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Critical flow velocity thresholds for preventing persistent thermal stratification and cyanobacterial blooms in rivers

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ABSTRACT

Toxic cyanobacterial harmful algal blooms (cHABs) are a major worldwide issue in freshwater environments, exacerbated by climate change with rising water temperatures and prolonged and intensified periods of thermal stratification. The Barwon-Darling River in Australia, a dryland river with a highly variable flow regime, often experiences persistent thermal stratification (PTS), i.e., continuous stratification for days or weeks, during periods of low discharge, commonly resulting in cHABs. This study evaluated whether a critical flow velocity threshold can prevent or disrupt the formation of PTS and subsequent cHABs. The relationships between gauged discharge and flow velocity were determined within six weir pools along the river using acoustic Doppler current profiling. These relationships were used to interpret 20 years of historic daily river discharge data as mean cross-sectional flow velocities which were then compared to cyanobacterial biovolumes over the same period, focusing predominantly on the potentially toxic genera *Dolichospermum*. An upper limiting relationship between flow velocity and *Dolichospermum* biovolume was found and almost all blooms > 4 mm^3/L (exceeding the Australian recreational safety guidelines for toxic cyanobacteria) occurred when maximum antecedent 7-day flow velocities were less than 0.05 m/s. Quantile regression estimates suggested maintaining flow velocities of 0.05 m/s can limit blooms to 3.96 mm^3/L while increasing flow velocities will reduce this limit. These findings support the premise of using river flow velocity thresholds for cHAB management when blooms are related to PTS. These flow velocities should be applicable to other rivers in similar climates while the approach could be utilised more widely.

1. Introduction

Toxic cyanobacterial harmful algal blooms (cHABs) are a major worldwide issue in freshwater environments including lakes, reservoirs and rivers (Watson et al., 2015). They can produce secondary metabolite toxins that can be harmful to humans including neurotoxins, hepatotoxins, cytotoxins and skin irritants. These toxic blooms can render the water unsafe to drink (Weirich and Miller, 2014) and may cause animal and livestock death (Trevino-Garrison et al., 2015) and ecological issues within waterways (Benayache et al., 2019). Climate change is increasing the incidence of cHABs through increased water temperatures (Paerl and Huisman, 2009; Paul, 2008), the increased extent and strength of thermal stratification periods (De Stasio et al., 1996) and reduced lake and river inflows (Jeppesen et al., 2009).

Freshwater ecosystems in dryland regions are characterised by low, unpredictable rainfall and highly variable river flow regimes, and may be particularly susceptible to cHABs. River flows are further impacted by increased pressure to fulfil human water demands for drinking water and irrigation (Richter et al., 2003; Vörösmarty et al., 2010). Hot and dry conditions in combination with reduced flows can lead to extensive algal blooms (Bowling and Baker, 1996) and large-scale fish kill events, such as occurred in the Lower Darling River, Australia in the summer of 2018/2019, where three events killed upwards of a million fish after low flows and extremely hot and dry conditions (Sheldon et al., 2021; Vertessy et al., 2019).

Rivers in regions that have high water demand, face frequent water

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shortages or experience extended dry periods are often impounded with weirs, dams, or locks to regulate flows and maintain water supply for domestic and agricultural uses. These impoundments can create slow-moving (or still) waters by backing up rivers, creating water reservoirs within the river channel. Weir pools can extend up to 30 km upstream and supply months of water access when flows are low or cease. Low discharge rates through these river systems can lead to the formation of persistent thermal stratification (PTS), the separation of the water column into distinct layers for multiple days. Extended periods (i.e., weeks) of PTS in these river systems can result in the development of cHABs (Mitrovic et al., 2003).

The Barwon-Darling River comprises the northern portion of Australia's most extensive river system, the Murray-Darling (Thoms and Sheldon, 2000) and is known to have frequent blooms of the saxitoxin-producing *Dolichospermum circinale* (Bowling and Baker, 1996; Mitrovic et al., 2003). These blooms have been linked to the formation of PTS under low flows (Mitrovic et al., 2003; Mitrovic, Hardwick, and Dorani, 2011; Sherman et al., 1998) where a more stable water column may allow cyanobacteria to utilise buoyancy regulation to access a greater quanta of light at the water surface (Mitrovic, Bowling, and Buckney, 2001; Walsby et al., 1991) as well as increased light availability through improved Zeu:Zmix ratios (Mitrovic, Hardwick, and Dorani, 2011). Increased turbulence leading to water column mixing and prevention of PTS can reduce the occurrences of blooms (Mitrovic, Bowling, and Buckney, 2001, 2011).

Establishing the river discharge required to maintain a regularly mixing water column may be useful when managing flows for reducing some cHABs such as *Dolichospermum circinale*. The required discharge will vary between sites due to differences in cross-sectional area and water depth but can be comparable if expressed as mean cross-sectional flow velocity (Mitrovic et al., 2003). It is therefore essential to accurately identify the flow velocity required to reduce PTS and hence related cyanobacterial blooms to enable calculation of site-specific discharge targets for management use. For example, it has been suggested that maintaining flow velocities above 0.03 m/s - 0.05 m/s may be useful for reducing PTS and *Dolichospermum* blooms during the hotter months of October to April (Mitrovic et al., 2003, 2006; Mitrovic, Hardwick, and Dorani, 2011). These velocities were determined using simple cross-sectional area profiles at relatively few sites. More precise cross-sectional area and flow velocity measurements, such as can be achieved with acoustic Doppler current profiling, are needed at additional sites across the river system under a wider range of flow conditions to more accurately define critical velocities for minimising cyanobacterial blooms in rivers. Furthermore, the availability of river discharge records and extensive algal biovolume data in the years following the initial proposal of these velocity thresholds in 2003 (Mitrovic et al., 2003) provides an opportunity to assess their effectiveness in reducing blooms and their suitability for river management.

This study aims to (1) determine the critical flow velocity and thus site-specific discharge targets for the prevention of PTS ($\geq$ 7 days) in the Barwon-Darling River using accurate in-situ flow velocity measurements and thermal stratification data and (2) compare historical cyanobacterial biovolume data with the flow velocity thresholds obtained in (1) using historic discharge records. This study will provide crucial information on how cHABs are influenced by flows and if they are suppressed under these thresholds, allowing water managers to better target discharge rates and associated flow velocities to reduce occurrences of PTS and related cyanobacterial blooms.

2. Methods

2.1. Site descriptions

Six major weir pools over 800 km of the Barwon-Darling River were selected as sites for examination: Collarenebri, Brewarrina, Bourke, Tilpa, Wilcannia and Menindee Weir 32 (Fig. 1). These weir pools extend further than 20 km upstream and range in depth from approximately 4 to 6 m close to the weir. They are all simple overflow concrete/rock design weirs with washout flows ranging from 2400 ML/day to 18,000 ML/day.

Menindee Weir 32, the southern-most site, is the only site where flows are directly regulated, with the main river channel diverted into the Menindee Lakes system and operational lake outlets controlling river flows. There are, however, several large storages on tributaries of the Barwon-Darling that can influence main channel flows at the other sites.

2.2. Flow measurements

River flow velocity measurements were made under multiple within-channel discharges at each site between September 2021 and February 2024 using a Teladyne RiverPro acoustic Doppler current profiler (ADCP). The ADCP creates a bathymetric profile of each site to determine the cross-sectional river area and measures discharge and mean cross-sectional flow velocity with each transect from bank to bank. Each sample consisted of at least 4 high-quality transects where all measurement values were within 5 % of the mean of all transects. This was done multiple (minimum 5) times at each site using either a kayak or boat to tow the ADCP at slow speed (~ 0.5 m/s).

2.3. Temperature profiles

Temperature profiles of the weir pools were measured using thermistor chains with temperature loggers (HOBO Pendant UA-001–64) attached to a buoy just below the surface (~10 cm) and at 1 m depth intervals until the bottom. Each logger was set to record temperature hourly and downloaded every 3 to 6 months between January 2021 and October 2024.

2.4. Cyanobacterial data

Cyanobacterial identification and cell count data from 2002 to 2022 were obtained from government agency records upon request. These records were compiled from various government research projects and routine monitoring. Samples were generally taken at a depth of 25 cm, with counts and identification conducted by relevant government agencies using the Lund cell technique with a precision of ± 20 % (Hötzel and Croome 1999). Taxa were analysed at the genus level. Using these records, cell counts were converted to biovolumes using the most appropriate conversion factors from Newcombe (2012) and Olenina et al. (2006). At the time of this study these were the entirety of the digital algal data recorded for the study sites.

2.5. Data analysis

A conservative outlier removal method was used to eliminate extreme outliers (velocity 3x the interquartile range) of algal samples recorded at high flows as 1) these are likely to represent algae that have been transported from upstream or developed on the floodplain rather than proliferated within the river channel and weir pool and 2) these cell counts were all relatively low, the highest being 5658 cells/mL (1.4 mm^3/L) during high flows of 28,415 ML/day. One other sample was manually removed at Menindee Weir 32 as it was considered an outlier bloom occurring at a much lower water temperature than usual (12.8 °C) and was likely advected from the adjacent Lake Menindee via a regulated flow release.

Correlation analyses were used to ensure that discharges recorded from gauge stations and discharges measured by ADCP were consistent ($r \geq 0.97$, $p < 0.05$). Linear regression analysis was then used to find the relationship between gauge station discharge records and velocity at each site to convert historical discharge data to flow velocity.

Thresholds used to determine whether a water body is considered stratified or not are often established empirically for each environment,

Fig. 1. Map of the Barwon-Darling with locations of the sample sites projected over the NSW border (grey area) and the Murray-Darling Basin.

with temperature gradient criteria ranging from 0.2 to 2 °C m^{-1} used to determine an established thermocline (Zhang et al., 2022). We used the threshold of a minimum daily temperature difference (ΔT_{min}) equal to or greater than 0.5 °C between the surface and the deeper layers of the water column over a 24-hour period to define thermal stratification. This threshold was previously determined by Mitrovic et al. (2003) to be indicative of thermal stratification in weir pools on the Barwon-Darling River and linked to the growth and dominance of *Dolichospermum circinale* (formerly *Anabaena circinalis*). Temperature loggers were routinely checked for consistency during high-flow isothermal periods, when the water column was fully mixed. An example of PTS forming and then ending as a result of a mixing event at Collarenebri can be seen in Fig. 2 where panel a. (top) shows water temperatures at different depths over 20 days with diel oscillations (most prominent in the 0 m line, i.e. surface water temperature) at the start and end of the timeseries showing regular diel stratification where mixing occurs at night as thermal layers reconverge. The middle section of panel a. shows a separation of thermal layers that do not reconverge for several days consecutively, indicating that nightly mixing has ceased and distinct thermal layers have formed. Minimum temperature differences between the surface and bottom waters are simplified and represented in panel b. with ΔT_{min} indicated. Panel c. shows the concurrent hydrograph at Collarenebri with fluctuations in discharge unable to mix the water column until flows reach ~750 ML/day, resulting in an isothermal water column thereafter.

With a typical doubling time of approximately 2 days, buoyancy regulating cyanobacteria, such as *Dolichospermum* spp., can proliferate into large growths/blooms from relatively low concentrations during extended periods of thermal stratification (Mitrovic et al., 2003). Hence, periods of PTS were compared to the maximum daily flow velocities recorded within the antecedent 7-day period to determine the relationship between flow velocity and PTS.

Logistic regression was used to construct a statistical model to describe the relationship between daily average flow velocities, daily maximum air temperatures, and the occurrence of persistent thermal stratification. Logistic regression is a suitable and widely used method for predicting the probability of a binary outcome based on one or more predictor variables (Hosmer Jr, Lemeshow, and Sturdivant, 2013). Here, stratification was defined as a binary response variable, where: daily $\Delta T_{min} < 0.5$ °C indicated an absence of stratification, and daily $\Delta T_{min} \geq 0.5$ °C indicated the presence of stratification. The predictor variables, daily average flow velocity (m/s) and daily maximum air temperature (°C) were used to estimate the likelihood of stratification occurring.

We determined the relationship between velocity and cyanobacterial

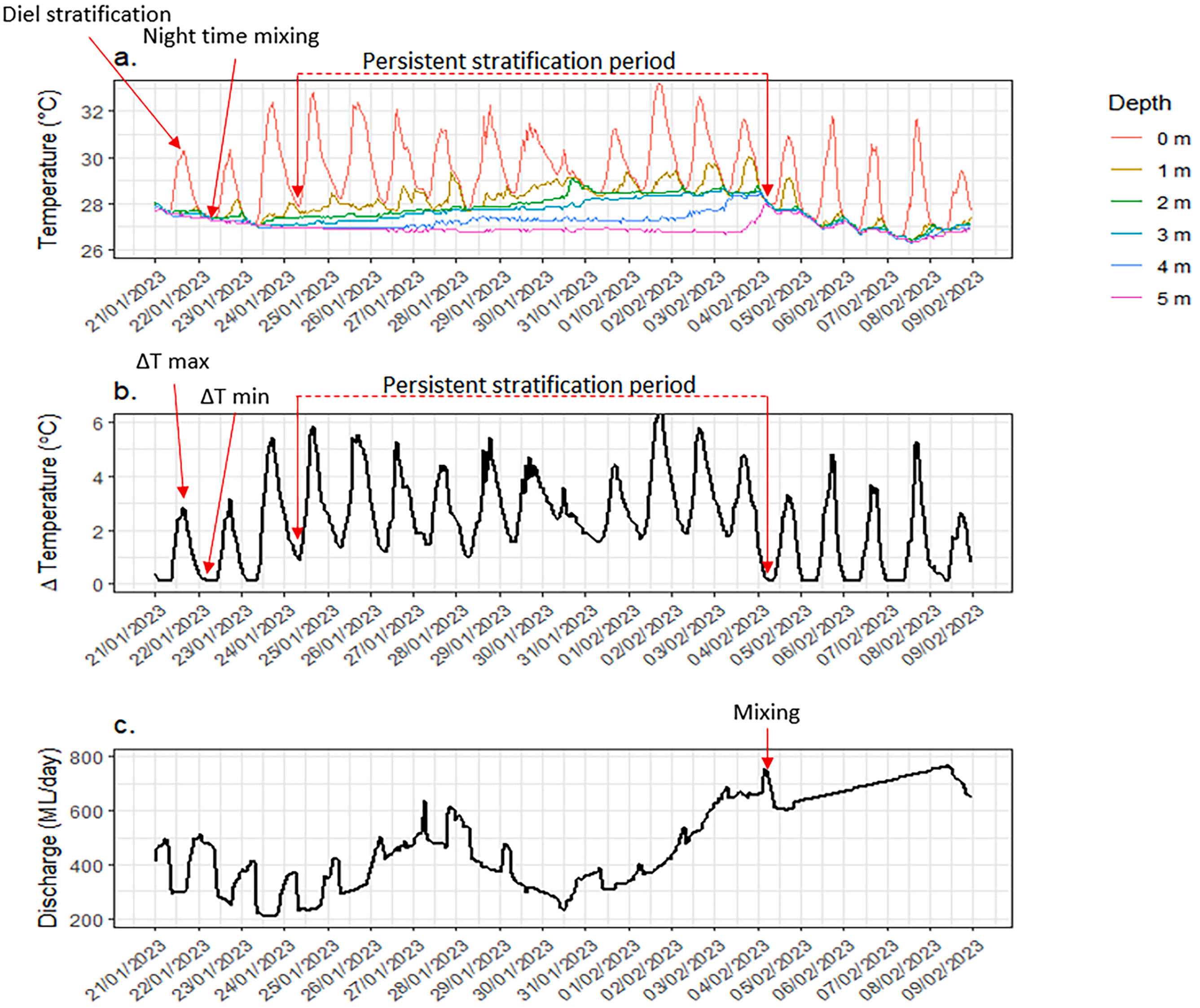

Fig. 2. Time series of water temperature at different depths with a period of stratification demarcated (a). The ΔT between the top and bottom depth (b) and the discharge hydrograph of this period (c).

biovolume using quantile regression. This model describes the upper limiting response of cyanobacteria to changes in velocity. These upper limiting relationship estimates were made at the highest quantile from which reliable predictions could be made for each genus (Rogers, 1992). *Dolichospermum* was the primary focus of the analyses due to its historical prevalence as a problem toxic cyanobacteria in the river, though other genera were also analysed if the sample size was greater than 100 (to allow for estimation up to the 95th quantile).

All statistical analyses were carried out using R base packages within R4.3.2 (R core team, 2023) in addition to “quantreg” for quantile regressions (Koenker, 2023). Data were visualised using “ggplot2” (Wickham, 2016).

3. Results

3.1. Discharge, flow velocity and stratification

There was a strong linear relationship between gauged discharge and flow velocity at all sites ($R^2 = 0.95$ to 0.99, $p < 0.05$, Supplementary Figure 1) over discharge sizes ranging from 31st percentile flows (lower than 69 % of days between 2002 and 2022) to 75th percentile flows (lower than 25 % of days between 2002 and 2022). These are low to moderate level, within-channel flow conditions. Using these relationships, flow velocity was estimated from historic gauged discharge data.

Across all the study sites there were 10 distinct periods of PTS amounting to 172 days, often occurring simultaneously between sites (63 days at Collarenebri, 69 at Brewarrina, 25 at Bourke, 8 at Tilpa, and 7 at Wilcannia). There were no periods of PTS at Menindee Weir 32. The maximum daily flow velocity during any of these periods was 0.05 m/s, equivalent to ~752 ML/day at Collarenebri and ~669 ML/day at Wilcannia. The maximum daily velocities at the other sites was 0.04 m/s, equivalent to ~848 ML/day at Brewarrina, ~832 ML/day at Bourke, and ~712 ML/day at Tilpa (Fig. 3).

The logistic regression model indicated that both water velocity and air temperature have a strong influence on the likelihood of thermal stratification occurring (Nagelkerke pseudo-$R^2 = 0.46$). Higher air temperatures were linked to an increased likelihood of thermal stratification. Each 1 °C increase in maximum daily air temperature raised the likelihood of thermal stratification occurring by 14.06 % (odds ratio = 1.14, 95 % CI: 1.12 - 1.17, $p < 0.001$). Conversely, higher flow velocities were associated with a decreased likelihood of thermal stratification. Each 0.01 m/s increase in flow velocity reduced the odds of thermal stratification occurring by 42.44 % (odds ratio = 0.58, 95 % CI: 0.54 – 0.61, $p < 0.001$). Fig. 4 shows the estimated 50 % and 5 % likelihood of thermal stratification occurring as predicted by the model with the observed occurrences of thermal stratification highlighted. A more comprehensive probability matrix can be seen in Supplementary Table 1. The daily maximum air temperatures during these recorded periods of thermal stratification ranged from 16.3 °C to 45.8 °C and as water velocity increased above 0.05 m/s, thermal stratification rarely occurred when maximum daily air temperatures were below 30 °C (Fig. 4). The logistic regression model estimates the likelihood of thermal stratification occurring when flow velocity is 0.05 m/s is 1 % when maximum daily air temperature is 16.3 °C, 8 % when maximum daily air temperature is 30 °C, and 42 % when maximum a daily air temperature is 45.8 °C.

3.2. Cyanobacteria and flow velocity

Four commonly occurring cyanobacteria genera were associated with low flows: *Dolichospermum, Merismopedia, Planktolyngbya* and *Pseudanabaena*. They were all found to bloom (exceeding the Australian

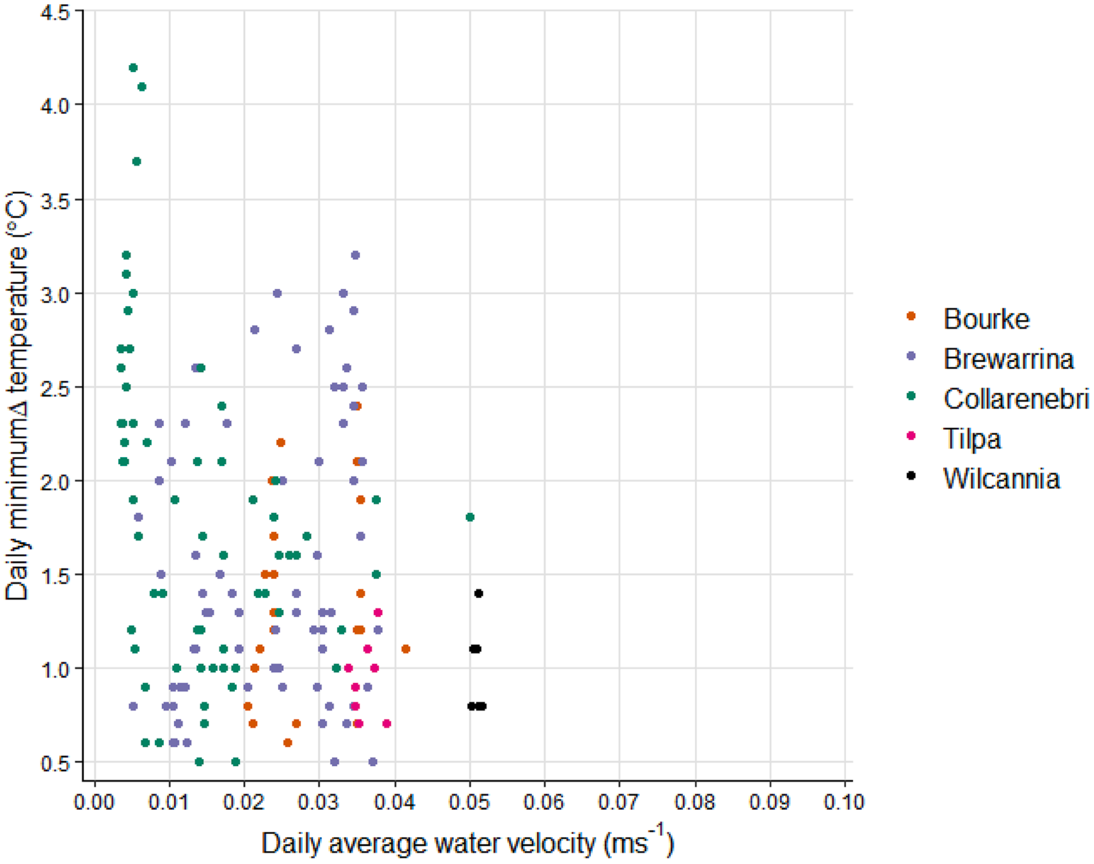

Fig. 3. Relationship between thermal stratification ($\Delta T_{min} \geq 0.5$ °C) and the recorded daily water velocity during periods of continuous stratification lasting at least 7 days.

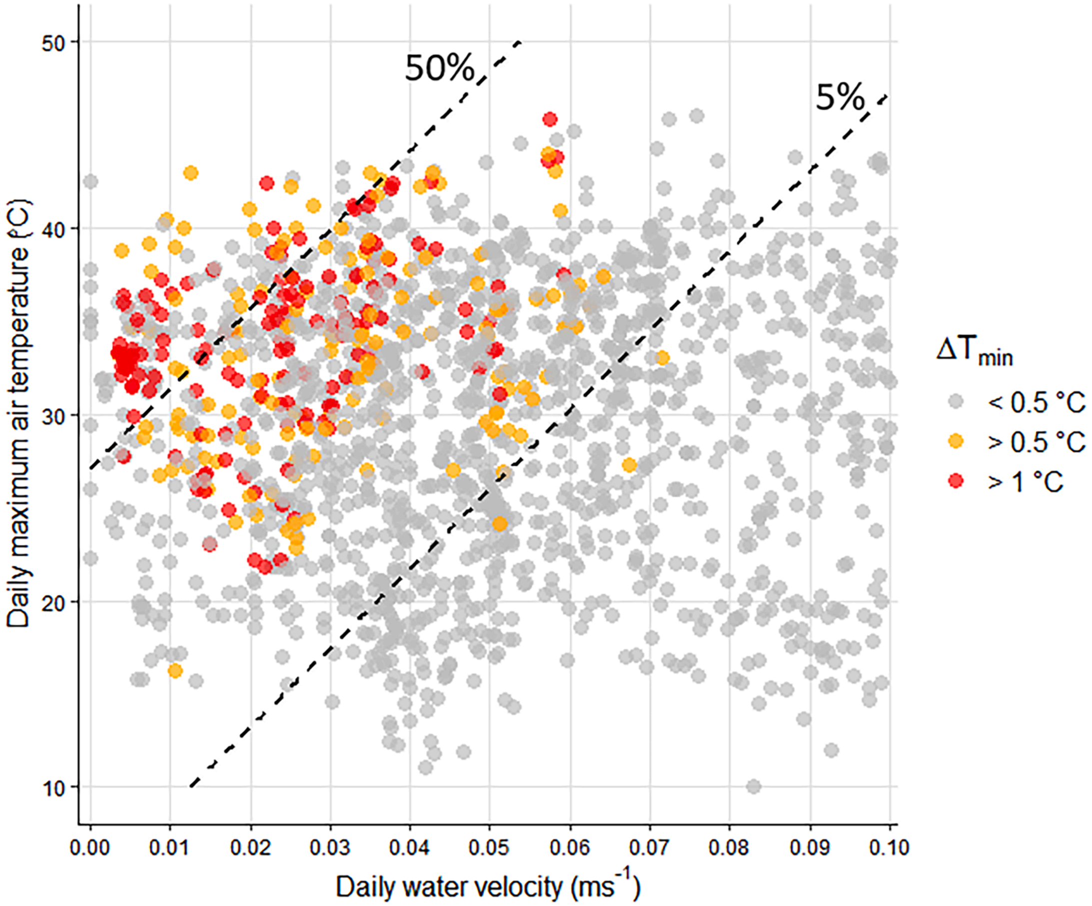

Fig. 4. Influence of daily maximum air temperature and the recorded daily water velocity on periods of thermal stratification ($\Delta T_{min} \geq 0.5$ °C). The dashed lines represent the 50 % odds (left) and 5 % odds (right) of stratification persisting over a 24-hour period.

recreational water use guidelines of 4 mm^3/L) under low flow velocities with most of these blooms occurring below 0.03 m/s (Fig. 5). Of the 50 *Dolichospermum* bloom samples exceeding 4 mm^3/L, only four occurred at flows above 0.03 m/s and only one above 0.05 m/s.

There were significant upper limiting relationships between the historic biovolumes of each of the different cyanobacteria and 7-day maximum antecedent flow velocities: *Dolichospermum* (n= 461, 96th quantile, p< 0.01), *Merismopedia* (n= 289, 98th quantile, p= 0.04), *Planktolyngbya* (n= 278, 98th quantile, p< 0.01), and *Pseudanabaena* (n= 273, 91st quantile, p= 0.04) (Fig. 6). All four genera exhibited a negative relationship with higher biovolumes occurring at lower flow velocities. Of the four genera, *Dolichospermum* formed high biovolume blooms the most often. Maximal 7-day antecedent flows of 0.05 m/s were estimated to be able to limit its biovolume to 3.96 mm^3/L (90 % CI: 2.85 mm^3/L, 5.50 mm^3/L), slightly below the recreational safety guideline threshold. Flows of 0.08 m/s would reduce that limit further to 2.33 mm^3/L (90 % CI: 1.38 mm^3/L, 3.93 mm^3/L) (Table 1). *Dolichospermum* only exceeded a 4 mm^3/L biovolume once when coinciding 7-day maximum antecedent flow velocities were greater than 0.05 m/s. *Merismopedia, Planktolyngbya,* and *Pseudanabaena* were all estimated to be limited below 4 mm^3/L at flows greater than 0.03 m/s, which was reflected in the sample data (Table 1, Fig. 6).

Cyanobacterial biomass typically followed seasonal trends, increasing in the warmer months and decreasing in cooler months. *Dolichospermum* blooms occurred starting around November (late spring) as daily maximum air temperatures commonly reached upwards of 30 °C and blooms have had time to develop. These blooms would then begin to die off around March (autumn) and were not found between May and September (only two blooms occurred in April and one late in October) (Fig. 7).

4. Discussion

We investigated the relationship between river flow velocity and the formation and breakdown of thermal stratification in the Barwon-Darling River to determine whether PTS can be suppressed by maintaining flows above a critical threshold. Additionally, we analysed historical cyanobacterial records to determine whether a similar flow velocity threshold can be applied to suppress cyanobacteria that benefit from stratified conditions, such as *Dolichospermum circinale*. We found that PTS and cHABs were both negatively associated with flow velocity and were greatly reduced by flow velocities exceeding 0.05 m/s. These findings suggest that a flow velocity threshold of 0.05 m/s may be useful for preventing or reducing PTS influenced cHABs from occurring in rivers.

4.1. River blooms and flow

River cyanobacterial blooms are an ongoing issue for water managers, river water users and for the ecological functioning of aquatic systems. The Darling River, Australia received worldwide attention in 1991/92 when an extensive bloom occurred over 1000 km of the river (Bowling and Baker, 1996). Subsequently, Mitrovic et al. (2003) identified PTS as an important driver of blooms in this system and minimum flow velocity thresholds have been suggested for preventing PTS and cyanobacterial blooms. For example, Mitrovic et al. (2003) suggested thresholds of greater than 0.05 m/s, while Mitrovic et al. (2006) and Mitrovic, Hardwick, & Dorani (2011) suggested that a threshold of 0.03

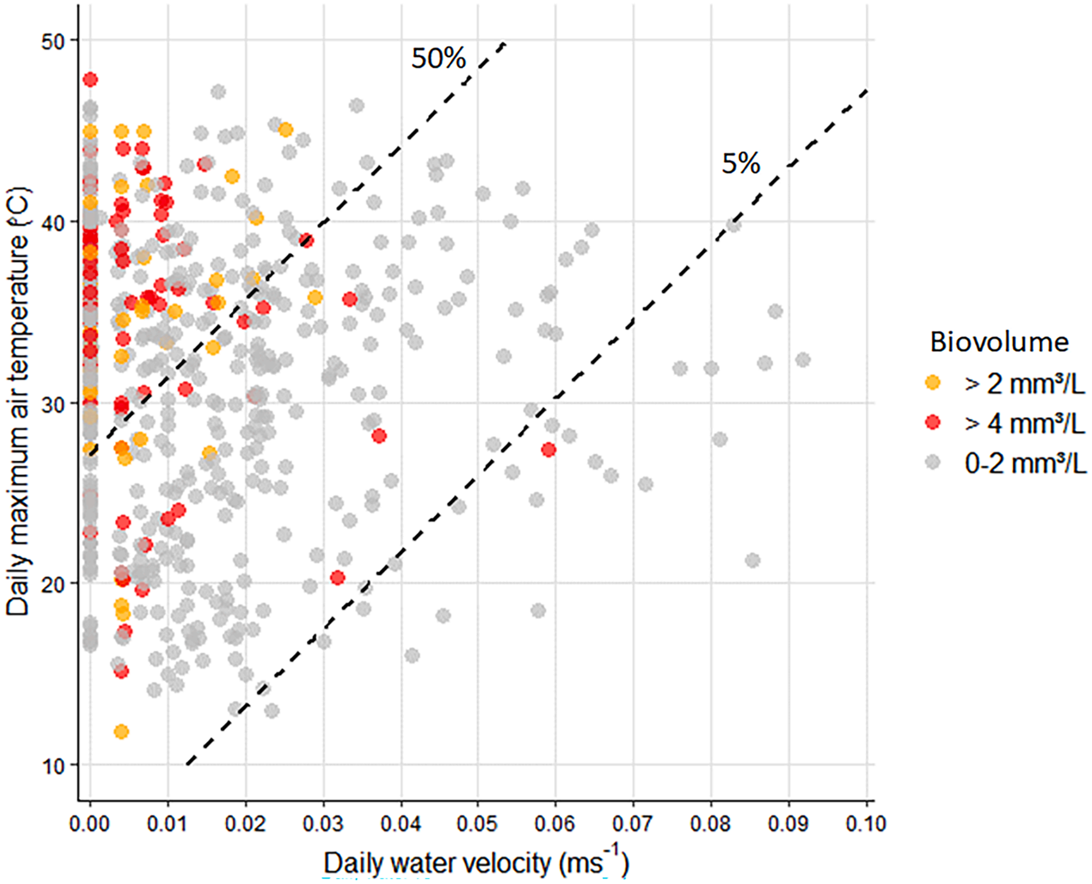

Fig. 5. Relationship between daily maximum air temperature, recorded daily water velocity and the total biovolume of Dolichospermum, Merismopedia, Planktolyngbya and Pseudanabaena. The dashed lines represent the 50 % likelihood (left) and 5 % likelihood (right) of stratification persisting over a 24-hour period.

m/s was sufficient. However, these thresholds were determined based on channel cross-sectional area measurements and gauged flow to determine velocity at relatively few sites. In our study, more precise measurements of flow velocity were taken using an acoustic Doppler current profiler at more sites and over a wider range of discharges, allowing a more accurate flow velocity management target to be determined. This is important in the Barwon-Darling River and other rivers where water availability may be low and efficient use of environmental water is critical.

4.2. *Flow velocity as a limiting factor for cyanobacteria growth and bloom formation*

While the need for extended periods of thermal stratification before the development of *Dolichospermum circinale* blooms is well known and has been reported multiple times (Mitrovic et al., 2003; Mitrovic, Hardwick, and Dorani, 2011; Sherman et al., 1998) there is a requirement to better determine flow velocities to suppress growth. Over the available 20-year historical record, cyanobacterial biovolumes were found to be highest during low flows and decreased as flow velocity increased. The relationships between these biovolumes and antecedent flow conditions indicate that while there may be various unmeasured factors influencing cyanobacteria growth, flow velocity is an upper limiting factor (Cade and Noon, 2003; Cade, Terrell, and Schroeder, 1999; Lancaster and Belyea, 2006). Our estimates indicated that a *Dolichospermum* biovolume upper growth limit of 3.96 mm^3/L (90 % CI: 2.85 mm^3/L, 5.5 mm^3/L) can be achieved when the maximum 7-day antecedent flow velocities are maintained above 0.05 m/s, limiting biovolume below the Australian recreational safety guideline threshold of 4 mm^3/L. Additionally, only one out of 50 *Dolichospermum* blooms > 4 mm^3/L recorded throughout the study occurred when antecedent flow velocities exceeded 0.05 m/s. No *Dolichospermum* blooms were recorded when the maximum 7-day antecedent flow velocities exceeded 0.07 m/s and our estimates indicated maintaining this flow velocity should create a *Dolichospermum* biovolume upper growth limit of 2.77 mm^3/L (90 % CI: 1.76 mm^3/L, 4.37 mm^3/L), further suppressing smaller, but still concerning growths that have the potential to quickly develop into more serious blooms. *Pseudanabaena*, another buoyancy regulating cyanobacteria, was estimated to be limited to sub-bloom concentrations when maximum 7-day antecedent flow velocities are maintained above 0.03 m/s. This demonstrates that proper management of *Dolichospermum* in this system should effectively also manage some other buoyancy regulating cyanobacteria.

Different mixing conditions can influence competition for light between phytoplankton species in a system and change algal community dominance (Huisman et al., 2004; Sherman et al., 1998). Buoyancy regulating cyanobacteria are often advantaged under stratified conditions as a stable water column allows for vertical migration into surface waters with greater light availability (Mitrovic et al., 2001). In contrast, non-buoyancy regulating phytoplankton will benefit more from higher turbulence as it facilitates their resuspension within the euphotic zone (Huisman et al., 2004; Sherman et al., 1998). However, while not directly benefitting from thermal stratification, non-buoyancy regulating cyanobacteria may indirectly benefit from other factors influenced by stratification such as increases in internal nutrient loading (Huber et al., 2012) or an improved light climate from reduced turbidity (Oliver, Mitrovic, and Rees, 2010). *Merismopedia* and *Planktolyngbya,* both non-buoyancy regulators, were estimated to be limited to sub-bloom concentrations under lower flow conditions than *Dolichospermum*, indicating that the potential advantages gained by

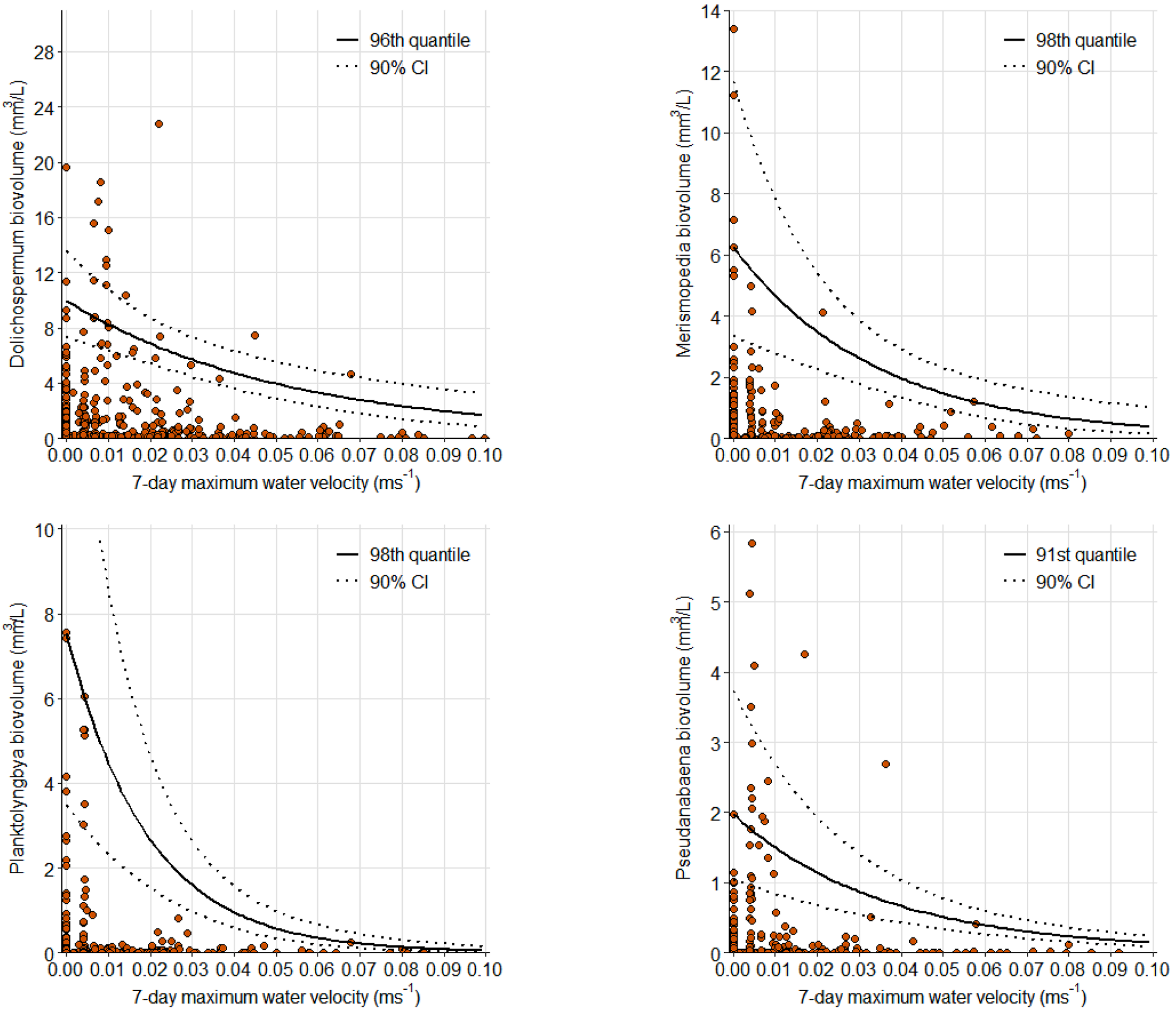

Fig. 6. Relationship between cyanobacteria biovolumes (*Dolichospermum* (top left), *Merismopedia* (top right), *Planktolyngbya* (bottom left), *Pseudanabaena* (bottom right)) and the antecedent 7-day maximum velocities at all sites (Bourke, Brewarrina, Collarenebri, Tilpa, Wilcannia, Menindee). The solid lines represent the regression quantiles and the dotted lines represent the 90 % confidence intervals.

resuspension are less than those of stratification for these genera and maintaining mixed conditions may be effective in reducing overall cyanobacterial concentrations.

4.3. *Thermal stratification dynamics*

Thermal stratification forms when the vertical transport of heat within a water column is much less than the rate at which heat is introduced by surface heating. The vast majority of vertical heat transport in rivers is due to turbulent mixing from flow (Williamson et at., 2015; Williamson et al., 2012), which can be quantified in terms of an eddy diffusivity, where the larger the diffusivity, the greater the vertical transport. The action of stratification and buoyancy on turbulence is complex and beyond the scope of this paper, however, previous work has shown that there are multiple flow regimes where stratification influences mixing in different ways (Issaev, Williamson, and Armfield, 2023; Issaev et al., 2022). In non-stratified flows, the eddy diffusivity is approximately proportional to flow velocity whereas in strongly stratified flows, the eddy diffusivity is more sensitive to changes in velocity, with some evidence suggesting the eddy diffusivity is proportional to the velocity squared (Issaev, Armfield, and Williamson, 2025). This suggests that once a river stratifies, the mixing rate decreases much more rapidly with further reductions in flow velocity, highlighting the importance of maintaining sufficient flow velocity for reducing periods of thermal stratification.

Throughout the 2021 – 2024 study, 10 periods of PTS were observed. During these periods, the maximum daily flow velocities recorded within any weir pool were 0.05 m/s, indicating that flow velocities greater than this are likely to generate sufficient turbulence to maintain regular water column mixing. High air temperatures will increase the likelihood of thermal stratification occurring, hence greater flow velocities are likely required in extreme heatwave events. At the highest air temperature recorded during the study period (45.8 °C), model predictions estimate a 42 % probability of thermal stratification forming on a given day when flow velocity is 0.05 m/s. Increasing the flow velocities in this scenario to 0.06 m/s or 0.07 m/s would reduce these probabilities to 29 % and 19 %, respectively. These estimations are based on a logistic regression model which uses flow velocity and air temperature as predictor variables and does not incorporate other factors known to contribute to stratification and mixing dynamics, such as

Table 1
Quantile regression estimates for the 7-day maximum antecedent velocities required to limit cyanobacteria to the corresponding biovolumes.

Genus	7-Day maximum velocity (ms^{-1})	Biovolume (mm^3/L)	90 % CI
Dolichospermum	0.03	5.69	(4.44, 7.30)
	0.04	4.74	(3.59, 6.28)
	0.05	3.96	(2.85, 5.50)
	0.06	3.31	(2.24, 4.88)
	0.07	2.77	(1.76, 4.37)
	0.08	2.33	(1.38, 3.93)
Merismopedia	0.03	2.61	(1.76, 3.86)
	0.04	1.96	(1.32, 2.91)
	0.05	1.48	(0.95, 2.30)
	0.06	1.12	(0.66, 1.89)
	0.07	0.85	(0.45, 1.58)
	0.08	0.64	(0.31, 1.34)
Planktolyngbya	0.03	1.59	(0.96, 2.62)
	0.04	0.95	(0.58, 0.16)
	0.05	0.58	(0.34, 0.98)
	0.06	0.35	(0.19, 0.65)
	0.07	0.21	(0.10, 0.44)
	0.08	0.13	(0.06, 0.30)
Pseudanabaena	0.03	0.87	(0.54, 1.41)
	0.04	0.66	(0.43, 1.04)
	0.05	0.51	(0.33, 0.78)
	0.06	0.39	(0.26, 0.59)
	0.07	0.30	(0.20, 0.46)
	0.08	0.23	(0.15, 0.36)

wind-speed and solar irradiance (Bormans and Webster, 1997). These unmeasured factors may have contributed to mixing and destratification (i.e. high winds, cloud cover and low solar irradiance) in periods of PTS, however, reliable data for these variables were not available for this analysis. Furthermore, the presence of high river banks along the river likely means that the effects of wind is limited or variable between sites.

Periods of thermal stratification up to 4 days long were observed at times when flow velocities were greater than 0.05 m/s (up to 0.07 m/s) with 19 total days recorded over 10 periods. These all occurred between September and March, usually during consecutive days of high air temperatures, with a mean daily maximum air temperature of 37.6 °C at these times. Thermal stratification was only able to persist for more than 24 h on two separate days when flow velocities reached 0.07 m/s and both times as discharge was increasing. These instances of stratification at higher velocities likely occurred because after stable stratification has formed, river pools can resist complete destratification for some time, from several hours to several days, even after the onset of higher, destratifying flows (Turner and Erskine, 2005; Webster et al., 2000). The destratification rate is determined by the prior stratified conditions, i.e., the greater the initial strength of stratification (ΔT) and the lower the turbulence (flow velocity), the longer the time requirement for destratification (Kirkpatrick et al. 2019). Hence, a strongly stratified weir pool may take longer to destratify under flow velocities of 0.05 m/s, while greater velocities will reduce this time.

While these shorter periods of stratification may not be necessarily critical for cHAB management, they may still contribute to other issues. Hypolimnial oxygen depletion can follow thermal stratification as advective reoxygenation below the thermocline from atmospheric diffusion and photosynthesis in the epilimnion are inhibited (Becker et al., 2010). This can reduce the amount of available habitat for aerobic organisms and potentially cause or contribute to fish kills if oxygen levels are low enough upon mixing, as happened in Menindee Weir 32 in the austral summer of 2019/2020 (Vertessy et al. 2019; Sheldon et al. 2021). Additionally, as hypoxia/anoxia develops within the hypolimnion, a decreased oxidation-reduction potential can lead to increased releases of sediment-bound nutrients and metals that may promote cyanobacterial growth after mixing (Turner and Erskine, 2005).

4.4. Flow velocity thresholds for cyanobacteria management

Our findings suggest a flow velocity threshold of 0.05 m/s should prevent *Dolichospermum* biovolumes from exceeding the Australian recreational water use safety guideline of 4 mm^3/L at almost all times (only one bloom was recorded when 7-day maximum antecedent flow velocities exceeded this). However, this is likely to be a conservative target at times given only three of 50 recorded *Dolichospermum* blooms occurred when velocities exceeded 0.03 m/s over the 20-year record. No *Dolichospermum* blooms occurred when flow velocity was sustained above 0.07 m/s. Flow velocity targets should be informed by the risk of a bloom occurring but also need to be balanced with water availability. Due to the limited water availability in the Barwon-Darling River, maintaining flow velocities > 0.07 m/s may not be a viable target for PTS and cyanobacterial management at all times. A temporally variable flow velocity management target that follows the yearly trends of *Dolichospermum* blooms and likelihood of PTS offers a more efficient use of water. Lower targets of 0.03 m/s could be implemented in Spring (September) and gradually increased to 0.05 m/s in Summer (January) during the hottest time of the year, then reduced back down to 0.03 m/s by the end of Autumn (May). Higher velocities (> 0.07 m/s) are recommended to be utilised during extreme heatwaves to minimise risks. cHABS have generally not been a concern in the cooler months of the year and thus far minimum flows for these purposes would not be required. However, Southeastern Australia is predicted to become hotter and drier with climate change (Cai and Cowan 2008) with longer periods of slow flowing, lentic conditions (Mallen-Cooper, and Zampatti, 2020). Combined with increased extreme temperature events as seen during the mass fish death events of 2018/2019 (Vertessy et al., 2019) this target window may expand into historically cooler months as stronger and longer periods of thermal stratification further increase the potential for cHAB growth, in particular for *Dolichospermum*.

Weir pools on other rivers with similar size to those in this study have also been found to have similar suggested critical discharge rates for controlling cHABs (Mitrovic et al., 2003; Webster et al., 2000), and we suggest that the flow velocity targets described here may be applied more broadly to other, comparably sized weir pools in similar climates. Weir pools in dissimilar climatic regions may have different critical flow velocity thresholds for preventing PTS, but these thresholds can be empirically derived using the approach outlined in this study. For example, weir pools on the Nakdong River, South Korea and the Saar River, Germany, are both cases where thermal stratification related to low flow velocity has been identified as an important driver of algal blooms (Engel and Fischer, 2017; Jung et al., 2023), indicating that a similar flow management approach has potential to be adopted as a control measure. Investigations of river blooms that have not specifically identified thermal stratification but rather periods of low discharge and

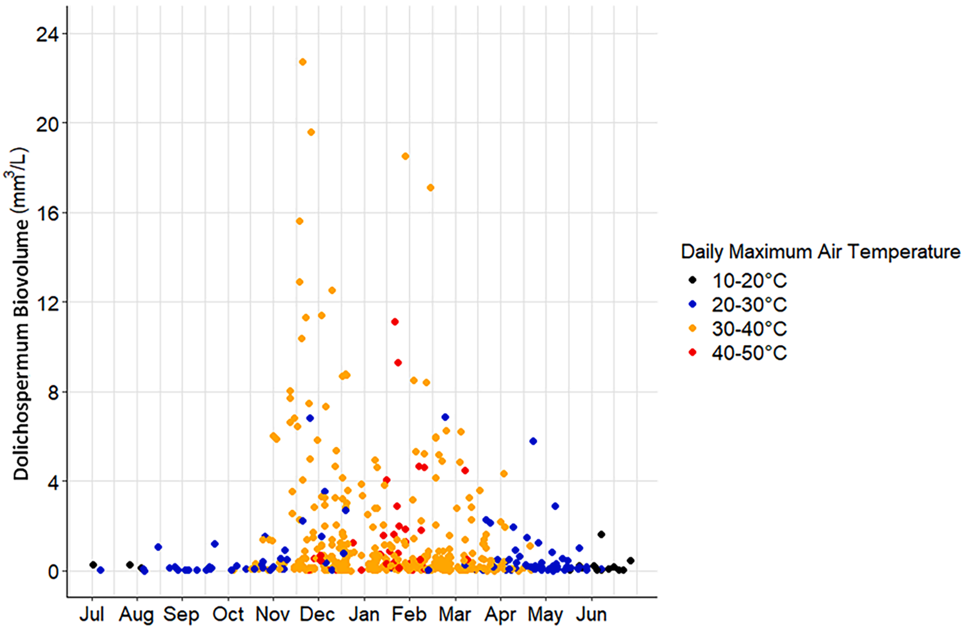

Fig. 7. Dolichospermum biovolume with the coinciding time of year and daily maximum air temperature.

high air temperatures (i.e. conditions conducive to thermal stratification) as a driver, such as on the Ohio River (Nietch et al., 2022) and Maumee River (Matson et al., 2020), USA, also potentially stand to benefit from investigating these relationships between flow velocity and PTS.

5. Conclusion

Our findings support previous studies' conclusions that PTS is a driver of *Dolichospermum* blooms in dryland rivers such as the Barwon-Darling River. Our study suggests that maintaining river discharge above a critical flow velocity threshold can be effective in preventing PTS from occurring and reducing the formation of toxic *Dolichospermum* blooms. We suggest that maintaining a flow velocity above 0.05 m/s is useful for preventing PTS and subsequent *Dolichospermum* blooms in the Barwon-Darling River. This threshold may also potentially be applied to other rivers within similar climates to suppress nuisance cyanobacterial growth. During periods prone to *Dolichospermum* growth, varying flow velocities from 0.03 m/s to above 0.05 m/s, depending on weather conditions such as air temperature, may be a useful strategy to improve water use efficiency in managing cHABs. Higher flows, such as 0.07 m/s or 0.08 m/s will further reduce the magnitude and duration of stratification, if water is available and may be required during extreme heatwave conditions. River systems in different climates will likely have different critical velocity thresholds depending on the characteristics of the waterbodies, but their determination can be achieved using similar methods.

CRediT authorship contribution statement

D.C. Davis: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J.A. Facey:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **A.J. Brooks:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **D.P. Westhorpe:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **M. Balzer:** Writing – review & editing, Supervision, Conceptualization. **N. Williamson:** Writing – review & editing, Conceptualization. **S.M. Mitrovic:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

Donald Davis reports financial support was provided by NSW Department of Climate Change, Energy, the Environment and Water. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.hal.2025.102962.

Data availability

Data will be made available on request.

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