) Rodger River**



c) Buchan River **c) Brodribb**

4.7 THERMAL IMPACTS OF HYPOLIMNIAL RELEASES

The longitudinal summer temperature profile of the Snowy River from Jindabyne Dam to Jarrahmond shows that the temperature of dam releases is very similar to the nearby Mowamba River, and that water temperatures in the Snowy River from Dalgety to Jarrahmond are higher and very similar (Figure 22). There is no apparent impact of Jindabyne Dam on mean summer water temperature in the Snowy River before or with EFR.

Elevated winter water temperatures from Jindabyne Dam releases are evident in the longitudinal winter temperature profile for the Snowy River (Figure 22). Mean water temperature at the syphon was 9°C before EFR which is 5 °C to 7 °C warmer than the nearby Mowamba River reference site, and 3 °C to 5 °C warmer than the Snowy River at Dalgety. The mean water temperature at the syphon is increased by a further 2 °C after the EFR to 11 °C, and is warmer even than mean winter water temperature at the most downstream lowland site at Jarrahmond (Figure 22). There is no apparent change in mean winter water temperatures at any other sites with EFR. Winter water temperatures increase longitudinally from Dalgety to Jarrahmond. There does not appear to be any elevation of winter water temperatures at Dalgety.

Figure 22. Longitudinal profile of mean summer and winter water temperatures in the Snowy River from 1999 to 2005, before and with EFR. Sites are shown left to right as upland to lowland from Jindabyne Dam (syphon) to near the estuary at Jarrahmond, including the Mowamba River as the source of EFR to the Snowy River.

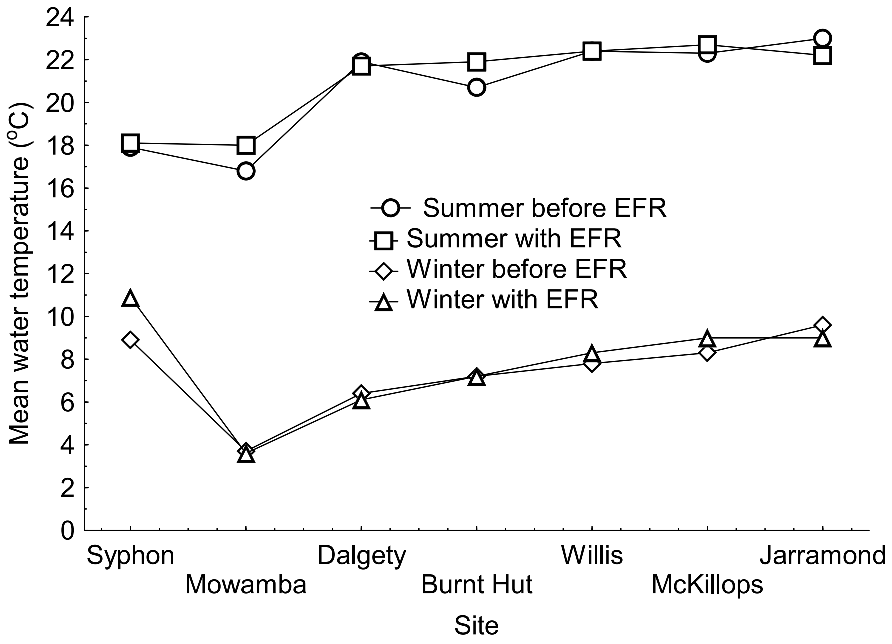
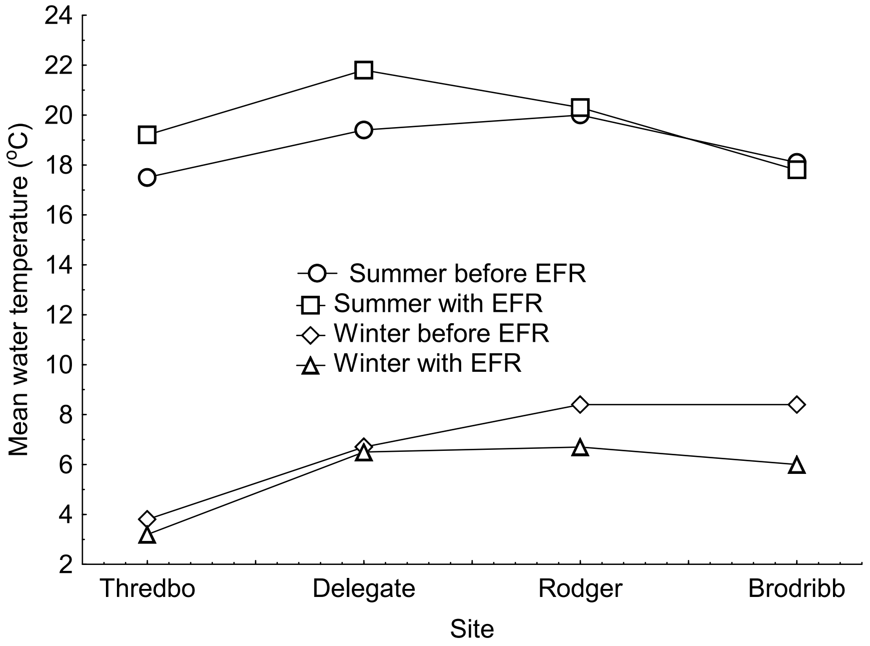


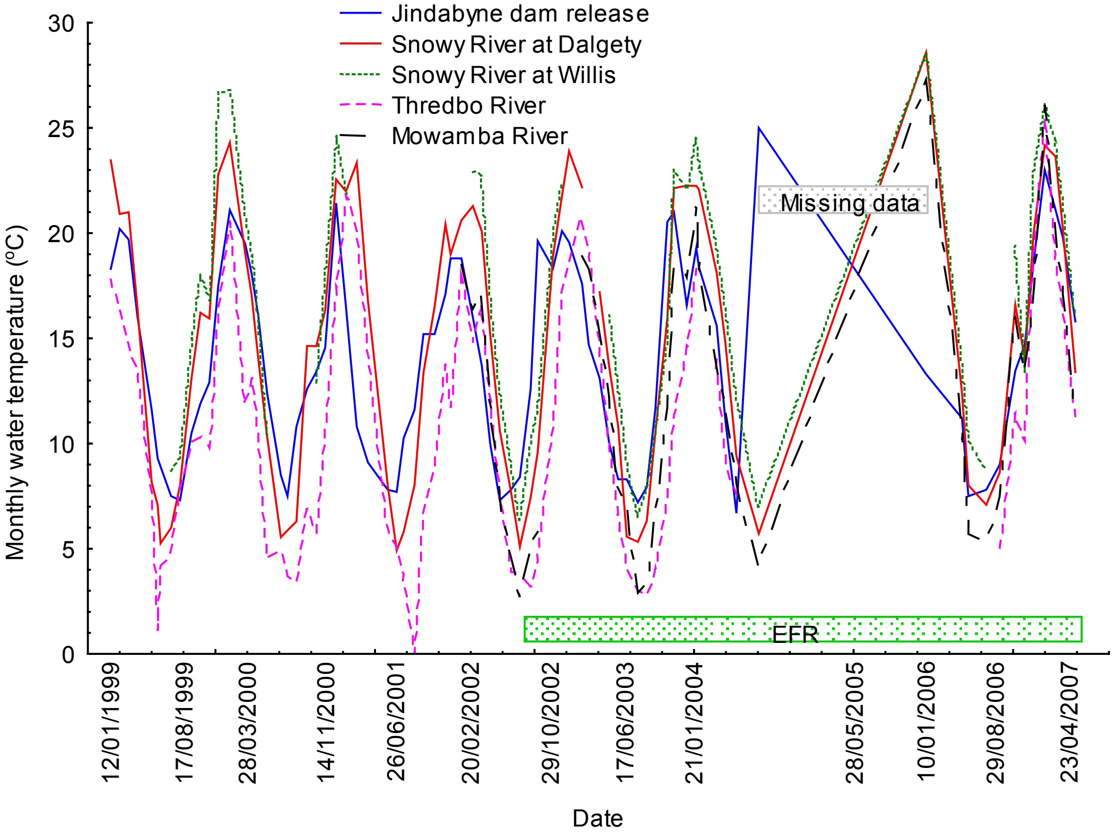
Figure 23. Longitudinal profile of mean summer and winter water temperatures in the reference sites from 1999 to 2005, before and with EFR. Sites are shown left to right as upland to lowland from Thredbo River (near Jindabyne Dam) to the Brodribb River (near the Snowy River at Jarrahmond).



Mean summer water temperatures in the lowland reference sites were somewhat cooler than the midland reference site at Delegate River and the midland and lowland Snowy River sites (Figure 22 and Figure 23). The mean winter water temperatures are similar to the respective Snowy River sites. The Thredbo River mean water temperatures are similar in summer and winter to the nearby Mowamba River, and 5 °C to 7 °C cooler than the syphon water temperature in winter (Figure 22 and Figure 23).

In addition to the elevated winter water temperatures of the syphon releases, another thermal impact of hypolimnial releases from Jindabyne Dam is a slight forward shift in the seasonal temperature regime before EFR, meaning that maximum and minimum temperatures for Jindabyne Dam tend to occur earlier than at sites further downstream at Dalgety and Willis and the nearby Thredbo and Mowamba River reference sites (Figure 24). The thermal effects of the hypolimnial releases are likely to be greatest close to the dam in the Jindabyne Gorge. The lowland Snowy River at Willis experiences warmer temperatures than Dalgety but follows a similar seasonal pattern (Figure 24). Water temperature and seasonality in the Thredbo and Mowamba Rivers are very similar.

Figure 24. Monthly water temperatures of Jindabyne Dam releases, the Snowy River at Dalgety and Willis, and the Thredbo and Mowamba River reference sites. Corresponding dates and times of the monthly water temperatures of the Snowy Hydro sites at Jindabyne Dam and the Thredbo River are taken from the continuous DWE sites on the Snowy and Mowamba Rivers, and are extended beyond the study period to 2007. The dates for the discretely sampled Victorian sites did not match up with the Snowy Hydro sampling dates so could not be compared.



5 Discussion

5.1 WATER QUALITY AND THE ASSESSMENT OF THE FIRST RELEASE

The purpose of this progress report is to provide an assessment of possible changes to water quality variables attributable to the first environmental flow releases to the Snowy River. Although the mean daily baseflow has almost doubled at Dalgety with the increase to 3.4% MANF, from the mean daily flow of 56 to 106.9 Mld^{-1}, it must be kept in context that 106.9 Mld^{-1} represents only 3.4% of the average daily baseflow that occurred before the dam was built. Additionally, the spatial extent of the hydrological signal was limited to the upper macro-reach. At all other sites on the Snowy River besides Dalgety, mean daily baseflows have actually decreased by 20% to 31% since the first flow release (Morton and Green, in prep.), presumably because of the regional drought. Therefore, any changes in water quality downstream of Dalgety are due to either reduced flows during the drought and/or a combination of other environmental factors, not due to increased flows. Changes in flow and water quality at Dalgety are likely to be a direct result of the Mowamba River flow releases, but the influence of the Mowamba River flows has dissipated downstream at Burnt Hut. The effect of EFR is likely to attenuate with increasing distance downstream, because of the increasing volume of discharge from tributaries along the course of the river. However, the 3.4% MANF flow release may have off-set the drought effect to some extent, as without the flow release, mean daily flows would presumably be even lower at all Snowy River sites during the drought.

Air temperature for the climate stations at Thredbo and Bombala show similar seasonal variability to the Snowy River at Dalgety and Willis and the Mowamba River reference site. There was no significant difference in air temperature in the periods coincident with before and after EFR, so any changes in water temperature with EFR are not caused by air temperature.

There was no direct evidence of an impact of environmental flow releases on water temperatures for the Snowy River at Dalgety. However, daily mean, maximum and minimum water temperatures were negatively correlated with the mean daily flow at Dalgety and positively correlated with inflows from the Mowamba River. Water temperature was also very strongly influenced by air temperature. Hence, it is likely that as the volume of water released from Lake Jindabyne is increased, water temperatures at Dalgety will be more strongly influenced by stream flow and less by atmospheric influences.

EFR had no significant impact on summer mean daily water temperatures at Dalgety after adjusting for the effects of air temperature and lags in air temperature. There was no significant effect of EFR on the modelled summer maximum daily water temperature, which were 23.7ºC before EFR and 23.5ºC with EFR. However, the maximum recorded summer water temperature at Dalgety is 27.5ºC, which is close to the maximum temperature tolerance of 28°C for some native fish species in the Snowy catchment (Koehn and O'Connor, 1990), so any significant increase in maximum water temperature would be of ecological concern.

There was no significant effect of EFR on winter mean daily water temperature at Dalgety. There was a negative effect of MDF on winter minimum water temperature. Although there was a decrease in the minimum daily water temperatures from 5.1ºC before EFR to 4.5ºC with EFR, there was no significant effect of EFR. Such a small change in water temperature is unlikely to be of ecological significance for aquatic biota, unless it is close to their lethal or sub-lethal temperature tolerance, or temperature requirements during lifecycle phases such as spawning. In the case of several native fish species recorded in the Snowy catchment (Gilligan, in prep.) the minimum water temperature tolerance is 5^{O}C (Koehn and O'Connor, 1990), so the decrease in water temperature to 4.5 ºC may have an ecological impact.

A statistically significant increase in both the diurnal range and the variability of daily fluctuations in the range of water temperatures in the Snowy River at Dalgety by 0.8 ^{o}C was detected with EFR, however this is a very small change which may be an artefact of the very large data set, and is unlikely to be ecologically significant. The variability of the diurnal variation increased with the magnitude of the diurnal range. That is, small values of the diurnal range had small variance and vice versa. A significant effect of EFR on diurnal variation was also shown in the Mowamba River coincident with the periods before and with EFR, which is not caused by EFR as this is a reference site, so is either due to climatic variability among years, or because with only nine months of water temperature records in the period coincident with before EFR there is no replication among years. Diurnal water temperature variability is consistently higher in the Mowamba River than in the Snowy River, which is likely to be because of the greater natural flow variability and smaller stream size of the Mowamba River. Daily variability in discharge and water temperature is important for certain life cycle stages of aquatic biota, including fish spawning and juvenile growth (Tetzlaff *et al*., 2005), and macroinvertebrate egg development and larval growth (Hering *et al*., 2005).

The elevated winter water temperatures and seasonal shifts in water temperature of the Jindabyne Dam syphon releases have been identified as thermal modifications to the temperature regime downstream of dams (Walker, 1979) and have been implicated in changes to macroinvertebrate communities (Ward and Stanford, 1979*).* Thermal profiles of Jindabyne Dam showed that releases from the bottom of the metalimnion or the very top of the hypolimnion (depending on storage level) at the 18m level were between 9 to 12^{o}C all year round (Acaba et al., 1998), which is substantially colder than the summer temperatures and warmer than the winter temperatures reported here*.* This is similar to findings on other south east Australian rivers, such as the Mitta Mitta River where flow releases from Dartmouth Dam decreased water temperature by up to 10^{o}C (Ryan and Koehn, 2001), and the Murrumbidgee River where temperatures dropped sharply by up to 18 ^{o}C downstream of a cold water influx from the Tumut River tributary below Blowering Dam (Astles, 2001). Sudden decreases in water temperature can cause temperature shock to the eggs or larvae of fish and macroinvertebrates, which can be lethal and can also prevent recruitment (Koehn, 2001). Flows from Jindabyne Dam need to be managed to prevent hypolimnial releases.

The thermal effects of releases from Jindabyne Dam are likely to be greatest close to the dam in the Jindabyne Gorge, with the elevated winter water temperatures appearing to lessen further downstream at Dalgety and Willis. The river valley at Willis is shallower and more open, allowing slight winter heating through solar radiation and warmer ambient air temperatures. Similarly, Cowx *et al*. (1987) found that elevated winter temperatures and other thermal impacts below a dam were reduced within 36 km downstream, although temperature changes can extend much further downstream than this depending on factors including the size of the dam and the volume of water released. Water temperature is generally cooler in upland river reaches in Australia because of higher altitude and more shade than in lowland river reaches (Boulton and Brock, 1999). Water temperatures in the Snowy River follow this longitudinal pattern of increasing water temperature with increasing distance downstream and lower altitude (Figure 22), with the exception of elevated winter water temperature of the Jindabyne Dam releases upstream of Dalgety. Water temperature in the Snowy River sites were similar to the reference sites apart from the lowland reference sites at the Rodger and Brodribb Rivers being somewhat cooler than the lowland Snowy River sites, and also cooler than the midland reference site at Delegate River. This is probably because in comparison to the Snowy and Delegate Rivers, the lowland reference sites have much taller and thicker riparian vegetation cover to provide shading, and are smaller streams with less surface area and discharge in more confined valleys. Being smaller, shallower and more shaded than the middle and lower Snowy River, the Rodger and Brodribb Rivers are likely to be more influenced by the cool ambient air temperatures in the Orbost region, where mean summer temperature is lower than Thredbo and Bombala.

Water temperature affects other water quality variables such as salinity and dissolved oxygen (Boulton and Brock, 1999), so water temperature changes may affect the salinity tolerances of macroinvertebrates or the dissolved oxygen tolerances of fish (Doeg and Heron, 2003). Macroinvertebrates in the Barwon River catchment in Victoria are reported by Kefford *et al*. (2005) to have relatively high tolerances to salinity (6400 to 32000 µscm^{-1}) compared to the maximum recorded electrical conductivity in the Snowy River of 640 µscm^{-1} and 880 µscm^{-1} in the Buchan River.

The continuous and discrete electrical conductivity data for the Snowy River below Jindabyne Dam and the reference sites is within the respective ranges for upland and lowland ecosystem types in slightly disturbed ecosystems in south-east Australia (ANZECC, 2000). The continuous data recorded at Dalgety and Willis has lower minimum and higher maximum values than those recorded at the same sites in the discrete sampling, because the higher frequency of continuous measurement picks up more extremes in the data than discrete sampling, however the median values were very similar. Whilst there was a statistically significant decrease in electrical conductivity at all Snowy River sites after the first flow release, this also occurred at two of the reference sites for the same time period, so the change in electrical conductivity cannot be attributed to the flow release except perhaps at Dalgety, particularly since flows in all sites except Dalgety are significantly lower than before the first flow release. A possible cause of these changes may be the drought, with the decreased runoff from the catchment to the rivers. At Dalgety where the flows did increase with EFR, the electrical conductivity decreased to a similar level as that of the Mowamba River, so the Mowamba River inflows are likely to be a contributing factor.

The water quality analysis in this report was undertaken using a linear mixed effects model which allowed serial correlation and heterogeneity of variances to be modelled. This approach also allowed for an explicit testing of impacts due to environmental flow releases via a dummy variable for EFR. However, the EFR variable assumed a step change whereas the impact of EFR might be expected to vary with the volume of the release. To some extent, this was accounted for by incorporating stream flow at Dalgety in the model as a predictor, although this predictor could not distinguish from flow contributions from the Mowamba River and Jindabyne Dam. In some cases, the mixed models did not track runs or fluctuations in water temperatures for short periods, but this is evident in the diurnal variability analysis. If, as recommended in section 7, continuous data were available for the outlet water temperature then a relationship could be developed between this and water temperatures at Dalgety in future analysis along with the available daily water temperature from the Mowamba River, taking into account time lags between the sites. The recommended continuous discharge from the Jindabyne outlet and Mowamba River could also provide an additional adjustment to these water temperatures. Similar information for other major tributaries like the Delegate River for modelling temperatures at Willis and the

Buchan River for modelling temperatures at Jarrahmond would also be useful for future modelling. Daily air temperature data for Dalgety and Willis would be beneficial for future modelling. Linear mixed models are useful for modelling variance heterogeneity (e.g. the diurnal temperature range) but the models are limited by data quality (such as gaps). In future, the antecedent water temperatures for Dalgety could be incorporated as predictors to improve the model. However, these would probably be strongly correlated with other predictors, introducing problems with multicollinearity.

Applying time series intervention analysis to the above additional data is also recommended, using the Jindabyne outlet data to predict water temperature at Dalgety and Willis, and additionally at sites 1, 7 and 10 if installed as recommended. Mowamba could be used as a control in such analysis. These types of models are described, giving clear examples of the method for water quality applications, by Hipel *et al*. (1975) and Welsh and Stewart (1989, 1991). The intervention analysis models would incorporate the outlet and Mowamba data using what are known as transfer functions. This would test the impact of EFR releases on downstream water temperatures as it would demonstrate a direct relationship (if one exists). The method does not incorporate multiple sites in the one model, so another model would need to be done for the “control” site (Mowamba) to demonstrate that water temperatures there were not connected with outlet temperatures. A separate Intervention analysis could also be used to examine various forms of response to an intervention (i.e. EFR) (see Hipel *et al*., 1975, for details).

5.2 PROJECT DESIGN

A number of issues with the study design and data were encountered in the analyses for this report. The design is unbalanced spatially and temporally, which limits the applicability of a BARI design, so the study is largely a time series analysis that looks at the “intervention” of EFR at each site. There are inconsistent periods of record between all sites, including those with continuous data, which limits the Before/After and Reference/Impact comparisons that can be made. There are significant gaps in the water quality data set at Willis, so these data were not used in the temperature analyses. The continuous Mowamba River data is of very limited usefulness because there is less than one year of records before EFR, however the water temperature data were analysed for comparison with the Snowy River at Dalgety. At the Snowy River and reference sites where discrete data are measured, there are insufficient data in the first three years of EFR to conduct seasonal analyses of water temperature, therefore only the temperature data from the continuously monitored sites can be used to test hypotheses 1 and 2. The long term discrete data, whilst not sufficient for seasonal temperature analyses, are useful for the electrical conductivity analyses and the longitudinal temperature analyses, however there are too few data after EFR to be confident in the results of these analyses. The testing of hypotheses one and two requires greater spatial and temporal water temperature data, so this issue needs to be addressed by increasing the number of sites with continuous water quality monitoring in both NSW and Victoria. Additional continuous discharge and water quality monitoring is recommended for the sites specified in section 7.

Air temperature data for the continuously monitored sites would be useful for future water temperature analysis.

6 Conclusion

This report presents the results of the first three years of environmental flow releases to the Snowy River. The water quality hypotheses were designed to test changes after 21% MANF flow releases. The initial EFR resulted in a small increase in flow at Dalgety from 1.9% MANF to 3.4% MANF, typically a doubling in base flow from 56 to 106.9 Mld^{-1}. A clear hydrological signal of the release could not be detected at the gauging stations downstream of Dalgety.

Typically over the study period, river discharge declined at all gauged sites except Dalgety as the region experienced a severe drought coincident with the EFR. Changes in water quality at sites downstream of Dalgety cannot be attributed to environmental water releases given the limited spatial influence of the releases, and are probably due to other environmental factors such as the drought.

In terms of the thermal regime at Dalgety, there was no significant change in mean, maximum or minimum water temperature at Dalgety with the environmental flow release. There were significant effects of mean daily flow and air temperature on water temperature at Dalgety, the former suggests that larger EFR would reduce stream water temperatures. Environmental flow releases significantly increased the diurnal water temperature range at Dalgety and increased the variability of daily fluctuations in the range of water temperatures, however the small changes are unlikely to be of ecological significance and are only detected because the data set is very large. The significant difference in diurnal variation at the Mowamba River reference site between the periods coincident with before and after EFR cannot be attributed to EFR because this is a reference site, so is either due to climatic variability or an artefact of the unbalanced data set. Diurnal variation in water temperature was consistently higher in the Mowamba River because of the more variable natural discharge and the smaller stream size compared to the Snowy River.

There was a statistically significant decrease in electrical conductivity at all Snowy River sites and two of the reference sites. The reduced electrical conductivity is likely to be due to reduced catchment runoff during the drought.

The design is spatially and temporally unbalanced, so interpretations are largely limited to within site comparisons. This limits the ability to test hypotheses one and two, which require greater spatial and temporal water quality data, so this needs to be resolved by installing additional continuous discharge and water quality monitoring stations in both NSW and Victoria. The analysis was constrained by inconsistent sampling frequencies and periods of record between sites. Very small changes in water temperature that are not ecologically significant have been detected as statistically significant in some of the analyses because of the large data sets. Recommendations are made for the monitoring program and future analyses.

7 Recommendations

The following recommendations regarding the environmental flow releases need to be considered by Government:

1. Environmental water releases from Jindabyne Dam need to be managed to prevent hypolimnial releases, to minimise water quality impacts such as cold water pollution, increased winter temperature and changes in the annual temperature cycle; and
2. Greater releases are required in-order to mix the water in river pools and thus introduce a more natural water quality regime.

The following recommendations regarding the water quality monitoring program need to be considered by Government:

3. Additional continuous discharge, water temperature and electrical conductivity monitoring stations should be installed on the Snowy River and reference sites in both NSW and Victoria as shown in Table 12, because the current design restricts the testing of hypotheses one and two (which require increased spatial and temporal water temperature data). Specifically, continuous discharge and water quality should be installed at the following sites (some stations only require modifications rather than full installation):

Table 12. Additional continuous discharge and water quality monitoring recommendations

Site	Discharge	Temperature	EC	Comment
Jindabyne Dam		*	*	Also TP#, TN# and depth profiles of temperature and dissolved oxygen
Jindabyne Dam release syphon	*	*	*	Also TP and TN
Thredbo River at Paddys corner (site 13)	Existing	*	*	
Mowamba River at Pats Patch	Existing	*	*	
Snowy River downstream Mowamba River (Site 1)	*	*	*	
Delegate River at Quidong (Site 11)	Existing	*	*	
Snowy River at McKillops Bridge (Site 7)	*	*	*	
Snowy River at Jarrahmond (Site 30)	*	*	*	
Roger River near Jackson’s Crossing (Site 31)	*	*	*	
Buchan River at Buchan (Site 32)	*	*	*	
Brodribb River at Sardine Creek (Site 33)	*	*	*	

TP = total phosphorus, TN = Total nitrogen

4. Snowy Hydro should undertake continuous water quality monitoring (including nutrients) in Jindabyne Dam and at the syphon. Jindabyne Dam monitoring should include continuous depth profile data on water temperature and dissolved oxygen.

5. Installation of *in situ* weather stations to monitor daily air temperature monitoring at continuous sites, particularly Snowy River sites 4 (Dalgety) and 6 (Willis) should be investigated and resourced if possible, as this would improve water temperature modelling.

6. Changes in turbidity and nutrients in response to environmental flow releases are of interest to the community and river managers, and should be monitored in the Snowy River when this can be resourced.

7. Future data analysis should incorporate all of the above additional data and sites into linear mixed models to test the effect of EFR on water temperature.

8. Time series Intervention analysis should also be undertaken for Dalgety, Willis and new continuous sites to test the impact of EFR on downstream water temperatures.

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