Copyright and Disclaimer

© 2005 CSIRO To the extent permitted by law, all rights are reserved and no part of this publication covered by copyright may be reproduced or copied in any form or by any means except with the written permission of CSIRO.

Important Disclaimer:

CSIRO advises that the information contained in this publication comprises general statements based on scientific research. The reader is advised and needs to be aware that such information may be incomplete or unable to be used in any specific situation. No reliance or actions must therefore be made on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, CSIRO (including its employees and consultants) excludes all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

Cover Photograph:

Description: Hume Dam
Photographer: Brad Sherman
© 2005 CSIRO
Table of Contents

1. EXECUTIVE SUMMARY ........................................................................................................ 1
2. OVERVIEW ............................................................................................................................. 5
3. PREVIOUS STUDIES ............................................................................................................... 7
4. DATA ACQUISITION ................................................................................................................ 9
   4.1. EQUIPMENT SPECIFICATIONS ....................................................................................... 9
   4.1.1. EQUIPMENT PERFORMANCE .................................................................................. 14
   4.2. DATA CAPTURE ............................................................................................................ 15
5. ANALYSIS ............................................................................................................................. 16
   5.1. WATER LEVEL ............................................................................................................. 16
   5.2. METEOROLOGY ............................................................................................................ 16
   5.2.1. CHARACTERISTICS OF THE WIND REGIME ......................................................... 20
   5.2.2. TURBULENT HEAT, MASS, AND MOMENTUM FLUXES ....................................... 26
   5.3. THERMISTOR CHAIN .................................................................................................. 28
   5.3.1. SURFACE MIXED LAYER TEMPERATURE ................................................................. 28
   5.3.2. SURFACE MIXED LAYER DYNAMICS .................................................................. 29
   5.3.3. INTERNAL WAVE ACTIVITY .................................................................................. 31
   5.4. SEA BIRD SBE19 PROFILER ....................................................................................... 32
   5.4.1. SPATIAL VARIABILITY ........................................................................................... 32
   5.4.2. INFLOW INTRUSIONS/UNDERFLOWS ................................................................. 37
   5.4.3. MITTA MITTA ARM ............................................................................................... 37
   5.4.4. MURRAY ARM ........................................................................................................ 38
   5.5. RIVER TEMPERATURES ............................................................................................... 39
      5.5.1. MITTA MITTA RIVER ........................................................................................... 41
      5.5.2. MURRAY RIVER ................................................................................................ 43
      5.5.3. HUME DAM DISCHARGE .................................................................................... 43
6. HEAT AND WATER BUDGETS ............................................................................................. 45
   6.1. WATER BALANCE ........................................................................................................ 45
   6.2. BUDGET ....................................................................................................................... 47
7. A SIMPLE CONCEPTUAL-ANALYTICAL MODEL OF HUME DAM DISCHARGE TEMPERATURE - IMPLICATIONS FOR FUTURE OPERATING CONDITIONS ................................................. 53
8. NUMERICAL MODELLING OF THE EFFECT OF ADDING A MULTI-LEVEL OFFTAKE CAPABILITY ON HUME DAM DISCHARGE TEMPERATURE .......................................................... 55
   8.1. MODEL DESCRIPTION ................................................................................................. 55
   8.2. ASSUMED HYDROLOGIC CONDITIONS ...................................................................... 56
      8.2.1. INFLOW ASSUMPTIONS ....................................................................................... 58
      8.2.2. INFLOW ASSUMPTIONS ....................................................................................... 58
      8.2.3. INITIAL STRATIFICATION .................................................................................. 59
   8.3. MODEL VALIDATION ................................................................................................... 60
   8.4. SCENARIO RESULTS .................................................................................................... 62
      8.4.1. HIGH WATER LEVEL .......................................................................................... 62
      8.4.2. LOW WATER LEVEL .......................................................................................... 67
   8.5. SUMMARY .................................................................................................................. 68
9. MITIGATION STRATEGIES - MANAGEMENT IMPLICATIONS .............................................. 69
10. CONCLUSIONS .................................................................................................................... 71
11. RECOMMENDATIONS ......................................................................................................... 73
12. REFERENCES ...................................................................................................................... 75
13. APPENDIX A - LONG-TERM MODEL SIMULATIONS .............................................................. 77
   13.1. MODEL INPUT DATA ................................................................................................. 77
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.1.1. METEOROLOGICAL DATA</td>
<td>77</td>
</tr>
<tr>
<td>13.1.2. INITIAL WATER LEVEL AND STRATIFICATION</td>
<td>82</td>
</tr>
<tr>
<td>13.1.3. RIVER DISCHARGE AND RESERVOIR LEVEL</td>
<td>83</td>
</tr>
<tr>
<td>13.2. MODEL RESULTS</td>
<td>83</td>
</tr>
<tr>
<td>13.3. REVISED LONG-TERM SIMULATION</td>
<td>84</td>
</tr>
<tr>
<td>13.3.1. RIVER MURRAY DISCHARGE</td>
<td>84</td>
</tr>
<tr>
<td>13.3.2. WIND SPEED CORRECTION</td>
<td>86</td>
</tr>
<tr>
<td>13.3.3. INFLOW TEMPERATURE CORRECTION</td>
<td>86</td>
</tr>
<tr>
<td>13.3.4. REVISED LONG-TERM SIMULATION RESULTS</td>
<td>87</td>
</tr>
<tr>
<td>13.4. CONCLUSION</td>
<td>89</td>
</tr>
</tbody>
</table>
List of Figures

Figure 4.1 Location of profiling sites in Hume Reservoir ................................................................. 11
Figure 4.2 River temperature monitoring stations ........................................................................... 12
Figure 4.3 a) Hume Reservoir water column depth at TC Hume; b) Water surface levels during 2001-2002 and 2002-2003 ................................................................. 15
Figure 5.1 Daily meteorological data measured approximately 2 m above the water near Hume Dam during 2001-2002 ..................................................................................................... 18
Figure 5.2 Daily meteorological data measured approximately 2 m above the water near Hume Dam during 2002-2003 ..................................................................................................... 19
Figure 5.3 Wind rose showing monthly changes in the directional dependence of average and maximum wind speeds at Hume Reservoir .................................................................................. 22
Figure 5.4 Wind rose showing monthly trends in daily wind run at Hume Reservoir ......................... 23
Figure 5.5 Monthly trends in daily mean a), monthly maximum (b), and daily maximum wind speeds at Hume Reservoir ........................................................................................................ 24
Figure 5.6 Composite diurnal variation in mean, minimum, and maximum ten-minute wind speeds during December 2002 (top) and January 2003 (middle) .................................................. 25
Figure 5.7 Monthly mean heat fluxes at Hume Reservoir ................................................................ 26
Figure 5.8 Daily mean temperature of the top 5 m of the water column at each thermistor chain during 2001-2002 (a) and 2002-2003 (b) .................................................................................. 28
Figure 5.9 a) Surface mixed layer depths at the thermistor chains located at Hume Dam, and near the confluences of the Mitta Mitta River and Bowna River .................................................................... 30
Figure 5.10 Surface mixed layer depths at the dam wall (Hume) and southern end (Mitta) of Hume Reservoir during 2002-2003 ................................................................. 31
Figure 5.11 Internal wave activity at Hume dam shown as displacement of 21 °C isotherm (a & b), and 16 °C isotherm (c) .................................................................................................................. 32
Figure 5.12 SeaBird SBE19 temperature profiles at Hume Reservoir on 13 December 2001 .......... 34
Figure 5.13 SeaBird SBE19 temperature profiles at Hume Reservoir on 14 February 2002 .......... 34
Figure 5.14 SeaBird SBE19 temperature profiles at Hume Reservoir on 21 February 2002 .......... 35
Figure 5.15 SBE 19 temperature profiles measured north (even numbered sites) and south (odd numbered sites) of the dam wall (site 01)) on 2 Oct 02, 8 Nov 02, 4 Dec 02 and 3 Jan 03 .... 36
Figure 5.16 Weekly temperature profile data measured with the SBE19 profiler at the dam wall (site 01), north of the main basin (site 06), and midway to the Mitta Mitta Arm in the main basin (site 05) ................. 37
Figure 5.17 Mean SeaBird SBE19 temperature in the top 5 m at profile sites along the Mitta Mitta Arm of Hume Reservoir ............................................................... 38
Figure 5.18 Mean Seabird SBE19 temperature in the top 5 m at profile sites along the Murray Arm of Hume Reservoir ............................................................... 39
Figure 5.19 Hume reservoir inflow daily volumes and temperatures in the Murray River at Jingellic and the Mitta Mitta River at Tallandoon ............................................................... 40
Figure 5.20 Surface layer (SeaBird SBE19) and inflow temperatures in the Murray and Mitta Mitta arms of Hume Reservoir ............................................................... 41
Figure 5.21 Discharge (heavy line) and measured temperature increase, ΔT (solid line), along the Mitta Mitta River between Dartmouth Dam (Colemans) and Hume Reservoir (Tallandoon) .......... 42
Figure 5.22 Mitta Mitta River temperatures just downstream of Dartmouth Dam (Colemans), just upstream of Hume Reservoir (Tallandoon and in Snowy Ck at Granite Flat) ............... 43
Figure 5.23 Temperature of Hume Dam discharge, T_{out}, and Murray River temperature measured downstream of Hume Dam at Heywoods ............................................................... 44
Figure 13.14 Observed (solid lines) and simulated (dashed lines) temperature profiles for Hume Reservoir during spring to early summer 1983 (top) and 1984 (bottom) using original input data for the model.
List of Tables

Table 1 Hume Reservoir temperature monitoring stations................................................................. 10
Table 2 Reservoir monitoring instrument specifications................................................................. 12
Table 3 Hume Dam (TC Hume) thermistor depths and data logger channel allocation.................. 13
Table 4 Hume Reservoir Mitta Mitta arm (TC Mitta) thermistor depths and data logger channel allocation........ 14
Table 5 Comparison of characteristic values of mean daily meteorological parameters during 1 Feb 02 - 13 Mar 02 and 1 Feb 03 - 13 Mar 03................................................................. 17
Table 6 Monthly surface heat fluxes, turbulent velocity scales and surface mixing layer depths for Hume Reservoir during 2002-2003................................................................. 27
Table 7 Surface mixed layer depths, Z_{sml} at Hume Reservoir.......................................................... 29
Table 8 Water balance error for 4 Oct 2002 - 26 Mar 2003 (174 days). .................................................. 45
Table 9 Components of the water balance for Hume Reservoir accumulated over the following periods: 24-27 Nov 01, 2 Feb 02 – 13 Mar 02, 29 Mar 02 – 23 Apr 02...................................................................................... 47
Table 10 Storage level/inflow outflow model scenarios ......................................................................... 62
1. Executive Summary

Hume Dam is the major regulating structure on the River Murray system and is located near Albury at the upstream end of the river. Large volumes of water (> 20,000 ML d⁻¹) are released from the dam to supply irrigation and South Australian water entitlements. Discharge occurs through two outlets, which are located well below the thermocline under normal operating conditions. As a consequence, discharge temperatures during spring and summer may be depressed by more than 5 °C relative to the temperature in the surface layer of the reservoir. This depression of discharge temperature is called 'cold water pollution' and is believed to have negative consequences for native fish.

Hume Dam receives water from Dartmouth Dam via the Mitta Mitta River and from the Snowy Hydro Scheme via the River Murray. Both of these sources may deliver unseasonably cold inflows to Hume Dam.

In response to concern regarding cold water pollution downstream of Hume Dam, CSIRO Land & Water was commissioned to undertake thermal monitoring and modelling of the storage. The primary objective of these studies was to establish whether or not an adequate supply of sufficiently warm water was available in the reservoir to justify possible future expenditure on infrastructure to mitigate the impact of cold water pollution by increasing discharge temperature at the dam.

The first monitoring project covered the period Nov 2001 - April 2002 and was reported on earlier (Sherman 2002). The first project experienced periods of missing record in the data set during spring and early summer limiting its usefulness for hydrodynamic modelling of the reservoir.

The continuation of drought conditions during 2002 resulted in very low storage levels in Hume Reservoir that are experienced only every 7 years or so. A second monitoring project was undertaken from Oct 2002 - Mar 2003 to fill the gap in meteorological data from the previous year (i.e. typical spring-summer conditions) and to monitor the impact of low water level on the thermal characteristics of the storage.

This report presents results from the 2002-2003 field season as well as relevant information from 2001-2002. In addition, results from both an analytical heat budget model and a hydrodynamic model are presented. The analytical model demonstrated that the low water level conditions during 2002-2003 represented a stringent test of the ability of the reservoir to supply warm discharges due to the relatively small surface layer volume and short residence times during which cold inflows can heat up.

Results for 2002-2003

Two thermistor chains and a meteorological station were deployed in the main basin of Hume Reservoir commencing 2 October 2002. Data capture was 100% for all instruments from 2 Oct 2002 - 26 Mar 2003 and from 24 Apr 2003 - 14 May 2003. The thermistor chain in the Mitta Mitta Arm was removed on 16 Dec 2002 due to falling water levels.

As a result of the drought, spring and summer water levels were 10-15 m lower during 2002-2003 as compared to the previous year and brought the thermocline closer to the offtakes. With a typical 7-9 m deep surface layer, warmer water was withdrawn from the surface layer and upper thermocline during the year resulting in significantly (at least 4-5 °C) warmer discharge temperatures than are observed during more 'normal' years. Reservoir water level conditions during 2002-2003 produced the best possible temperature increase that could be expected in the future should a multi-level offtake be constructed.
It is unlikely that outflow temperatures in excess of 22 °C could be sustained prior to late December - early January.

The observed temperature increase along the Mitta Mitta River between Dartmouth and Hume Dams varied inversely with discharge. As discharge increased, travel time between Dartmouth and Hume Dam decreased and river water depth increased. Both factors served to reduce the temperature increase between the dams. During most of summer 2002, the release from Dartmouth Dam was less than 1000 ML d⁻¹ and the river warmed by 4 – 8 °C between Dartmouth Dam and Tallandoon. The following summer discharge averaged roughly 10,000 ML d⁻¹ and the temperature increase between stations averaged just 1 °C.

Meteorological data showed the expected seasonal trends in solar radiation, air temperature and relative humidity. Mean daily wind speed was 2.7 m/s during the 197-day period of record and blew overwhelmingly from the southeast during 2002-2003. The previous year (2002) was 20% windier, 3.4 °C colder with 30% higher relative humidity and 10% less shortwave radiation during the corresponding periods of record.

Inflow temperatures were typically 1-4 °C colder than the surface layer at the upstream ends of both arms of the reservoir during 2001-2002 (when Hume reservoir extended into the arms. Profiler data shows evidence of cold underflows at the extremities of the reservoir during both years. The presence of underflows has little or no bearing on the potential to mitigate cold water pollution by withdrawing water from the surface layer and upper thermocline.

**Model results**

A simple analytical model based on conservation of volume and representative values of surface heat fluxes and surface mixed layer depths indicated that there would always be adequate supplies of sufficiently warm water in the surface layer to satisfy downstream release requirements. In this case, 'sufficiently warm' means not appreciably different from the natural surface layer temperature in the absence of cold inflows.

The one-dimensional numerical model DLM (Dynamic Layer Model) was used to simulate the effect on Hume Dam discharge temperature of providing multi-level offtake (MLO) capability to mitigate cold water pollution. MLO capability was simulated by setting the offtake invert level at each time step to a depth of 8.5 m below the simulated level of the water surface. The 8.5 m minimum depth is an operational constraint to prevent air being sucked into the hydropower plant penstock. This caused the model to track the water level in a way consistent with hydropower plant operating procedures while guaranteeing access to the warmest water in the reservoir. Results of the adjustable outlet simulations were compared with reference simulations configured with the existing offtake levels which are fixed relative to the bottom of the dam.

Six scenarios were simulated. Low (1947), median (1964) and high (1982) inflow/outflow conditions were considered for both high (Oct 1998) and low (Oct 1993) initial storage levels.

During model validation, predictions of discharge temperature tended to be lower than observed (RMS difference of 1.1 °C) with the difference increasing near the end of the simulation period (February-March). Surface layer temperature was typically within 0.5 °C of observed values.

As expected, high initial storage levels provided the greatest scope for increase in discharge temperature. Simulations for the high water level scenarios predicted an average 5.6 °C increase in discharge temperature from 3 October through 31 January when the offtake level tracked the water surface.
An unexpected result was that predicted discharge temperature from 1 February through 24 March using the adjustable offtake was 3.4 °C colder than the reference condition which used the existing fixed offtake level.

**Mitigation options**

Two options appear feasible for the mitigation of cold water pollution at Hume Dam:

- Construction of a multi-level offtake
- Deployment of a submerged curtain

The submerged curtain option is expected to produce the greatest discharge temperature.

A third option, the use of surface impellers, is unlikely to be feasible due to its inability to produce satisfactory temperature gains and some significant deployment challenges especially as regards safe mooring during spill conditions and the large number of impellers required.

A consequence of implementing a mitigation strategy is that the residence time of the hypolimnion will increase. This may lead to anoxic conditions followed by enhanced sediment nutrient release and increased algal biomass in the reservoir. At present, the deep discharges appear to prevent the development of anoxia.

**Recommendations**

Feasibility studies comparing the costs and benefits of the two mitigation options, a multi-level offtake and a submerged curtain, should be undertaken.

An investigation into the effects of increased hypolimnetic residence time should be undertaken. This may include the deployment of benthic chambers to measure, in situ, the sediment oxygen demand and nutrient release rate that may be expected should hypolimnetic residence time increase.
2. Overview

Cold water pollution (CWP) downstream of reservoirs occurs principally as a result of withdrawing water from storages through outlets located below the surface layer, a warmer mixed region and typically 3 - 7 m deep in most Australian storages. The deeper the outlet, the colder the temperature because the sun's energy does not penetrate sufficiently far to warm the reservoir at the level of the outlet. The most feasible ways to mitigate cold water pollution are: modify the outlet structure to allow withdrawal of surface layer water; use pumps to move surface layer water into the withdrawal layers adjacent to existing outlets; and use curtains upstream to block the downstream movement of cold water (Sherman 2000).

Furthermore, Hume Dam receives unseasonably cold inflows from Dartmouth Dam via the Mitta Mitta River and from Snowy Hydro operations via the River Murray. CWP downstream of Dartmouth Dam is believed to have been instrumental in the local extinction of Murray cod in the Mitta Mitta River between Dartmouth and Hume dams (Koehn et al, 1995). The fate of these cold inflows has implications for CWP mitigation downstream of Hume Dam.

The operation of Hume Dam causes cold water pollution of the Murray River because there is no facility to release water from the surface layer. Discharge from the dam passes either through a hydroelectric plant with intakes that span from 162.535 to 168.679 m AHD or through irrigation valves that span 157.710 to 161.367 m AHD. When full, the water level in the reservoir is at 192.076 m so the uppermost intake is roughly 25 m deep – much deeper than the typical 3-8 m surface layer depth typical of most storages in the Murray-Darling Basin. Even at 27% of capacity, when the water level is 177.119 m AHD, the intake is typically below the surface layer and discharge temperatures will be depressed.

The MDBC and NSW State Water are considering implementing cold water pollution mitigation measures at Hume Dam. Because the scope of the required engineering works is quite large and expensive, it was considered prudent to undertake a study to ascertain to what extent such works were capable of producing temperature increases in discharges from the dam. Simple back-of-the-envelope calculations undertaken at the CWP workshop held at Hume Resort during June 2001 indicated that when full, desired temperature increases likely were achievable but that at lower operating levels this may not be the case when discharge and inflows are high.

The first step in determining the feasibility of CWP mitigation for Hume Dam is to determine whether or not there is a supply of sufficiently warm water within the reservoir to satisfy environmental objectives downstream. This requires an understanding of the stratification dynamics of the reservoir by answering the following questions:

- At what rate does the reservoir heat up or cool down?
- How is this rate coupled to the local climate?
- How does the temperature distribution vary spatially in the reservoir?
- What is the fate of inflows from the Murray and Mitta Mitta rivers? How do they pass through the reservoir and by how much do they warm up prior to being discharged downstream?

To answer these questions requires continuous monitoring of: energy fluxes between the atmosphere and the water; water column temperature; and inflow temperatures. Ideally these data should be collected during spring, summer and autumn.

State Water retained CSIRO to acquire and analyse thermistor chain and meteorological data collected at Hume Reservoir, compute a heat budget for the reservoir, and use a numerical...
model to predict expected discharge temperatures for a range of storage levels and inflow/outflow scenarios. In related work, State Water collected depth profiles of conductivity, temperature, and dissolved oxygen (CTDO) at 16 sites within the dam using a SeaBird SBE19 profiler. As well, DIPNR collected water temperature data from various locations in the Murray River using Hobo loggers provided by CSIRO and in the Mitta Mitta River using Tidbit loggers provided by DNRE (Victoria).

During 2001-2002 field data collection commenced and heat and water budgets were computed as a check on the accuracy and completeness of the field data acquisition program. Dry conditions and low storage levels during winter 2002 led to the continuation of data acquisition during 2002-2003. This provided an opportunity to observe conditions over a greater range of reservoir levels, provide an indication of interannual climate variability and extend the data record to include periods that were missed due to equipment malfunction during 2001-2002.

The field data were subsequently used to drive a numerical model of reservoir stratification dynamics in order to predict potential achievable increases in discharge temperature for a range of reservoir levels and inflow/outflow conditions.

This report presents an analysis of the field data collected by CSIRO, State Water and DIPNR, and the results of the heat budget calculations and numerical model simulations. Some of the analysis presented here was published earlier by Sherman (2002) and has been included here for completeness.

**Acknowledgements**

This project could not have been successfully executed without the help of the staff at Hume Dam, the power station and DIPNR. In particular I would like to thank Graeme Hind, John Stevenson, Peter Demeo, Emily Maher, Peter Huhta and Rod Kerr for their help with the maintenance of the instruments and provision of field data.
3. Previous studies

The Murray-Darling Freshwater Research Centre (Brymner 1985) conducted a study that examined thermal and chemical stratification in Hume Dam during July 1982 - June 1985. Sampling consisted of fortnightly depth profiling near the dam wall. Temperature was measured at 1 m intervals; dissolved oxygen at 1-5 m intervals depending on the chemocline; pH, Fe and Mn were measured at the surface, bottom and 2 intermediate depths. The study period encompassed severe drought conditions, flooding, and strong winds.

Earlier studies referred to by Brymner showed a stratified period from Oct/Nov to Mar/Apr. Prior to 1982 the Murray and Mitta Mitta rivers had temperatures similar to that of the surface mixed layer. Dartmouth Dam was not yet operational at the time. These studies also reported that bottom releases from Hume Dam drew down the thermocline from a depth below the surface of 10-12 m in spring to about 20 m prior to turnover.

1982-1983 brought drought conditions and the reservoir was 15 m shallower than usual in spring with a bottom water temperature of 17 °C – significantly warmer than the typical 12–14 °C at this time of year. During this period the Mitta Mitta R inflow underflowed whereas the Murray R water was at a similar temperature to the surface layer. In November 1982, the Mitta Mitta temperature increased to 18 °C and formed an intrusive flow that entered the storage at mid-depth. In mid-February 1983 the Mitta Mitta temperature decreased to 11 °C due to a change to the lower outlet at Dartmouth dam causing it to underflow into Hume Reservoir again. September-October inflows were generally colder and underflowed. It appears from Brymner's report that stratification in Hume Reservoir develops from below due to these underflows as well as from above due to surface heating.

The surface layer temperature during spring is of particular relevance to cold water pollution mitigation because this is when many species of native fish spawn. During the 3-year study period, the surface layer temperature ranged from 12-15 °C during October and from 14-20.5 °C during November. A maximum temperature of 18 – 19 °C appears typical of November conditions. Significantly, a temperature of 18 °C is considered a desirable temperature for spawning of Trout cod and 20 °C for Murray cod at this time of year (Koehn et al. 1995). In addition to improved spawning, Ryan et al. (2002) reported vastly improved growth rates for Murray cod fingerlings when water temperature increased from 15.5 to 18.5 °C.
4. Data acquisition

4.1. Equipment specifications

Two thermistor chains and a meteorological station were deployed in the main basin of Hume Reservoir commencing 2 October 2002. The locations of the thermistor chains and CTDO profiling sites are indicated in Figure 4.1 and Table 1. The primary site (HUME01) was located near the dam wall and consisted of: a meteorological station measuring up- and downwelling shortwave and longwave radiation, air temperature, relative humidity, wind speed and wind direction; and a string of 20 thermistors. This was the same site that was used during the previous year's study. An additional thermistor chain was located in the Mitta Mitta (HUME05, TC Mitta) arm of the reservoir. Note that TC Mitta was deployed at HUME09 during 2001-2002. The low water levels in the storage during the monitoring program prevented deployment of a third thermistor chain in the Murray arm.

Because of the falling water level, TC Mitta was removed from the reservoir on 16 December when access by boat was becoming difficult. The low water levels also required relocation of some of the profiling sites. HUME07 was relocated on 3 Oct 2002. Sites HUME04, 08, 09 and 10 were relocated on 15 Nov 2002. Sites HUME05 and HUME06 were relocated on 12 Feb 2003 after a previous relocation of HUME06 on 15 Jan 2003. The new locations are shown as blue triangles in Figure 4.1.

All instruments were sampled every 10 seconds and mean values output every 1 minute for wind data and every 10 minutes for all other parameters. Wind speed and direction, air temperature and relative humidity instruments were located approximately 2 m above the water surface. Radiometers were located roughly 0.5 m above the deck on the north side of the raft to avoid shading by the anemometer mast. TC Mitta was recorded as 2-minute averages from 09:24 on 21 Nov 2002 until the thermistor chain was removed at 09:16 on 16 Dec 2002.

A combination of Hobo and Tidbit temperature loggers were deployed at various locations in the Murray and Mitta Mitta rivers upstream of Hume Reservoir. A map of the catchment showing river temperature monitoring sites upstream of the reservoir is shown in Figure 4.2. Specifications for the various sensors are listed in Table 2.

Thermistor depths for the thermistor chains are given in Table 3-Table 4. The depths of the Mitta chain may vary by up to 50 cm as the depth of the top thermistor was not precisely measured. Thermistors that were damaged during the 2001-2002 measurement program and consequently not used during 2002-2003 are denoted by grey type in the tables.
Table 1 Hume Reservoir temperature monitoring stations. Vertical profiles of conductivity, temperature, and dissolved oxygen were collected at each station. The primary thermistor chain and meteorological station were located at HUME01. An additional thermistor chain was deployed at HUME05. Italics indicate locations after relocation due to falling water level; **bold** type indicates a thermistor chain; greyed type shows stations used during 2001-2002 but not during 2002-2003.

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Station Acronym</th>
<th>Profiles #</th>
<th>Longitude E</th>
<th>Latitude S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hume Dam @ Dam Wall (TC Hume)</td>
<td>HUME01</td>
<td>29</td>
<td>2 Oct 2002 23 Apr 2003</td>
<td>147 36</td>
</tr>
<tr>
<td>Hume Dam @ Middle Main Basin</td>
<td>HUME02</td>
<td></td>
<td>147 36</td>
<td></td>
</tr>
<tr>
<td>Hume Dam @ Main Basin Eastern Shore</td>
<td>HUME03</td>
<td></td>
<td>147 36</td>
<td></td>
</tr>
<tr>
<td>Hume Dam @ Heywood Bay</td>
<td>HUME04</td>
<td>29</td>
<td>2 Oct 2002 23 Apr 2003</td>
<td>147 36</td>
</tr>
<tr>
<td>Hume Dam @ Ebden</td>
<td>HUME05</td>
<td>28</td>
<td>2 Oct 2002 23 Apr 2003</td>
<td>147 36</td>
</tr>
<tr>
<td>Hume Dam @ Peacocks Bay</td>
<td>HUME06</td>
<td>17</td>
<td>2 Oct 2002 23 Apr 2003</td>
<td>147 36</td>
</tr>
<tr>
<td>Hume Dam @ Ludlows</td>
<td>HUME07</td>
<td>5</td>
<td>27 Nov 2002 3 Jan 2003</td>
<td>147 36</td>
</tr>
<tr>
<td>Hume Dam @ Calder Bay (TC Bowna)</td>
<td>HUME08</td>
<td>12</td>
<td>2 Oct 2002 3 Jan 2003</td>
<td>147 36</td>
</tr>
<tr>
<td>Hume Dam @ Huon (TC Mitta)</td>
<td>HUME09</td>
<td>8</td>
<td>2 Oct 2002 21 Nov 2002</td>
<td>147 36</td>
</tr>
<tr>
<td>Hume Dam @ Goonok Point</td>
<td>HUME10</td>
<td>9</td>
<td>2 Oct 2002 4 Dec 2002</td>
<td>147 36</td>
</tr>
<tr>
<td>Hume Dam @ Narrows Elbow</td>
<td>HUME11</td>
<td></td>
<td>147 36</td>
<td></td>
</tr>
<tr>
<td>Hume Dam @ Morroh Bay</td>
<td>HUME12</td>
<td></td>
<td>147 36</td>
<td></td>
</tr>
<tr>
<td>Hume Dam @ Tallangatta</td>
<td>HUME13</td>
<td></td>
<td>147 36</td>
<td></td>
</tr>
<tr>
<td>Hume Dam @ Wymah Ferry</td>
<td>HUME14</td>
<td>6</td>
<td>2 Oct 2002 8 Nov 2002</td>
<td>147 36</td>
</tr>
<tr>
<td>Hume Dam @ Causeway</td>
<td>HUME15</td>
<td></td>
<td>147 36</td>
<td></td>
</tr>
<tr>
<td>Hume Dam @ Granya Bay</td>
<td>HUME16</td>
<td></td>
<td>147 36</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.1 Location of profiling sites in Hume Reservoir. Blue triangles denote relocated profiling sites. Thermistor chains were located at HUME01 (TC Hume, dam wall) and HUME05 (TC Mitta). The meteorological station was located at HUME01. Photo courtesy DIPNR.
Figure 4.2 River temperature monitoring stations. Bullhead Ck station is also referred to as Mitta Mitta River at Ernbank.

Table 2 Reservoir monitoring instrument specifications. All sensors were sampled every 10 seconds and mean values output at the specified logging frequency.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Instrument</th>
<th>Logging frequency</th>
<th>Accuracy</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed</td>
<td>Vaisala WAA15</td>
<td>1 min</td>
<td>± 0.17 m s⁻¹</td>
<td>na</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>Vaisala WAA15</td>
<td>1 min</td>
<td>± 2.8 °</td>
<td>5.63 °</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>Vaisala HMD30YB</td>
<td>10 min</td>
<td>± 0.2 °C</td>
<td>0.01 °C</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Vaisala HMD30YB</td>
<td>10 min</td>
<td>± 3% RH</td>
<td>0.15 % RH</td>
</tr>
<tr>
<td>SW radiation (up and downwelling)</td>
<td>Kipp &amp; Zonen CM14</td>
<td>10 min</td>
<td>± 3 W m⁻²</td>
<td>&lt; 0.1 W m⁻²</td>
</tr>
<tr>
<td>LW radiation (up and downwelling)</td>
<td>Kipp &amp; Zonen CG2</td>
<td>10 min</td>
<td>± 10%</td>
<td>0.1 W m⁻²</td>
</tr>
<tr>
<td>Water Temperature</td>
<td>Thermometrics P60</td>
<td>10 min</td>
<td>± 0.02</td>
<td>0.007 °C</td>
</tr>
</tbody>
</table>
Table 3 Hume Dam (TC Hume) thermistor depths and data logger channel allocation. Adjustments are the range of offsets applied to the data to bring thermistor temperature to within ± 0.015 °C of the average surface layer temperature. Grey type denotes unserviceable thermistors that were damaged during 2001-2002. nd = not determined because field performance was within expected tolerance of ± 0.02 °C.

<table>
<thead>
<tr>
<th>DT Channel</th>
<th>Thermistor ID</th>
<th>Location</th>
<th>Hume Depth (m)</th>
<th>Calibration Stability (°C)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:05</td>
<td>55</td>
<td>1</td>
<td>0.1</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>2:06</td>
<td>53</td>
<td>2</td>
<td>0.5</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>1:05</td>
<td>46</td>
<td>3</td>
<td>1.0</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>1:07</td>
<td>15</td>
<td>4</td>
<td>1.5</td>
<td>± 0.05 except see comments</td>
<td>-0.1 to -0.4 adjustments 28 Feb 03 - 30 Apr 03</td>
</tr>
<tr>
<td>1:06</td>
<td>44</td>
<td>5</td>
<td>2.0</td>
<td>± 0.05 except see comments</td>
<td>0.03 to 0.17 adjustments 10 Oct 02 - 12 Mar 03</td>
</tr>
<tr>
<td>2:09</td>
<td>28</td>
<td>6</td>
<td>3.0</td>
<td>± 0.05 except see comments</td>
<td>-0.03 to -0.18 adjustments 10 Oct 02 - 14 May 03</td>
</tr>
<tr>
<td>2:03</td>
<td>14</td>
<td>7</td>
<td>4.0</td>
<td>± 0.03</td>
<td>-0.03 adjustments 30 Apr 03 - 14 May 03</td>
</tr>
<tr>
<td>1:09</td>
<td>16</td>
<td>8</td>
<td>5.0</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>1:03</td>
<td>24</td>
<td>9</td>
<td>6.0</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>2:04</td>
<td>18</td>
<td>11</td>
<td>8.0</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>1:02</td>
<td>4</td>
<td>12</td>
<td>10.0</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>1:04</td>
<td>20</td>
<td>13</td>
<td>12.0</td>
<td>nd</td>
<td>see Fig 3a</td>
</tr>
<tr>
<td>2:07</td>
<td>30</td>
<td>14</td>
<td>14.0</td>
<td>nd</td>
<td>on sediment 14 Dec 02</td>
</tr>
<tr>
<td>1:10</td>
<td>29</td>
<td>15</td>
<td>16.0</td>
<td>damaged 3 Jan 02</td>
<td></td>
</tr>
<tr>
<td>2:01</td>
<td>27</td>
<td>16</td>
<td>18.0</td>
<td>nd</td>
<td>on sediment 26 Nov 02</td>
</tr>
<tr>
<td>2:08</td>
<td>13</td>
<td>17</td>
<td>20.0</td>
<td>damaged 1 Feb 02</td>
<td></td>
</tr>
<tr>
<td>2:02</td>
<td>21</td>
<td>18</td>
<td>25.0</td>
<td>nd</td>
<td>on sediment 7 Nov 02</td>
</tr>
<tr>
<td>1:01</td>
<td>23</td>
<td>19</td>
<td>27.0</td>
<td>nd</td>
<td>on sediment 2 Oct 02</td>
</tr>
<tr>
<td>1:08</td>
<td>19</td>
<td>20</td>
<td>29.0</td>
<td>nd</td>
<td></td>
</tr>
</tbody>
</table>
Table 4 Hume Reservoir Mitta Mitta arm (TC Mitta) thermistor depths and data logger channel allocation. "On sediment" denotes the time when temperature data indicate the thermistor first touches the sediment due to the falling water level. Grey type denotes unserviceable thermistors that were damaged during 2001-2002. nd = not determined because field performance was within expected tolerance of ± 0.02 °C.

<table>
<thead>
<tr>
<th>DT Channel</th>
<th>Thermistor</th>
<th>Location</th>
<th>Depth (m)</th>
<th>Calibration Stability (°C)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:10</td>
<td>11</td>
<td>1</td>
<td>0.2</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>0:10</td>
<td>10</td>
<td>2</td>
<td>1.1</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>1:10</td>
<td>20</td>
<td>3</td>
<td>2.0</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>0:01</td>
<td>1</td>
<td>4</td>
<td>2.9</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>1:09</td>
<td>19</td>
<td>5</td>
<td>3.8</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>0:02</td>
<td>2</td>
<td>6</td>
<td>4.0</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>1:08</td>
<td>18</td>
<td>7</td>
<td>4.3</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>0:03</td>
<td>3</td>
<td>8</td>
<td>4.5</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>1:07</td>
<td>17</td>
<td>9</td>
<td>4.8</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>0:04</td>
<td>4</td>
<td>10</td>
<td>5.3</td>
<td>nd</td>
<td>on sediment 10 Dec 02</td>
</tr>
<tr>
<td>1:06</td>
<td>16</td>
<td>11</td>
<td>5.8</td>
<td>nd</td>
<td>on sediment 6 Dec 02</td>
</tr>
<tr>
<td>0:05</td>
<td>5</td>
<td>12</td>
<td>6.2</td>
<td>nd</td>
<td>on sediment 5 Dec 02?</td>
</tr>
<tr>
<td>1:05</td>
<td>15</td>
<td>13</td>
<td>6.7</td>
<td>nd</td>
<td>on sediment 1 Dec 02</td>
</tr>
<tr>
<td>0:06</td>
<td>6</td>
<td>14</td>
<td>7.2</td>
<td>nd</td>
<td>on sediment 25 Nov 02</td>
</tr>
<tr>
<td>1:04</td>
<td>14</td>
<td>15</td>
<td>8.2</td>
<td>nd</td>
<td>on sediment 17 Nov 02</td>
</tr>
<tr>
<td>0:07</td>
<td>7</td>
<td>16</td>
<td>9.2</td>
<td>nd</td>
<td>on sediment 5-7 Nov 02</td>
</tr>
<tr>
<td>1:03</td>
<td>13</td>
<td>17</td>
<td>10.2</td>
<td>nd</td>
<td>on sediment 20 Oct 02</td>
</tr>
<tr>
<td>0:08</td>
<td>8</td>
<td>18</td>
<td>11.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:02</td>
<td>12</td>
<td>19</td>
<td>12.2</td>
<td>nd</td>
<td>on sediment 2 Oct 02</td>
</tr>
<tr>
<td>0:09</td>
<td>9</td>
<td>20</td>
<td>13.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.1.1. Equipment performance

At the time of writing, the calibrations of the thermistor chains have not yet been tested in the CSIRO calibration facility but inspection of all field data indicates that the thermistor chains have performed within their specification. Some adjustments (shown in Table 3) were made to the calibrations of the 4, 5, 6, and 7 m thermistors at TC Hume when mixed conditions allowed them to be compared to temperatures reported by all other thermistors within the surface mixing layer. The adjustments were applied as a constant offset in blocks, typically of 2 weeks duration, and brought the reported temperatures back into a range of ± 0.015 °C of the mean surface layer temperature.

Note also that as the water level fell in the dam (Figure 4.3) the lower thermistors would rest on the bottom of the reservoir causing their temperatures to deviate conspicuously (colder) from those above. This was particularly evident at TC Mitta and the dates shown in Table 4 were verified against SeaBird profiler cast depths and observed changes in reservoir water level.
The anemometer calibration was stable to within 6% and typically better than 2% with calibration offsets of 0.01 to 0.06 m s\(^{-1}\).

4.2. Data capture

Data capture was 100% for all instruments from 2 Oct 2002 - 26 Mar 2003 and from 24 Apr 2003 - 14 May 2003. Note that TC Mitta was removed on 16 Dec 2002 due to falling water levels. The gap in the record from 26 Mar 2003 - 24 Apr 2003 arose because the memory cards could not be downloaded at this time. Note that the formally contracted period of data acquisition ended 31 Mar 2003, giving an overall data capture of 97%.

Figure 4.3 a) Hume Reservoir water column depth at TC Hume; b) Water surface levels during 2001-2002 and 2002-2003. Red circles indicate dates when various thermistors first contacted (or emerged from for 12 m) the sediment.
5. Analysis

5.1. Water level

Figure 4.3b compares water levels recorded during 2001-2002 and 2002-2003. The impact of the drought is clearly evident in the lower water level at the beginning of spring 2002. Hydropower operations ceased on 18 Dec 02 because of the low water level and after this date all water was released through the irrigation outlet. During 2002-2003, the water level was stabilised at 168-170 m AHD through a combination of high discharges from Dartmouth Reservoir and diminishing irrigation releases during autumn.

Assuming a surface layer depth of 7-9 m, it is clear that during 2002-2003 the hydro outlet was adjacent to the surface layer from the outset of spring and withdrew water from the surface layer and the top of the thermocline. During the previous year, the water level was 10-15 m deeper from spring through summer and so the top of the outlet was typically 10 m or more below the base of the surface layer and discharges were drawn from the hypolimnion and lower thermocline. Discharge temperature during 2002-2003 therefore is expected to be significantly warmer than during the previous year.

5.2. Meteorology

Mean daily values for all meteorological parameters are shown for 2001-2002 in Figure 5.1 and in Figure 5.2 for 2002-2003. The expected seasonal trends in air temperature (13-30 °C), relative humidity (80-40%), shortwave radiation (125-390 W m⁻²) and downwelling longwave radiation (320-420 W m⁻²) are readily apparent in the 2002-2003 data. More striking is the relative absence of obvious seasonal trends in net longwave radiation and wind speed, albeit the wind speed does trend down very slightly (~10%) in late summer. Over the 197-day period of record the mean daily wind speed was 2.7 (s.d. = 0.8) m s⁻¹ and the average of the daily maximum wind speeds was 5.8 (s.d. = 1.6) m s⁻¹. Net longwave radiation was relatively constant at -49 (s.d. = 24) W m⁻². The lack of any seasonal trend in net longwave radiation reflects the fact that changes in both the downwelling and upwelling components tend to compensate one another during the year.

The only period of record allowing a direct comparison of interannual variability was 1 Feb - 13 Mar during both 2002 and 2003. Statistical properties of the main meteorological variables during this six-week period are given in Table 5. The previous year (2002) was 20% windier, 3.4 °C colder with 30% higher relative humidity and 10% less shortwave radiation. The implications of this in terms of atmosphere-water heat fluxes are described in the next section.
Table 5 Comparison of characteristic values of mean daily meteorological parameters during 1 Feb 02 - 13 Mar 02 and 1 Feb 03 - 13 Mar 03.

<table>
<thead>
<tr>
<th></th>
<th>wind</th>
<th>max wind</th>
<th>SW</th>
<th>LW&lt;sub&gt;down&lt;/sub&gt;</th>
<th>LW&lt;sub&gt;up&lt;/sub&gt;</th>
<th>LW&lt;sub&gt;net&lt;/sub&gt;</th>
<th>Air Temp</th>
<th>RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>1.4</td>
<td>4.1</td>
<td>35</td>
<td>324</td>
<td>416</td>
<td>-101</td>
<td>15.7</td>
<td>52.3</td>
</tr>
<tr>
<td>Maximum</td>
<td>7.8</td>
<td>11.4</td>
<td>353</td>
<td>440</td>
<td>454</td>
<td>-2</td>
<td>26.3</td>
<td>90.2</td>
</tr>
<tr>
<td>Mean</td>
<td>3.0</td>
<td>6.6</td>
<td>231</td>
<td>377</td>
<td>433</td>
<td>-56</td>
<td>20.2</td>
<td>68.1</td>
</tr>
<tr>
<td>Median</td>
<td>2.8</td>
<td>6.3</td>
<td>230</td>
<td>372</td>
<td>436</td>
<td>-57</td>
<td>19.6</td>
<td>66.7</td>
</tr>
<tr>
<td>Std Dev</td>
<td>1.0</td>
<td>1.7</td>
<td>80</td>
<td>24</td>
<td>10</td>
<td>22</td>
<td>2.5</td>
<td>9.5</td>
</tr>
<tr>
<td>2003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>1.4</td>
<td>3.1</td>
<td>61</td>
<td>331</td>
<td>426</td>
<td>-94.9</td>
<td>14.5</td>
<td>38.1</td>
</tr>
<tr>
<td>Maximum</td>
<td>4.6</td>
<td>10.0</td>
<td>320</td>
<td>446</td>
<td>451</td>
<td>-5.1</td>
<td>29.1</td>
<td>80.7</td>
</tr>
<tr>
<td>Mean</td>
<td>2.5</td>
<td>5.4</td>
<td>256</td>
<td>395</td>
<td>439</td>
<td>-44.0</td>
<td>23.6</td>
<td>51.8</td>
</tr>
<tr>
<td>Median</td>
<td>2.4</td>
<td>5.1</td>
<td>276</td>
<td>393</td>
<td>442</td>
<td>-48.4</td>
<td>24.1</td>
<td>50.1</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.8</td>
<td>1.6</td>
<td>55</td>
<td>28</td>
<td>7</td>
<td>20.4</td>
<td>3.4</td>
<td>9.4</td>
</tr>
</tbody>
</table>
Figure 5.1 Daily meteorological data measured approximately 2 m above the water near Hume Dam during 2001-2002.
Figure 5.2  Daily meteorological data measured approximately 2 m above the water near Hume Dam during 2002-2003.
5.2.1. Characteristics of the wind regime

Wind speed and direction are particularly important for the heat budget and the thermal stratification due to their effects on surface heat fluxes and seiching. Instantaneous latent and sensible heat fluxes vary linearly with wind speed beyond a certain wind velocity threshold. Internal wave activity (seiching) depends on wind speed, duration and direction. Winds blow the warmer surface layer water toward the downwind side of a lake. Winds aligned with the long axis of a lake will cause the greatest displacement of the thermocline with a deep, warm surface layer developing at the downwind end and a much shallower, and often cooler, surface layer at the upwind end.

Wind speed as a function of direction on a monthly basis is shown in Figure 5.3. There are lobes in the average wind speed distribution indicating a tendency for faster average wind speeds to blow from either the southeast or the southwest. Maximum wind speeds were higher from the southwest during Oct 2002 - Jan 2003. During February of both years there was a tendency for stronger winds to have come from the southeast. In summary, the strongest winds are likely to blow from the southwest (across the waist of the reservoir) or from the southeast (along the long axis of the southern basin).

The wind run data plotted in Figure 5.4 reveals the overwhelming bias towards southeasterly winds at Hume Reservoir. The wind run is the distance traveled in a day by the wind in a particular direction. The wind blew overwhelmingly from the southeast from October through April during both measurement seasons (2001-2002, 2002-2003).

The most important consequence of the dominant southeasterly winds, as regards discharge temperatures at Hume Dam, is that warm water will accumulate in a relatively deeper surface layer at the dam wall. During February and April the prevailing orientation was marginally more easterly, (5-15 °) in 2002 as compared to 2003. This is unlikely to have a significant impact on the hydrodynamic response of the reservoir.

Mean, median, and maximum wind speeds calculated on a monthly basis from the one-minute wind speed data are shown in Figure 5.5. The monthly mean wind speed is fairly constant in the range 2.5-3 m s\(^{-1}\). Of all months with > 50% data capture, the only conspicuous departure from this range occurred during February 2003 when the mean monthly wind speed was approximately 2.3 m s\(^{-1}\). Despite the absence of a strong seasonal trend in mean daily wind speed, the maximum daily wind speeds peaked in mid-summer and eased as autumn approached during both years.

An interesting feature of the wind field at Hume Reservoir is the diurnal variation in wind speed. During summer the average wind speed is fairly constant throughout the day even though maximum winds are highest in late afternoon (Figure 5.6, top and middle panels). This figure depicts a typical daily wind cycle by averaging wind speeds at a particular time of day over a period of days (1 month in the top and middle panels, and the entire record for the bottom panel). When all data are averaged winds are typically greatest at night (Figure 5.6, bottom panel). Other sites that have been studied (Chaffey Reservoir, Hinze Reservoir, Fitzroy River Barrage) using the same methodology typically exhibit an increase in wind speed during daylight hours (Figure 5.6, bottom).

The mid-late afternoon peak in wind speed results from the growth of the atmospheric mixed layer as it heats up and comes in contact with high winds in the atmosphere above. Shear stress is transmitted through the mixed layer and accelerates the wind at ground level. At night-time, the mixed layer recedes leading to a drop in wind speed.

The night-time increase in wind speed observe at Hume Dam is due to its being located in a region with steep slopes rising to a relatively high plateau. Air temperatures on the plateau are
much colder than in the river valley, especially at night, and this drives a density current
called a katabatic wind. The higher night-time winds represent the drainage of this cold air
from higher elevations.
Figure 5.3 Wind rose showing monthly changes in the directional dependence of average and maximum wind speeds at Hume Reservoir.
Figure 5.4 Wind rose showing monthly trends in daily wind run at Hume Reservoir. Wind run is the distance traveled by the wind in a given direction.
Figure 5.5  Monthly trends in daily mean a), monthly maximum (b), and daily maximum wind speeds at Hume Reservoir. Percentages on bars indicate the fraction of the month for which data were available.
Figure 5.6 Composite diurnal variation in mean, minimum, and maximum ten-minute wind speeds during December 2002 (top) and January 2003 (middle). Each point is the average of all data during a month for a given time, e.g. the 08:00 is the average of all 31 08:00 readings for the month. Bottom panel shows composite diurnal wind computed from all available 1-minute data during 2001-2002 (Hume 02) and 2002-2003 (Hume 03). Also shown are equivalent diurnal wind regimes at Chaffey Reservoir (NSW), Fitzroy River (QLD), and Hinze Dam (SE QLD).
5.2.2. Turbulent heat, mass, and momentum fluxes

Heat, mass (evaporation), and momentum fluxes between the atmosphere and the water were computed following the method of Liu et al. (1979). This method uses an iterative approach to incorporate the effects of atmospheric stability on the fluxes computed using bulk aerodynamic formulae. The atmosphere becomes unstable close to the water surface when the water surface temperature is greater than the air temperature so that the density of the air at the air-water interface is less than that of the air above. The less dense air adjacent to the water surface will rise until it reaches a level where its density matches that of the surrounding atmosphere. Conversely, if the water surface temperature is less than the air temperature the atmosphere is considered to be stably stratified and vertical motions are suppressed. As atmospheric stability increases, the turbulent fluxes of heat, mass and momentum between the water and the atmosphere are reduced.

The ten-minute stability-corrected turbulent fluxes for Hume Reservoir are compiled on a monthly basis in Table 6 and shown in Figure 5.7. The net radiative flux due to shortwave and longwave radiation, $Q_{\text{rad}}$, shows the expected sinusoidal pattern with a peak in December. The latent heat flux, $Q_{\text{lat}}$, compensated for the seasonal increase in $Q_{\text{rad}}$ in such a way that the net surface heat flux varied within a narrow range of 106 to 124 W m$^{-2}$ (mean 110 W m$^{-2}$) from October through February. The net heat flux decreased substantially during March - May yet remained positive (the reservoir was gaining heat) throughout the period of record.

Unstable conditions cause an increase in the latent (evaporative) and sensible fluxes. On average, the inclusion of stability effects increased the latent heat flux for Hume Reservoir by 6-7% as compared to the standard bulk aerodynamic formula used in some models which assume neutral atmospheric stability.

Under very low wind speeds, bulk aerodynamic formulae may underestimate fluxes because of their linear dependence on wind speed, i.e. they predict no flux under calm conditions. The mean latent heat flux into still air (Tennessee Valley Authority, 1972) computed for Hume Reservoir conditions averaged 21 W m$^{-2}$. This value corresponds approximately to the turbulent flux computed for wind speeds < 0.9 m s$^{-1}$ and therefore is not an important consideration for Hume Reservoir where the typical wind speed is seldom less than 2 m s$^{-1}$ (Figure 5.6) and wind speeds < 0.9 m s$^{-1}$ occur less than 12% of the time.

Figure 5.7 Monthly mean heat fluxes at Hume Reservoir. $Q_{\text{rad}}$ = net radiative (shortwave + longwave); $Q_{\text{lat}}$ = turbulent latent heat flux; $Q_{\text{sens}}$ = turbulent sensible heat flux; $Q_{\text{net}}$ = net surface heat flux.
### Table 6 Monthly surface heat fluxes, turbulent velocity scales and surface mixing layer depths for Hume Reservoir during 2002-2003.

QRAD = net radiative flux (shortwave + longwave), QLAT = latent heat flux (evaporation), QSENS = sensible heat flux (conduction), QNET = QRAD + QLAT + QSENS; u* = turbulent velocity due to wind stirring, w* = turbulent velocity due to penetrative convection (surface cooling); ZSML = surface mixing layer depth.

<table>
<thead>
<tr>
<th>Days of record</th>
<th>QRAD (W m⁻²)</th>
<th>QLAT (W m⁻²)</th>
<th>QNET (W m⁻²)</th>
<th>QSENS (W m⁻²)</th>
<th>u* (m s⁻¹)</th>
<th>w* (m s⁻¹)</th>
<th>ZSML (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 2002 30 min</td>
<td>-7</td>
<td>-223</td>
<td>-37</td>
<td>-34</td>
<td>0.0023</td>
<td>0.0013</td>
<td>2.65</td>
</tr>
<tr>
<td>max</td>
<td>274</td>
<td>-35</td>
<td>201</td>
<td>27</td>
<td>0.0095</td>
<td>0.0060</td>
<td>14.03</td>
</tr>
<tr>
<td>mean</td>
<td>195</td>
<td>-83</td>
<td>106</td>
<td>-6</td>
<td>0.0040</td>
<td>0.0028</td>
<td>7.78</td>
</tr>
<tr>
<td>std dev</td>
<td>63</td>
<td>40</td>
<td>62</td>
<td>14</td>
<td>0.0015</td>
<td>0.0009</td>
<td>3.42</td>
</tr>
<tr>
<td>November 2002 30 min</td>
<td>69</td>
<td>-190</td>
<td>-39</td>
<td>-36</td>
<td>0.0016</td>
<td>0.0008</td>
<td>1.21</td>
</tr>
<tr>
<td>max</td>
<td>298</td>
<td>-34</td>
<td>254</td>
<td>20</td>
<td>0.0067</td>
<td>0.0051</td>
<td>10.00</td>
</tr>
<tr>
<td>mean</td>
<td>236</td>
<td>-104</td>
<td>124</td>
<td>-8</td>
<td>0.0037</td>
<td>0.0028</td>
<td>5.21</td>
</tr>
<tr>
<td>std dev</td>
<td>57</td>
<td>41</td>
<td>73</td>
<td>12</td>
<td>0.0010</td>
<td>0.0010</td>
<td>2.13</td>
</tr>
<tr>
<td>December 2002 31 min</td>
<td>48</td>
<td>-284</td>
<td>-225</td>
<td>-93</td>
<td>0.0023</td>
<td>0.0016</td>
<td>1.45</td>
</tr>
<tr>
<td>max</td>
<td>328</td>
<td>-63</td>
<td>267</td>
<td>21</td>
<td>0.0081</td>
<td>0.0076</td>
<td>13.74</td>
</tr>
<tr>
<td>mean</td>
<td>265</td>
<td>-144</td>
<td>110</td>
<td>-10</td>
<td>0.0041</td>
<td>0.0034</td>
<td>6.27</td>
</tr>
<tr>
<td>std dev</td>
<td>75</td>
<td>66</td>
<td>125</td>
<td>25</td>
<td>0.0014</td>
<td>0.0014</td>
<td>3.17</td>
</tr>
<tr>
<td>January 2003 31 min</td>
<td>56</td>
<td>-303</td>
<td>-119</td>
<td>-43</td>
<td>0.0020</td>
<td>0.0015</td>
<td>0.80</td>
</tr>
<tr>
<td>max</td>
<td>322</td>
<td>-58</td>
<td>230</td>
<td>33</td>
<td>0.0066</td>
<td>0.0053</td>
<td>9.67</td>
</tr>
<tr>
<td>mean</td>
<td>248</td>
<td>-138</td>
<td>106</td>
<td>-3</td>
<td>0.0037</td>
<td>0.0030</td>
<td>4.67</td>
</tr>
<tr>
<td>std dev</td>
<td>65</td>
<td>54</td>
<td>94</td>
<td>16</td>
<td>0.0011</td>
<td>0.0010</td>
<td>2.17</td>
</tr>
<tr>
<td>February 2003 28 min</td>
<td>64</td>
<td>-206</td>
<td>-44</td>
<td>-25</td>
<td>0.0016</td>
<td>0.0014</td>
<td>2.49</td>
</tr>
<tr>
<td>max</td>
<td>271</td>
<td>-32</td>
<td>221</td>
<td>12</td>
<td>0.0043</td>
<td>0.0046</td>
<td>8.00</td>
</tr>
<tr>
<td>mean</td>
<td>209</td>
<td>-105</td>
<td>102</td>
<td>-3</td>
<td>0.0030</td>
<td>0.0028</td>
<td>4.27</td>
</tr>
<tr>
<td>std dev</td>
<td>51</td>
<td>41</td>
<td>74</td>
<td>9</td>
<td>0.0008</td>
<td>0.0009</td>
<td>1.27</td>
</tr>
<tr>
<td>March 2003 26 min</td>
<td>116</td>
<td>-332</td>
<td>-278</td>
<td>-91</td>
<td>0.0010</td>
<td>0.0017</td>
<td>1.95</td>
</tr>
<tr>
<td>max</td>
<td>231</td>
<td>-42</td>
<td>171</td>
<td>32</td>
<td>0.0070</td>
<td>0.0093</td>
<td>15.40</td>
</tr>
<tr>
<td>mean</td>
<td>186</td>
<td>-132</td>
<td>38</td>
<td>-16</td>
<td>0.0037</td>
<td>0.0042</td>
<td>8.10</td>
</tr>
<tr>
<td>std dev</td>
<td>32</td>
<td>68</td>
<td>106</td>
<td>25</td>
<td>0.0015</td>
<td>0.0021</td>
<td>4.15</td>
</tr>
<tr>
<td>April 2003 7 min</td>
<td>60</td>
<td>-62</td>
<td>-16</td>
<td>-14</td>
<td>0.0018</td>
<td>0.0017</td>
<td>3.00</td>
</tr>
<tr>
<td>max</td>
<td>139</td>
<td>-18</td>
<td>98</td>
<td>10</td>
<td>0.0052</td>
<td>0.0029</td>
<td>10.02</td>
</tr>
<tr>
<td>mean</td>
<td>95</td>
<td>-36</td>
<td>55</td>
<td>-4</td>
<td>0.0028</td>
<td>0.0024</td>
<td>7.04</td>
</tr>
<tr>
<td>std dev</td>
<td>23</td>
<td>13</td>
<td>34</td>
<td>8</td>
<td>0.0010</td>
<td>0.0005</td>
<td>2.84</td>
</tr>
<tr>
<td>May 2003 14 min</td>
<td>59</td>
<td>-141</td>
<td>-75</td>
<td>-25</td>
<td>0.0018</td>
<td>0.0023</td>
<td>3.75</td>
</tr>
<tr>
<td>max</td>
<td>96</td>
<td>-29</td>
<td>52</td>
<td>-2</td>
<td>0.0052</td>
<td>0.0064</td>
<td>15.30</td>
</tr>
<tr>
<td>mean</td>
<td>84</td>
<td>-57</td>
<td>12</td>
<td>-14</td>
<td>0.0030</td>
<td>0.0040</td>
<td>11.81</td>
</tr>
<tr>
<td>std dev</td>
<td>12</td>
<td>27</td>
<td>33</td>
<td>6</td>
<td>0.0009</td>
<td>0.0010</td>
<td>4.50</td>
</tr>
</tbody>
</table>
5.3. **Thermistor Chain**

5.3.1. Surface mixed layer temperature

Because the surface mixed layer is the only source of relatively warm water to mitigate cold water pollution, its temperature is of particular relevance. Figure 5.8 shows the daily mean temperature in the surface layer at each of the thermistor chains during 2001-2002 and 2002-2003. The surface layer temperature was calculated by averaging the temperatures measured within the top 5 m of the water column (see 5.3.2) except for TC Mitta during 2002-2003 when it was taken to be the observed mean depth of 3.5 m. The 5 m depth corresponds to the mean surface layer depth during Nov-Feb (Figure 5.10) and best represents conditions during late spring and early summer.

The surface layer temperatures at the dam wall (TC Hume) fell within the range reported by Brymner (1985). The overall patterns and magnitudes of temperatures were the same during both years. Temperatures in the Bowna arm (TC Bowna) were quite similar to those at the dam wall during 2001-2002 whereas temperatures at the Mitta Mitta arm (TC Mitta) were consistently colder by about a degree during both years. The sudden drop in temperatures in early December 2002 was caused by the passage of a cold front and provides a good indication of the natural short-term variability of the system.

![Figure 5.8 Daily mean temperature of the top 5 m of the water column at each thermistor chain during 2001-2002 (a) and 2002-2003 (b). During 2002-2003 only the top 3.5 m of TC Mitta were averaged.](image-url)
5.3.2. Surface mixed layer dynamics

Surface mixed layer depths, $Z_{sml}$, can be derived from the thermistor chain data. Figure 5.9 and Figure 5.10 show $Z_{sml}$ during 2001-2002 and 2002-2003 determined as the depth at which there is a minimum 0.05 °C temperature change, i.e. the surface layer temperature is at least 0.05 °C greater than the temperature of the next thermistor down the chain. Table 7 lists the relevant statistics.

The lower wind speeds during 2002-2003 resulted in shallower surface layer depths in the reservoir. At TC Hume (near the dam wall) the surface layer was 2.5 m shallower and at TC Mitta it was 1 m shallower compared to the previous season.

During both field measurement seasons, the surface mixed layer depth was much deeper at the dam wall than at the other thermistor chain locations. This reflects the orientation of the reservoir and the prevailing wind direction, which combine to produce significant seiching on occasion. For example, the very strong ESE winds from 3-7 Feb 2002 (Figure 5.9) produced a surface layer depth of 17 m near the dam wall (TC Hume) whereas it remained relatively much shallower at the other two stations due to the limited fetch. This seiche rapidly raised the water temperature adjacent to the hydroelectric plant intake on the dam wall (12-18 m depth) by approximately 4 °C during the wind event. Penstock temperature data collected by the hydroelectric plant operators confirmed a 3 °C increase in discharge temperature during this event.

Figure 5.9 b-d illustrates the response of the mixed layer to wind speed and direction. Increases in wind speed produce deeper mixed layers, especially at the dam wall. When wind speeds reduce, the mixed layer rapidly becomes shallower. The role of wind direction can be seen during 17 Feb - 3 Mar when fairly uniform winds produced a deeper mixed layer at TC Hume when the wind direction was from the E and SE than when the wind blew from the west.

Table 7 Surface mixed layer depths, $Z_{sml}$, at Hume Reservoir.

<table>
<thead>
<tr>
<th></th>
<th>Mitta (m)</th>
<th>Hume (m)</th>
<th>Bowna (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season</td>
<td>01-02</td>
<td>02-03</td>
<td>01-02</td>
</tr>
<tr>
<td>Maximum</td>
<td>13.0</td>
<td>12.0</td>
<td>18.0</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.9</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Days</td>
<td>78</td>
<td>75</td>
<td>88</td>
</tr>
<tr>
<td>Mean</td>
<td>4.6</td>
<td>3.6</td>
<td>9.0</td>
</tr>
<tr>
<td>Median</td>
<td>3.8</td>
<td>2.7</td>
<td>8.0</td>
</tr>
<tr>
<td>Std Dev</td>
<td>2.9</td>
<td>3.2</td>
<td>5.3</td>
</tr>
</tbody>
</table>
Figure 5.9 a) Surface mixed layer depths at the thermistor chains located at Hume Dam, and near the confluences of the Mitta Mitta River and Bowna River. Also shown are mixed layer depth (b), wind speed (c) and direction (d) for 28 Jan 02 - 14 Mar 02.
Figure 5.10 Surface mixed layer depths at the dam wall (Hume) and southern end (Mitta) of Hume Reservoir during 2002-2003. The horizontal line indicates the mean surface layer depth at TC Hume.

5.3.3. Internal wave activity

Internal wave activity near the dam wall during 2001-2002 is illustrated by the displacement of the 16 °C and 21 °C isotherms shown in Figure 5.11. The line in these plots represents the depth below the surface where a particular temperature is found near the dam wall. Oscillations of this parameter imply large-scale vertical movement in the water column at the location of the thermistor chain. There is very little relative motion between the thermistor chain and the water column induced by surface waves. What motion does exist would have a period of less than 8 s (a typical period for wind-generated surface waves) and be effectively filtered out by the 10-minute averaging of the thermistor chain data.

The internal wave spectrum was dominated by oscillations with a period of 0.5 days, a period which is very close to the characteristic period for an internal wave traveling the length of the main basin (4700 m, the distance between the dam wall and site Hume 05) at the level of the isotherm (16 m depth). The typical root mean square (RMS) displacement, i.e. the internal wave amplitude, was 1.06 m during most of February (Figure 5.11b). An internal wave of this amplitude will have little material effect on the temperature of water discharged from the dam.

During 2002-2003 the analysis of internal wave activity was confounded by the shallow water depth and relatively small temperature contrast between top and bottom of the water column. Isotherms typically intersected either the surface layer or the bottom every 2 days. Within these 2-day periods, activity was similar to observations the year before with typical internal wave amplitudes of approximately 1 m.
5.4. SeaBird SBE19 profiler

5.4.1. Spatial variability

The extent of spatial variability in the temperature field can be explored in the temperature profile data collected by State Water using the SeaBird SBE19 CTDO (conductivity, temperature, depth, dissolved oxygen) profiler. Example profiles for 2001-2002 are shown in Figures 5.12 - 5.14 and for 2002-2003 in Figures 5.15 - 5.16. The profiles on 14 Feb 02 and 21 Feb 02 illustrate the effect of wind direction with downwind sites generally warmer with a deeper surface mixed layer than upwind locations. However, temperatures always decreased as one moved upstream along the Murray Arm beyond site 10 during February when the storage was much shallower. This reflects the influence of the inflowing water temperature as well as the more rapid decrease in temperature that occurs in shallow water for a given rate of heat loss from the surface. The latter phenomenon is called ‘differential cooling’.
Temperatures near the dam wall (site 02) are consistently colder than in the Bowna Arm (site 08). No such generalisation can be made regarding the temperature distribution between the dam and the Mitta Mitta Arm (site 09) other than that the water is warmer at the downwind end. In the transverse direction near the dam wall (sites 01-03) temperatures vary by up to 1 °C again with warmer water in the downwind direction.
Figure 5.12 SeaBird SBE19 temperature profiles at Hume Reservoir on 13 December 2001. See Figure 4.1 for station locations. Shaded regions show locations of intakes for the hydroelectric plant and irrigation releases.

Figure 5.13 SeaBird SBE19 temperature profiles at Hume Reservoir on 14 February 2002. Preceding winds were steady from the southeast at approximately 3.4 m s⁻¹. Shaded regions show locations of intakes for the hydroelectric plant and irrigation releases. See Figure 4.1 for station locations.
Figure 5.14 SeaBird SBE19 temperature profiles at Hume Reservoir on 21 February 2002. Prevailing winds were from the west southwest at approximately 2.8 m s\(^{-1}\). Winds blew from the east the preceding two days. Shaded regions show locations of intakes for the hydroelectric plant and irrigation releases. See Figure 4.1 for station locations.
The profiler data collected during 2002-2003 show similar trends in the Mitta Arm with temperatures decreasing steadily as one moves south from the dam wall (Figure 5.15). Temperature profiles taken north of the dam wall as one approaches the Bowna Arm, revealed generally warmer temperatures as one moved in a northerly direction. However, this pattern was not consistent over time and there was some indication of larger scale motions arising from seiching causing larger temperature oscillations below the thermocline than were observed during 2001-2002. Note also that the shallow water depths at stations 7, 8, 9, 10 and 14 meant that profiles at these sites predominantly reflect activity within the surface layer.

Temperature profiles at individual sites during the latter half of summer (Figure 5.16) show fairly predictable warming of the water column through late February in the main basin of the reservoir (Sites 01, 05). North of the dam in the Murray River branch (Site 06) the behaviour was less predictable. This may be due to the combination of shallow profile depths and the
site being located at the downwind end of the reservoir. There is also a suggestion of a cold underflow below 4-5 m on 030129 and 030211. A more detailed analysis may require 2- or 3-dimensional numerical modelling and is beyond the scope of this report.

The expected influence of cold Mitta Mitta River inflow temperatures is consistent with the relatively colder temperatures at Sites 05, 07, and 09 (3 Jan 03, for example). However, the prevailing wind direction also contributes to this effect. Shallow water depths contributed to the lack of convincing evidence of persistent cold underflows in the profiler data. It is quite conceivable that the cold inflows have been substantially entrained into the surface layer as they propagated into the reservoir given the shallow slope of the channel.

5.4.2. Inflow intrusions/underflows

The presence of a cold underflow in the Mitta Mitta arm is apparent below 4 m at site 13 and below 11 m depth at site 9 on 13 Dec 2001 (Figure 5.12). This corresponds to a period of relatively high discharge from Dartmouth Dam (Figure 5.19) with a temperature at Tallandoon of approximately 13-14 °C. As the inflow entered the storage it entrained surface layer water and warmed as it propagated into the reservoir. The underflow had a temperature of 17-19 °C and probably intruded into the main basin of the storage at a depth of between 13 and 17 m. On the same day there is evidence at site 7 of a colder underflow below 16 m depth which has intruded and caused the slight bulge in the temperature profile at site 2 between 17.5 and 19 m. Note that the intrusions are located just above the top of the hydropower intake. This suggests strongly that intrusions can 'short circuit' the reservoir by intruding close to or directly into the withdrawal layer thereby passing through the reservoir without warming more than a degree or two between station 13 and the dam wall.

Although there is evidence of an underflow at site 14 in the Murray arm (Figure 5.13), its significance further downstream in the reservoir is not clear from the data.

There was no compelling evidence of cold underflows or intrusions playing a significant role in the reservoir during 2002-2003.

5.4.3. Mitta Mitta Arm

The surface layer at the upstream end (sites 11, 13, 15 depending on water level) of the Mitta Mitta Arm was nearly always colder than at site 9 (Figure 5.17) in the main basin of the
storage. The lack of a consistent trend between sites 9 and 11 suggests that temperature variability in the Mitta Mitta Arm is unlikely to have a significant effect on the heat budget calculations.

Low water levels preclude a similar analysis during 2002-2003.

![Mitta Mitta Arm Temperature Graph](image)

Figure 5.17 Mean SeaBird SBE19 temperature in the top 5 m at profile sites along the Mitta Mitta Arm of Hume Reservoir.

5.4.4. Murray Arm

Surface layer temperatures along the Murray Arm showed no consistent trends through January 2002. After this time the surface layer temperature decreased as one moved upstream from site 8. This trend most likely reflects the decreasing depth of the water column and the effect of surface heat losses, i.e. differential cooling.

Low water levels preclude a similar analysis during 2002-2003.
River temperatures

Inflow conditions may impact upon discharge temperature depending on the volume and temperature of the two rivers feeding Hume Reservoir. The depth at which inflowing water enters the water column of the reservoir depends on the temperature of the inflow and the amount of entrainment of reservoir water into the inflow as it plunges to find its level of neutral buoyancy. The amount of entrainment depends on river channel morphometry and the inflow volume.

Once the inflow has intruded into the reservoir, the residence time during which it may warm by conduction and solar heating prior to release depends upon the discharge rate from the dam and the outlet elevation. Should the withdrawal layer at the dam outlet coincide with the level of the inflow intrusion, then the inflow may experience an unexpectedly short residence time because it may pass straight through the reservoir with little or no mixing into adjacent strata. This mechanism is believed to have been responsible for the rapid passage of an inflow believed to be contaminated with cryptosporidium oocysts through Warragamba Dam during 2001.

Murray and Mitta Mitta river inflow volumes and temperatures at the closest gauging stations upstream of Hume Reservoir are shown in Figure 5.19. During 2001-2002 most inflow was supplied from the Murray River whereas during 2002-2003 Dartmouth Dam release via the Mitta Mitta River was the dominant source. The period of relatively small Mitta Mitta River flows during 2001-2002 saw relatively warmer inflow temperatures throughout the summer.
During 2002-2003 the prolonged dry conditions required maximum releases from Dartmouth Dam at the channel capacity of ~ 10,000 ML d⁻¹ and temperatures at Tallandoon were colder as a result of reduced travel time and a deeper river water column. The upward trend in Mitta Mitta temperature during 2002-2003 may reflect the low water level in Dartmouth Reservoir which resulted in the upper outlet being located much closer to the water surface than is typically the case. Mitta Mitta River temperatures are unlikely to ever be higher than shown here under bank-full discharge conditions and normal operating levels in Dartmouth Dam.

A prominent decrease in temperature occurred in the Murray River at Jingellic during January 2003. This corresponded to an increase in discharge and presumably reflects conditions in Snowy Hydro storages and the impact of decreased travel time between Khancoban and Jingellic.

![Figure 5.19 Hume reservoir inflow daily volumes and temperatures in the Murray River at Jingellic and the Mitta Mitta River at Tallandoon.](image)

Figure 5.20 shows the mean temperature over the top 5 m of the reservoir from the weekly CTD profiles as well as the temperatures of the Murray River at Talmalmo and the Mitta Mitta River at Tallandoon (see Figure 4.2 for site locations) during 2001-2002 when the reservoir extended up along the Murray and Mitta Mitta Arms. These data show that inflows are 1-4 °C colder than the surface layer at the upstream ends of both arms of the reservoir. Because of their colder temperatures, inflows can be expected to form intrusions that enter the reservoir below the surface mixed layer, possibly forming underflows that follow the drowned river channels towards the dam wall. This allows for the possibility of a 'short-circuit' in which inflows pass through the reservoir in the stratum adjacent to the outlets.

This study's findings differ somewhat from those of Brymner (1985). Brymner found that inflows from both rivers prior to 1982 entered the reservoir's epilimnion, and that subsequent deep-water releases from Dartmouth Dam formed underflows along the Mitta Mitta Arm of the storage. The present data indicate that Murray River inflows are nearly always colder than the epilimnion and can be expected to intrude into the reservoir below the surface layer. The present data do, however, confirm Brymner's observations of cold underflows in the Mitta Mitta Arm.
5.5.1. Mitta Mitta River

The thermal characteristics of Dartmouth Dam releases are vitally important to cold water pollution mitigation efforts at Hume Dam. Specifically, it is necessary to be able to predict the temperature of water arriving from the Mitta Mitta River when this river constitutes the major source of water to Hume Dam as was the case during 2002-2003.

Figure 5.20 Surface layer (SeaBird SBE19) and inflow temperatures in the Murray and Mitta Mitta arms of Hume Reservoir. Station 8 corresponds to TC Bowna, station 9 corresponds to TC Mitta. Station numbers increase in the upstream direction.
Figure 5.21 shows discharge and temperature at two stations along the Mitta Mitta River and the temperature increase, \( \Delta T \), realised between the two stations. Colemans is located just downstream of Dartmouth Dam and Tallandoon is the last gauging station upstream of Hume Dam. During most of 2002, the release from Dartmouth Dam was less than 1000 ML d\(^{-1}\) and during the summer months the river warmed by 4-8 °C before entering Hume Reservoir. During December 2001 discharge from Dartmouth Dam exceeded 4000 ML d\(^{-1}\) and the observed temperature increase on the way to Hume Reservoir was reduced to between 1 and 3 °C. The following summer discharge averaged roughly 10,000 ML d\(^{-1}\) and the temperature increase between stations averaged just 1 °C.

Higher discharges take less time to reach Hume Reservoir and produce a deeper river that heats up more slowly.

Snowy Ck is an unregulated stream and, if it is considered representative of 'natural' conditions in the Mitta Mitta catchment, provides an interesting comparison with Mitta Mitta River temperatures. Dartmouth Dam releases (Mitta Mitta R @ Colemans) were 4-7 °C colder than flows at Snowy Ck @ Granite Flat during spring and summer (Figure 5.22). During winter, the Mitta Mitta R was several degrees warmer than Snowy Ck. This is a classic thermal pollution example.

By the time the Mitta Mitta River reached Eskdale, i.e. downstream of the confluence with Snowy Ck, the temperature averaged 0.4 °C greater than the temperature in Snowy Ck for the period after 1 Jan 02 when Dartmouth Dam release was < 1000 ML d\(^{-1}\), and about 3 °C colder during December 2001 when discharge from Dartmouth Dam averaged 3200 ML d\(^{-1}\). Under low flow (< 1000 ML d\(^{-1}\)) conditions, there appears to be minimal thermal pollution impact by the time the Mitta Mitta River reaches Hume Reservoir. At higher flows (> 3000 ML d\(^{-1}\)) cold water pollution persists all the way to Hume Reservoir.
5.5.2. Murray River

Fewer data were available for the Murray River upstream of Hume Reservoir. These data indicate that the Murray River warms by approximately 5 °C between Brigadoon and Talmalmo for discharges in excess of 5000 ML d\(^{-1}\). However, as shown previously, this inflow is still likely to intrude below the epilimnion of Hume Reservoir.

5.5.3. Hume Dam discharge

Ultimately one must consider whether or not there is water available at a satisfactory temperature to satisfy the requirements of native aquatic organisms. Figure 5.23 shows predicted and measured Hume Dam discharge temperatures as well as seasonal target temperatures for improved spawning of several different native fish species. The predicted discharge temperature, \(T_{\text{out}}\), was estimated as,

\[
T_{\text{out}} = \frac{V_{\text{hydro}}T_{\text{hydro}} + V_{\text{irrig}}T_{\text{irrig}}}{V_{\text{hydro}} + V_{\text{irrig}}}
\]

where the \(T_{\text{hydro}}\) and \(T_{\text{irrig}}\) were the mean temperatures adjacent to the hydropower plant and the irrigation release intakes determined from the thermistor chain data and \(V_{\text{hydro}}\) and \(V_{\text{irrig}}\) are the daily volumes discharged through the corresponding intakes\(^1\).

---

\(^1\) The hydropower intake spans from 162.535 to 168.679 m AHD and the irrigation intake spans from 157.71 to 161.367 m AHD. Full surface level is 192.076 m.
Figure 5.23 Temperature of Hume Dam discharge, $T_{\text{out}}$, and Murray River temperature measured downstream of Hume Dam at Heywoods. Shaded regions indicate temperature ranges for breeding of several native fish species.

Hume Dam discharge temperatures as well as Murray River temperatures downstream of the dam at Heywoods were 3-4 °C warmer during spring and early summer of 2002-2003 compared to the year before. This was due to the low water level in the reservoir which had the effect of raising the outtakes relative to the water surface.

The low water levels of 2002-2003 raised discharge temperatures into the desired range for both Trout cod and Murray cod during several weeks of their spawning seasons. This occurred during a time when inflow temperatures were 5-6 °C colder than the discharge temperature, reservoir volume was low and both inflow and release volumes were relatively high. The latter factors ensured that the inflows experienced the minimum residence time likely to occur in the dam under any conditions and therefore the smallest amount of warming prior to release downstream.

Surface layer temperatures measured with the thermistor chain and SBE19 profiler are compared to outflow temperatures in Figure 5.24. Surface layer temperatures are typically 2 °C warmer than the discharge temperature during spring and summer. Even if a method could be devised to ensure that all discharge originated from the surface layer, it seems unlikely that temperatures in excess of 22 °C could be sustained prior to late December - early January.

Figure 5.24 Mean daily Hume Reservoir surface mixed layer temperature, $T_{\text{sml}}$, weekly profiler surface layer temperature, $T_{\text{sml SBE19}}$, and outflow temperature, $T_{\text{out}}$, during 2002-2003.
6. Heat and Water Budgets

The section presents calculation of heat and water budgets using the field data collected at Hume Dam. These budgets provide valuable checks on the accuracy and adequacy of the field data set for use in the modelling of the thermal dynamics of Hume Reservoir (Section 1).

6.1. Water Balance

In order to correctly interpret the heat budget it is necessary to assess the errors in the water balance that underpins the heat budget. The water balance of Hume Reservoir was assumed to equal the volume budget for the storage, i.e. density is assumed to be constant for the purpose of this calculation.

The water balance is simply,

\[ \Delta \text{Volume} = V_{\text{Mitta Mitta}} + V_{\text{Murray}} + V_{\text{rain}} - V_{\text{outflow}} - V_{\text{evaporation}} \]

where \( \Delta \text{Volume} \) is the change in reservoir volume and \( V \) denotes the daily volumes of water lost through discharge and evaporation and gained from the inflowing Murray (at Jingellic) and Mitta Mitta (at Tallandoon) rivers as well as from rainfall. Calculations were performed on a daily basis with evaporation and rainfall volumes computed by multiplying the measured values at the dam by the surface area of the reservoir. Only days with complete 10-minute meteorological data were considered.

During 2002-2003 the error in the water balance, i.e. the difference between observed change in volume versus that predicted (\( \Delta \text{Volume} \)) as a percentage of observed reservoir volume, averaged - 0.2% over the entire period with a typical daily (RMS) error of ± 0.5% (Table 8). The RMS error corresponds to an error of 0.02 m in estimating the water surface level.

Table 8 Water balance error for 4 Oct 2002 - 26 Mar 2003 (174 days). \( V_{\text{bar}} \) is the mean daily storage, \( \Delta V_{\text{err}} \) is the difference between the observed change in storage, \( \Delta V_{\text{obs}} \), and that computed from the water balance (\( \Delta \text{Volume above} \)). \( V_{\text{out}} \) and \( V_{\text{in}} \) are outflow and inflow volumes, respectively. \( \Delta w_{\text{sl}} \) is the change in reservoir level corresponding to \( \Delta V_{\text{err}} \).

<table>
<thead>
<tr>
<th></th>
<th>( V_{\text{bar}} ) (m(^3))</th>
<th>net flow (m(^3))</th>
<th>( \Delta V_{\text{err}} ) (m(^3))</th>
<th>( \Delta V_{\text{err}}/V_{\text{bar}} )</th>
<th>( \Delta V_{\text{err}}/V_{\text{out}} )</th>
<th>( \Delta V_{\text{err}}/V_{\text{in}} )</th>
<th>( \Delta V_{\text{err}}/\Delta w_{\text{sl}} ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>1.55e+08</td>
<td>-1.04e+07</td>
<td>-4.24e+06</td>
<td>-0.017</td>
<td>-0.312</td>
<td>-0.289</td>
<td>-19.910</td>
</tr>
<tr>
<td>Max</td>
<td>8.49e+08</td>
<td>7.46e+06</td>
<td>1.95e+06</td>
<td>0.013</td>
<td>0.123</td>
<td>0.147</td>
<td>2.637</td>
</tr>
<tr>
<td>Mean</td>
<td>3.85e+08</td>
<td>-2.80e+06</td>
<td>-7.60e+05</td>
<td>-0.002</td>
<td>-0.048</td>
<td>-0.054</td>
<td>-0.250</td>
</tr>
<tr>
<td>Median</td>
<td>2.61e+08</td>
<td>-3.45e+06</td>
<td>-7.56e+05</td>
<td>-0.002</td>
<td>-0.045</td>
<td>-0.054</td>
<td>0.090</td>
</tr>
<tr>
<td>RMS</td>
<td>4.49e+08</td>
<td>5.15e+06</td>
<td>1.30e+06</td>
<td>0.005</td>
<td>0.085</td>
<td>0.093</td>
<td>2.084</td>
</tr>
<tr>
<td>Std Dev</td>
<td>2.31e+08</td>
<td>4.34e+06</td>
<td>1.06e+06</td>
<td>0.004</td>
<td>0.070</td>
<td>0.077</td>
<td>2.075</td>
</tr>
</tbody>
</table>

There were no strong correlations between the error, \( \Delta V_{\text{err}} \), and any terms in the water balance equation (Figure 6.1). Nor was there a correlation between the error expressed in terms of water level, \( \Delta w_{\text{sl}} \), and wind speed.
Figure 6.1 Linear correlations between the water balance error and mean daily reservoir volume, outflow, inflows from the Murray and Mitta Mitta rivers and wind speed.

The observed change in reservoir volume is plotted against the net flow computed from the above equation in Figure 6.2. On average, the observed change in reservoir volume appears to be just over 3% greater than the sum of the individual components of the water balance. However, the 95% confidence limit on the slope of the regression is ± 0.079 and so it is not possible to assert any systematic error exists as the expected range of slopes spans a value of 1 which corresponds to no error at all. It would be difficult to improve upon this due to the intrinsic uncertainties in measuring streamflow where 5% is considered good-very good accuracy. Errors in precipitation and evaporation would be negligible compared to the
uncertainties in the flow data. Pan evaporation data was 15% greater than the estimated evaporative flux using the 10 minute meteorological data and following the method of Liu, Katsaros and Businger (1979). Alternatively, using a evaporation pan coefficient of 0.6 (rather than 0.7) provides an accurate match between the two methods.

Table 9 Components of the water balance for Hume Reservoir accumulated over the following periods: 24-27 Nov 01, 2 Feb 02 – 13 Mar 02, 29 Mar 02 – 23 Apr 02. Evaporation was computed from the observed 10-minute meteorological data following Liu et al. (1979).

<table>
<thead>
<tr>
<th>Term</th>
<th>Volume (ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>9,491</td>
</tr>
<tr>
<td>Evaporation</td>
<td>36,742</td>
</tr>
<tr>
<td>Mitta Mitta River inflow</td>
<td>84,220</td>
</tr>
<tr>
<td>Murray River inflow</td>
<td>294,300</td>
</tr>
<tr>
<td>Hume Dam discharge</td>
<td>1,103,620</td>
</tr>
</tbody>
</table>

Figure 6.2 Daily water balance for Hume Reservoir during 2001-2002 and 2002-2003. Observed change in volume versus net inflow/outflow computed as the sum of Murray and Mitta Mitta inflows plus rainfall less evaporation.

6.2. Heat Budget

Computing a heat budget for Hume Reservoir allows us to perform a check on the accuracy of much of the physical field data. By comparing the change in heat content of the reservoir, $HC$, with the contributions made by inflows, outflows, rainfall, and surface heat fluxes during a
time interval $\Delta t$, we can test the field data for internal consistency. All heat budget calculations were computed using a daily time step.

The heat content of the reservoir at any given time is,

$$\text{HC} = \rho C_p \int_0^{\text{inf} A(z) T(z) \, dz}$$

where $\text{HC}$ is the heat content (J), $\rho$ is the density (kg m$^{-3}$) and $C_p$ is the heat capacity of water (J kg$^{-1}$ °K$^{-1}$), $A(z)$ is the area of the reservoir at height $z$ above the bottom (m$^2$), and $T(z)$ is the corresponding temperature of the water column (°K). The observed change in heat content during $\Delta t$ is simply $\Delta \text{HC}_{\text{obs}} = \text{HC}(t+\Delta t) - \text{HC}(t)$. The temperature profile, $T(z)$, was taken from the thermistor chain data near the dam wall and the heat content computed for each 10-minute sample. The mean daily heat content was computed and used in subsequent calculations to eliminate artifacts caused by seiching with periods < 1 day. The standard deviation of the computed daily heat content was < 0.5% of the mean and about 30% of the observed daily change in heat content.

Both the density and the heat capacity of water are functions of temperature. Throughout the entire period of record, water temperatures varied between 14 and 28 °C. To simplify calculations, a typical value for $\rho C_p$ was assumed to be 4.173x10$^6$ J m$^{-3}$ °K$^{-1}$ (equivalent to a temperature of 20.7 °C) which is accurate to within a few tenths of one percent.

The heat contributed during $\Delta t$ by inflows, $\text{H}_{\text{in}}$, and outflows, $\text{H}_{\text{out}}$, is,

$$\text{H}_{\text{in}} = \rho C_p \int_0^{\Delta t} \left( Q_{\text{Murray}}(t) T_{\text{Murray}}(t) + Q_{\text{Mitta}}(t) T_{\text{Mitta}}(t) \right) \, dt$$

$$\text{H}_{\text{out}} = \rho C_p \int_0^{\Delta t} Q_{\text{out}}(t) T_{\text{out}}(t) \, dt$$

where $Q$ is the discharge (m$^3$ s$^{-1}$), $T$ is the temperature (°K), $t$ is the time (s) and subscripting denotes inflow or outflow. All inflow is assumed to come from the Murray and Mitta Mitta rivers.

Rainfall and surface heat transfers including evaporation act over the surface of the reservoir. The rain was assumed to have the same temperature as the air on the same day giving a heat contribution of,

$$\text{H}_{\text{rain}} = \rho C_p R(t) T_{\text{air}}(t) A(t)$$

where $R$ is the rainfall (m) and $A$ is the surface area of the reservoir (m$^2$) at time $t$.

Sensible, $Q_{\text{sens}}$, and latent, $Q_{\text{lat}}$, heat fluxes (W m$^{-2}$) were computed on a 10-minute basis using the on-site meteorological and water surface temperature data following Liu et al. (1979). These fluxes respectively averaged -1.5 and -84 W m$^{-2}$ during 24 – 29 Nov 2001 and -22 and -125 W m$^{-2}$ from early February to mid-April. Downwelling shortwave and longwave radiative fluxes were measured independently with Kipp & Zonen radiometers, reflected shortwave radiation was neglected and upwelling longwave radiation was computed from the water surface temperature. These values were combined and used as net values, $Q_{\text{sw,net}}$ and $Q_{\text{lw,net}}$. The surface heat flux contribution is,

$$\text{H}_{\text{surf}} = \int_0^{\Delta t} \left( Q_{\text{sens}}(t) + Q_{\text{lat}}(t) + Q_{\text{sw,net}}(t) + Q_{\text{lw,net}}(t) \right) A(t) \, dt$$

If all data are internally consistent, the predicted change in heat content,
\[ \Delta H_{\text{C, predicted}} = H_{\text{in}} - H_{\text{out}} + H_{\text{rain}} + H_{\text{surf}} \]

should exactly match \( \Delta H_{\text{C, obs}} \). Note that \( H_{\text{surf}} \) can be negative when a net loss of heat to the atmosphere occurs.

Heat budget calculations were performed on a daily basis for the 57 days during which all field data were available (2 Feb 2002 - 13 Mar 2002, 29 Mar 2002 - 14 Apr 2002).

![Figure 6.3 Component terms of the Hume Reservoir heat budget.](chart)

Figure 6.3 shows the components of the heat budget calculations during the entire study period. The heat budget is dominated by the change in reservoir heat content, outflow heat content and the heat contained in the Murray River inflow during 2001-2002 and Mitta Mitta River inflow during 2002-2003. Outflow accounts for roughly twice the amount of heat as the remaining terms combined whereas the contribution from surface heat fluxes is extremely small compared to the other terms.

The error in closing the heat budget, \( \varepsilon_{\Delta H_{\text{C}}} \), is simply the difference between predicted and observed changes in heat content,

\[ \varepsilon_{\Delta H_{\text{C}}} = \Delta H_{\text{C, observed}} - \Delta H_{\text{C, predicted}} \]

and is shown in Figure 6.3 also. The observed change in heat content is virtually always less (i.e. more negative) than the predicted change as \( \varepsilon_{\Delta H_{\text{C}}} \) is nearly always less than zero. In other words, more heat appears to be lost from the system when computing the observed change in heat content than is predicted from the corresponding inflow, outflow and meteorological data. Excluding the heat content of the outflow and the reservoir, the error in closing the heat
budget was much greater than the heat contributed by any of the remaining terms except for the Murray River inflow during 2001-2002. The following year the magnitude of the error was somewhat less despite the addition of large flows in the Mitta Mitta River. The error appears to be independent of the various terms of the heat budget.

To close the heat budget, i.e. to reduce the error term, would require some combination of decreased changes in reservoir storage, reduced inflow, or increased discharge volumes. The first change makes $\Delta H_{\text{observed}}$ less negative (during falling water levels) whereas the latter two changes make $\Delta H_{\text{predicted}}$ more negative.

If we plot $\Delta H_{\text{observed}}$ vs $\Delta H_{\text{predicted}}$ (Figure 6.4) we see that the observed change in heat content is 12% greater than the predicted change if the regression line is forced through zero. However, the slope reduces to just 4% if an offset of $-1 \times 10^{15}$ J is allowed. This offset corresponds quite closely with the heat content associated with the -750 ML offset from the water balance (i.e., the y-intercept in Figure 6.2 regressions) assuming an average water temperature of 20 °C ($HC = -9 \times 10^{14}$ J).

![Graph showing observed change in reservoir heat content versus predicted change of heat content computed from streamflow and meteorological data. Line of best fit for 2002-2003 data only.](image)

Figure 6.4 Observed change in reservoir heat content versus predicted change of heat content computed from streamflow and meteorological data. Line of best fit for 2002-2003 data only.

To identify the most likely cause of the closure error, it is useful to express it in terms of equivalent errors in the terms that make up the heat budget. Closure of the heat budget for 2002-2003 could be achieved by any of the following: a 3% increase in outflow, a 5% decrease in Mitta Mitta River inflow, or a 0.3% decrease in the reservoir storage vs elevation rating (i.e. 0.3% less volume at any storage level). Attempting to close the heat budget by adjusting water temperature data or meteorological fluxes would require changes orders of magnitude greater than the measurement accuracy of the instrumentation and so this option can safely be dismissed. The most likely source of error appears to be uncertainty in the storage table.
A more refined estimate of the mean reservoir temperature was computed using all of the thermistor chain data at the 3 locations during 2001-2002. The mean daily thermistor chain data were interpolated every 0.5 m and the average of the 3 chains computed at each depth. These mean temperatures were subtracted from the temperatures at TC Hume (dam wall) and the average of all the resulting differences was 0.49 °C. This small change would have a negligible effect on the heat budget calculations.
7. A simple conceptual-analytical model of Hume Dam discharge temperature - Implications for future operating conditions

It is possible to extrapolate the results of the existing monitoring to cover the full range of operating scenarios, i.e. higher water levels and lower discharges. In this section a simple conceptual model and associated calculation are presented to demonstrate that 2002-2003 conditions represented a stringent test of the ability of the storage to deliver warmer discharges and that the observed discharge temperatures were the highest relative to the surface layer temperature that can reasonably be expected using existing infrastructure.

As water is released from the surface layer of the reservoir through the dam, the maintenance of a constant surface layer depth requires that discharged water is either replaced by inflows directly into the surface layer or by entrainment of underlying water into the surface layer. Field data confirm relatively little variation in average surface layer depth in Hume Reservoir.

The depth of the surface layer is controlled by local meteorological conditions and reflects a balance between daytime heating of the water column night-time cooling plus wind mixing. During spring and summer there is a net heating of the water column that produces a strongly stable temperature stratification. The mixing energy introduced by night-time cooling and wind stirring is only enough to mix out this stratification to a depth of 5-7 m and this depth defines the volume of the surface layer, \( V_{sl} \).

The increase in temperature of the surface layer, \( \Delta T_{sl} \) after a time interval, \( \Delta t \), depends on the heat flux, \( Q_{net} \), and the depth of the surface layer, \( Z_{sl} \).

\[
\Delta T_{sl} = \frac{Q_{net}}{\rho C_p Z_{sl}} \Delta t
\]

Depending on the transparency of the water, some fraction of \( Q_{net} \) might penetrate below the surface layer. To compute the temperature increase experienced as water passes through the surface layer one simply replaces \( \Delta t \) with the residence time of the surface layer.

The residence time, \( \tau \), depends, in turn, on the volume of the surface layer and the release of surface layer water from the dam originating from within the surface layer,

\[
\tau = \frac{V_{sl}}{V_{out}}
\]

where \( V_{out} \) is the daily discharge from the dam.

The temperature increase experienced by the surface layer for a given \( Q_{net} \) will decrease as \( \tau \) decreases. The minimum value of the residence time, and therefore the minimum temperature increase, occurs when the discharge volume, \( V_{out} \), is at its greatest and the surface layer volume, \( V_{sl} \), is its smallest.

This simple model can be tested using the data for 2002-2003. Assuming a surface layer depth range of 5-7 m and using the mean observed outflow of 19300 ML d\(^{-1}\) gives surface layer residence times of 22-29 d in October and 9-10 d at the end of December. During this period the weighted mean inflow temperature (combined Murray and Mitta Mitta rivers) increased nearly linearly with time from 11 to 16 °C and the net observed heat flux was 113 W m\(^{-2}\). After applying the formula for \( \Delta T_{sl} \) the inflow is predicted to reach 21-23 °C prior to discharge and assuming the discharge is entirely from the surface layer. Despite being a crude

\[\text{Matveev's (pers. comm.) light attenuation data collected in Hume Reservoir during 1994-1996 shows the attenuation coefficient ranging from 0.5-0.75 m}^{-1}\text{ during spring and summer which corresponds to 82-97\% absorption of solar energy in the top 5 m.}\]
Thermal modelling of Hume Dam

prediction for the surface layer temperature, this result is remarkably consistent with the observed mixed layer temperature (Figure 5.24).

The surface layer residence time during 2002-2003 was as short as is likely to ever occur. Very low water levels (the hydroelectric plant had to cease operation) meant the reservoir's surface area was close to the minimum possible value and therefore $V_{sl}$ was minimal. At the same time, drought conditions resulted in very high irrigation releases (approx 20,000 ML d$^{-1}$) which would seldom be exceeded. Recall that $Q_{np}$ and $Z_{sl}$ depend solely on the meteorology and can be assumed to be relatively constant during spring. At the same time inflow to the dam was roughly 15000 ML d$^{-1}$. Taken together, this suggests that $T_{sl}$ observed during 2002-2003 is close to the smallest possible value. At higher water levels and/or lower discharges the residence time of the surface layer must increase and so too $\Delta T_{sl}$.

The one remaining variable to consider is the initial temperature of the surface layer. The lowest possible value would correspond to low storage levels, high discharge and high inflows of cold water from both the Snowy Hydro Scheme and Dartmouth Dam. All of these conditions were met during 2002-2003 with the qualification that Mitta Mitta inflow temperatures could have been 2-3 °C colder (mainly from Dec onwards) had Dartmouth Dam been more full, i.e. deeper, at the start of the release period. This latter condition would represent a worst-case scenario.

In the worst-case scenario, surface layer temperatures would be correspondingly (2-3 °C) colder. To overcome this, the residence time would have to increase by 4-7 days. The impact of inflow temperature becomes negligible when the volume of Hume Dam exceeds approximately 20% at which point the surface layer residence time under high release conditions is roughly 18 days - long enough for a 9 °C temperature increase.
8. Numerical modelling of the effect of adding a multi-level offtake capability on Hume Dam discharge temperature

In this section the one-dimensional numerical model DLM (Dynamic Layer Model) is used to simulate the time-dependent thermal stratification of Hume Reservoir. The emphasis is on predicting the effect that providing multi-level offtake (MLO) capability to Hume Dam would have on discharge temperature. Twelve runs were performed in total; two runs for each of six initial storage level - inflow/outflow scenarios that covered both high and low storage levels and 20, 50, and 80 percentile flows.

8.1. Model description

The numerical model used for the simulation of discharge temperature from Hume Dam is called the Dynamic Layer Model, or DLM. It is currently developed by Prof Geoff Schladow at the University of California, Davis and is a derivative of DYRESM, developed by the Centre for Water Research at the University of Western Australia.

DLM is a one-dimensional (vertical) model that simulates the stratification dynamics in small-medium sized reservoirs, however, it has been used successfully on lakes as large as Lake Tahoe. (The suitability of the 1D modelling approach for simulating Hume Dam is discussed later.) DLM represents a reservoir as a series of Lagrangian layers that move up and down and which swell and contract in response to inflows and outflows. The water column absorbs shortwave solar radiation following the Lambert-Beer Law. Turbulent heat, mass (evaporation), and momentum fluxes at the air-water interface are computed from the observed meteorological data following Liu et al. (1979). Upwelling longwave radiation is emitted from the reservoir as the fourth power of water temperature following the Stefan-Boltzman Law and downwelling longwave radiation absorbed by the water surface is input from the directly measured field data values.

Surface mixed layer dynamics are computed using an energy budget approach in which the turbulent kinetic energy introduced at the water surface by surface cooling (penetrative convection) and wind stirring and at the top of the thermocline by shear (internal waves) is compared with the potential energy of the density stratification. The surface mixed layer deepens by entraining successive model layers so long as the kinetic energy available for mixing exceeds the energy required to entrain the next layer below. Selective withdrawal dynamics are computed following Hocking et al. (1988) and inflow dynamics are simulated following Fleenor (2003).

DLM was selected for two reasons. Firstly, it is much easier to read and modify the code – necessary to include the tracking of surface layer height. Secondly, it offers a capability to better simulate entrainment into plunging inflows where inflowing streams enter a lake unconfined by channel boundaries. Most models assume that the plunge occurs in a parallel-walled inundated channel and in this case they can safely neglect the entrainment that occurs across the roughly vertical interface between plunging inflow and receiving reservoir. This interface coincides with the 'plunge line' that is often visible when waters of different turbidities mix. In natural lakes, inflows generally enter the water body without lateral constraint and spread out as a radial plume. In this case, significant entrainment of ambient water across the interface may occur.

During the very low water level in Hume Reservoir during 2002-2003, the Mitta Mitta River entered the storage at roughly right angles to the main basin extending southeast from the dam wall. In effect, Hume Reservoir was better represented as a lake than an inundated river channel during this period.
8.2. Assumed hydrologic conditions

The low, median, and high flow hydrologic scenarios considered in the model runs were the 20th, 50th, and 80th percentile inflows and outflows. Figure 8.1 shows the exceedence plots for the 110 years of hydrologic data provided by MDBC.

Figure 8.1 Exceedance plots of inflows, outflows and August storage levels at Hume Dam. Blue-shaded regions denote ≤ 20 percentile and ≥ 80 percentile. Based on 110 years of data provided by MDBC.
Figure 8.2 shows the annual hydrologic year flows relative to the percentile bands. The low and median flow scenarios were taken to be 1947 and 1964, respectively. Inflows and outflows for both years were in the appropriate percentile categories. The high flow scenario was taken to be the 1982 hydrologic year which had flows slightly higher than the 80th percentile.
8.2.1. Outflow assumptions

All discharge up to 16900 ML d\(^{-1}\) was assumed to be routed through the hydropower plant. Additional discharge was routed through the irrigation valves. The assumption was that maximum electrical production was the primary goal.

8.2.2. Inflow assumptions

All inflow was attributed to the Mitta Mitta River up to 10000 ML d\(^{-1}\). Additional inflows are routed through the Murray River.

The inflow temperatures were based on observed temperatures in the Mitta Mitta River at Tallandoon during bank-full releases from Dartmouth Dam and likely underestimate the inflow temperatures during low and median inflow years (Figure 5.21). Inflow temperatures for both rivers were assumed to increase linearly with time from 10.6 °C to 13.6 °C during the course of the simulation (Figure 8.3). This rate was based on measured temperatures in the Mitta Mitta River at Tallandoon during Sep – Nov and extrapolating the rate of increase with time through the end of the simulation. The extrapolation was done to remove the effect of the falling water level in Dartmouth Dam during 2002-2003 which may have caused uncharacteristically warm inflows from Dec 2002 onwards (Figure 5.21, temperature at Coleman's).

![Mitta Mitta inflow temperature](image)

*Figure 8.3 Assumed inflow temperatures (dashed line) for model scenarios.*
8.2.3. Initial stratification

The thermal stratification at the start of each simulation is shown in Figure 8.4. The starting profile was produced by extrapolating downwards from the observed temperature profile on 2 October 2002. This was accomplished simply by adding an additional 1 or 2 depth-temperature data pairs at the bottom of the profile. Historically, the bottom temperature in Hume Reservoir has been approximately 12.5 °C at this time of year.
8.3. Model validation

The numerical model does not allow for calibration apart from specifying the divergence angle, delta, where the inflow enters the reservoir at low water level. This angle controls the amount of initial mixing across the river/reservoir interface where the inflow plunges below the surface of the reservoir to become either an underflow or interflow.

All meteorological forcing of surface heat, momentum and mass (evaporation) transfer used data measured on the reservoir near the dam wall. The light attenuation coefficient was fixed at 0.65 m⁻¹, a central value based on the measurements of Matveev (pers. comm.) during spring-summer periods from 1994-1996.
Comparisons between modelled and observed temperature profiles (Figure 8.5) are disappointing and may indicate limitations of the 1-dimensional modelling approach. The surface layer temperature was typically within 0.5 °C of observed values which is satisfactory. There was no consistent trend towards over-prediction or under-prediction of the surface layer depth. Hume Reservoir experiences substantial wind-driven motions that make it difficult to select a 'typical' temperature profile for comparison to model output.

The divergence angle, delta, was chosen by visual inspection of model outputs to be 45°. This produced the best overall match to observed bottom temperatures through early February, about ±1 °C. Bottom temperatures were more than 2 °C too cold from late February through late March.

Modelled and observed discharge temperature through Hume Dam Power Station show reasonable agreement during the period of power station operation (Figure 8.6a). When compared to the average discharge temperature of both outlets estimated from thermistor
chain data there was a trend towards increasing under-prediction during late summer (Figure 8.6b). There is also evidence of a slight mismatch in the timing of the outflow temperatures with modelled temperatures leading thermistor chain estimates by 2-3 days. This offset most likely arises from an error in the timing of the arrival of inflows. Overall, the RMS deviation between model and estimated discharge temperatures, $\Delta T$, was 1.1 °C with a bias towards under-predicting discharge temperature during February – March (Figure 8.6c).

### 8.4. Scenario results

Six scenarios were considered consisting of 12 model runs. The modelled scenarios are listed in Table 10. Note that the high and low storage years were determined by the storage level in August whereas the simulations commenced on 3 Oct using the storage level on that date as the initial condition. Each of the six scenarios consisted of a reference model run for which the existing offtakes were used and a model run for which the outlet level was assumed to be 8.5 m below the water surface (denoted as 'track' in the figures). Results are presented as both absolute discharge temperature and as the difference in discharge temperature between reference and 'tracking' model runs. The high water level – high inflow/outflow scenario is described in detail to illustrate the main aspects of the simulations.

### 8.4.1. High water level

#### 8.4.1.1. Evolution of stratification - high inflow/outflow

The impact of having the offtake track the water surface is evident in the evolution of the thermal stratification shown in Figure 8.7. The high offtake leads to the water column becoming strongly two-layered with an extremely sharp thermocline separating the epilimnion from a cold hypolimnion at the level of the offtake invert (8.5 m depth). In effect what has happened is that the cold inflows have inserted near the bottom of the hypolimnion and displaced the bottom of the thermocline upwards. This accelerates the development of a shallower surface layer than occurs in the reference run. Releases from the assumed outlet (invert at 8.5 m depth) withdraw water roughly 50% from the surface layer and 50% from the top of the hypolimnion. Under reference conditions, i.e. the existing offtake structure, the epilimnion is much deeper and the total heat content of the reservoir is much higher as cold hypolimnetic water has been preferentially released.

Epilimnion temperatures were up to 1 °C warmer for the tracking offtake simulation during the first 3 months (Oct – Dec) because the higher outlet level promoted the development of a shallower surface mixed layer. The warmer surface layer in turn increased the evaporative,

---

3 Recall that the inflow algorithm tended to predict colder bottom temperatures than were observed during the validation run. Hypolimnetic temperatures predicted in the scenario testing may also be too cold if either the assumed inflow temperature was unrealistically low or the model underestimated entrainment of ambient reservoir water during the long trip along the bottom of the reservoir to the dam wall.
Thermal modelling of Hume Dam

Conductive, and longwave radiative heat losses thereby decreasing the net heat flux slightly (Figure 8.8). From late February onwards the reference simulation predicted warmer surface layer temperatures largely because of the much greater amount of heat stored below 9 m depth when the existing offtakes are used. As the net heat flux across the water surface decreases in late summer and becomes negative during autumn there is a greater reservoir of stored heat to satisfy the demands of the surface heat flux and the surface layer temperature decreases more slowly with time as a consequence.

Figure 8.7 Simulated temperature profiles for high water level, high inflow/outflow scenario. a) Offtake level tracks water surface. b) Existing offtake levels. Date format is yyyyddd where ddd is the Julian date, e.g. 2003040 = 9 Feb 2003.
Figure 8.8  Mean monthly heat flux components for high storage level – high inflow/outflow scenario. a) Evaporative and conductive heat flux. b) Net radiative heat flux. c) Net heat flux.
8.4.1.2. Impact on discharge temperature

Simulations commencing with a full reservoir showed an average 5.6 °C increase in discharge temperature from 3 October through 31 January accruing from the use of the tracking outlet (Figure 8.9a) for all inflow/outflow scenarios. During this period, discharge temperature for the tracking outlet ranged from 18-22 °C (Figure 8.9b). Discharge temperatures were predicted to decrease to 16-18 °C during February and March with the lowest temperatures corresponding to the highest inflow/outflow scenario. The colder discharge temperatures during late summer early autumn appear to result from a weakening of the thermocline, especially the lower half, which led to relatively more water being withdrawn from below the outlet invert, i.e. the withdrawal layer extended further downwards below the assumed offtake invert level.

---

Figure 8.9 a) Change in discharge temperature, ΔT, between tracking offtake and reference runs for high initial storage level and high, median, and low inflow/outflow conditions. b) Predicted discharge temperature using tracking offtake (8.5 m below water surface) for high initial storage level and high, median, and low inflow/outflow conditions.
Shoaling of the lower thermocline finished by mid-January representing a quasi-equilibrium condition between the filling of the hypolimnion with cold inflows and discharge of water from the top of the hypolimnion. From mid-January onwards relatively more cold water was withdrawn (approximately 50%) from below the thermocline. Surface layer temperatures peak in late January at approximately 27 °C and after this time the discharge temperature decreased as a result of decreasing epilimnion temperature.

It would be desirable to establish with fish biologists the ecological implications of the depression in discharge temperature during late summer-early autumn.
8.4.2. Low water level

Under low initial storage level conditions the tracking offtake scenarios predicted less increase in discharge temperature than the corresponding high storage level scenarios (Figure 8.10a). The predicted increase in temperature ranged from 1 to 5 °C from October through mid-December. From mid-December onwards there was no consistent change in discharge temperature between tracking offtake and reference conditions when all flow scenarios are considered. Note that the combination of initial storage level and inflow/outflow scenarios resulted in drawdown of the reservoir to below the existing offtakes in the low flow and high flow scenarios.

Predicted discharge temperatures (Figure 8.10b) were similar to field observations during 2002-2003 (Figure 8.6b). The slightly colder discharge temperatures in the scenario runs
(Figure 8.10b) largely reflect the much colder inflow temperatures. This result simply confirms past observations that low storage levels produce warmer discharge temperatures because the thermocline is located within the withdrawal region of the existing offtakes.

8.5. **Summary**

The change in Hume Dam discharge temperature resulting from the use of a high level offtake was simulated using the one-dimensional reservoir hydrodynamic model DLM. The offtake level was allowed to continuously track the water surface to ensure maximum accessibility to the warmest epilimnetic water.

Not surprisingly, the greatest change in discharge temperature occurred when the reservoir was full at the beginning of the simulation and the existing offtakes were located deep below the thermocline. By providing access to warm surface layer water the use of the tracking high-level offtake increased discharge temperature by an average 5.6 °C from October through January. During this period a strong two-layered stratification developed with the thermocline located at a depth of 8 m and a very cold hypolimnion forming as cold inflows arrive and displace warmer water towards the surface.

A significant consequence of the strong two-layered stratification observed in the high-storage scenarios was that discharge temperatures from February through March were lower on average by 3.4 °C in the tracking offtake scenario compared to the reference condition of using the existing offtakes. Late summer-early autumn discharge temperatures were predicted to be as low as 16-18 °C which may of itself constitute cold water pollution at this time of year.

When the initial storage level was low, use of the tracking offtake increased discharge temperature by 2.6 °C from October through mid-December. After this time there was no consistent trend in the predicted temperature change.

Simulation of the thermal dynamics of Hume Reservoir may be pushing the applicability of the one-dimensional numerical modelling approach to its limits because of the unusual shape of the reservoir. Despite this limitation the validation run of the DLM model predicted discharge temperatures within 1.1 °C of field observations. This suggests that model predictions of the changes in discharge temperature when the offtake is allowed to track the water surface as compared to using the existing offtake levels should be reliable.

In practice it probably would not be feasible to construct a ‘tracking’ offtake. Instead, a multi-level design would be built. Because of the discreet changes in outlet level and continuous changes in water level the stratification may not develop in quite the same way as shown in the model scenario runs.
9. Mitigation strategies - management implications

The field data collected during 2001-2003 indicate that there is sufficient warm water available in the surface layer of the reservoir under virtually all conditions to provide a temperature increase of 4-5 °C during spring and summer. This would bring the discharge temperature into the 18-20 °C range. The challenge is to find a way to access this supply of warm water.

The three most promising engineering options are: construction of a multi-level offtake structure; use of surface pumps; and installation of a submerged curtain.

The use of surface pumps is unlikely to be feasible for two reasons. Firstly, to pump 20,000 ML d⁻¹ would require at least 15 of the 5 m-diameter impellers used by the Tennessee Valley Authority to raise dissolved oxygen levels in turbine flows (Sherman 2000). Anchoring such a large array of impellers in such a way as to guarantee delivery of the pumped flow into the withdrawal layer of the existing turbine intake will be quite challenging especially when having to make allowance for spills over the dam during flood conditions. The use of impellers is better suited to situations where spill occurs well away from the location of the impellers. Furthermore, the unconfined jet produced by the pumps will entrain ambient water prior to discharge and this will reduce the realised discharge temperature increase substantially. A 2 or 3 °C reduction seems likely but this estimate would have to be confirmed by numerical modelling of the entire impeller system.

Installation of a submerged curtain may be feasible provided it is deployed at a sufficient distance from the outlet valves to keep mean velocities over the curtain below 0.1-0.2 m s⁻¹. To accomplish this the curtain length would have to be > 500 m or so. A comparable-sized curtain has been deployed in the United States at a cost of USD $1.8m. Consideration must be given to material reliability to ensure there is very little chance of the fabric tearing and being carried through the hydroelectric turbines. The life expectancy of a curtain is approximately 9 years. A submerged curtain should provide the greatest increase in discharge temperature of the three options considered here.

Retrofitting the dam with a multi-level offtake is the final option. The challenge here is to come up with a design that allows access to surface layer water over the range of water levels experienced by the reservoir. The existing offtakes are 3.5 (irrigation) and 6 m (hydro) tall; presumably the multi-level offtake ports will have similar dimensions. A continuous array of 3.5 m tall ports should provide satisfactory flexibility to produce discharge temperatures similar to those observed during 2002-2003.

There is another important consideration regardless of which option is selected. Water is presently withdrawn from the hypolimnion of Hume Dam at a rate, which appears to prevent anoxic conditions from developing in the reservoir. Mitigation of cold water pollution will require the substitution of surface layer water for hypolimnetic water and this will increase the residence time of the hypolimnion significantly. It is possible that the hypolimnetic residence time will be increased sufficiently to allow the development of anoxic conditions, which potentially could stimulate the release of nutrients from the sediments. This internal nutrient load might in turn fuel enhanced phytoplankton growth in the reservoir.
10. Conclusions

A thermal monitoring program was implemented at Hume Reservoir during 2001-2003. The instrumentation consisted of 3 thermistor chains during 2001-2002 and 2 in 2002-2003 (due to low water levels) in the reservoir; a meteorological station located on the surface of the reservoir near the dam wall; and numerous temperature loggers located both upstream and downstream of Hume Dam. Data capture was 97% for all instruments during 2002-2003 but just 58% during 2001-2002 due to instrument malfunctions and mooring failures that occurred prior to February 2002. The data record has allowed accurate heat and water budgets to be calculated for Feb 2002 - Mar 2002 and Oct 2002 - Mar 2003. It also has allowed some assessment of interannual variability of meteorological conditions and the associated thermal response of the reservoir.

The net surface heat flux averaged 113 W m$^{-2}$ during October-December 2002. This is sufficient to warm the top 5 m by roughly 0.5 °C d$^{-1}$. Atmospheric heat fluxes averaged 231 W m$^{-2}$ for net radiation, -8 W m$^{-2}$ for sensible heat flux and -110 W m$^{-2}$ for latent heat flux (evaporation). The observed warming of the water column was consistent with historical temperature profile data collected during 1982-1985.

Thermistor chain and SeaBird SBE19 profile data revealed that the mean temperature of the surface layer (top 5 m) near the dam wall was consistently warmer than at the southern end of the storage (Mitta Mitta arm). This was caused by the persistent southeasterly winds. When they blow, the thermocline tilts as warm surface layer water accumulates at the downwind end (dam wall) and colder water upwells at the upwind end. As a consequence, the mean surface mixed layer depth varied from 3.6 m at the south end of the reservoir (TC Mitta) to approximately 6.5 m near the dam wall during 2002-2003. During the previous year the corresponding surface layer depths were somewhat deeper at 4.6 m and 9 m, respectively.

No such trend was observed between the dam wall and the Bowna Arm (TC Bowna) located to the northeast. Surface layer temperatures were quite similar at both sites whereas the surface layer depth was 4-5 m shallower at TC Bowna. A full analysis of the causal mechanism behind this observation is beyond the scope of this report but it seems likely that the change in orientation (by about 60°) and narrowing of the basin north of the dam greatly restricts (if not prevents) further wind-driven movement of the surface layer during southeasterly winds.

Internal wave activity was analysed during 2001 - 2002 and showed a typical displacement of ± 1.06 m. A similar analysis could not be performed the following year owing to rapidly changing and low water levels in the reservoir.

Profiler data revealed the presence of relatively colder underflows in both the Murray and Mitta Mitta arms. The characteristics of the underflows depended upon inflow volumes and temperatures, wind conditions, and reservoir water level. During 2001-2002 the Murray River was typically 1 –2 °C colder and the Mitta Mitta River was 2 – 4 °C colder than the surface layer where these rivers enter the storage. The actual intrusion depths will vary in time depending on prevailing wind direction and the amount of ambient water entrained as the inflow passes through the shallow upstream regions of the storage. Only the Mitta Mitta River underflow was observed to propagate into the main basin of the reservoir.

During 2002-2003 the Murray River inflow and temperature at Jingellic were variable. During early summer, when discharge was < 3000 ML d$^{-1}$, its temperature was not significantly different to that of the surface mixed layer. When discharge increased in mid-January to > 5000 ML d$^{-1}$ the temperature dropped appreciably and was 6-8 °C colder than the surface layer temperature at Hume Dam. The extent of warming between Jingellic and the reservoir was probably 3-4 °C. Mitta Mitta River inflow rate was much greater at 10000 ML
Thermal modelling of Hume Dam and was 4-7 °C colder than the surface layer temperature at the south end of the main basin of Hume Reservoir. The greater temperature difference was the result of the reduced travel time from Dartmouth to Hume reservoirs, which reduced the amount of warming that took place prior to the inflow entering the reservoir. During 2001-2002 this warming was 3-7°C whereas in 2002-2003 it was < 1 °C.

A heat budget was computed to quantify the fluxes of heat within the reservoir. Atmospheric heat fluxes comprise a small fraction of the overall heat budget. The heat budget is dominated by the heat contained in the inflows and outflows. The most likely source of error in the heat budget was uncertainty in the reservoir’s storage table. However, this uncertainty is very small (about 0.3%) and quite acceptable. The heat budget verified the adequacy of the field monitoring program for predicting the temperature dynamics of the reservoir.

There appears to be an adequate supply of sufficiently warm water in the surface layer of Hume Reservoir to raise discharge temperatures to 18-22 °C during late spring and early summer regardless of reservoir level and inflow/outflow discharge rates. Both the analytical and numerical models confirmed this. The challenge will be to access this supply.

Conditions during 2002-2003 were close to the worst case scenario from the point of view of mitigating cold water pollution. The reservoir volume was quite small and both discharges and inflows were large. Together these factors yield the shortest possible residence time in the surface layer during which cold inflows are able to warm up prior to being released downstream into the River Murray. The low reservoir level also resulted in the existing offtakes drawing water off from the surface layer and upper thermocline regions during most of the year. The observed discharge temperatures therefore give a good indication of what is achievable under more normal operating conditions provided it is possible to access this region of the water column.

The most promising methods to provide access to surface layer water are construction of a multi-level offtake and deployment of a submerged curtain. The submerged curtain is likely to provide the greatest temperature increase.

An important consequence of any cold water pollution mitigation strategy is that the residence time of the hypolimnion will increase relative to current conditions. This may result in the development of anoxia in the hypolimnion leading to an increase in sediment nutrient release and ultimately higher algal biomass in the reservoir.
11. **Recommendations**

It would be useful to **determine more accurately the extent of cold water pollution downstream of Hume Dam**. Such a study should include an assessment of the impact of inflows of unregulated tributaries such as the Kiewa and Ovens rivers. These tributary flows may contribute towards the mitigation of the impact of cold discharges from Hume Dam and this contribution needs to be quantified.

The question of optimising the increase in discharge temperature throughout the entire simulation period was not addressed. That the large discharge temperature increase during October – January was followed by a temperature decrease in February – March (full reservoir scenario) suggests that **it may be possible to optimise the discharge temperature to some specified seasonal criterion by using a combination of offtakes at different times of year**. Such an exercise could be undertaken using the model presented here.

The predicted discharge temperature and the change in temperature between reference and tracking offtake scenarios will depend upon the inflow temperature. The most conservative, i.e. coldest, inflow temperatures were assumed for the results presented in this study. In reality inflow temperatures would likely be warmer. It may be possible to **improve the accuracy of the model predictions by better representing the heating of inflows prior to their entering the reservoir**. In this case the base temperature of the inflows would be defined to vary seasonally and an additional temperature increase would be computed as a function of discharge to better represent the heating of the inflow as it travels along either the Murray or Mitta Mitta rivers. Recall that discharge-dependent temperature increases of 1-8 °C were observed in the Mitta Mitta River as part of this study.

**An investigation into the potential of increased hypolimnetic residence time to increase internal nutrient loads and algal biomass should be undertaken prior to implementing a cold water pollution mitigation strategy.** Such a study should include, but not necessarily be limited to, the deployment of benthic chambers to quantify sediment oxygen demand and nutrient release rates under field conditions. This information would be used subsequently as input to a reservoir water quality model (or possibly a simpler Vollenweider-type model) used to predict potential changes in algal biomass.

The most promising techniques to achieve warmer discharge temperatures are (1) construction of a multi-level offtake structure and (2) deployment of a submerged curtain. **The costs to provide access to surface layer water during all water level conditions should be determined by conducting feasibility studies into these two options.**
12. References


13. **Appendix A - Long-term model simulations**

As a variation to the original contract, State Water requested CSIRO to perform long-term numerical model simulations using DLM and to provide predicted discharge temperatures to SKM for further manipulation. Two cases were considered: a reference scenario assuming business-as-usual using existing infrastructure; and a 'tracking' scenario for which the inverts of the offtakes were allowed to track the water surface so that they were always located 8.5 m below the water surface. This 8.5 m depth is the minimum depth of cover required for operation of the hydroelectric power station at the dam. These are the same scenarios described in Section 8.

Simulations were performed for the period 1 Jan 1980 through 31 Dec 2003, a period of 24 years. For most of this period there was little on-site meteorological data available. As well, inflow temperatures were not well-known. This section describes these simulations, the assumptions made regarding input data, and some problems encountered with the input data provided to CSIRO for use in the model.

As is the case with all numerical model simulations, the quality of the output depends heavily on the quality of the input data. The accuracy of the long-term simulations should be considered as poor-fair in absolute terms and fair in relative terms, i.e. when comparing the difference between reference and 'tracking' scenario outputs.

### 13.1. Model input data

#### 13.1.1. Meteorological data

All meteorological and hydrological input data were provided to CSIRO by SKM. The input meteorological data are shown in their entirety in Figure 13.1. Note the synthetic shortwave radiation data during 1996-1997.

#### 13.1.1.1. Longwave radiation

No measurements of downwelling longwave, upwelling longwave or net radiation were available. Consequently, downwelling longwave radiation had to be derived from an estimate of cloud fraction - the portion of the sky assumed to be covered by clouds. The cloud fraction was computed as octal coverage/8 where cloud cover data were provided. There were periods of missing record for the cloud cover data. During periods of missing record cloud cover was estimated as 0.96-0.000026*swinc, where swinc is the incident downwelling shortwave irradiance at Hume Dam.

Cloud cover is used to compute the downwelling longwave radiation using Swinbank's formula (Tennessee Valley Authority, 1972),

\[
Q_{LW} = \left(1 - \alpha\right) c_{LW} \left(1.0 + 0.17 \text{ cloud}^2\right) \left(273.15 + T_{\text{air}}\right)^6
\]

where cloud is the fractional cloud cover, \(T_{\text{air}}\) is the air temperature, the longwave albedo of the water surface, \(\alpha\), is 0.03 and the coefficient \(c_{LW} = 5.313e^{13} \text{ [W m}^{-2} \text{ C}^{-6}]\). Despite providing a generally good fit to observed downwelling radiation data, formulae such as this can be in error by up to 30 W m\(^{-2}\) depending on prevailing atmospheric conditions at a particular site.

The data and regression are shown in Figure 13.3 and clearly the filled data have a very high uncertainty associated with them. This is why measured downwelling longwave is always preferable!
13.1.1.2. **Shortwave radiation**

The supplied incident shortwave data from Hume Dam had long periods of missing record. These were filled using the regressions shown in Figure 13.4 when only Dartmouth data were provided and from Figure 13.5 when data from Wagga Wagga were available. It is clear from the plots that shortwave radiation measurements from Wagga Wagga bear a much closer resemblance to those measured at Hume Dam and are preferable to the measurements at Dartmouth Dam.

13.1.1.3. **Mapping of long-term climate data to local conditions**

A comparison of the data provided by SKM with corresponding data collected by CSIRO using instruments deployed on a raft with sensors located 2 m above the water surface (Figure 13.2) revealed significant discrepancies between the data sources. The regression equations shown in Figure 13.2 were used to map the data provided by SKM into equivalent values for 2 m above the water surface which in turn were used to force the model simulation.

Another difficulty was encountered on days when the wind speed was zero. This indicates that the actual wind speed was less than the stall speed of the anemometer. No information regarding the stall speed was provided. In addition to being extremely unlikely, days with zero wind speed cause a problem for the atmospheric stability correction algorithm used to compute bulk aerodynamic fluxes. This was circumvented by increasing the mean wind speed to 0.10 m s\(^{-1}\) on those days where it had been previously specified as 0.0 m s\(^{-1}\).
Figure 13.1 Long time series meteorological data used for Hume simulation.
Figure 13.2 Comparison between SKM-provided meteorological data from Hume and corresponding CSIRO data collected 2 m above the water surface.
Figure 13.3 Fractional cloud cover versus downwelling incident shortwave irradiance at Hume Dam.

Figure 13.4 Incident shortwave radiation at Hume Dam versus shortwave radiation at Dartmouth Dam.
13.1.2. Initial water level and stratification

The initial water level was set to the observed value on 1 Jan 1980 of 189.50 m. The initial profile was assumed to be the same as measured by the thermistor chain on 1 Jan 2002 (Figure 13.6). The temperature at the bottom of the water column was extrapolated...
downwards from the maximum observation depth of 29 m to the bottom of the deeper water column in 1980. This introduces a likely error in the temperature below 10 m, the assumed temperature is probably too warm, but this error should only effect the 1980-1981 results as winter overturn in 1981 will effectively reset the stratification.

13.1.3. River discharge and reservoir level

Significant problems were encountered with the inflow and reservoir storage level data. The reservoir volume data initially provided were converted to the equivalent water levels using the storage table for the dam. These derived levels differed from observed levels (as recorded in the HYDSYS database) by up to 5 m (Figure 13.7).

Inflow, outflow and storage data could not be reconciled as originally supplied, i.e. there were significant water budget errors. Ultimately, a revised inflow data set was supplied and flows in the River Murray were adjusted to fit a simple water mass balance assuming the other data were correct.

![Hume Dam levels](image)

*Figure 13.7 Observed (red) water level at Hume Dam compared to model predictions (black) and levels derived from storage volumes provided by SKM (blue).*

13.2. Model results

The model was run using the input data described above with the result that less increase in discharge temperature was predicted than was expected based on the field observations and arguments presented earlier in this report. Subsequent inspection of predicted thermal stratification implied a significant error in one or more aspects of the input data. The model predicted bottom temperatures that were 4-5 °C higher than observed (Figure 13.14). Not only were hypolimnetic temperatures too high, the level and strength of the thermocline were poorly predicted.

The implication of the poor simulation of the stratification is that the temperature increase arising from the use of the 'tracking offtake' scenario will be much less than would reasonably be expected to occur. This happens because the discharge temperature for the reference condition is predicted to be too high. For example, in Figure 13.14 it is apparent that near-bottom release of water (i.e. the reference condition) during December 1984 would be
expected to have a temperature in the range 14-16 °C (thin green line) rather than the 19.5 °C that the model predicted.

13.3. Revised long-term simulation

Another long-term simulation was run in March 2005 in order to improve the accuracy of the predictions of Hume Reservoir discharge temperature and stratification following a detailed comparison of observed temperature profile data from Brymner's (1985) report. This analysis led to the following modifications of the input data: the River Murray discharge correction was altered; inflow temperatures were reduced, and a correction was made to the wind speed data. These corrections are discussed below followed by the resultant change in simulated reservoir stratification.

13.3.1. River Murray discharge

A water balance was performed using observed flows for the River Murray at Jingellic, the Mitta Mitta River at Tallowood, recorded outflow from Hume Dam and observed water levels in the dam. This provided a quick check on the internal consistency of the inflow, outflow and storage data at the reservoir. Daily reservoir water level data were converted to storage volumes using the rating table for the storage. The daily change in observed storage volume was then compared with the net inflow/discharge from the dam after making an allowance for rainfall and evaporation based on measured values at the dam. A pan coefficient of 0.6 was applied to the evaporation pan data based on calculations presented earlier in this report.

The water balance is given by

\[ \sum error = \int_0^T (\Delta Vol_{obs}(t) - \Delta Vol_{predicted}(t)) dt \]

\[ \Delta Vol_{predicted} = Inflow - Outflow + Rain - Evaporation \]

where inflow is the sum of the Murray and Mitta Mitta discharges and \( \sum error \) is the cumulative water balance error. All calculations were performed on daily data.

Figure 13.8 shows the major terms in the water balance equation along with the cumulative error. The cumulative error increases in a step like fashion every winter and implies that either inflow is too low or outflow is too high. Outflow data are unlikely to be in significant error so the inflow data were inspected for a possible correlation with the cumulative error.

Figure 13.9 shows an expanded view of a typical winter 'step' in the water balance error. The only common factor between the water balance error and the terms of the equation during these periods of rapid cumulative error increase was the flow in the River Murray (measured at Jingellic). Inspection of inflow data over a number of such steps in the cumulative error suggested a correlation between the steps and River Murray discharges greater than roughly 10000 ML d\(^{-1}\).

Figure 13.10 shows the mean daily error vs mean daily discharge in the Murray during periods of rapid error accumulation. This plot suggests that the measured discharge in the Murray may be 40% smaller than the true value. There was no significant correlation between mean daily error and either the Mitta Mitta River discharge or the release from Hume Dam. A comparison of cumulative adjusted flow with the cumulative flow derived from closing the water balance showed that an increase of 30% applied to discharges greater than 10 000 ML d\(^{-1}\) provided the best fit over the 23 years of data.
The requirement for an increase in River Murray inflow may reflect partially the contributions from ungauged local runoff entering the reservoir from the sub-catchments downstream of Jingellic and Tallandoon.

For the revised model simulation, inflow in the River Murray was increased by 30% for all discharges greater than 10 000 ML d$^{-1}$. Note that the previous long-term simulation already used inflow data that satisfied a daily water balance, but the water balance appeared to be based on incorrect reservoir storage level data.

**Figure 13.8 Terms in the Hume Dam water balance.**

**Figure 13.9 Typical winter water balance error.**
13.3.2. Wind speed correction

The regression originally used to map wind speed data provided by SKM to values 2 m above the water surface was forced through zero. This had the effect of reducing low wind speeds and increasing high wind speeds. The increase in high wind speeds is particularly important as mixing energy scales with the square of the wind speed. A linear regression applied to the data in Figure 13.2 without forcing the fit through zero yielded a new relation to map SKM data to conditions just above the reservoir surface.

13.3.3. Inflow temperature correction

A bias towards warmer temperatures was found in data provided for both the Murray and Mitta Mitta rivers when compared with field data presented in Sherman (2002, 2003). The figures below show that the model input data (Mitta Mitta_{SKM}, Murray_{SKM}) were often 1-2 °C warmer than the observed values at Jingellic and Tallandoon. This was especially the case during autumn and winter. Such a high bias in inflow temperatures would have contributed to the model's poor verification performance during 1982-1984 where offsets between observed and modelled temperatures imply a combination of inflow temperatures that were too high and net air-water heat fluxes that were also too high (too much heat entering the water column).

The bias in the inflow temperatures was compensated for by applying an offset of -2 °C to all inflow temperatures.
13.3.4. Revised long-term simulation results

The impact of the input data modifications on the predicted temperature stratification are shown in Figure 13.13. For convenience, the previous results are shown in Figure 13.14. The reduction in high wind speeds and decrease in inflow temperatures have improved the simulation results significantly. Bottom temperatures are still predicted to be warmer than observed, but the error has reduced from 5-6 °C to approximately 2 °C. The location and strength of the thermocline is much better predicted as well.

In terms of the long-term prediction of discharge temperatures, the new simulation will predict temperatures that are roughly 2 °C too high from Oct - Dec. However, as surface temperatures are also predicted to be too warm by a comparable amount the predicted
increase in discharge temperature using the 'tracking offtake' scenario should be relatively more accurate, say within 1 °C of the likely actual value.

Figure 13.13 Observed (solid lines) and simulated (dashed lines) temperature profiles for Hume Reservoir during spring to early summer 1983 (top) and 1984 (bottom) using revised input data for the model.
Figure 13.14 Observed (solid lines) and simulated (dashed lines) temperature profiles for Hume Reservoir during spring to early summer 1983 (top) and 1984 (bottom) using original input data for the model.

13.4. Conclusion

The revised long-term simulations of discharge temperature are much more accurate than the original simulations. The revised model predictions of hypolimnetic temperatures during spring and early summer typically are 3-4 °C colder than the original predictions yet still appear to be 1-2 °C higher than actually occur based on observations during 1982-1984. There was also a tendency to predict surface layer temperatures that are warmer by a similar amount. This suggests that the input meteorological data produce overestimates of the net heat flux into the reservoir during spring and summer. These errors partially compensate for each other in the calculation of top-to-bottom temperature difference – probably improving the accuracy of the predicted increase in temperature achieved by the 'tracking offtake' scenario as compared to the reference 'business as usual' scenario.

This may have implications for any forecasts of ecological condition which have been based on the original model simulations. Any such forecasts should be repeated using the new simulation results. In addition, sensitivity of ecological responses to temperature should be considered as well. For example, the 31 Oct 1984 simulation would predict a discharge temperature through the hydroelectric plant of roughly 13 °C whereas the field data suggest it
would be just less than 12 °C. A process representation with a threshold temperature (say egg survival) between these two values could come to different conclusions depending on whether the observed or the predicted discharge temperature was used.

Despite the challenges of using a one-dimensional hydrodynamic model to simulate such a large, geometrically complex and dynamic storage as Hume Reservoir, it appears that the model successfully produces reasonable estimates of the potential changes in discharge temperature accruing from discharging water from the surface layer as compared to the present reality of deep-water discharges only.