Minimising persistent thermal stratification and algal blooms using improved flow velocity and discharge targets

Taskforce MER Plan: Project 08.5 Report

A research collaboration between UTS and DPE – Water

June 2021

Dr Jordan Facey
Dr Matthew Balzer
Dr Andrew Brooks
Doug Westhorpe
Dr Nicholas Williamson
Prof. Simon Mitrovic

Freshwater and Estuarine Research Group
University of Technology Sydney
Simon.Mitrovic@uts.edu.au

Acknowledgement of Country

The Department of Planning and Environment acknowledges that it stands on Aboriginal land. We acknowledge the Traditional Custodians of the land and we show our respect for Elders past, present and emerging through thoughtful and collaborative approaches to our work, seeking to demonstrate our ongoing commitment to providing places in which Aboriginal people are included socially, culturally and economically.

Published by NSW Department of Planning and Environment

dpie.nsw.gov.au

Minimising persistent thermal stratification and algal blooms using improved flow velocity and discharge targets

Published: June 2021

ISBN: 978-1-76058-559-4

CM9 location: V19/8299#2

Copyright and disclaimer

Contents

1. Executive Summary

Severe cyanobacterial blooms are a common occurrence in the Barwon-Darling River and low discharge rates and persistent thermal stratification are often key drivers. Persistent stratification also influences other biogeochemical processes such as low hypolimnial (bottom water) oxygen and sediment nutrient release. Further, the rapid breakdown of stratification after prolonged periods can sometimes lead to fish kill events as anoxic conditions can establish throughout the water column, as seen in the Lower Darling River in 2018/19. Flow rules have the capacity to influence the development and breakdown of persistent thermal stratification in both weir pools and within the non-weir influenced river sections. The ability of a target river flow velocity to prevent persistent thermal stratification is linked to the discharge at particular sites, and this will vary between sites due to differences in cross-sectional area as well as local weather.

This research aims to define the threshold flow velocity required for the breakdown of stratification, and to link this data with site-specific discharge rates. To determine this, the bathymetry, flow velocity and temperature profiles of 11 sites were measured under different flow conditions using an Acoustic Doppler Current Profiler (ADCP) over the summer of 2020/2021. This information may be useful to set flow thresholds in the Barwon-Darling River for more effective flow management to reduce algal blooms and the risk of fish kill events.

Results showed that maximum daily velocities were variable between sites. Strong persistent stratification was not observed at any sites above 0.0506 m/s maximum daily velocity. Hence, maintaining flow velocity above 0.05 m/s should be sufficient to prevent the formation of persistent thermal stratification that may result in algal blooms and potential fish kills. Persistent thermal stratification was common at most weir pool sites and coincided with periods of low flow. Brewarrina was the only site that did not regularly undergo maximum daily velocities below the 0.05 m/s threshold and no persistent stratification was measured. In contrast, at both Menindee sites, which were frequently persistently stratified, maximum daily velocity was between 0.02 and 0.04 m/s for large periods of the study. All other sites underwent maximum daily velocities <0.03 m/s on at least one occasion throughout this study, significantly below the calculated threshold.

At the Louth site, located outside of the weir pool, persistent thermal stratification was rare. This suggests that weir pools may be more prone than unregulated stretches of river to the effects of stratification. Although this project helps set some better quantified benchmark velocities and discharges for reducing persistent stratification, further information is needed to better define these thresholds over a variety of weather conditions, particularly very hot summers and, also over fine spatial scales within weir pools.

2. Background

Severe cyanobacterial blooms are a common occurrence in the Barwon-Darling River and the extent of these blooms can be large, sometimes reaching over 1000 km of river (Bowling and Baker 1996). Low discharge rates and subsequent thermal stratification of the water column, sometimes persisting for weeks (referred to hereafter as persistent stratification), are key drivers of bloom events in the Barwon-Darling River, especially for the saxitoxin producing *Dolichospermum circinale* (previously known as *Anabaena circinalis*) (Mitrovic *et al*. 2003). Persistent stratification also influences other biogeochemical processes such as low bottom water oxygen (hypoxia/anoxia) which can influence the release of nutrients from sediments into the bottom water column, known as the hypolimnion. The increased dissolved nutrient concentrations can be made available to algae in surface waters when the water column mixes following a period of persistent stratification. Further, the rapid breakdown of stratification after prolonged periods of persistent stratification can sometimes lead to fish kill events as anoxic conditions can establish throughout the water column (Vertessy et al. 2019).

Flow rules on the Barwon-Darling River are focused on protecting flow events, maintaining connectivity in the river and maintaining important low flow thresholds. These rules have the capacity to influence the development and breakdown of persistent thermal stratification in weir pools and within the non-weir influenced river sections. The ability of a target river flow velocity to stop persistent thermal stratification is linked to the discharge at particular sites, and this will vary between sites due to differences in cross sectional area as well as weather (air temperature and wind speed) at the time. For example, it requires considerable thermal energy for persistent stratification to form and hence it will typically only form during the hotter months of October to April in NSW. During these hotter months, if flows are kept above critical thresholds, it is possible to prevent persistent stratification from occurring. Mitrovic et al. (2003) suggested a flow velocity of greater than 0.05 m/s could be used to reduce blooms in the Darling and Namoi Rivers. Further work suggested that keeping flows above a minimum flow velocity of 0.03 m/s should be sufficient for reducing stratification and *Anabaena* blooms (Mitrovic et al. 2006; 2011). This work was based on simple cross sectional area determinations, discharge at gauges and then mathematical determination of the average flow velocity. This flow velocity was similar to the 0.029 m/s suggested through mathematical theoretical modelling in the study by Viney et al. (2007) for the Murrumbidgee River. To convert these suggested values of flow velocity to discharge for management use, and the testing of water sharing plan success, in-situ flow velocity readings under different flow conditions are required. The velocity data needs to be more accurately linked to the formation and breakdown of thermal stratification, bathymetry and cross-sectional area data over extended distances of the river to ensure its robustness. This information can be then used to set flow thresholds in the Barwon-Darling River for more effective flow management to reduce algal blooms and the risks of fish kill events.

UTS were engaged by DPIE-Water to study thermal stratification and its relationships to flow on the Barwon-Darling River and, in particular, to study the thermal profile, flow velocity, cross sectional area and bathymetry at numerous locations. This research aims to refine the threshold flow velocity required for the breakdown of stratification and to link this velocity data with site-specific discharge rates for management purposes. This research is part of a range of projects designed to:

- Inform northern Basin WSP rules related to active management, flow class access rules and flow targets, and
- Guide s324 advice and management.

3. Methods

The bathymetry and flow velocity of 11 sites (Figure 1) were measured using an Acoustic Doppler Current Profiler (ADCP) (Teledyne RiverPro). Thermistor chains were deployed at each site, which were made using floats, chain and temperature loggers (HOBO Pendant UA-001-64) placed at 1 m intervals. Sites were primarily in weir pools as these locations are most likely to have reduced flow velocity and increased depth, conditions conducive to thermal stratification. Flows that reduce stratification at these sites will likely also prevent stratification in areas of the river outside of weir pools due to greater flows required for the deeper weir pools.

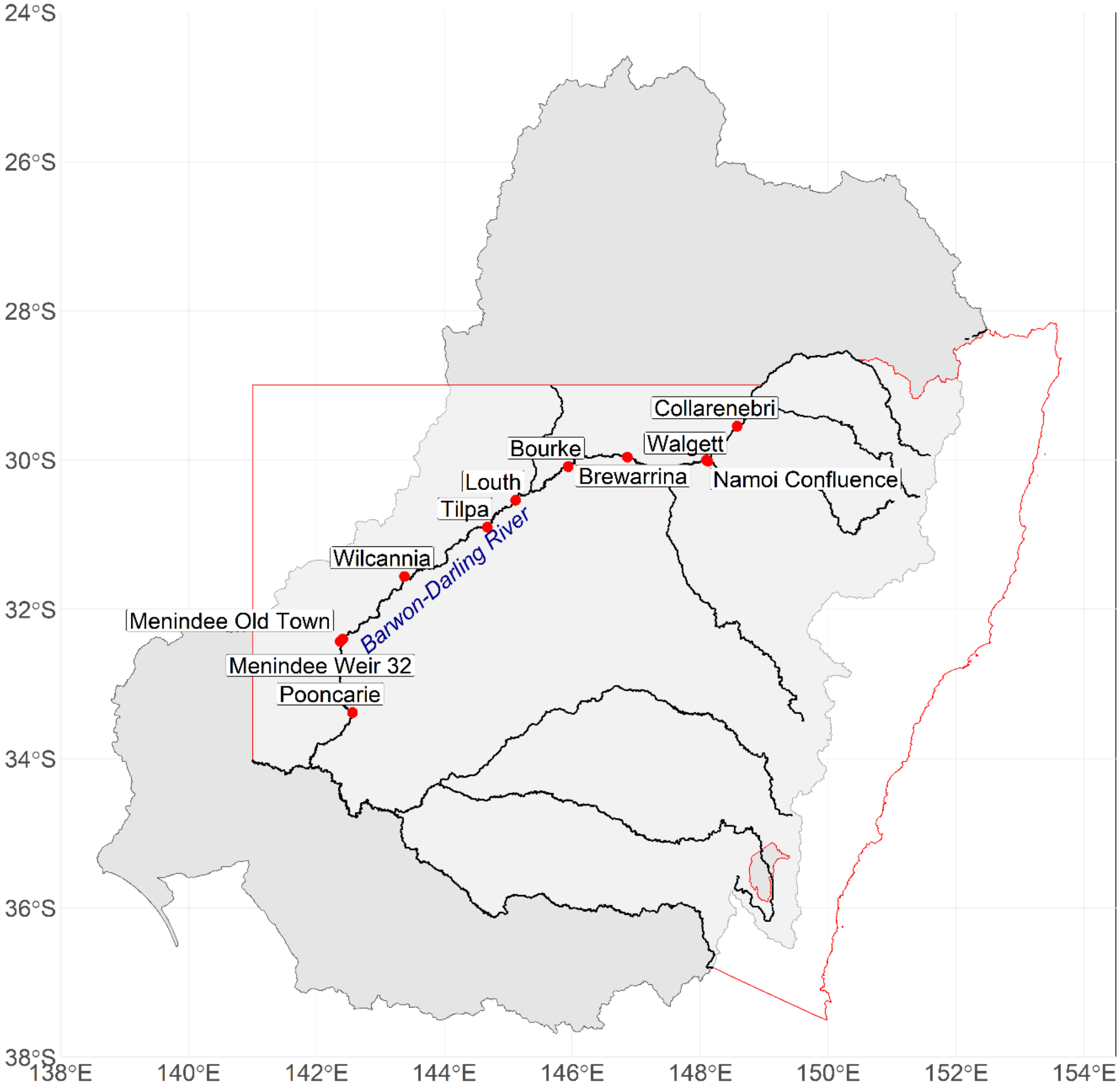


Figure 1: Map displaying locations of study sites within the Barwon-Darling Basin

Critical flow velocity was determined to allow comparison to other locations within similar climatic regions. Once the common threshold velocity was determined, site-specific critical discharge was then back calculated by accounting for differences in cross-sectional area of the channel (Mitrovic et al. 2003). Given that cross-sectional area will change with varying river heights, river cross section was estimated based on the ADCP measurements and river height data from WaterNSW.

4. Results and Discussion

A summary of bathymetry and flow characteristics (maximum depth, cross sectional area, flow velocity and discharge) of each site are presented in Table 1. On average, Walgett and Brewarrina weir pools had the greatest maximum depth. Whereas Bourke and Brewarrina had the largest cross-sectional areas (excluding sites in flood conditions).

Table 1: Results of ADCP measurements of bathymetry and flow characteristics at different sites and at different times. Numbers in parentheses indicate different visits (1), (2) etc.

Site	Coordinates	Date	Max depth (m)	Cross sectional area (m^2)	Flow velocity (m/s)	Discharge - ADCP (ML/D)	Discharge – WaterNSW (ML/D)	Gauge
Collarenebri (1)	29°32'46.5"S 148°34'58.8"E	2/2/21	4.60	159.83	0.090	1242.84	1343.82	Barwon @ Collarenebri (422003)
		15/6/21	4.91	163.63	0.057	805.85	948.48	
Collarenebri (2)	29°32'47.6"S 148°34'42.2"E	17/3/21	3.80	146.88	0.048	609.14	790.99	
Collarenebri (3)	29°32'49.2"S 148°34'41.8"E	17/3/21	3.80	146.17	0.045	568.31	790.99	
Walgett (1)	29°59'58.5"S 148°05'58.5"E	8/6/21	5.39	153.10	0.088	1164.05	1589.12	Barwon @ Dangar Bdge (422001)
Walgett (2)	29°59'57.2"S 148°05'59.7"E	8/6/21	4.19	102.72	0.160	1420.00	1589.12	
Namoi confluence (1)	30°00'54.1"S 148°07'14.3"E	18/3/21	2.50	54.59	0.030	141.50		None available
		7/4/21	7.40	562.56	0.249	12102.69		
Namoi confluence (2)	30°00'53.8"S 148°07'13.3"E	18/3/21	2.50	58.08	0.033	165.60		
		28/4/21	3.75	123.75	0.017	243.23		
		19/5/21	2.57	65.68	0.030	170.24		
		9/6/21	2.45	61.01	0.057	300.46		
Brewarrina (1)	29°56'55.5"S 146°51'58.5"E	17/3/21	5.20	226.49	0.065	1271.97	1437.60	Barwon @ Brewarrina (422002)
		16/6/21	5.39	225.94	0.077	1503.13	1601.01	
Brewarrina (2)	29°56'55.7"S 146°51'56.2"E	17/3/21	5.20	208.63	0.073	1315.87	1437.60	
		16/6/21	5.63	228.13	0.074	1458.57	1601.01	

Bourke (1)	30°05'12.4"S 145°53'44.0"E	3/2/21	3.70	178.13	0.042	646.40	687.09	Darling @ Bourke Town (425003)
		17/3/21	3.75	193.48	0.126	2106.30	2083.63	
		16/6/21	3.95	180.11	0.102	1587.27	1688.34	
Bourke (2)	30°05'13.0"S 145°53'48.0"E	3/2/21	3.80	213.80	0.033	609.59	687.09	
		17/3/21	3.75	235.55	0.086	1750.23	2083.63	
Tilpa (1)	30°55'04.9"S 144°27'36.6"E	4/2/21	3.80	171.44	0.058	859.12	895.16	Darling @ Tilpa (425900)
		17/6/21	4.19	193.01	0.106	1767.66	1969.93	
Tilpa (2)	30°55'07.2"S 144°27'29.8"E	17/6/21	4.43	188.47	0.103	1677.23	1969.93	
Louth	30°32'05.0"S 145°06'49.9"E	3/2/21	1.50	54.90	0.127	602.41	848.17	Darling @ Louth (425004)
		16/6/21	2.81	87.91	0.208	1579.85	1878.53	
Menindee (Old Town Weir)	32°23'12.3"S 142°26'01.7"E	9/2/21	3.85	156.95	0.024	325.45	341.64	Darling @ U/S Weir 32 (425012)
		2/6/21	4.91	193.95	0.024	402.17	3741.40	
Menindee (Weir 32)	32°24'08.2"S 142°23'49.7"E	9/2/21	3.00	159.96	0.034	469.90	341.64	Darling @ U/S Weir 32 (425012)
		2/6/21	3.95	183.11	0.022	348.06	3741.40	
Wilcannia	31°33'54.6"S 143°24'22.1"E	4/2/21	3.30	133.91	0.077	890.88	1098.22	Darling @ Wilc. Main C (425008)
		17/6/21	4.19	181.35	0.129	2021.25	2012.73	
Pooncarie	33°22'50.3"S 142°33'48.5"E	10/2/21	2.10	54.61	0.044	207.61		Darling @ Pooncarie (425005)

Thermistor data was recorded every 30 minutes at 1 m intervals at all sites. A minimum temperature difference between the surface and bottom water (minimum ΔT) of >1 °C, over a 24-hour period provides a good indication of strong persistent stratification. Descriptions of stratification and flow for each site are provided below.

4.1 Collarenebri

The Collarenebri Weir is one of eight weirs located between Mungindi and Walgett, covering a total distance of 344 km. It is a concrete weir, with an estimated depth of approximately 5-m (Table 1). River flows ≥18,000 ML/day will drown out Collarenebri Weir. Major tributaries entering this section include the Border Rivers (Macintyre and Weir Rivers), the Boomi River, Gwydir River and Namoi River (NSW DPIE, 2019a). The thermistor chain was installed approximately 1 km upstream of the weir on the 2nd of February 2021. Thermistor data for the duration of the study at the Collarenebri site is presented in Figure 2a.

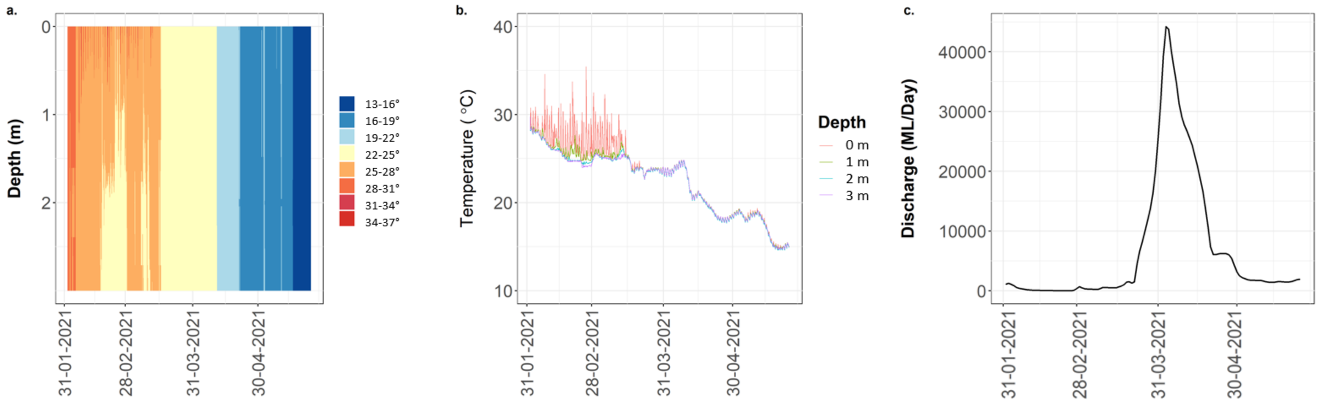


Figure 2: Temperature (a, b) and flow data (c) from Collarenebri weir pool over duration of study

Diel stratification occurred from the onset of the project in early February until mid-March 2021 (Figure 2b). A period of prolonged low discharge occurred between the 10th and 28th February when flows were <200 ML/D) (Figure 2c). Figure 3a illustrates a period of persistent stratification (minimum ΔT > 1°C) first observed on the 12th of February, when maximum daily discharge dropped to 110.13 ML/D (Figure 3b). Persistent stratification occurred regularly in this low-flow period until the 27th of February when maximum daily discharge increased above 625 ML/D (velocity 0.045 m/s). Another brief period of persistent stratification occurred on the 12th of March, coinciding with a maximum daily discharge of 569.30 ML/D. In periods of persistent stratification flow velocity ranged from 0.044 to 0.001 m/s. A large flood event began in late May (Figure 2c), after which the water-column was well mixed.

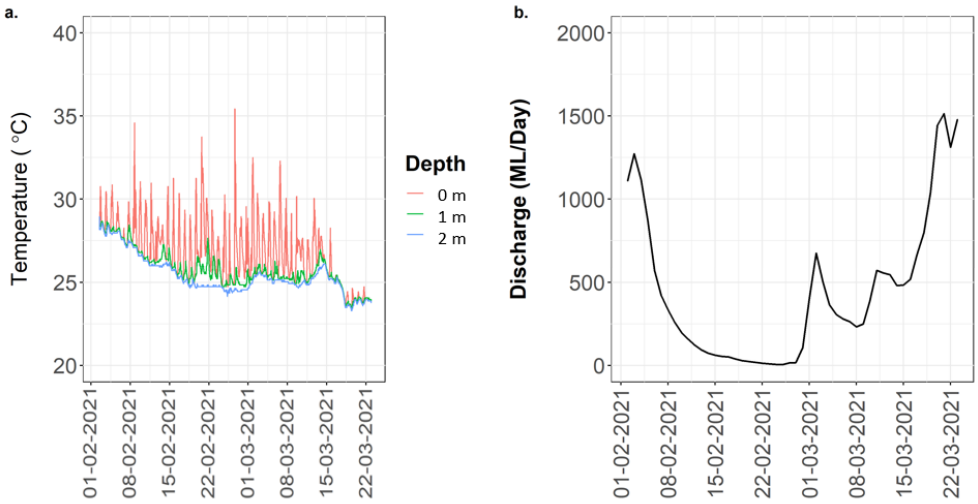


Figure 3: Detailed illustration of thermal stratification (a) and discharge at Collarenebri between 1/2/21 and 22/3/21 (b).

The period of persistent stratification in February coincided with high air temperatures (daily maximum air temperatures >30 °C) (Supplementary Data, Figure 1). There were no significant weather events that occurred when the water column mixed, indicating that increased discharge was the primary cause of the breakdown in stratification. The relationship between maximum daily discharge and thermal stratification is shown in Figure 4. Strong persistent stratification was not observed above ~600 ML/d.

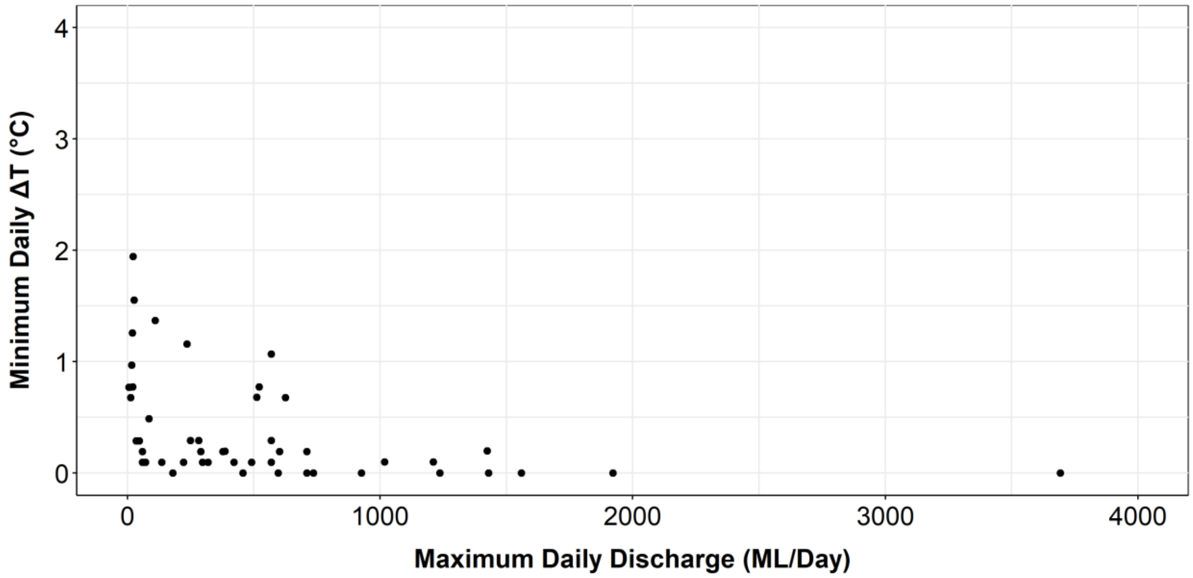


Figure 4: Relationship between maximum daily discharge and thermal stratification at Collarenebri, represented by a greater ΔT

4.2 Walgett

Walgett weir on the Barwon River has been recently upgraded (2021) raising the weir by 1-m, with the inclusion of a vertical slot fishway (NSW DPIE, 2019a). The estimated maximum depth is about 5.5-m (Table 1). The thermistor chain was installed approximately 100 m upstream of the weir on the 2nd of February 2021. Thermistor data for the Walgett site is presented in Figure 5a.

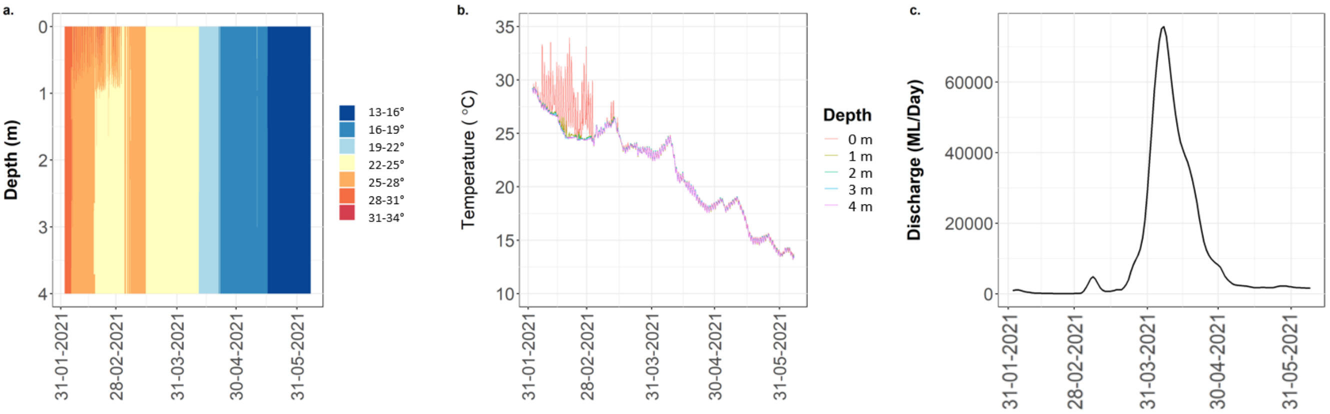


Figure 5: Temperature (a, b) and flow data (c) from Walgett weir pool over duration of study

Stratification patterns followed similar trends to those at the Collarenebri site, likely due to their close proximities and similar bathymetry. Diel stratification was common throughout February and early March (Figure 5b). Despite discharge being very low for extended periods in February and March (Figure 5c), strong persistent stratification was intermittent. Figure 6a illustrates several brief periods of persistent stratification that occurred between the 20th of February and 28th of February under low flow conditions (Figure 6b). During this period velocity was <0.01 m/s.

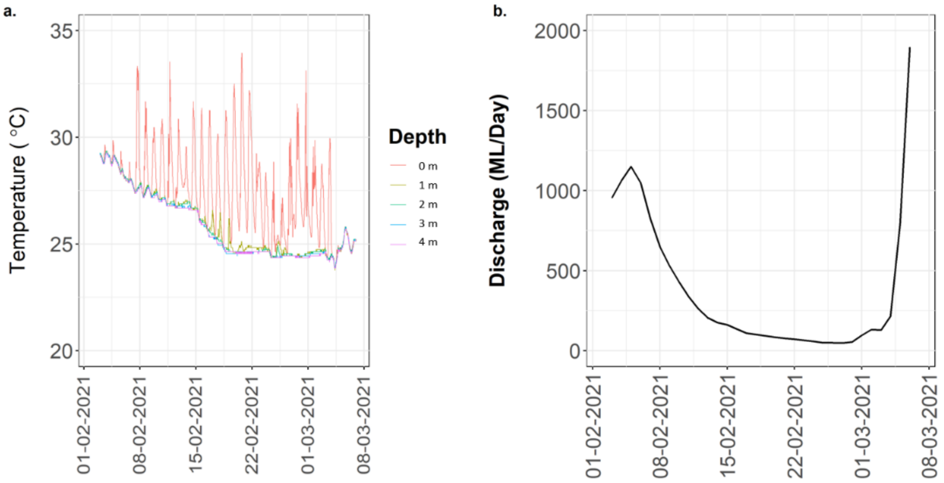


Figure 6: Detailed illustration of thermal stratification (a) and discharge (b) at Walgett between 1/2/21 and 7/3/21.

The lack of consistent stratification in these low flow periods may be due to high wind speeds that were evident throughout much of February (Supplementary Data, Figure 1). Increased discharge may have also contributed to the breakdown in stratification in early March. The relationship between maximum daily discharge and thermal stratification is shown in Figure 7. Strong persistent stratification was not observed above ~250 ML/d.

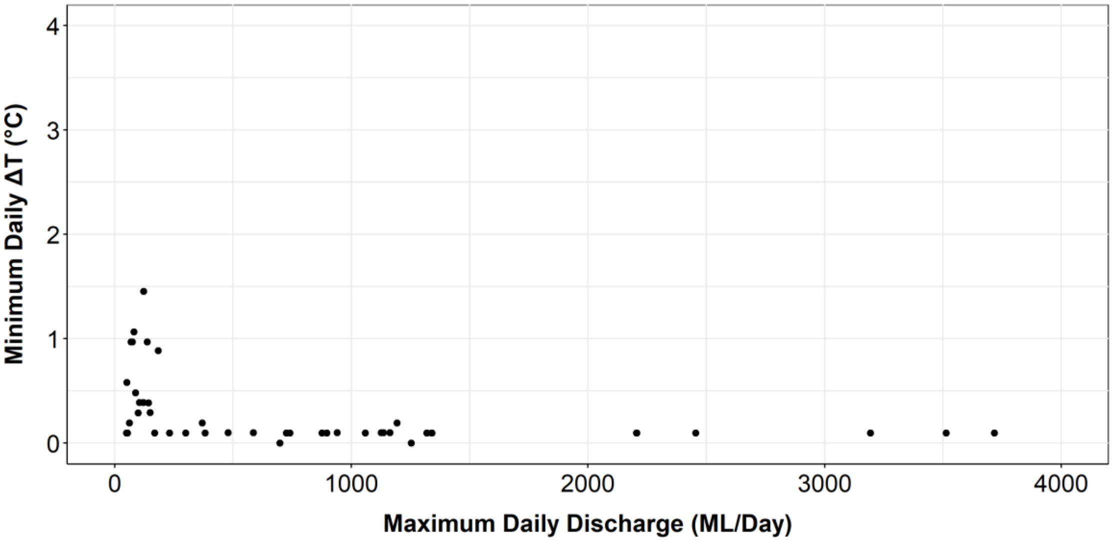


Figure 7: Relationship between maximum daily discharge and thermal stratification at Walgett, represented by a greater ΔT

4.3 Brewarrina

The river reach between Walgett and Brewarrina Weir is 325 km long. A concrete weir / fishway with dropboards, with an estimated depth of about 5.5-m (Table 1). The fishway was installed at Brewarrina Weir in 2013, providing fish passage at low flows along a substantial length of river between Walgett and Bourke. Major tributaries that flow into this reach are the Namoi, Macquarie-Castlereagh, Narran and Bokhara rivers (NSW DPIE, 2019a). The thermistor chain was installed approximately 1.5 km upstream of the weir on the 17th of March 2021. Thermistor data for the Brewarrina site is presented in Figure 8a.

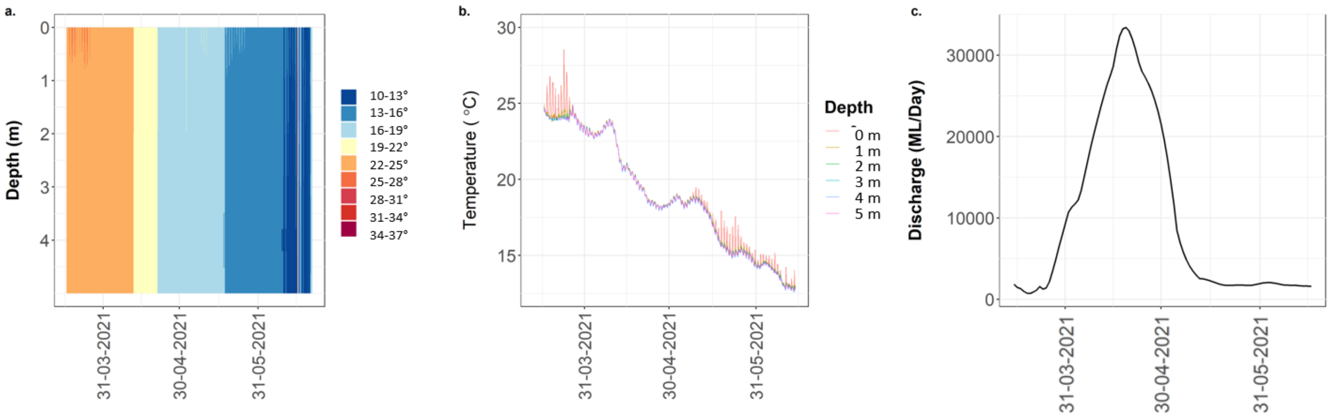


Figure 8: Temperature (a, b) and flow data (c) from Brewarrina weir pool over duration of study

While diel stratification occurred at Brewarrina early in the study period, no persistent stratification was evident (Figure 8b). Maximum daily discharge remained above 800 ML/D at all times (Figure 8c) and the minimum flow velocity measured was 0.046 m/s. This discharge was sufficient to prevent persistent stratification. The relationship between maximum daily discharge and thermal stratification is shown in Figure 9. Given that persistent stratification did not occur, the threshold discharge at Brewarrina cannot be determined, however strong diel stratification was occurring in these periods of lower flow velocity which may suggest that these flows are near the threshold.

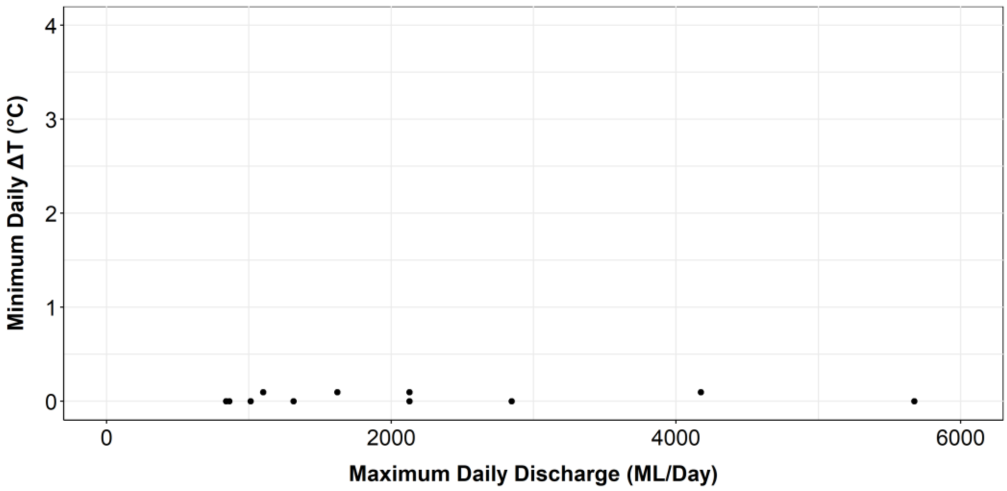


Figure 9: Relationship between maximum daily discharge and thermal stratification at Brewarrina, represented by a greater ΔT

4.4 Bourke

The estimated depth of Bourke Weir is 4-m (Table 1). The river section between Brewarrina Weir and Bourke Weir is 250 km long. River flows ≥10,000 ML/day drown out Bourke Weir. Major tributaries entering this section include the Bogan River from the east and the Culgoa River from the north-west (NSW DPIE, 2019a).

The thermistor chain was installed approximately 100 m upstream of the weir on the 3rd of February 2021. Thermistor data for the Bourke site is presented in Figure 10a.

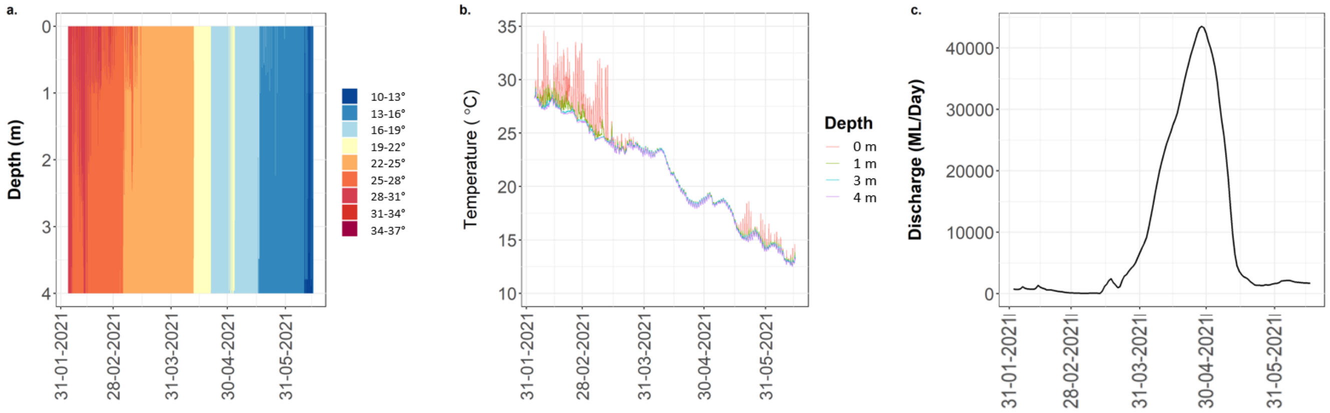


Figure 10: Temperature (a, b) and flow data (c) from Bourke weir pool over duration of study

In the period between the 4th of February and 11th of March, Bourke weir pool appeared to be on the brink of persistent stratification (Figure 10b) when flow was low (Figure 10c). As seen in Figure 11a, a sustained temperature gradient was evident in multiple periods (18-23rd February, 26th February, 2nd March, 10th-12th March). These periods of stratification coincided with periods of flow <750 ML/D (Figure 11b). However, the minimum daily ΔT was below 1 °C at all times, indicating that this temperature gradient was relatively weak. Given that discharge was below 100 ML/D for an extended period in early March, velocity was as low as 0.003 m/s and depth was >3.3 m, it is surprising that persistent stratification was not stronger and more sustained. This may be due to localized pumping near the thermistor chain or the consistently windy conditions (Supplementary Data, Figure 1).

Two figures side by side. The first shows detailed illustration of thermal stratification. The Y axis is temperature in Celsius and the X axis is the date spanning the sample period. There is a key for the three different colours of lines on the graph, these correspond with depths at 0 metres, 1 metre and 2 metres.

The second graph shows discharge in megalitres per day on the Y axis, with date on the X axis

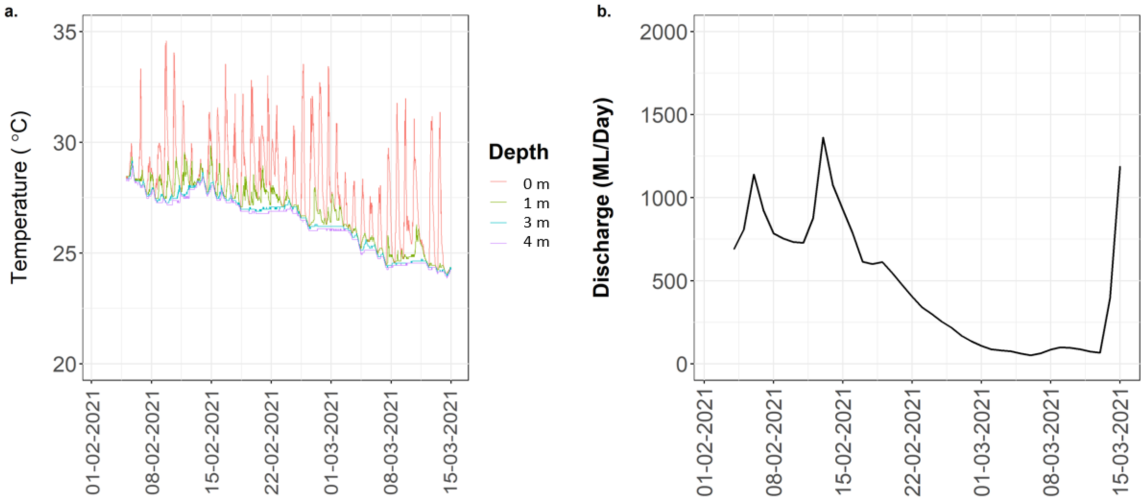


Figure 11: Detailed illustration of thermal stratification (a) and discharge (b) at Bourke between 1/2/21 and 14/3/21.

The relationship between maximum daily discharge and thermal stratification is shown in Figure 12. Weak persistent stratification (between 0.5 and 1 °C minimum daily ΔT) was observed at discharges <1500 ML/d.

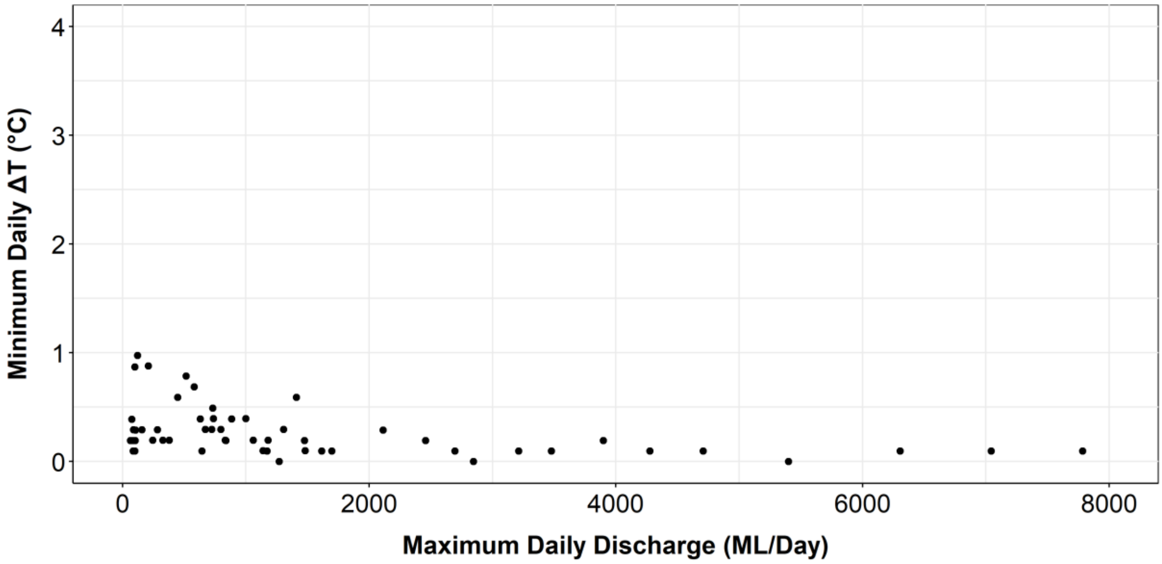


Figure 12: Relationship between maximum daily discharge and thermal stratification at Bourke, represented by a greater ΔT

4.5 Louth

The estimated maximum depth for Louth Weir is about 2.8-m (Table 1). The river reach between Bourke Weir and Louth Weir spans 308 km of the darling River. The Warrego River is the major tributary entering this section of the river. Louth Weir is drowned out at flows ≥ 9,000 ML/day (NSW DPIE, 2019a).

The thermistor chain was installed approximately 30 river km upstream of the weir on the 3rd of February 2021 to give an indication of temperature dynamics higher in the weir pool or in unregulated stretches of river. Thermistor data for the Louth site is presented in Figure 13a.

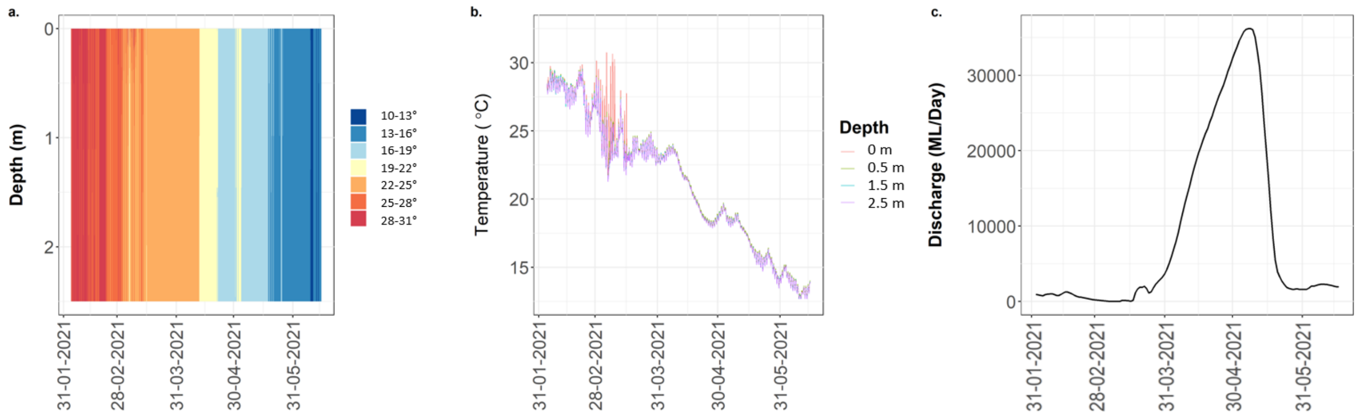


Figure 13: Temperature (a, b) and flow data (c) from Louth over duration of study

While very low flow conditions occurred at Louth in early March (<10 ML/d) (Figure 13c, persistent stratification only occurred briefly on one occasion (Figure 13b). This is likely because of the very shallow depth <1.5 m during low flow periods (Figure 14). When river depth is low, solar irradiance is strong enough to penetrate into the bottom layers of the water column, preventing the formation of distinct thermal layers. This is more likely to occur in unregulated stretches of river as opposed to at weir sites where water will pool. Wind action is also more effective at mixing when the water column is shallower.

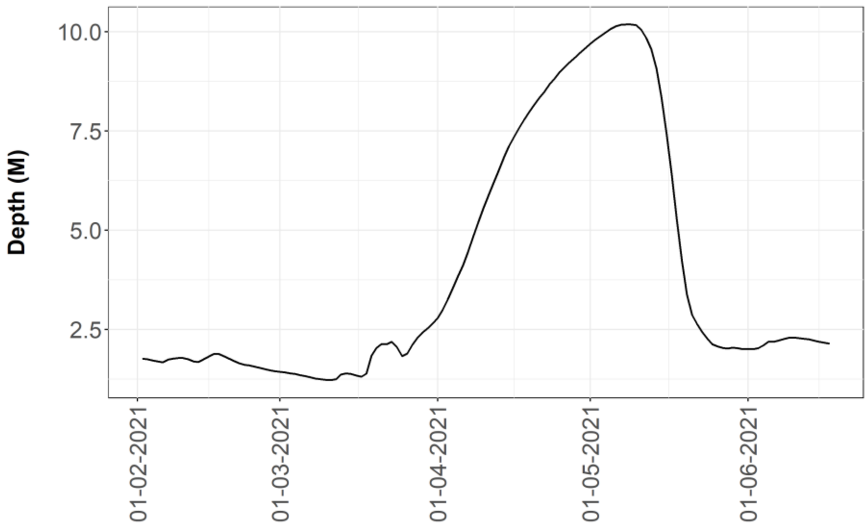


Figure 14: River depth at Louth site over duration of study

The relationship between discharge and thermal stratification is presented in Figure 15. The brief occurrence of strong stratification coincided with extremely low flow (2.6 ML/d maximum daily flow on 10th of March). It is unclear why stratification occurred on this particular day and not on other occasions when flow was at similar levels. Weather data is not available for Louth, but extremely high air temperatures were recorded at Bourke in the period leading up to the brief formation of stratification which may have been a contributing factor (>35 C daily maximum temperatures in the period between 7-10th March) (Supplementary data, Figure 1).

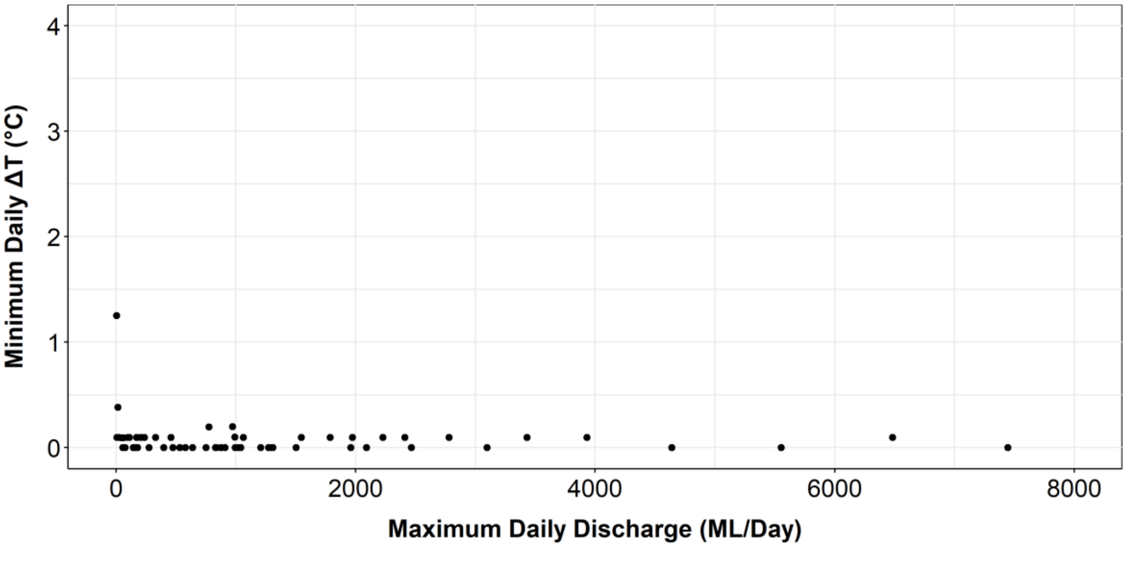


Figure 15: Relationship between maximum daily discharge and thermal stratification at Louth, represented by a greater ΔT

4.6 Tilpa

The estimated maximum depth at Tilpa Weir is about 5.5-m (Table 1). Flows of 2,400 ML/day will drown out Tilpa Weir. The river section between Louth Weir and Menindee Weir is 747 km long. The two major weirs are at Tilpa and Wilcannia (NSW DPIE, 2019a).

The thermistor chain was installed approximately 100 m upstream of the weir on the 4th of February 2021. Discharge data at Tilpa is measured downstream of the weir. Thermistor data for the Tilpa site is presented in Figure 16a.

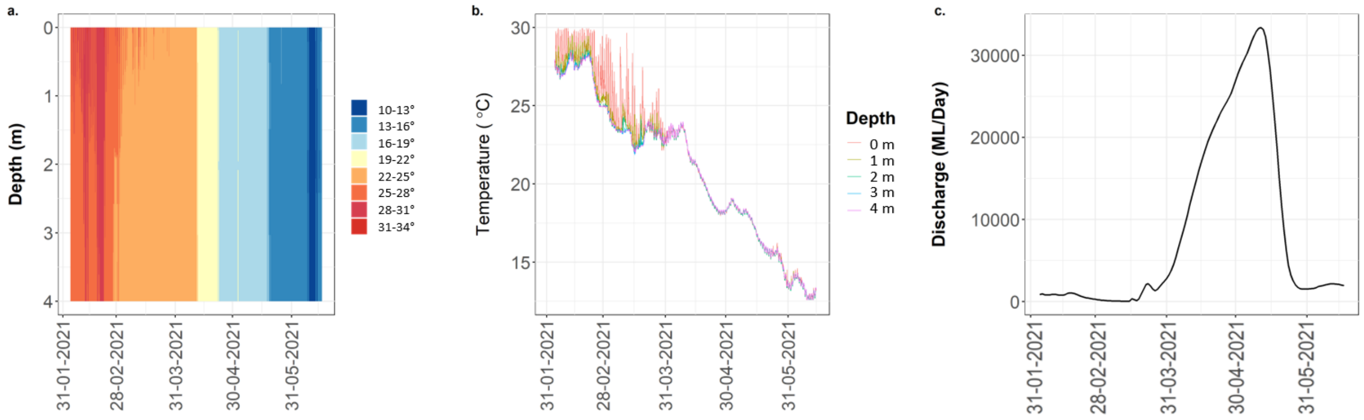


Figure 16: Temperature (a, b) and flow data (c) from Tilpa over duration of study

Despite periods of very low flow (Figure 16c, Tilpa did not undergo persistent stratification at any time in the study period (Figure 16b). Minimum ΔT was below 1 °C at all times. This is surprising as maximum daily velocity was as low as 0.004 m/s at times. Figure 17 displays the temperature profile (a) and discharge (b) throughout February and early March, it suggests that Tilpa may have been near the threshold for persistent stratification as a gradient is sometimes evident, for example the 28th February – 1st March, 12th – 13th March, and 21st – 22nd March. The lack of persistent stratification may be due to shallow depth or weather events. Unfortunately, depth and weather data were not available for this site.

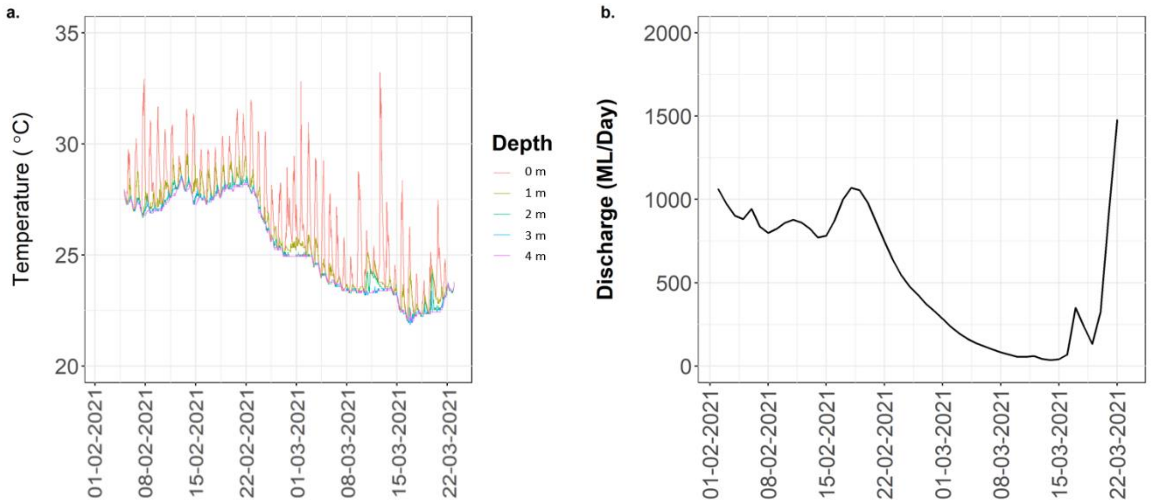


Figure 17: Detailed illustration of thermal stratification (a) and discharge (b) at Tilpa between 1/2/21 and 21/3/21.

The relationship between maximum daily discharge and thermal stratification is shown in Figure 18. Weak persistent stratification (between 0.5 and 1 °C minimum daily ΔT) was observed at discharges <1200 ML/d.

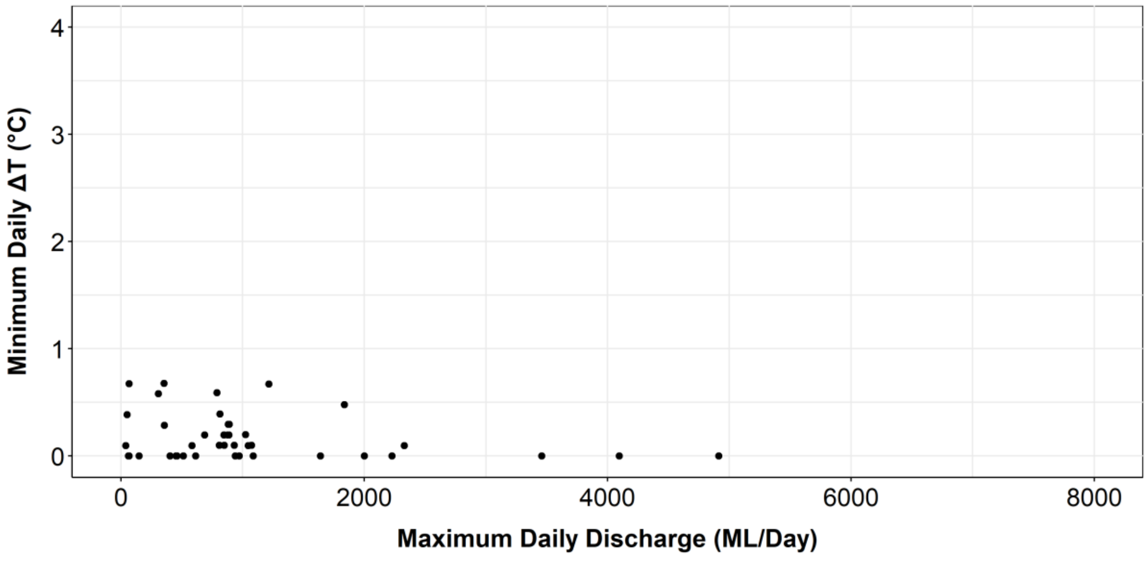


Figure 18: Relationship between maximum daily discharge and thermal stratification at Tilpa, represented by a greater ΔT

4.7 Wilcannia

The estimated maximum depth at Wilcannia Weir is about 4.2-m (Table 1). Flows of 7,900 ML/day will drown out Wilcannia Weir (NSW DPIE, 2019a).

The thermistor chain was installed approximately 2 km upstream of the weir on the 4th of February 2021. Unfortunately, loggers located at 1 m and 2 m depth were damaged and the data could not be recovered. Surface and bottom data were obtained, which is sufficient to test for the presence of stratification. Thermistor data for the Wilcannia site is presented in Figure 19a.

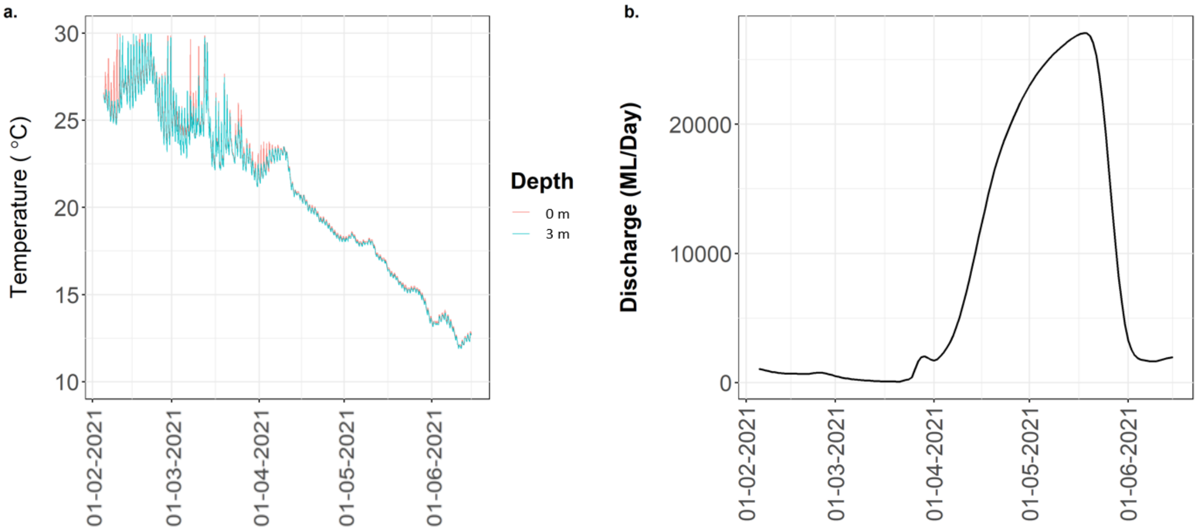


Figure 19: Temperature (a) and flow data (b) from Wilcannia over duration of study

Persistent stratification was observed for a short period in early March at Wilcannia. During this period, maximum daily discharge was between 370 and 295 ML/D (Figure 19b),equating to flow velocity of 0.044 and 0.037 m/s. Discharge reduced further in March, getting as low as 63.99 ML/D (0.011 m/s) (Figure 20b). Interestingly, persistent stratification was not observed over the majority of this period of very low flow (Figure 20a), despite flow velocity and air temperature being conducive to stratified conditions. Low water depth and high wind speeds (Supplementary Data, Figure 1) may have contributed to the instability of the water column.

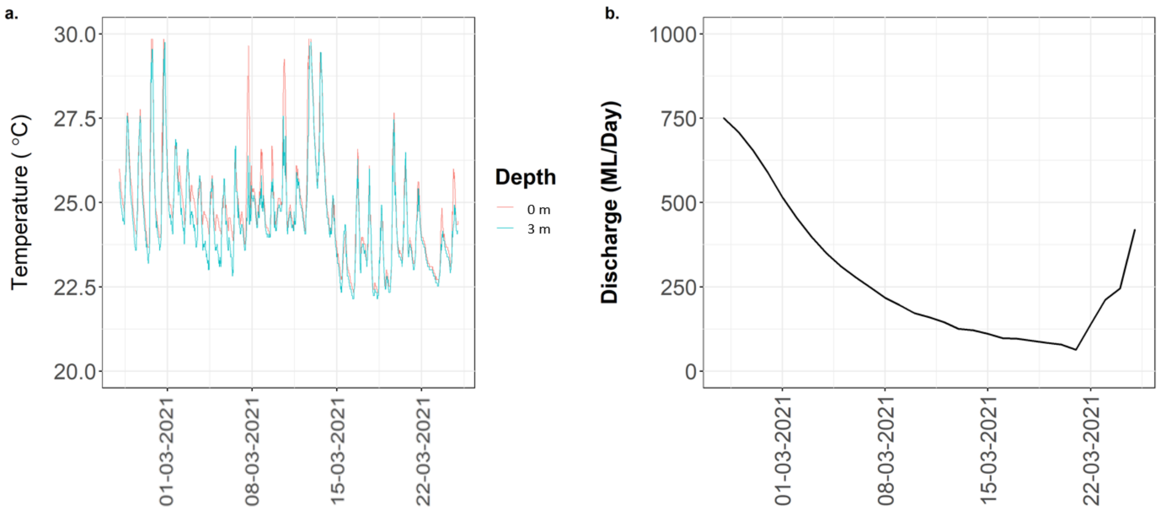


Figure 20: Detailed illustration of thermal stratification (a) and discharge (b) at Wilcannia between 25/2/21 and 25/3/21.

The relationship between maximum daily discharge and thermal stratification is shown in Figure 21. Weak persistent stratification (between 0.5 and 1 °C minimum daily ΔT) was observed at discharges <800 ML/d while strong persistent stratification occurred briefly when flow was <400 ML/d.

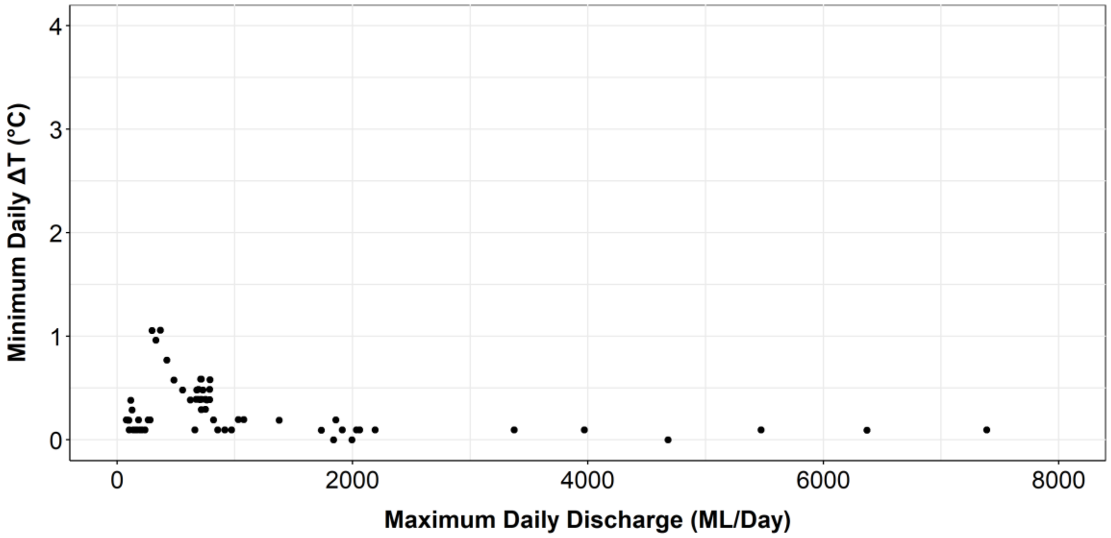


Figure 21: Relationship between thermal stratification at Wilcannia, represented by minimum ΔT, and maximum daily discharge.

4.8 Menindee Weir 32

Weir 32 is the first stream gauging station downstream of the Menindee Lakes. Weir 32 near Menindee was constructed in 1958 to conserve water for Menindee's town water supply and the Broken Hill pumping station (NSW DPIE, 2019b). The estimated maximum depth at Weir 32 is about 4-m (Table 1). The thermistor chain was installed approximately 9 km upstream of the weir on the 1st of December 2020. Thermistor data for the Menindee site upstream of Weir 32 is presented in Figure 22a.

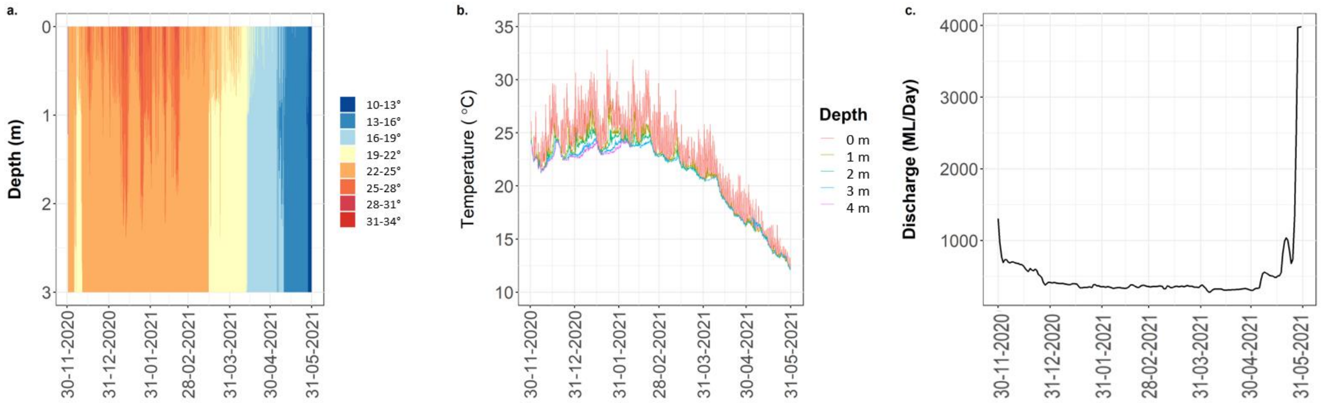


Figure 22: Temperature (a, b) and flow data (c) from Menindee Weir 32 over duration of study

Persistent thermal stratification was common between December 2020 and March 2021 at Weir 32 (Figure 22b) in periods of low discharge (Figure 22c). The water column was well mixed at the onset of the study. After the maximum daily discharge reduced to below 678 ML/D (flow velocity 0.0467 m/s) on the 14th December, persistent thermal stratification ensued (minimum ΔT > 1 °C). After this point discharge was consistently lower than 500 ML/D (Figure 23b) and thermal stratification was prevalent (Figure 23a). Some mixing events occurred, likely driven by weather events.

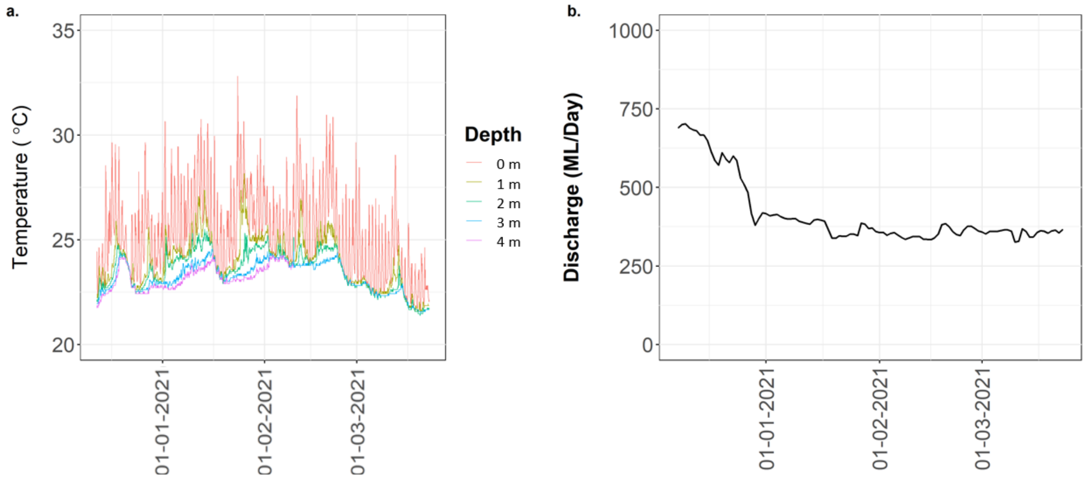


Figure 23: Detailed illustration of thermal stratification (a) and discharge (b) at Menindee Weir 32 between 1/12/20 and 31/3/21.

The relationship between maximum daily discharge and thermal stratification is shown in Figure 24. Weak persistent stratification (between 0.5 and 1 °C minimum daily ΔT) began to occur when discharge was below ~750 ML/d while strong persistent stratification was observed at discharges as high as 678 ML/d.

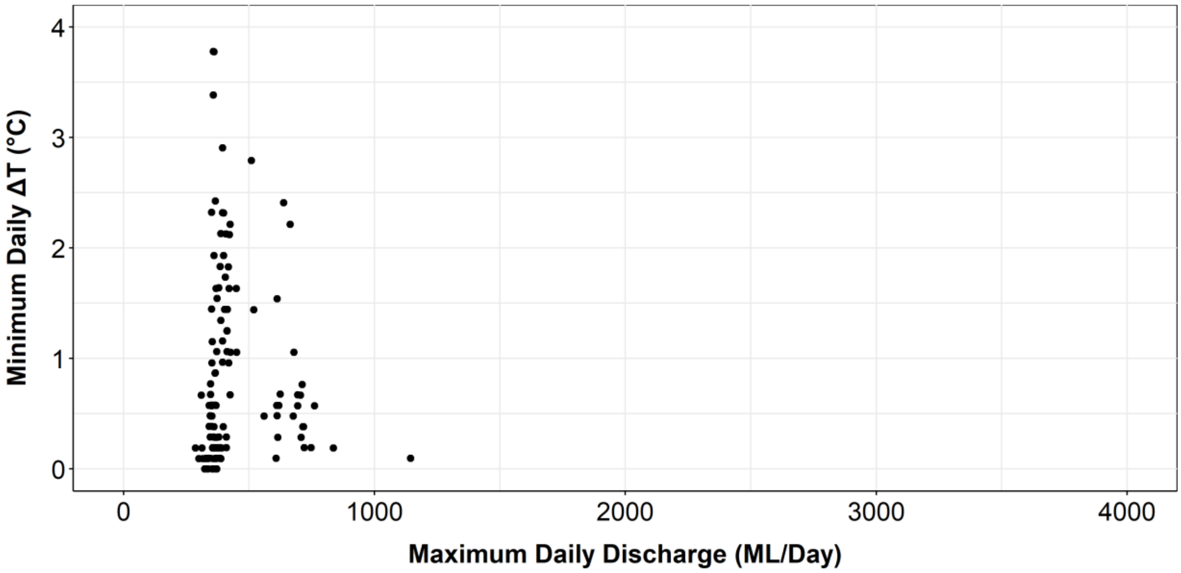


Figure 24: Relationship between thermal stratification at Menindee Weir 32, represented by minimum ΔT, and maximum daily discharge.

4.9 Menindee Old Town Weir

The Lower Darling River flows for 530 km from the Menindee Main Weir to the Murray River near Wentworth (NSW DPIE, 2019b). The estimated maximum depth is about 4.9-m (Table 1). The thermistor chain was installed approximately 100 m upstream of the weir on the 1st of December 2020. Thermistor data for the Menindee site upstream of the old town weir is presented in Figure 25a.

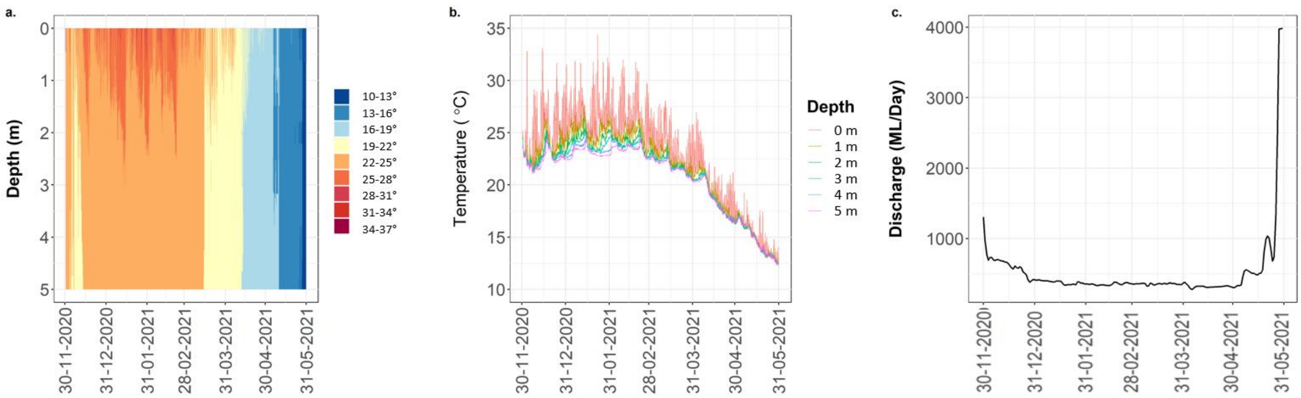


Figure 25: Temperature (a, b) and flow data (c) from Menindee Old Town Weir over the duration of study.

Old Town Weir followed similar trends to those of Weir 32. Persistent stratification was prevalent throughout December-March (Figure 25b), corresponding to a period of extended low flow (Figure 25c). Figure 26 illustrates temperature (a) and discharge (b) data during periods of strongest thermal stratification. Minimum ΔT at Old Town Weir was consistently higher than Weir 32, indicating a stronger temperature gradient. Furthermore, Old Town Weir was persistently stratified for a total of 54 days in this study, compared to 40 days at Weir 32. This is likely due to the greater depth at Old Town Weir. The prevalence of persistent stratification and greater cross-sectional area suggests that a higher discharge is required to break down stratification at this site compared to Weir 32.

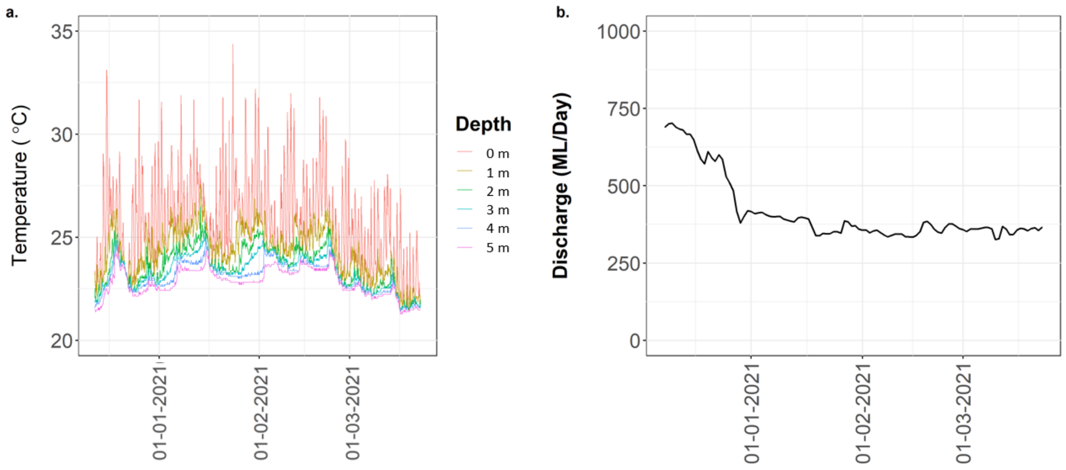


Figure 26: Detailed illustration of thermal stratification (a) and discharge (b) at Menindee Old Town Weir between 1/12/20 and 31/3/21.

The relationship between maximum daily discharge and thermal stratification is shown in Figure 27. Similarly to Weir 32, weak persistent stratification began to occur when discharge was below ~750 ML/d while strong persistent stratification was observed at discharges as high as 678 ML/d.

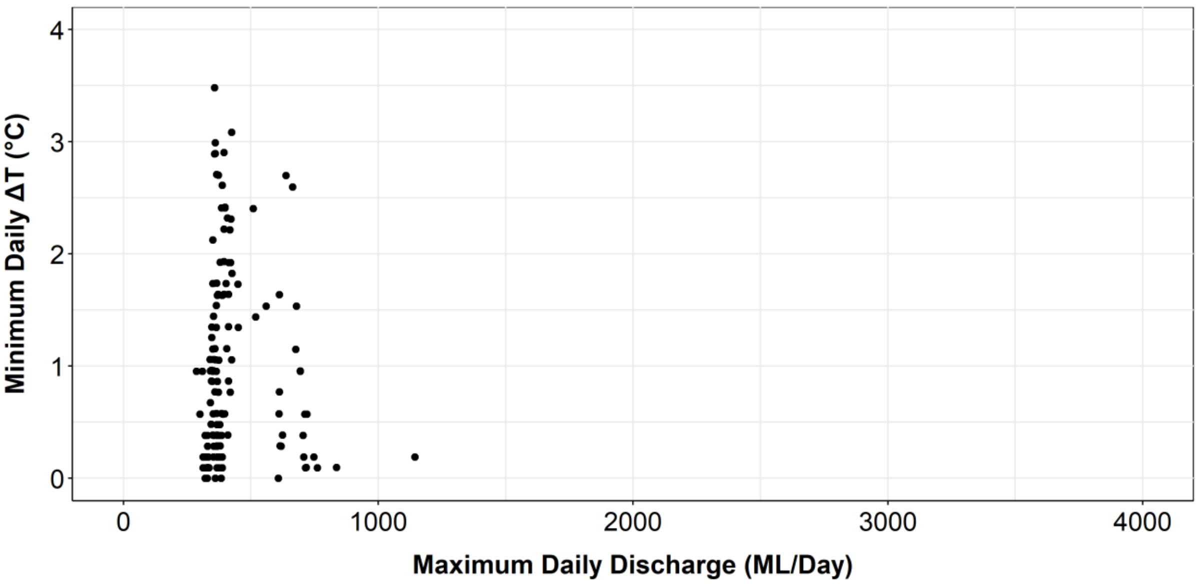


Figure 27. Relationship between thermal stratification at Menindee Old Town Weir, represented by minimum ΔT, and maximum daily discharge.

4.10 Critical Velocity

Maximum daily velocities were variable between sites (Figure 28). Velocity was consistently higher than 0.05 m/s at Brewarrina, where persistent thermal stratification was not observed. Brewarrina was the only site that did not regularly undergo maximum daily velocities below the 0.05 m/s threshold calculated by Mitrovic et al. (2003). Contrastingly, at both Menindee sites, which were frequently persistently stratified, maximum daily velocity was between 0.02 and 0.04 m/s for large periods of the study. All other sites underwent maximum daily velocities <0.03 m/s on at least one occasion, significantly below the threshold.

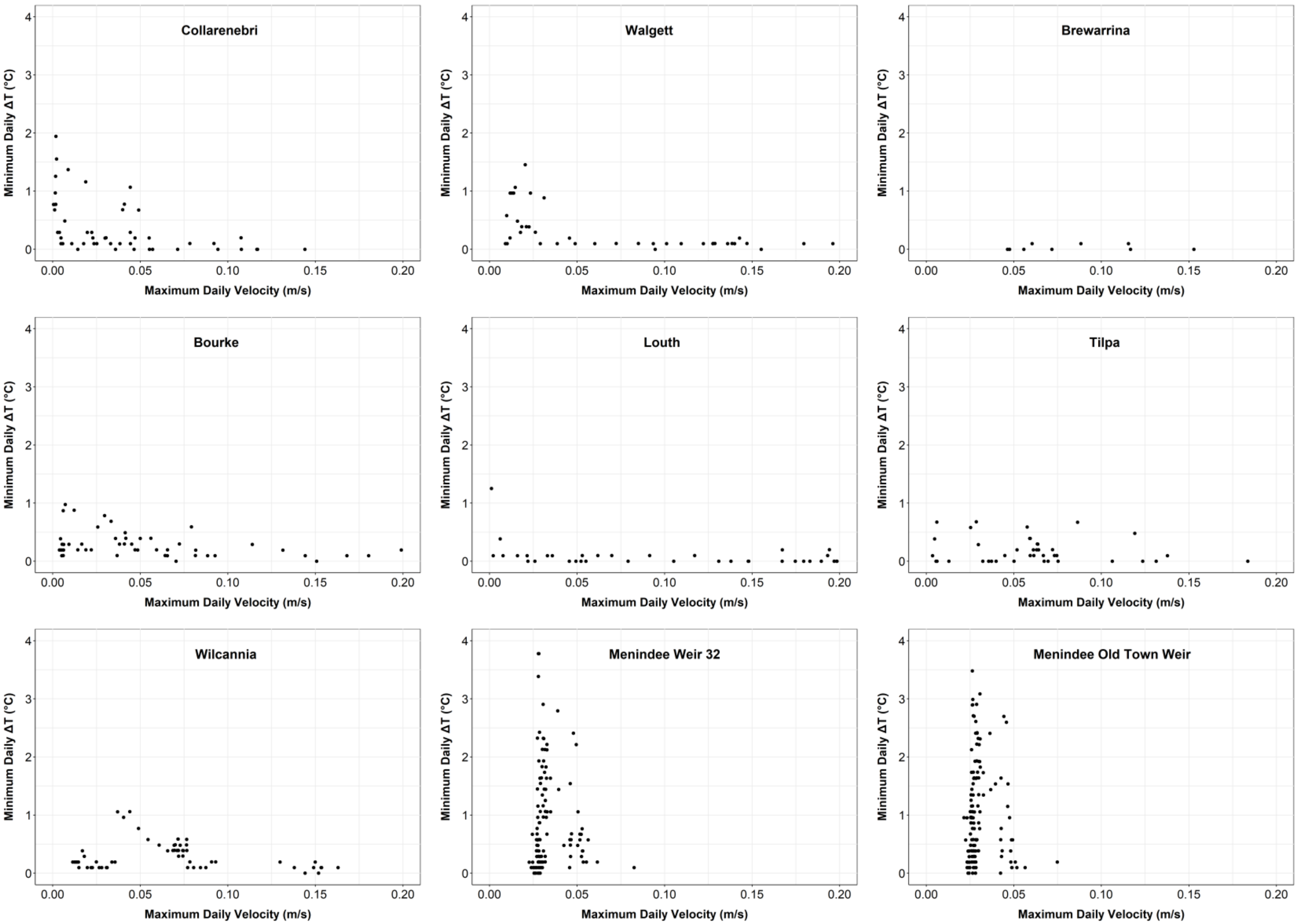


Figure 28. Relationship between thermal stratification, represented by minimum ΔT, and maximum daily velocity.

The relationship between thermal stratification and maximum daily velocity at all sites is displayed in Figure 29. Data after April 30th has been excluded as persistent thermal stratification typically does not occur in cooler months. Strong persistent stratification (>1 °C minimum ΔT), was not observed at any site above 0.0506 m/s maximum daily velocity. Based on the data presented in this study, maintaining flow velocity above 0.05 m/s may be sufficient to prevent the formation of persistent thermal stratification.

There were many occasions when flows dropped below the 0.05 m/s threshold, but persistent thermal stratification did not occur. This reflects other environmental variables such as cooler air temperatures, shallow river depth or wind conditions (particularly high wind) that also influence the development of stratification (Weinke and Biddanda, 2019). When river depth is low, solar irradiance is strong enough to penetrate the bottom layers of the water column. In addition, stratification may be more easily broken down by wind action. This prevents the formation of strong distinct thermal layers.

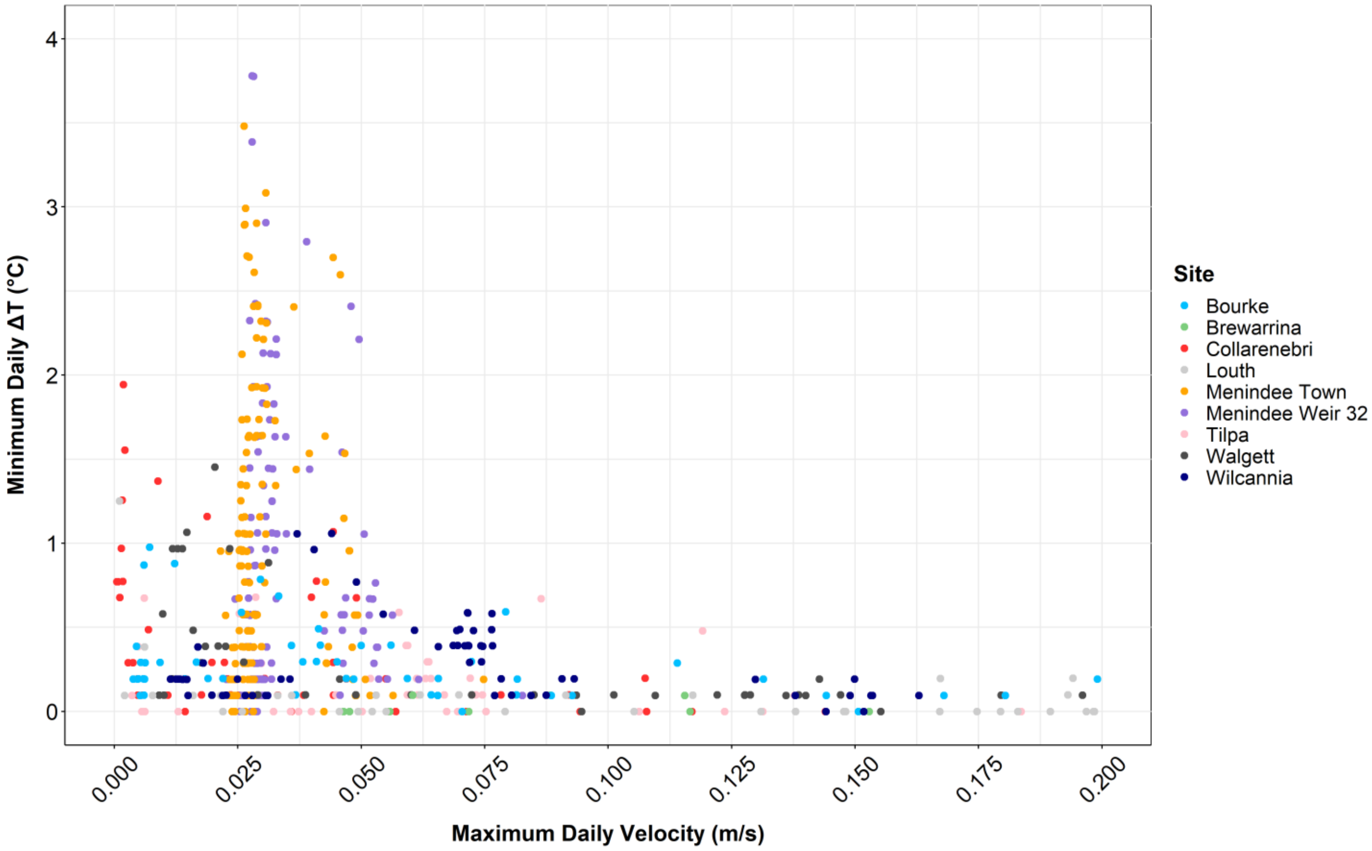


Figure 29. Relationship between thermal stratification, represented by minimum ΔT, and maximum daily velocity at all sites.

The data was also examined using quantile regression analysis to determine discharge thresholds that corresponded to greater than 1 °C minimum daily temperature difference between surface and bottom waters (ΔT = >1°C) based on this modelling. Figure 30 shows the modelled curves for 90th, 95th and 99th quantiles. Using these curves the velocity thresholds to prevent ΔT being greater than 1 °C are shown to be 0.0071 for 90th percentile, 0.0159 for the 95th percentile and 0.0535 for the 99th percentile. Table 2 shows the corresponding flows for these three percentiles for each site. The 99th percentile would be the most likely to prevent the formation of persistent stratification. Although this gives some preliminary information about stratification formation, more research is required to better develop these relationships.

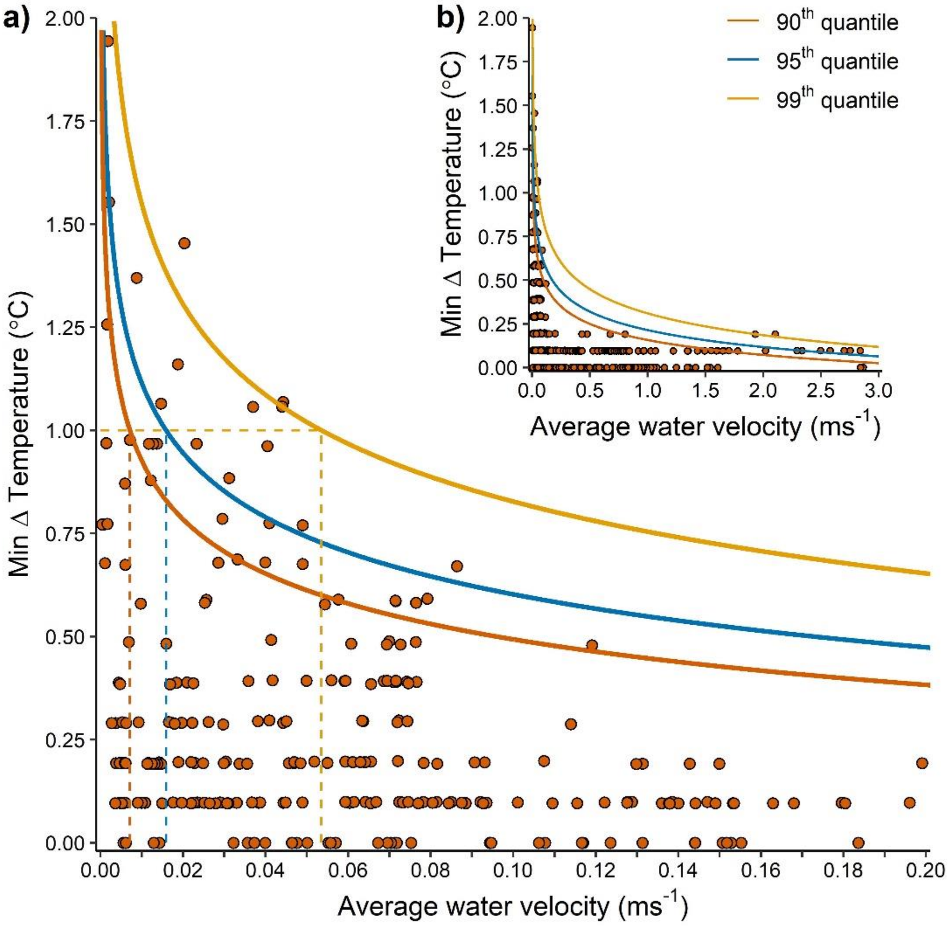


Figure 30. Relationship between average water velocity within pools (Bourke, Brewarrina, Collarenebri, Tilpa, Walgett, Wilcannia) and minimum Δ water temperature (surface and bottom). Lines represent quantile regressions at the 90th, 95th and 99 quantiles. a) shows relationships over the full range of velocities measured and b) shows the same relationship restricted to velocities ≤ 0.2 ms^{-1}. Dotted lines represent the estimated velocity at ΔT = 1 for the different quantiles used to calculate discharge in

Table 22.

Table 2. Discharge thresholds estimated from quantile regression relationships between velocity and $\Delta T = 1$ for the 90th, 95th and 99th quantiles.

	Discharge threshold (ML day^{-1})		
velocity threshold (m s^{-1})	0.0071	0.0159	**0.0535**
regression quantile	90th	95th	**99th**
Bourke	79.7	214.0	**945.3**
Brewarrina	69.3	183.9	**798.2**
Collarenebri	70.9	174.7	**679.2**
Tilpa	47.7	143.2	**748.4**
Walgett	23.4	68.2	**341.2**
Wilcannia	16.4	63.4	**485.5**

5. Management Implications

Results from this study demonstrate that maintaining flow velocity above 0.05 m/s may be sufficient to prevent the formation of persistent thermal stratification that may result in algal blooms and potential fish kills. This is consistent with previous findings (Mitrovic et al. 2003) and is slightly higher than the 0.03 m/s recommendation in Mitrovic et al. (2006; 2011) and modelled by Viney et al. (2007). This difference is likely due to the use of improved techniques for measuring river cross sections, such as the ADCP to determine site specific discharge and flow velocities which has improved data accuracy.

Table 3 gives suggested velocities to reduce the impact of persistent thermal stratification at the sites studied. These are indicative and further data over multiple years and climatic conditions is required to provide a more accurate determination. This would better account for extreme heat wave conditions such as one that occurred during the Menindee fish kills in 2018 (Vertessy et al. 2019). The suggested discharges are still useful as a resource but would value from further refinement with more data over different summers. The location within the weir pool may also be important with locations closer to the weir experiencing less persistent stratification due to greater susceptibility to mixing forces as a result of surface waters being moved over the overshot weir. This needs further study to confirm, but may in part explain why less stratification was seen at Bourke and Tilpa, where chains were placed closer to the weir.

Table 3. Suggested discharge targets (ML/d) to reduce persistent thermal stratification formation.

Site	Data available to suggest mixing velocities	Estimated cross sectional area when site was near 0.05 m/s velocity (m^2)	Calculated discharge at 0.05 m/s (ML/d)	Predicted discharge for 0.05 m/s based on quantile regression	Discharge suggested for management with 25% leeway
Bourke	Partial	205.24	887	945	1109
Brewarrina	No	209.65	906	798	1133
Collarenebri	Yes	148.93	643	679	804
Louth	Partial	37.00	160		200
Menindee Old Town Weir	Yes	168.31	727		909
Menindee Weir 32	Yes	168.15	726		908
Namoi confluence	Not available	61.01	264		330
Pooncarie	Not available	54.61	236		295
Tilpa	Partial	147.72	630	748	788
Walgett	Yes	71.04	307	341	384
Wilcannia	Partial	99.99	432	485	540

The sites at Menindee appear to be the most prone to stratification compared to other sites on the Barwon Darling. When standardized to a common sampling period (5/2/21- 24/5/21) Menindee Old Town Weir had by far the highest number of days of persistent stratification compared to all other sites (17 days). Menindee Weir 32 was persistently stratified for 8 days within this period. Collarenebri also appeared relatively prone to persistent stratification, which occurred on 6 days. All other sites underwent stratification on <3 occasions during this period. Thermistor chains were deployed earlier at the Menindee sites and over the hottest parts of the year (December/January) as it was possible to deploy thermistor chains at these sites prior to the start of the project. As such, there were additional stratification events observed at these sites. Strong persistent stratification occurred regularly and for long periods of time, particularly during December and January. In total, persistent stratification occurred on 40 days at Weir 32 and 54 days at Old Town Weir. This may be of particular interest given recent mass fish kill events in Darling River near Menindee. A further finding from this study was the discharge and flow velocity from Main Weir or Lake Wetherell in the

Lower Darling can be influenced by releases from Menindee Lakes. On our sampling trip in early June, releases were being made from Menindee (>3500 ML/d) as well as from the Main Weir. As the gauge for Weir 32 is near the weir itself, the flows here may not represent the whole river stretch. During this sampling trip velocities at the Weir 32 site were 0.022 m/s and at Old Town Weir were 0.024 m/s, not reflecting the gauged flows. This suggests that releases from Menindee Lakes will impact flow velocities in the Lower Darling above the inflow point and may make this area more susceptible to persistent thermal stratification even when the Weir 32 gauge may show high discharges.

The thermistor chain located in the Namoi River nearby the confluence with the Barwon could not be retrieved following the flood in April 2021. While thermistor data is not available, based on the velocities and depths measured on the 18th March, 28th April and 19th May, velocity was well below 0.05 m/s. Therefore, this site is likely prone to persistent thermal stratification. The close proximity of this site to the main channel of the Barwon River means that any negative effects on water quality (such as toxic algal blooms or low dissolved oxygen) could be transmitted downstream to the Barwon. Maintaining flow above the 0.05 m/s threshold in tributaries where possible may be an important management consideration. Also due to rain and unsealed road access only, the thermistor chain at Pooncarie could not yet be retrieved. This will be done when possible, and this data added as an updated report.

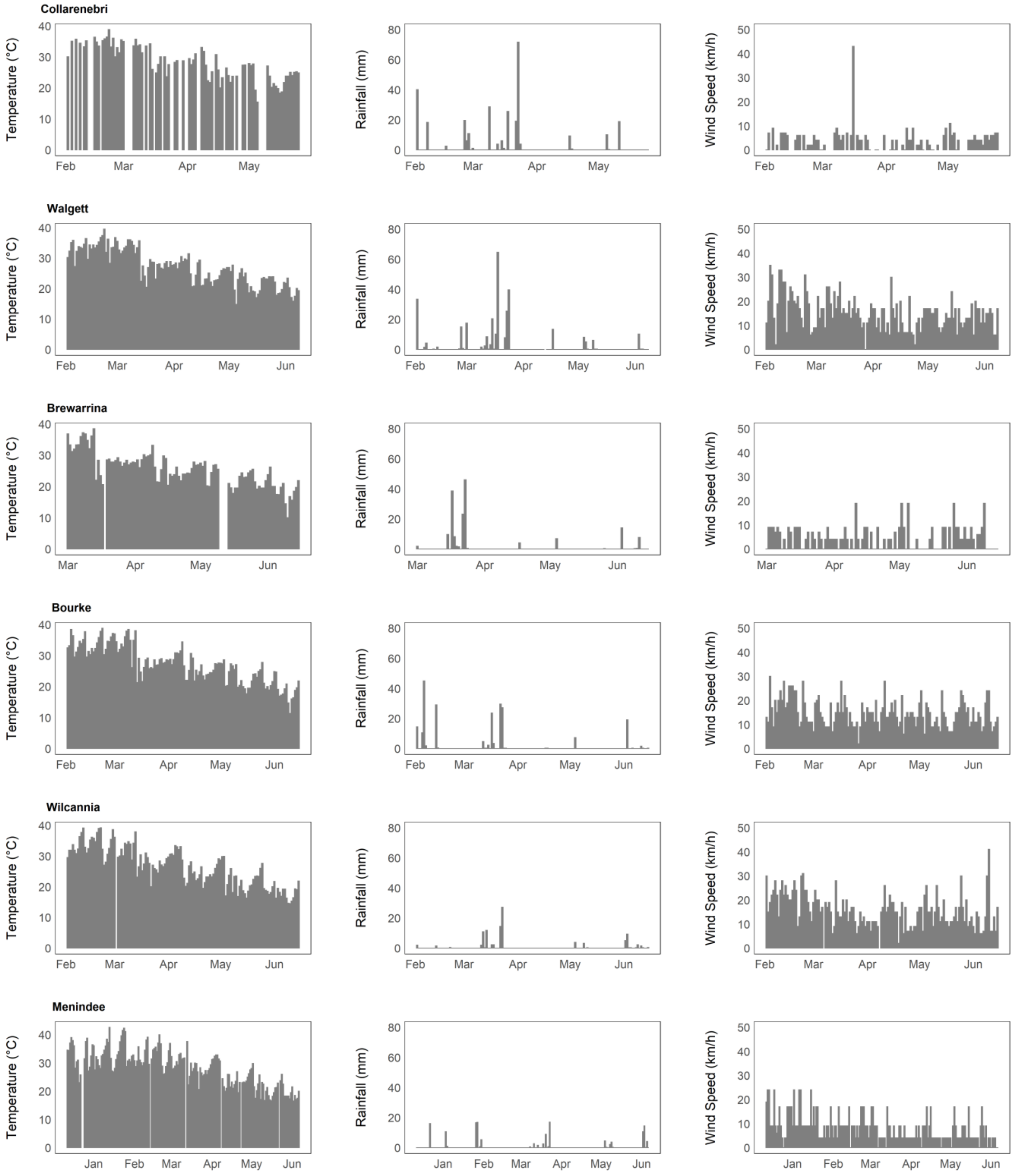
6. Future work

There were occasions when flow velocities and weather conditions appeared conducive to persistent stratification, but stratification was not observed. This could be due to localized disturbances such as pumping as well as weather effects. Although this project helps set some better quantified benchmark velocities and discharges for reducing persistent stratification, further information is needed to better define these thresholds over a variety of weather conditions, particularly very hot summers and also location within a weir pool (i.e. proximity to weir, depth of pool). Some suggestions for future work are given below.

1. More data on stratification in the weir pools is required to better understand the flow thresholds to reduce stratification. This study period followed a long dry period, so water levels were lower than average. As persistent stratification does not appear to occur when water levels are low, this likely reduced the prevalence of stratification in this study. Given the La Niña climate patterns evident in 2021, rainfall has been very high. The summer of 2021-22 may provide an excellent opportunity to further study the formation of persistent stratification and build a larger dataset by sampling at different discharges, river heights and sites. It is suggested that this study be extended for another 1-3 years to better define the suggested thresholds.
2. Little is known about longitudinal patterns of stratification within a weir pool and the degree of fine-scale variability. For example, how far persistent stratification stretches upstream, the influence of water movement over the weir nearer this location or whether isolated pockets of stratified water occur with mixed areas in-between. These questions may be an important management consideration for understanding how much of a river may be affected by stratification, particularly if artificial mixing is considered, which can be a successful management strategy in lakes (Heo & Kim, 2004, Visser et al., 2016).
3. While the link between thermal stratification and cyanobacterial blooms in the Barwon-Darling has already been established (Mitrovic et al. 2003), it may be beneficial to combine temperature and flow monitoring with cyanobacterial counts to compare the occurrence of blooms (both historically and currently) with velocities and discharges, to better understand the link between cyanobacterial blooms and flows. This is particularly relevant as the species of cyanobacteria occurring in the Murray-Darling River are changing over time with climate shift (Crawford et al., 2017). New toxic species such as *Cylindrospermopsis* and *Chrysosporum* are now occurring in the river and their links to stratification have not yet been quantified in this river.
4. Build a detailed stratification algal bloom model to predict when blooms will occur and to be able to nuance the flows in the river to minimize their occurrence. By better understanding how stratification interacts with algal growth, flow management strategies can be developed to minimize problematic growths while maximizing water use efficiency. This will also reduce the risk of fish kills and will allow forward planning to reduce environmental impacts.

5. Examine modelled flow data using IQQM to see how the current rules, previous rules and other rule options may influence the formation of persistent stratification and toxic blue-green algal blooms at different points on the river. This could help justify the current flow rules, and also suggest where changes may be possible to improve outcomes.
6. Examine the use of pulsed flows as a way of reducing cyanobacterial blooms, persistent stratification and fish kill events in the lower Darling River. The use of pulsed high flows interspersed with lower flow periods may be a way of controlling problematic stratification, while using overall considerably less water than a consistent suppressing flow. This would also help bring back some flow variability into the river. A project to test these types of releases would be useful for the Lower Darling as well as other river parts where flows could be manipulated.
7. Cyanobacteria can be enumerated at different depths in the water column. This will allow the opportunity to assess whether cyanobacteria are regulating their buoyancy during different levels of stratification, and whether cyanobacterial dominance occurs in weakly stratified conditions (such as when minimum daily $\Delta T < 1$ °C) or sporadically stratified conditions. This may also help inform whether stratified conditions have to persist for a minimum amount of time to instigate a bloom event.

7. Supplementary Data



Supplementary Figure 1. Weather data for all sites (temperature = left, rainfall = middle, wind = right)

8. References

Bowling, L.C. and Baker, P.D., (1996) Major cyanobacterial bloom in the Barwon-Darling River, Australia, in 1991, and underlying limnological conditions. *Marine and Freshwater Research*, 47(4), pp.643-657. https://doi.org/10.1071/MF9960643

Crawford A., Holliday J., Merrick C., et al (2017) Use of three monitoring approaches to manage a major Chrysosporum ovalisporum bloom in the Murray River, Australia, 2016. *Environmental Monitoring and Assessment* 189: https://doi.org/10.1007/s10661-017-5916-4

Heo W.M., Kim B. (2004) The effect of artificial destratification on phytoplankton in a reservoir. *Hydrobiologia*. https://doi.org/10.1023/B:HYDR.0000036142.74589.a4

Mitrovic S.M., Chessman B.C., Bowling L.C., Cooke R.H. (2006) Modelling suppression cyanobacterial blooms by flow management in a lowland river. *River Research and Applicatio*ns. https://doi.org/10.1002/rra.875

Mitrovic S.M., Hardwick L., Dorani F. (2011) Use of flow management to mitigate cyanobacterial blooms in the Lower Darling River, Australia. *Journal of Plankton Research* 33:229–241. https://doi.org/10.1093/plankt/fbq094

Mitrovic S.M., Oliver R.L., Rees C., et al (2003) Critical flow velocities for the growth and dominance of Anabaena circinalis in some turbid freshwater rivers. *Freshwater Biology*. https://doi.org/10.1046/j.1365-2427.2003.00957.x

NSW DPIE (2019a). *Barwon-Darling Watercourse Resource Plan: Draft Surface Water Resource Description.* September 2019. https://www.industry.nsw.gov.au/__data/assets/pdf_file/0003/273747/appendix-a-barwon-darling-resource-description.pdf

NSW DPIE (2019b). *NSW Murray and Lower Darling Water Resource Plan: Surface Water Resource Description.* April 2018. https://www.industry.nsw.gov.au/__data/assets/pdf_file/0008/145394/Murray-and-Lower-Darling.pdf

Vertessy, R., Barma, D., Baumgartner, L., Bond, N., Mitrovic, S. and Sheldon, F. (2019) Independent assessment of the 2018–19 fish deaths in the lower Darling. https://www.mdba.gov.au/sites/default/files/pubs/Final-Report-Independent-Panel-fish-deaths-lower%20Darling_4.pdf

Viney, N.R., Bates, B.C., Charles, S.P., Webster, I.T. and Bormans, M. (2007) Modelling adaptive management strategies for coping with the impacts of climate variability and change on riverine algal blooms. *Global Change Biology*, 13(11), pp.2453-2465. http://dx.doi.org/10.1111/j.1365-2486.2007.01443.x

Visser P.M., Ibelings B.W., Bormans M., Huisman J (2016) Artificial mixing to control cyanobacterial blooms: a review. *Aquatic Ecology*. https://doi.org/10.1007/s10452-015-9537-0

Weinke A.D., Biddanda B.A. (2019) Influence of episodic wind events on thermal stratification and bottom water hypoxia in a Great Lakes estuary. *Journal of Great Lakes Research*. https://doi.org/10.1016/j.jglr.2019.09.025