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Research article

Annual water residence time effects on thermal structure: A potential lake restoration measure?

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ABSTRACT

Innovative methods to combat internal loading issues in eutrophic lakes are urgently needed to speed recovery and restore systems within legislative deadlines. In stratifying lakes, internal phosphorus loading is particularly problematic during the summer stratified period when anoxia persists in the hypolimnion, promoting phosphorus release from the sediment. A novel method to inhibit stratification by reducing residence times is proposed as a way of controlling the length of the hypolimnetic anoxic period, thus reducing the loading of nutrients from the sediments into the water column. However, residence time effects on stratification length in natural lakes are not well understood. We used a systematic modelling approach to investigate the viability of changes to annual water residence time in affecting lake stratification and thermal dynamics in Elterwater, a small stratifying eutrophic lake in the northwest of England. We found that reducing annual water residence times shortened and weakened summer stratification. Based on finer-scale dynamics of lake heat fluxes and water column stability we propose seasonal or sub-seasonal management of water residence time is needed for the method to be most effective at reducing stratification as a means of controlling internal nutrient loading.

1. Introduction

Anthropogenic eutrophication is a problem in lakes worldwide (Smith and Schindler, 2009), characterised by excess algal growth, low oxygen, and high turbidity. The scale of the problem has motivated extensive research and management action to reverse degradation. Primarily, action has focused on controlling the external loading of nutrients, mainly phosphorus (P), to improve water quality. However, internal sources of P, accumulated in the sediments, can continue to cause water quality problems and prolong recovery from eutrophication, despite external load reductions (Søndergaard et al., 2003; Schindler, 2006). In stratifying lakes, internal P loading predominantly occurs during the summer stratified period. During summer stratification, high biological oxygen demand in the hypolimnion depletes oxygen and, as oxygen cannot easily be mixed downwards from the surface, results in persistent anoxia (Spears et al., 2007; Foley et al., 2012). Anoxia leads to reducing redox conditions which promote increased fluxes of highly-bioavailable soluble P to the overlying water, a key driver of P accumulation in the hypolimnion (Mortimer, 1942; Nürnberg, 1984).

Lake thermal structure can play a critical role in the development and persistence of anoxia. Longer stratification can prolong the period of anoxia (Foley et al., 2012; Snortheim et al., 2017; Jane et al., 2021) by supressing downwards mixing. Lake thermal structure is primarily controlled by the interaction of surface heat fluxes (short-wave and long-wave radiation and sensible and latent heat fluxes) but throughflows also contribute to the heat budget, quantified by the advective heat flux (Livingstone and Imboden, 1989; Fenocchi et al., 2017). Previous research suggests that, in some lakes, throughflows can be a

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dominant heat loss term, annually (Richards et al., 2012), particularly acting to cool the lake in the summer (Carmack et al., 1979; Colomer et al., 1996; Richards et al., 2012). By increasing inflow discharge, the effect is increased (Smits et al., 2020) and the river exerts a greater cooling flux (Smits et al., 2020).

Increased discharge reduces the lake's water residence time (WRT). WRT is the lake volume divided by discharge (see Equation (6) below) and describes the time lake water spends within a lake basin (Kalff, 2002; Andradóttir et al., 2012). WRT is often discussed relating to its importance for nutrient and sediment loading (Jones and Elliott, 2007), time available for biogeochemical processes to occur (Evans et al., 2017) and flushing of biota from the lake (Havens et al., 2016). However, there has not been extensive research on WRT effects on the advective heat flux and its control of stratification, with what has been done suggesting that shortening WRTs may present a viable method to manage stratification and internal loading. Field observations suggest that large episodic inflow events (e.g. storms) temporarily increase the inflow cooling (Andersen et al., 2020) and, generally, shorter WRT systems have shorter periods of summer stratification (León et al., 2016). Modelling studies have also looked at short vs long WRT scenarios in reservoirs and found that shorter WRTs are associated with weaker and shorter periods of summer stratification (Straškraba and Hocking, 2002; Li et al., 2018; Yang et al., 2020), although these studies did not investigate WRT changes systematically and maintained constant flow rates, unrealistic in natural lakes. As throughflows have been shown to contribute to the lake heat budget, especially at shorter WRTs, and their effect is typically a cooling one in the summer, reducing WRT may be expected to weaken stratification and shorten the stratified period, suggesting a potential mechanism through which to control anoxia and internal loading.

Water residence time manipulation has been used in past restorations as a flushing or dilution method for algal control, to some effect (Welch et al., 1992; Jagtman et al., 1992; Dai et al., 2020) but has not previously been targeted to impede stratification and internal loading. Other in-lake methods have been used to target internal P load reduction (Søndergaard et al., 2007; Lürling and Mucci, 2020), including dredging (Bormans et al., 2016), the addition of chemical binding agents to sediments (Mackay et al., 2014a; Spears et al., 2016), and aeration and withdrawals of the hypolimnion to reduce hypolimnetic anoxia (Bormans et al., 2016; Preece et al., 2019). Artificial mixing, as a means of destratification, using bubblers and axial flow pumps, is also used in some lakes (Cooke et al., 2005; Visser et al., 2016). While these physical and chemical techniques have had some success in controlling internal loading, success has not been consistently long-term (Cooke et al., 2005; Huser et al., 2016), some methods can be ecologically destructive (Gołdyn et al., 2014), and capital and running cost high (Mackay et al., 2014a). Therefore, further novel methods, if practicable and effective, may be valuable in managing internal loading.

WRT manipulation, to control stratification, is likely to be most applicable in small lakes where hydrological control is most achievable (Paerl et al., 2016) and WRT markedly changed. It is also likely that only at short residence times, will the change induced by an increased advective flux be sufficient to overcome surface heat flux effects during peak summer. Small lakes (0.1–1 km^2) are numerically dominant globally, representing 87% of the global total and 26% of lakes have a short residence time (<100 days; Messager et al., 2016). Given this, if the technique is effective, it has the potential to be viable in numerous lakes globally.

Despite the potential for WRT changes to influence stratification, a whole-lake application of the method failed to induce the desired changes (Olsson et al., 2022). In 2016, a restoration effort in a small stratifying UK lake, Elterwater, used WRT manipulation to target stratification in an attempt to limit the length of the anoxic period and control the internal loading of nutrients (Olsson et al., 2022). Annual WRT (AWRT) was reduced by approximately 38% (5 days) through the rerouting of water from a nearby stream into the basin via a diversion pipeline. Results showed that there was little improvement in water quality (assessed by phosphorus or chlorophyll *a* concentrations) and stratification and hypolimnetic anoxia persisted, despite some reductions in summer water temperatures and water column stability (Olsson et al., 2022). The failure to reduce stratification length significantly suggests that the change to WRT was insufficient to induce large changes in the thermal structure (Olsson et al., 2022). The investigation highlighted the need for a more systematic assessment of the interaction of WRTs, lake heat fluxes, and stratification dynamics in short residence time lakes to understand how much impact changing flow could have on stratification.

In this paper, we aim to understand how lake management, targeting physical controls on internal nutrient loading, may better utilise WRT manipulations to modify the advective heat flux and control stratification. We hypothesise that,

a) Increasing throughflow discharge will increase the summer cooling effect of the stream and therefore reduce summer water temperatures and increase mixed depth,
b) Stratification length and strength will be modified by changes to WRT, with shorter WRTs weakening and shortening periods of summer stratification,
c) Management strategies can be optimised to control stratification, and the consequent anoxia and internal loading, by considering the seasonality of discharge and flow impacts on in-lake water temperatures.

We use a systematic modelling approach, maintaining natural flow variability, to look at the effect of modifying AWRT on annual thermal dynamics, with a particular focus on the summer stratified period. A modelling approach allows for the examination of the impacts of incremental changes in flow rates across many scenarios.

2. Methods

2.1. Site description

Elterwater is a small monomictic lake in the northwest of England, UK (Lat: 54.4287°, Long: -3.0350°). The lake has three distinct basins; inner, middle, and outer (Fig. 1). Elterwater's main inflow, Great Langdale Beck, discharges into the middle and outer basins, with the outflow, the River Brathay, also flowing out of the outer basin. Additional smaller inflows discharge into the inner and middle basins. Due to the hydrology of the system, average WRTs vary between the basins, previously estimated to be around 15-20 days in the inner and middle basins to as little as 0.5 days in the outer basin (Beattie et al., 1996; APEM, 2012) with high seasonal variability.

The inner basin (Elterwater-IB; maximum depth = 6.5 m, mean depth = 3.3 m, area = 0.03 km^2, catchment area = 1.0 km^2), the smallest and most enriched of the basins, was historically the location of wastewater effluent discharge (Zinger-Gize et al., 1999) and the target of the unsuccessful WRT management, to control stratification and anoxia. Elterwater-IB is eutrophic and bottom waters become anoxic during the summer stratified period (Olsson et al., 2022). Elterwater-IB is the focus of the modelling study reported here.

2.2. Model description

The General Ocean Turbulence Model (GOTM), a 1-D process-based water column model, was used to model the impacts of changing WRTs on the lake's thermal structure. GOTM uses measured meteorological data, specified bathymetry and inflow data to model vertical mixing dynamics, lake surface heat fluxes, and temperatures in natural waters (Umlauf et al., 2005; Burchard et al., 2006). The model has been applied to several lakes since its development (Kerimoglu et al., 2017; Moras et al., 2019; Darko et al., 2019) and is able to replicate, accurately,

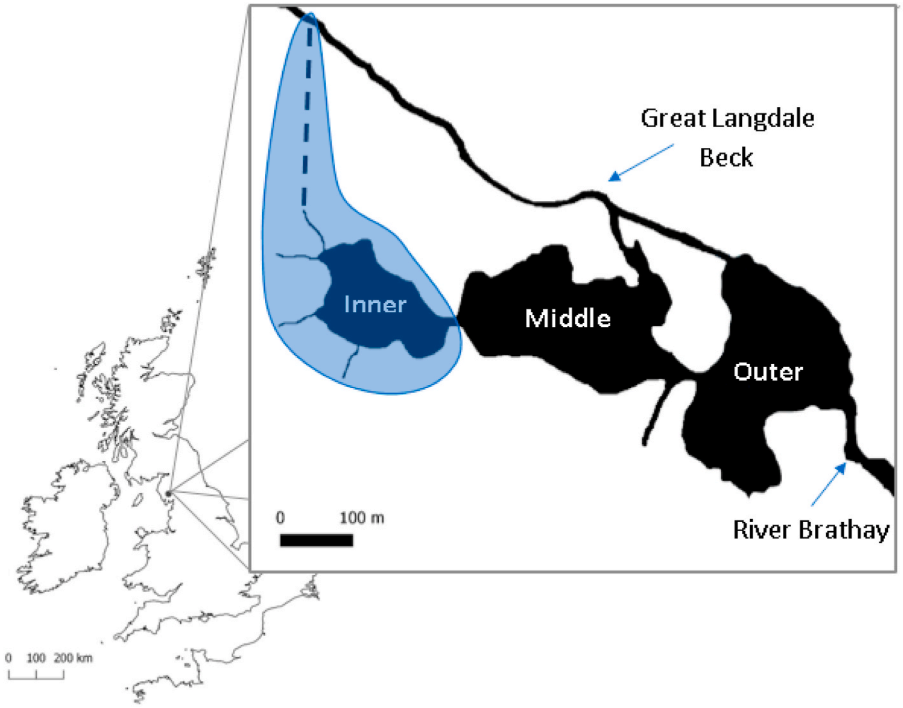

Fig. 1. Map of Elterwater. The main inflow (Great Langdale Beck) and outflow (River Brathay) are shown alongside the restoration diversion (dashed line). Elterwater inner basin, the modelled system, is highlighted.

in-lake thermal conditions. GOTM was run at an hourly timestep with a spatial resolution of 0.12 m (50 layers) over the top 6 m of the water column.

2.3. Input and validation data

Meteorological data (air temperature, wind speed, relative humidity, and short-wave radiation) was obtained from the automatic water quality monitoring buoy at Blelham Tarn (surface area = 0.1 km^2, see https://www.ceh.ac.uk/our-science/monitoring-site/lake-observatories), which is close to the study site (<5 km; Lat: 54.3959°, Long: -2.9780°). Data were collected January 2018–December 2019 at 4-min intervals, 2.5 m above the lake surface (see Table 1) and hourly averaged.

Gap filling of meteorological data was done using linear interpolation for small gaps (<24 h) and relationships with other meteorological stations for larger gaps (Supplementary information1). As meteorological variables can alter significantly with height, the 2.5 m observed data were corrected to the required 2 m for temperature and relative humidity and 10 m for wind speed, using modified equations from Lake Heat Flux Analyzer (Woolway et al., 2015b). Cloud cover was estimated by comparing observed short-wave radiation and the maximum clear-sky radiation on any given day (Supplementary information 2). The average for the previous day was used as an estimate for night-time cloud cover and where observations of short-wave radiation were missing.

Inflow into Elterwater-IB from small ungauged tributaries and ephemeral streams, is estimated as 2% of the lake outflow measured at the River Brathay gauging station (Environment Agency, 2000). Since the WRT managment, additional discharge from the diversion pipeline has increased the flow into the basin. The full Elterwater-IB inflow discharge was the sum of these two inflow measurements. Inflow discharge and water temperature data from the pipeline was obtained from measurements taken by the South Cumbrian Rivers Trust. Outflow temperature was assumed to be equal to the lake surface temperature and discharge equal to inflow, thus maintaining water level.

Lake water temperature was recorded from January 2018 to December 2019 every 4 min using a chain of temperature loggers every metre from 1 to 6 m depth (Table 1), at the deepest point in the inner basin. These data were hourly averaged and used as initial conditions and for model calibration and validation. Secchi disk extinction depth was also recorded monthly from January 2018–December 2019.

Table 1
Data collected at Elterwater and Blelham Tarn for model boundary conditions.

Driving data	Sensor type	Accuracy	Source
Meteorological			Blelham tarn in situ meteorological monitoring buoy (hourly data) see UKLEON website (https://ukleon-data.ceh.ac.uk/)
Wind speed	Vector Instruments A100LK anemometer	1% ± 0.1 ms^{-1}	
Air Temperature	Onset HOBO U23_001 logger	±0.21 °C	
Relative Humidity	Onset HOBO U23_001 logger	±2.5%	
Short-wave Radiation	Kipp & Zonen CMP6 pyranometer	Expected daily uncertainty <5%	
Inflow			
Temperature	Onset HOBO (U20L-01)		South Cumbrian Rivers' Trust
Pipeline discharge	Onset HOBO (U20L-01)		
Ungauged tributaries			Estimated as 2% of the gauged flow on River Brathay. Data obtained from the Environment Agency.
In-lake temperature profiles	RBR Solo T	±0.002 °C	Thermistor chain at deepest point in Elterwater's IB
Hypsograph			See supplementary information 1 (Haworth et al., 2003)

2.4. Model calibration/validation

Model fit was assessed against observations of water column temperature at an hourly timestep. The calibration period was 01/01/2018 to 31/12/2018. The autocalibration tool, ACPy (Storn and Price, 1997; Bolding and Bruggeman, 2017), was used for the model calibration. ACPy uses a differential evolution method to estimate the best parameter set based on a maximum-likelihood measure. Each calibration routine had 2000 model runs, each with different parameter values, trending towards a best fit. GOTM was calibrated using six parameters (Table 2): three non-dimensional scaling factors relating to wind speed, short-wave radiation, and outgoing surface heat flux plus the physical parameters minimum kinetic turbulence and visible and non-visible light attenuation. The non-visible light extinction was estimated as 0.45, based on the median from Woolway et al. (2015a,b). The range of visible light extinction (g_2) used in the calibration was calculated as the maximum and minimum of,

$$g_2 = \frac{1}{k} \tag{1}$$

where k, the light extinction coefficient, is derived from measurements of Secchi disk extinction depths (Z_{SD}) taken in 2018 and 2019, calculated according to Kalff (2002):

$$k = \frac{1.7}{Z_{SD}} \tag{2}$$

The calibration minimised the difference between modelled and measured water temperatures and was assessed based on three metrics: root mean square error (RMSE), Nash-Sutcliffe efficiency (NSE) and mean absolute error (MAE), calculated as,

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(mod - obs)^2}{n}} \tag{3}$$

$$NSE = 1 - \frac{\sum (obs - mod)^2}{\sum (obs - \overline{obs})^2} \tag{4}$$

$$MAE = \frac{\sum |mod - obs|}{n} \tag{5}$$

where *mod* and *obs* are the modelled and observed water temperatures. Parameters were calibrated to produce modelled output that minimised RMSE and MAE and gave NSE values closest to 1. The calibration was run three times and the optimum set of parameters (Table 2) gave a model fit with an RMSE of 0.90 °C, a NSE of 0.94 and a MAE of 0.71 °C and show a good visual fit between observed and modelled temperatures (Fig. 2).

Table 2
Parameters optimised during the calibration route. The maximum, minimum and final parameter values are shown. Parameters calibrated were the non-dimensional scaling factors for short-wave radiation (swr), surface heat flux (shf), and wind speed (wsf), minimum kinetic turbulence (k-min) and visible light extinction e-folding depth (g2). Using the parameters estimated in the calibration (Table 2), a validation run was completed using 2019 driving data and observations. The model fit for the validation period resulted in a good fit (RMSE = 0.98 °C, NSE = 0.92, MAE = 0.74 °C).

Calibration factor	Min allowable value	Max allowable value	Final parameter value
swr	0.85	1.1	0.954
shf	0.8	1.2	0.800
wsf	0.9	1.1	1.082
k-min	1.4 e^{-4}	1.0 e^{-5}	1.4 e^{-7}
g2	0.5	2	0.611

2.5. Model experiments

Using this calibrated and validated model, scenarios were run with modified annual WRT (AWRT). AWRT was calculated as,

$$AWRT = \frac{lake\ volume}{mean\ annual\ discharge} \tag{6}$$

AWRTs were modified by multiplying the inflow discharge by values from 0.1 to 10 in steps of 0.1, giving 100 scenarios with AWRTs for Elterwater-IB ranging from <1 day to 88.6 days. Additionally, the instantaneous WRT was calculated for each hourly time step, using the hourly measured discharge.

2.6. WRT impacts

2.6.1. Heat fluxes

GOTM calculates the following lake surface heat fluxes at each timestep: net surface short-wave radiation (Q_{sin}), the net long-wave (Q_{lnet}), sensible heat flux (Q_h) and latent heat flux (Q_e). These heat fluxes were summed to give the total lake surface heat flux (Q_{surf_tot}).

Modifying WRTs changes the heat exchange by throughflows, termed the advective heat flux, Q_{adv} (W m^{-2}), diagnosed following Livingstone and Imboden (1989) as,

$$Q_{adv} = \frac{F_{inflow} \times C_{pw} \times \rho_w \times (T_{stream} - T_{lake})}{A_0} \tag{7}$$

where F_{inflow} is the inflow discharge (m^3 s^{-1}) and (T_{stream} – T_{lake}) is the temperature difference between the inflow and the lake outflow (°C), where the outflow temperature is assumed to be equal to the lake surface temperature. A_0 is the lake's surface area (m^2) and C_{pw} and ρ_w are the specific heat capacity and density of water, given as the constants 4200 J kg^{-1} °C and 1000 kg m^{-3}, respectively. For each AWRT scenario, Q_{adv} and Q_{surf_tot} were calculated at each time step.

A Generalized Additive Model (GAM) curve was fitted through a three-day moving average of each of the heat fluxes, using the mgcv R package (Wood, 2011). The GAM used a REML method with a smoothing parameter for date.

Additionally, Q_{adv} was evaluated based on absolute direction (heating or cooling) and its direction relative to Q_{surf_tot} (additive or counter), giving four possible effects: counter cooling, counter heating, additive cooling, and additive heating.

2.6.2. Stratification metrics

A minimum density difference of 0.1 kg m^{-3} between the top and bottom of the water column was used to define when stratification occurred, with density calculated using the R package rLakeAnalyzer (Read et al., 2011). Occurrence of stratification can vary depending on the density difference threshold used (Gray et al., 2020) so the calculation was repeated with other thresholds, but there was no difference in the patterns observed in the data (see Supplementary information 3). Using the 0.1 kg m^{-3} difference, the following stratification metrics were calculated:

1. total frequency of "normal" stratification (number of hourly time steps for which surface temperature exceeds bottom temperature and the density difference threshold is exceeded),
2. frequency of inverse stratification (number of time steps for which bottom temperature exceeds surface temperature and the density difference threshold is exceeded),
3. length of the longest continuously stratified period (the length of the longest continuous period for which the density difference threshold is exceeded)
4. start and end dates of the longest stratified periods (the date bounds for the longest continuously stratified period, as defined above)

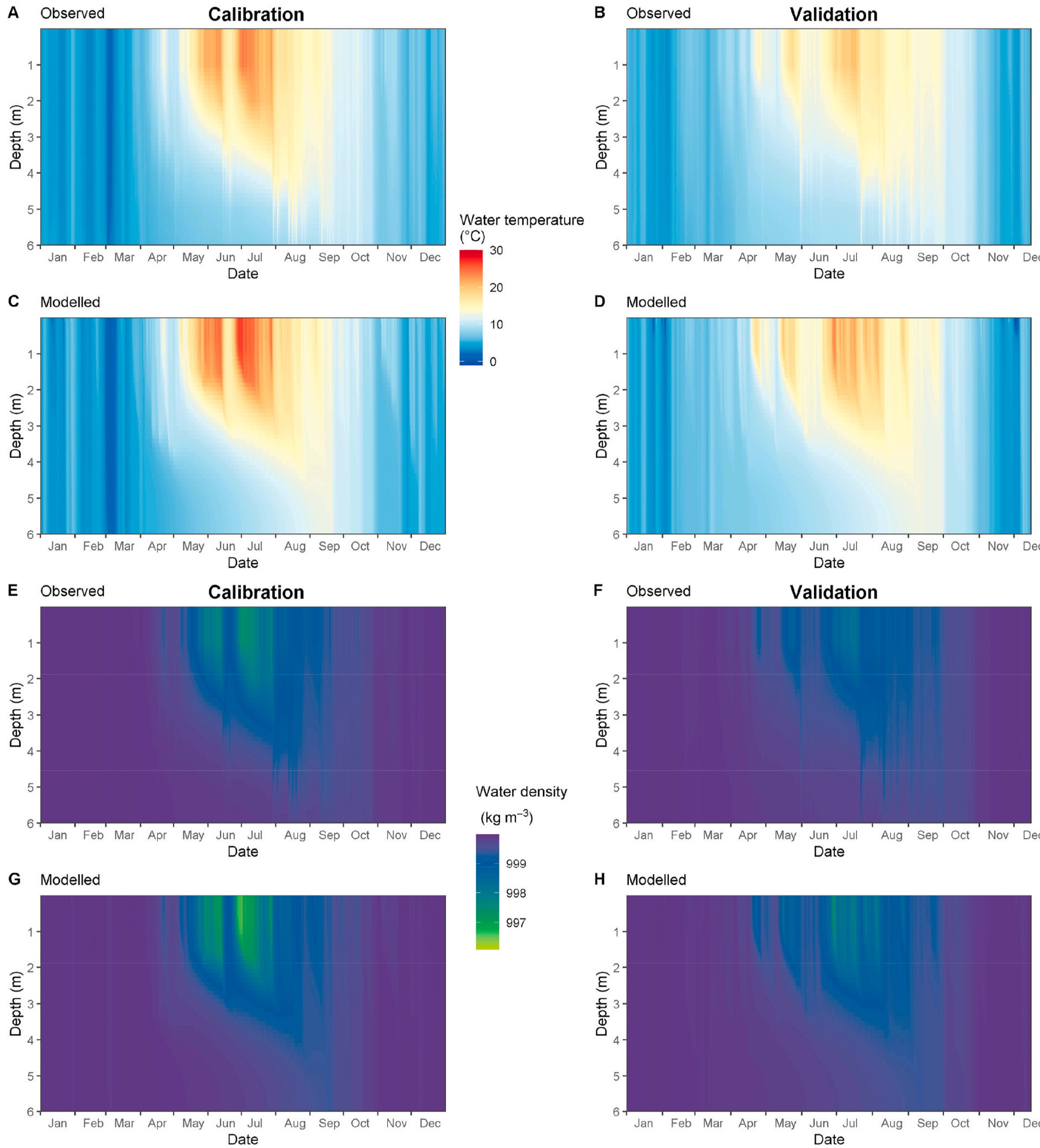

Fig. 2. Model fit between observed and modelled water temperatures (panels a–d) and water density (panels e–h) for the calibration period (2018) and validation period (2019).

Water column stability, quantified using Schmidt stability (Idso, 1973), S_T, was calculated using the LakeAnalyzer R package (Read et al., 2011). Mixed depth was calculated using a modified version of the LakeAnalyzer meta.depths function, using a density difference threshold (0.1 kg m^{-3}) between the top and bottom water layers and a gradient threshold of 0.1 kg m^{-3} m^{-1}. All metrics were compared across AWRTs scenarios on a monthly and seasonal scale to assess seasonally different responses. Seasons were defined as: spring = March, April, and May; summer = June, July, and August; autumn = September, October, and November; winter = December, January, and February.

3. Results

3.1. Changes to the advective heat flux

The inflow-lake temperature difference and the inflow discharge controlled the magnitude and direction of Q_{adv} and are both highly seasonal. Discharge was considerably larger in the winter than the summer (Table 3 and Fig. 3a). In the summer, the unmodified discharge into the inner basin was estimated to be as little 0.002 m^3 s^{-1} compared to an estimated maximum flow of 2.17 m^3 s^{-1} during a storm event. This was reflected in the instantaneous water residence times which varied from >500 days to <1 day (Fig. 3a). WRTs are longer in summer than annual WRTs, with the summer average of 15 days (Table 3). Similarly, the difference between inflow and lake temperature varied with season

Table 3
Seasonal mean discharge, residence time and inflow-lake surface water temperature (LSWT) differences in Elterwater inner basin under unchanged conditions. Values in brackets show the median values of inflow related parameters.

Season	Average inflow discharge (median), $m^3 s^{-1}$	WRT (median), days	Temperature difference (inflow-LSWT), °C	Q_{adv} (median), W m^{-2}	Q_{surf_tot} W m^{-2}
Winter	0.21 (0.21)	6 (5)	1.3	43.6 (36.1)	−47.4
Spring	0.09 (0.08)	13 (15)	−1.3	0.172 (−4.0)	14.9
Summer	0.07 (0.01)	15 (83)	−6.2	−33.5 (−13.1)	14.1
Autumn	0.16 (0.06)	7 (19)	−0.3	3.19 (−0.2)	−18

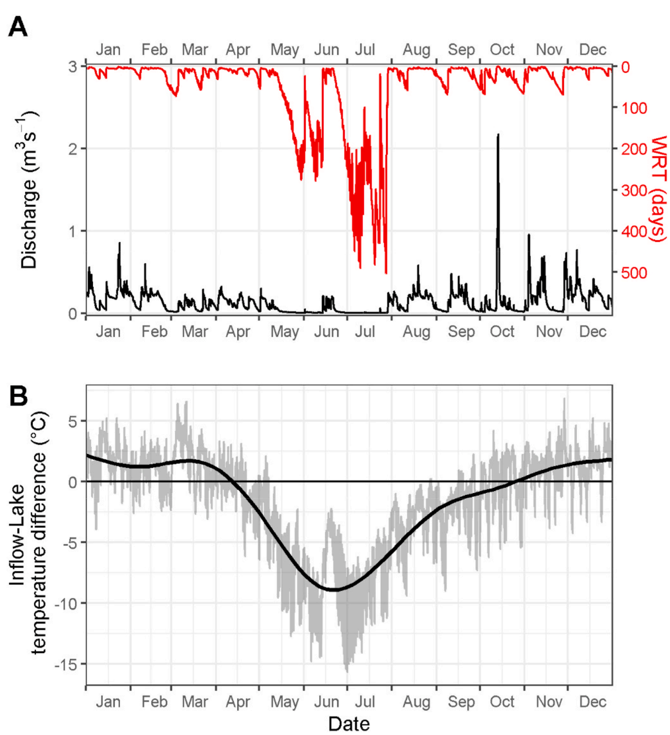

Fig. 3. Controls on the advective heat flux during the baseline scenario (2018) a) discharge and WRT and b) inflow-lake temperature difference.

(Fig. 3b). In the winter, the inflow water was slightly warmer than the lake temperature, whereas in the summer the inflow was substantially cooler than the lake water. Due to the seasonality of inflow-lake temperature differences and inflow discharge, Q_{adv} also showed a distinct seasonal cycle (Fig. 4), a positive, warming flux in the winter and a negative, cooling flux in the summer (Table 3).

Changing AWRT modified Q_{adv} dynamics, primarily affecting the magnitude of Q_{adv}, rather than the direction (Fig. 4a), as the discharge is multiplicative in the advective heat flux calculation (Equation (7)). The magnitude of Q_{adv} was smaller at longer AWRTs and larger at shorter AWRTs (Fig. 4a). At shorter AWRTs, there were greater increases in Q_{adv} in winter than summer, as the discharge is already large. The general pattern for Elterwater-IB is that winter has a small temperature difference and a large discharge and summer a large temperature difference but a small discharge.

3.2. Contribution of the inflow heat flux to the overall heat budget

Q_{adv} and Q_{surf_tot} showed differing seasonal dynamics (Fig. 4b). Therefore, at different times of the year the contribution of Q_{adv} to the overall heat budget of the lake differed. The seasonal patterns for the two heat fluxes generally showed an opposite pattern (Fig. 4b). On average, Q_{surf_tot} acted to cool the lake in the winter and warm the lake in the summer, in contrast to the Q_{adv} dynamics. Q_{surf_tot} and Q_{adv} switched between warming or cooling around the same time, during the early spring and autumn (Fig. 4b). During this transition from warming to cooling and vice versa, both the advective and lake surface heat fluxes both became small.

3.3. Changes to temperature dynamics

AWRT-driven changes to Qadv modified temperature dynamics and the thermal structure within the lake. An average water column temperature, accounting for layer volume, was calculated along with surface water temperature. Both volume-average and surface temperatures changed with AWRT, but the direction of the change was seasonal (Fig. 5 and Supplementary information 4). In the summer, shorting AWRTs caused decreases in water temperatures. However, in the winter, shorter AWRTs slightly increase water temperatures. Conversely, longer AWRTs caused warming in the summer and cooling in the winter. The largest temperature changes were seen in the summer, when AWRT is $<$ 1 day, resulting in a $>$2 °C decrease in surface temperature in June and August (Supplementary information 5). The largest increase is only around 1 °C, in January, at shorter AWRTs. The effect diminishes with lengthening residence time, especially in the summer (Fig. 5).

3.4. Changes to stratification

AWRT was positively related to the length of the summer stratified period. Shortening AWRTs caused a decrease in the length of summer stratification, with longer continuously stratified periods at longer AWRTs (Fig. 6a). The shortening of summer stratification at shorter AWRTs was driven by later spring onset (up to 16 days later) and an earlier autumn overturn (up to 19 days earlier) (Fig. 6b). However, the main change was in the timing of overturn, except at the two shortest AWRTs. There was no change in stratification onset when AWRT was increased above unchanged values.

The changes in AWRT also modified the strength of the stratification. June and July remain stratified in all AWRT scenarios, so we used these months to look at changes to stratification strength that are not affected by changes to stratification length. Lengthening the AWRT resulted in increased water column stability during June and July, by around 8% (Fig. 6c). Conversely, when the AWRT was shortened, there was up to a 20% decrease in water column stability (Fig. 6c). Despite the decrease in stability at shorter AWRTs, there was no AWRT scenario that completely inhibited stratification forming during the summer months, with June and July being consistently stratified across all AWRTs. The mixed depth in June and July was unchanged by variations in discharge (Supplementary information 6), remaining around 1.5 m for all scenarios.

Changes to the AWRT also have an effect outside the summer stratified period. At longer AWRTs, there was an increase in the frequency of winter inverse stratification, with no inverse stratification occurring below an AWRT of 14 days (Fig. 7a). Overall, at shorter AWRTs, there was an increase in the frequency of normal stratification throughout the year (Fig. 7b), despite a decrease in longest period of continuous stratification (Fig. 6a). This is driven by increases in transient stratification throughout the autumn and winter that exceeded the reduction in stratified days in the summer.

4. Discussion

The aim of this study was to establish how manipulations of WRTs

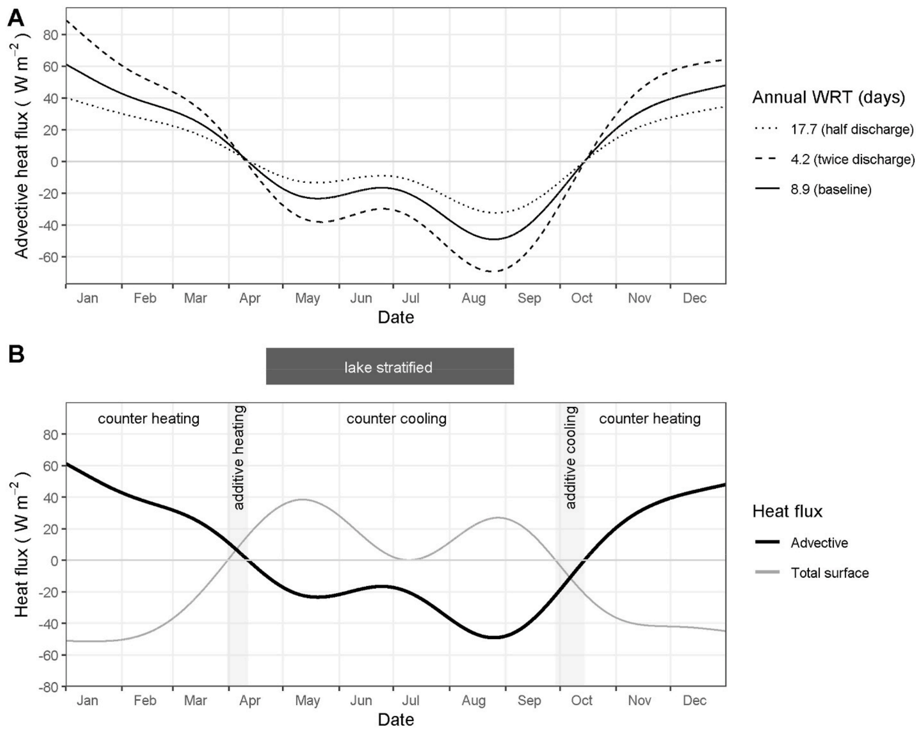

Fig. 4. a) General Additive Model fit to three-day average values comparing the advective heat flux (Q_{adv}) for 2018 at different annual water residence times and b) a General Additive Model fit to three-day average values of the baseline advective flux (Q_{adv}) and the total lake surface heat flux (Q_{surf_tot}), including labels of the impact of the advective flux on the total lake surface heat flux. The duration of the longest continuous stratified period under unmodified conditions is also shown.

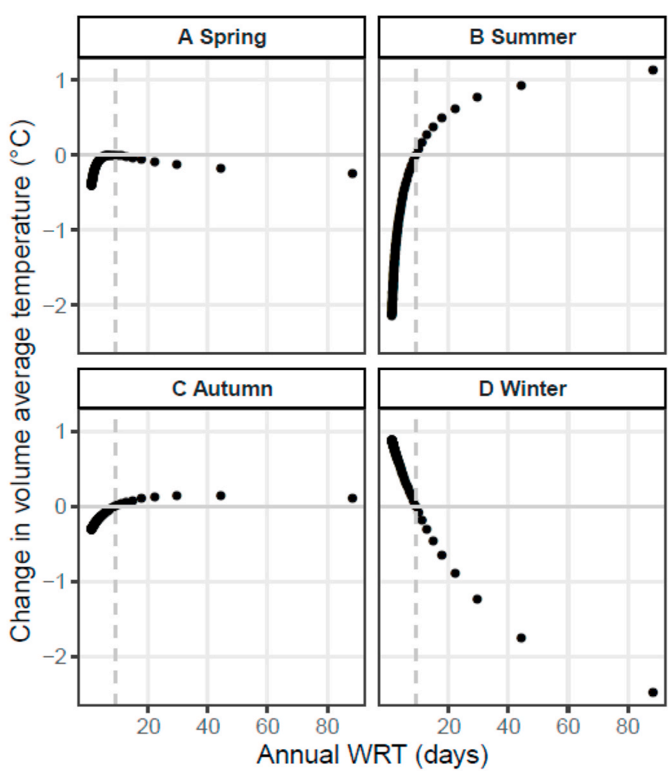

Fig. 5. Change in volume averaged lake temperature across different seasons. Dotted lines represent unchanged AWRT.

affect the summer stratified period, with a view to controlling internal nutrient loading, which can be problematic for lake recovery. Understanding the effects of WRT changes on thermal dynamics will inform how management may be able to utilise manipulations of WRT to reduce internal loading. We also wanted to understand WRT effects on the year-round thermal dynamics of a lake.

Our results show that the heat flux exerted by the throughflow affects the lake water temperature and has a different effect depending on the season, a warming flux in the winter and cooling flux in the summer. Furthermore, the AWRT determined the magnitude of Q_{adv}, either warming or cooling, magnifying the natural seasonality at shorter WRTs (Andersen et al., 2020; Smits et al., 2020). This supports hypothesis 1 that increasing discharge increases the summer cooling effect, reducing in-lake summer temperatures as well as the modelled impact of the water residence time manipulation carried out at Elterwater (Olsson et al., 2022). Other studies have also shown the seasonality of advective heat fluxes (Carmack, 1979; Fink et al., 2014), generally finding an overall cooling effect of throughflows with the exception of warming in the early spring (Carmack et al., 1979; Carmack, 1979; Fenocchi et al., 2018). Seasonal- and climatological-specific relationships between lake and inflow temperature are important to determine the seasonality of Q_{adv} (Laval et al., 2012; Fenocchi et al., 2018). For example in higher altitude/latitude settings, a much larger cooling flux is likely in the early spring from snowmelt entering the lake (Flaim et al., 2019; Smits et al., 2020), compared to this temperate system. As well as the direction of Q_{adv}, the magnitude was also seasonal, generally being larger in the winter than the summer. Coupled with reduced surface fluxes in winter, Q_{adv} has a larger effect on the overall heat budget in winter than during the summer when surface heating is large and Q_{adv} smaller, due to lower inflow discharge (Table 3).

At shorter AWRTs, increased advective cooling shortened and weakened the period of continuous summer stratification, results supporting previous modelling (Straškraba and Hocking, 2002; Li et al., 2018) and the second hypothesis outlined. Our results show the changes to AWRT had the most effect on the overturn of stratification. Overturn was earlier with shorter AWRTs, with changes to stratification onset only occurring at the shortest AWRTs. Earlier overturn has been identified previously when WRT is shorter (Wang et al., 2012; Huang et al.,

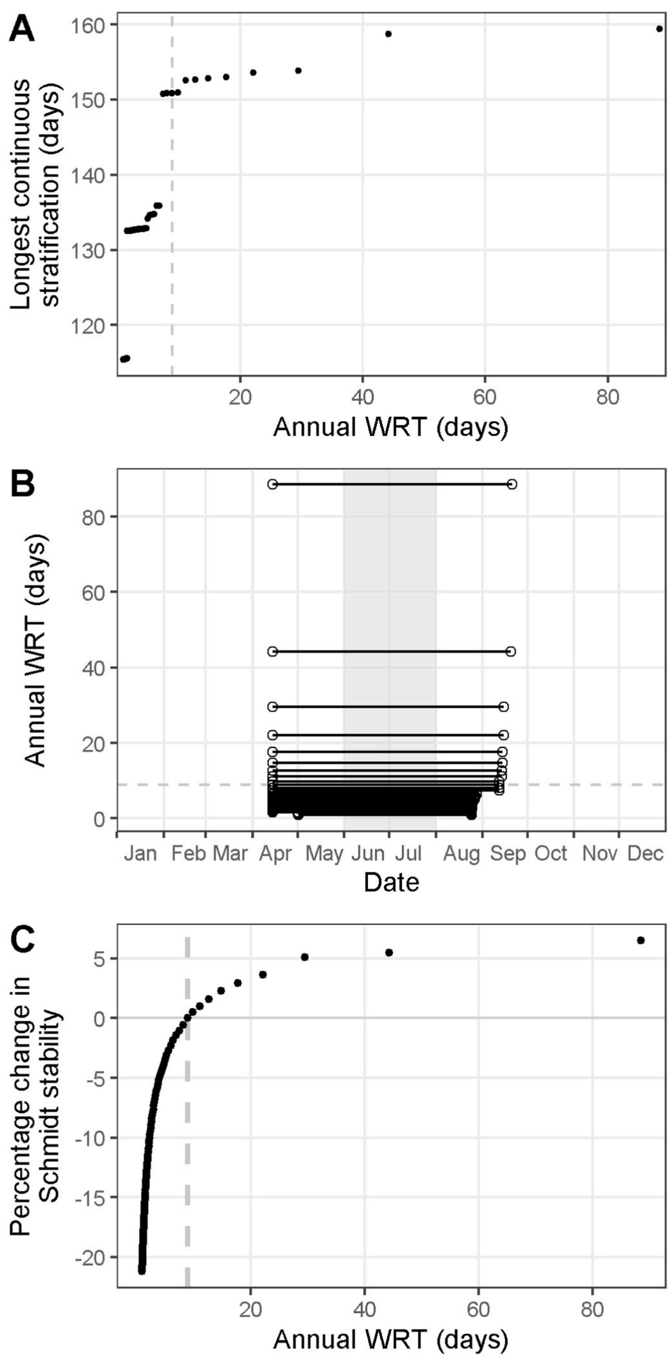

Fig. 6. a) Change to the length of the longest continuous stratified period. b) Dates of onset and overturn at different AWRT. The solid black lines indicate the period of continuous stratification. The grey shading covers June and July, which are stratified under all AWRTs tested. c) Percentage change to stratification strength (as Schmidt stability) during June and July. Dotted lines represent unchanged AWRT.

2014; Li et al., 2018) and supports previous work also suggesting that changes to stratification length are more pronounced by expediting overturn than preventing onset (Li et al., 2018). Controlling WRT at the end of the stratified period, when the inflow is cooling faster than the lake (Laval et al., 2012), increases the effect of advective cooling on weakening stratification, resulting in the potential for an earlier overturn and shorter stratified period. Although shortening stratification, which is the aim of the management, there is a risk that earlier overturn may bring internally loaded nutrients into the photic zone (Radbourne et al., 2019) in larger quantities and earlier in the growing season (Kalff, 2002), promoting algal growth. This may be detrimental for water quality in the short term but, if the biomass is flushed out quickly, could improve water quality in the longer term by increasing nutrient export from the system (Radbourne et al., 2019).

However, no scenario of shorter AWRT completely inhibited stratification and mixed depth remained unchanged. Mixed depth did not show deepening as expected, remaining at 1.5 m for all scenarios, and perhaps demonstrates the importance of atmospheric forcing (wind speed and solar radiation) in determining mixed depth (Straškraba and Hocking, 2002). Consequently, deepening of the mixed depth is more likely to occur during storms where increased flow is coupled with higher wind speeds and reductions in solar radiation (Woolway et al., 2018; Andersen et al., 2020).

Shortening AWRT to weaken stratification, although not inhibiting, may still be useful for management as it makes the lake more likely to undergo a mixing event from a storm, for example, replenishing deep water oxygen levels that become depleted during stratification (Huang et al., 2014). A storm is more likely to cause complete mixing if a lake is less strongly stratified before the event (Stockwell et al., 2020). Oxygen depletion has also been found to be lower under weaker stratification (Foley et al., 2012), maintaining oxic conditions longer despite continued stratification, which would reduce the potential for the accumulation of nutrients in the hypolimnion.

As well as the summer effects, our results have shown that, the seasonality of responses to changes in AWRT will cause year-round effects in lake systems. Shortening AWRTs acts to increase warming in the winter, promoting transient periods of stratification and warmer water temperatures. There has been little previous research on AWRT changes effecting winter water temperatures, although there is evidence for inflow warming of lakes during the winter months (Colomer et al., 1996). Increased warming may be detrimental to water quality during the winter, encouraging winter algal growth (Weyhenmeyer, 2001). Winter lake warming may also advance onset of stratification and spring blooms the following year (Rodgers, 1987; Yang et al., 2016) and modify the phytoplankton assemblage of spring bloom (Yang et al., 2016).

4.1. Future management

Modifying WRT on an annual scale did not change the summer WRT sufficiently to overcome summer stratification. By considering the year-round effects and the seasonality of both the direction and magnitude of Q_{adv} and Q_{surf_tot}, and water column stability a more appropriate management strategy is considered. Specifically, targeting the period around overturn in Elterwater is more conducive to manipulation as a means of shortening the stratified period and implementing different management approaches at other times of year.

The inflow-lake temperature difference controls when Q_{adv} switches from winter warming to summer cooling in the spring. The timing of this switch from a heating flux in the winter to a cooling flux in the summer, relative to the lake surface heat fluxes and water column stability, will determine when WRT interventions might be most useful (hypothesis 3). Based on the smoothed dynamics of the advective and surface heat fluxes and water column stability, we have identified four periods within the annual cycle for which different management strategies will be appropriate, in the context of this temperate system (Fig. 8):

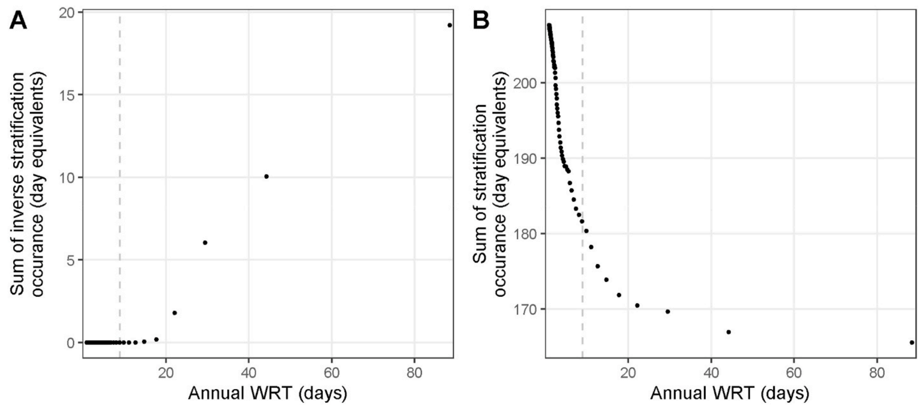

Fig. 7. A) Occurrence of inverse stratification, converted into days, at each AWRT; B) total occurrence of normal stratification, converted to days. Dashed lines indicate the unmodified AWRT.

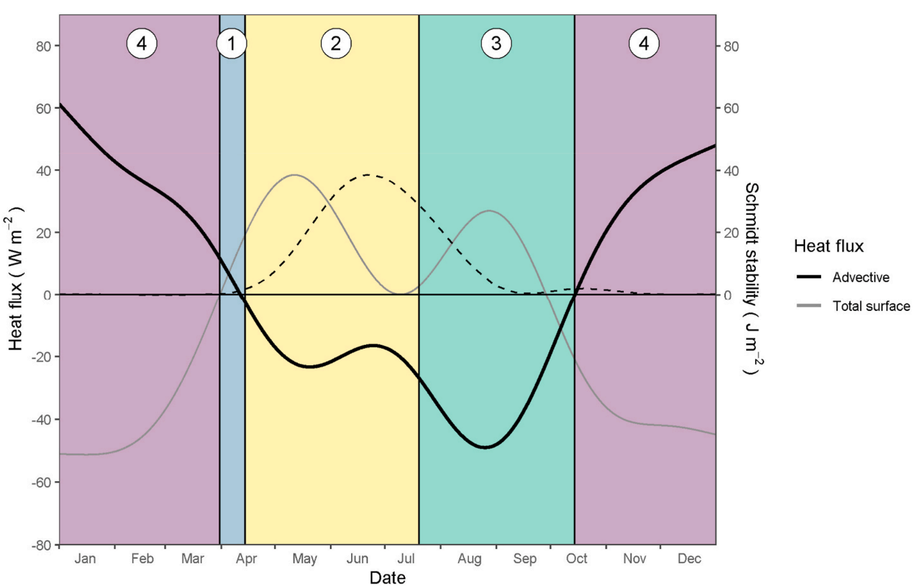

Fig. 8. Conceptualization of the timings of different management strategies proposed for Elterwater. Labelled numbers relate to the periods discussed in the text. Dashed line shows a smooth of the Schmidt stability under unmodified conditions.
1. Prior to stratification (both the stream and lake surface fluxes are warming): no change in WRT recommended; 2. Peak summer (stratification is at its strongest): decreases in WRT will only weaken stratification; 3. Run-up to overturn (Q_{surf_tot} is positive but small, Q_{adv} cooling): changes in WRT will expedite overturn; 4. Post-overturn and winter (Q_{adv} is warming): no artificial increases in discharge, prevent increased warming.

1. Spring and early summer, prior to stratification

Both the advective and lake surface fluxes are warming. Therefore, decreases in WRT at this time of year would have the effect of bringing forward stratification onset, rather than delaying it.

2. Peak summer

Stratification is at its strongest. At these times, temperature differences between the lake and inflow are such that the throughflows act to cool the lake. However, at these times discharge is low, so shortening WRT will only be able to weaken stratification.

3. Run-up to overturn

The inflow-lake temperature differences and inflow discharge are sufficient that changes in WRT will be able to expedite overturn. Q_{surf_tot} is positive but small, and stability decreasing, therefore increased Q_{adv} cooling, at shorter WRTs, promotes overturn of stratification.

4. Post overturn and winter

Q_{adv} is a warming flux and no artificial decreases in WRT are recommended to prevent increased warming and transient stratification impacts.

This finer-scale approach to management of seasonal WRTs may be more appropriate than a coarser scale change to AWRT.

5. Conclusions

Our results demonstrate the seasonality of responses to changes in AWRT. In this study, the advective heat flux induced lake warming in the winter and cooling in the summer and was reflected in the response to changes in WRT. Importantly, no AWRT scenario inhibited stratification completely, suggesting that finer scale management may be needed if WRT manipulations are to be used to control internal loading via stratification inhibition. By using understanding of warming and cooling effects of throughflows, and their contribution to a lake's heat budget throughout the year, managers can target periods when WRT manipulation will be most effective in specific systems. Modelling, as we have done here, is useful pre-intervention to understand the effects of management strategies before costly engineering work is carried out and should consider lake-specific heat flux and stability dynamics.

Credit author statement

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Conceptualization, Review & Editing Sian Davies: Conceptualization, Resources, Data Curation, Review & Editing, Supervision Ruth Hall: Conceptualization, Resources, Supervision Bryan Spears: Conceptualization, Methodology, Review & Editing, Supervision Jayne Wilkinson: Resources, Data Curation, Review & Editing Ian D. Jones: Conceptualization, Methodology, Writing, Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115082.

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