Modeling Seasonal Thermal Stratification and Mixing Variability in a Subtropical Reservoir

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Abstract

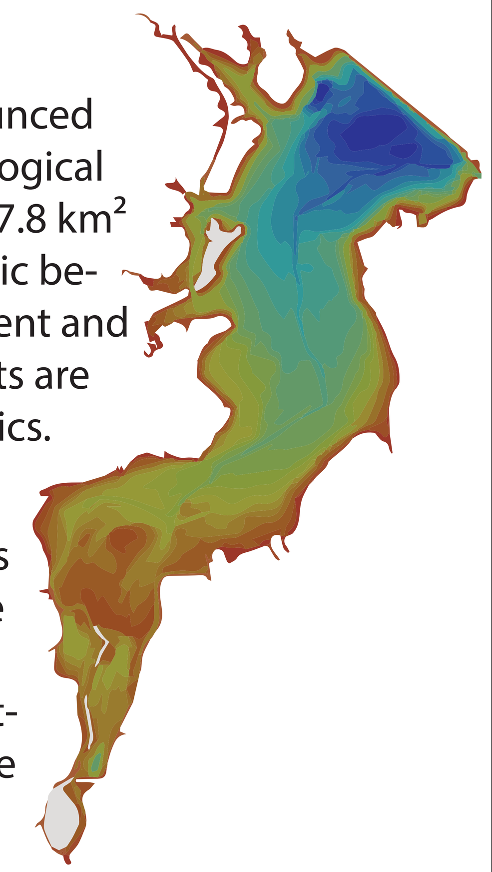
This study assesses how climate variability affects thermal stratification and mixing in Lake Arlington, a subtropical reservoir in North Central Texas. Using in-situ temperature profiles and a 1D heat diffusion model, we examine the impact of seasonal and episodic meteorological events on lake hydrodynamics since September 2023. Weekly measurements enable observation of crucial stratification and mixing transitions, key to understanding the lake's stability and ecological health.

Preliminary findings show that atmospheric changes, notably early fall surface heating, significantly shift stratification depths, creating distinct thermocline and oxycline patterns. As solar radiation decreases, progressive mixing affects dissolved oxygen levels and nutrient distribution, impacting water quality and aquatic life. Future work will integrate data assimilation techniques to refine model predictions, enhancing reservoir management in response to climate change.

Study Site

Lake Arlington, set in a subtropical climate with pronounced seasonal variations, is a eutrophic reservoir critical for ecological stability, recreation, and resource management. Covering 7.8 km^2 and reaching a depth of 15.6 meters, it displays monomictic behavior, undergoing annual mixing that ensures even nutrient and oxygen distribution. Weekly samplings at its deepest points are crucial for monitoring its thermal and hydrological dynamics.

We hypothesize that regional climate variability will alter thermal stratification and mixing in Lake Arlington, as indicated by seasonal temperature changes. We anticipate that rising air temperatures and varying precipitation patterns will delay and shorten thermal mixing periods, affecting dissolved oxygen levels and nutrient distribution in the lake.

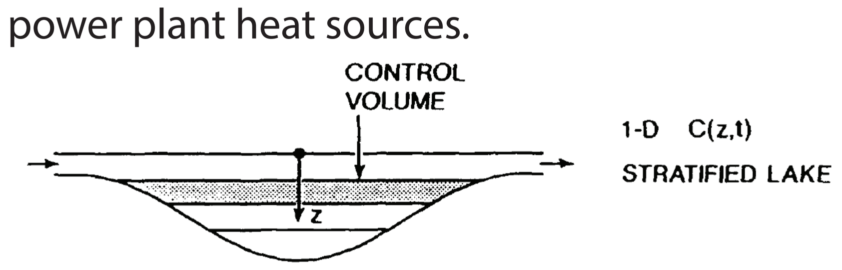


Methods: Lake and Meteorological Data

- Frequency and Location: Conduct weekly sampling at the deepest point of Lake Arlington to capture comprehensive temperature profiles essential for accurate modeling.
- Instrumentation and Data Collection:
  - Lake Data: temperature (T), conductivity (C), and dissolved oxygen (DO) measurements carried out with YSI ProSolo at 1 m intervals (accuracy for T ± 0.2; C ± 0.001 mS/cm; DO ± 0.1 mg/L)
  - Meteorological Data: Kestrell 5500 wind meter (accuracy for SAT ± 0.5 K, dew point ± 0.5 K, humidity ± 0.2 %, and wind speed ± 0.3 m s^{-1})
  - Meteorological and hydrological record using USGS (lake level)and NWS COOP (SAT, precipitation, solar radiation).

Methods: Model Description

Adapting Stefan's 1-D water quality model, we aim to capture Lake Arlington's thermal dynamics, evolving from basic heat diffusion to depth-variable eddy diffusivity and incorporating solar and power plant heat sources.



Basic Heat Diffusion Equation

$$\frac{\partial T}{\partial t} = K\frac{\partial^2 T}{\partial z^2} \quad (1)$$

T= temperature (°C), t = time (s), z = depth (m), K = constant eddy diffusion coefficient

Depth-dependent Eddy Diffusivity in Lakes

$$A(z)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K(z)A(z)\frac{\partial T}{\partial z}\right) \quad (2)$$

A(z) = area at depth z,
K(z) = depth-dependent eddy diffusion coefficient,
$\frac{\partial}{\partial z}\left(K(z)A(z)\frac{\partial T}{\partial z}\right)$ = heat flux changes with depth

Incorporating External Heat Source

$$A(z)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K_Z(z)A(z)\frac{\partial T}{\partial z}\right) + \frac{H}{\rho c} \quad (3)$$

H = internal heat source due to solar radiation (W/m^3)
ρ = density of water (kg/m^3)
c = specific heat capacity of water (J/kg·K)

Heating Source by Power Plant

$$A(z)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(K_Z(z)A(z)\frac{\partial T}{\partial z}\right) + \frac{H}{\rho c} + Q_{pp} \quad (4)$$

Q_{PP} = thermal input from a power plant
$Q_{pp} = \frac{\Delta T}{k}$
ΔT: Observed temperature change (°C)
k: Time constant for the process

Results: Temperature Dynamics and Model Comparison

- Observed temperature profiles illustrate seasonal thermal stratification in summer and mixing from fall to spring.

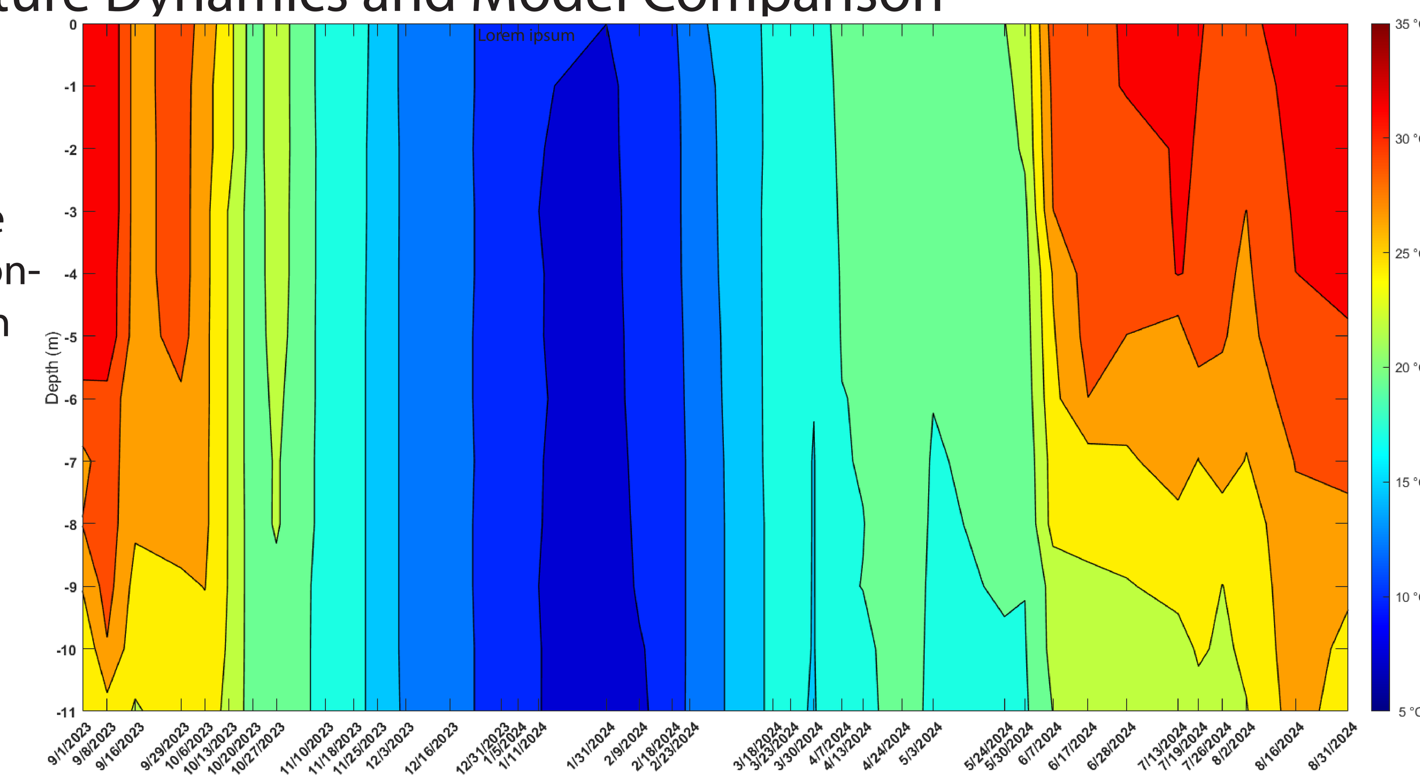


Figure 1. Hovmöller diagram of observed temperature profiles in Lake Arlington

- Simulated profiles from a 1-D heat diffusion model tuned with wind-dependent mixing reproduce broad seasonal patterns but under represent short-term variability.

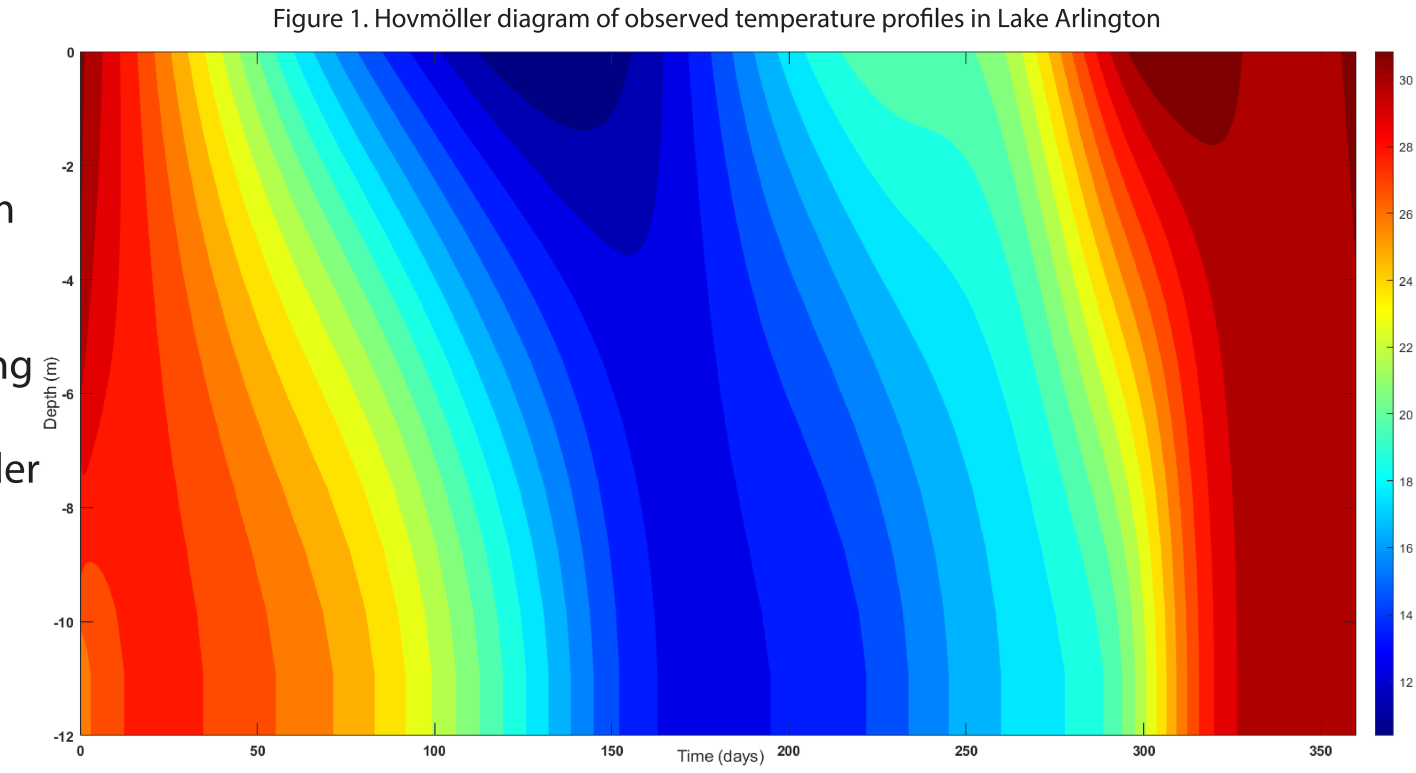


Figure 2. Simulated temperature distribution from 1-D heat diffusion model with wind-driven eddy diffusivity

Results: Thermal Stability

- Schmidt Stability (S) quantifies the energy (J/m^2) required to fully mix the water column to uniform density (Schmidt, 1928):

$$S = \int_{-d}^{0} (z - \bar{z}_\rho)\, r(z)\, [\rho(z) - \bar{\rho}]\, dz \quad (5)$$

z = depth, z_ρ = center of volume, $\rho(z)$ = density at depth z, $\bar{\rho}$ = mean water column density

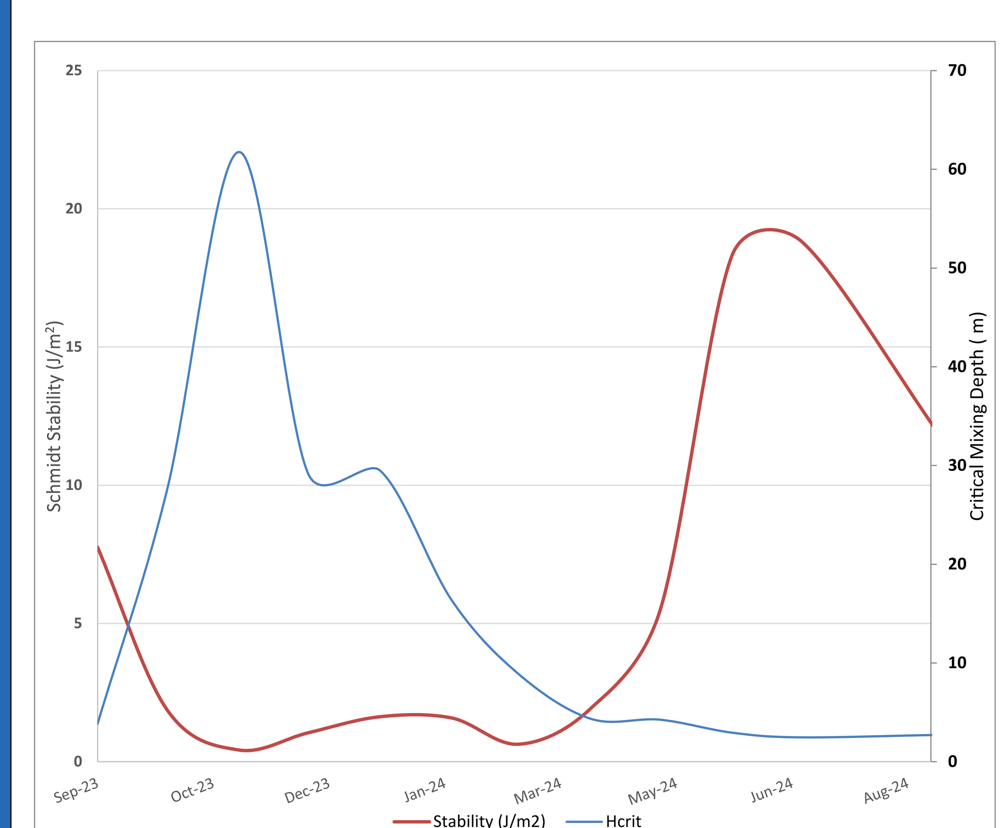


Figure 4: Seasonal Variation in Schmidt Stability and H_{crit}

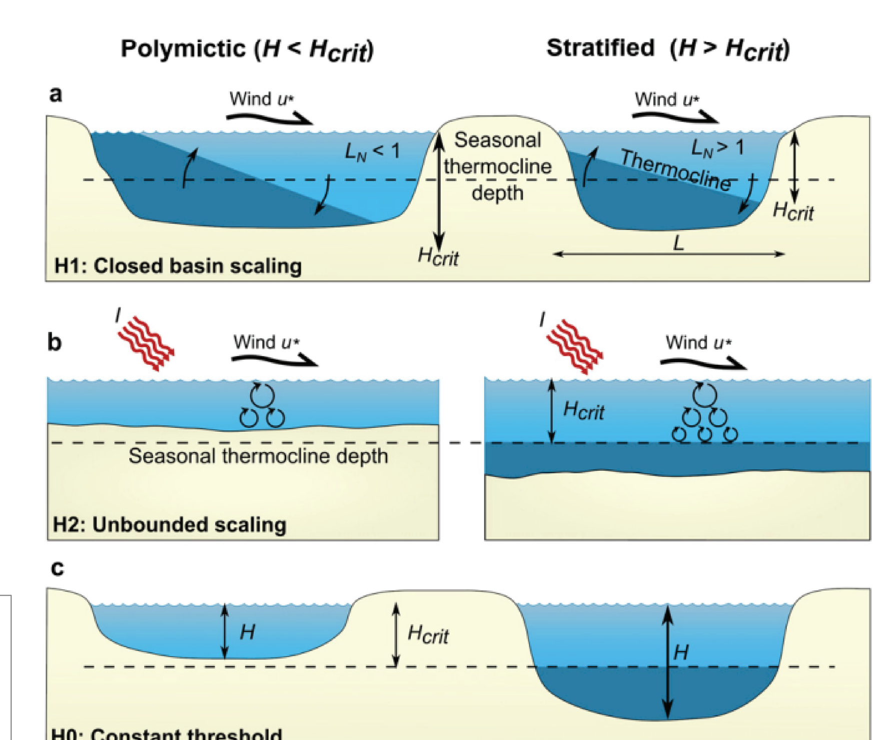


Figure 5: Conceptual Models of Lake Mixing Regimes Based on H_{crit} and Wind Forcing (Krillin and Shotwell 2016)

- Low stability and high H_{crit} (Nov–Feb) indicate full mixing, while summer stratification (Jun–Jul) features shallow H_{crit} and strong resistance to wind-driven mixing.

Results: Dissolved Oxygen Dynamics

- Seasonal hypoxia develops in deeper layers during summer stratification (Jun–Aug), when mixing is limited.

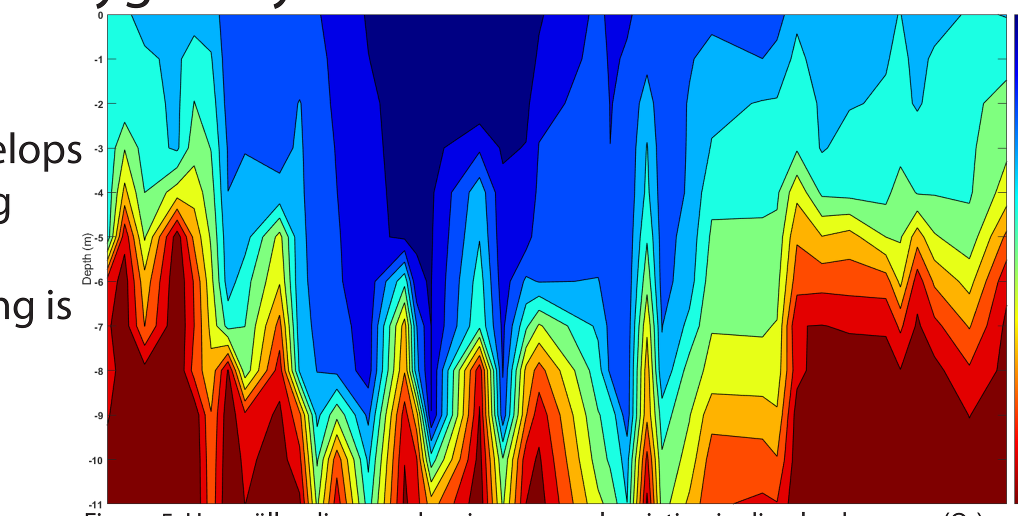


Figure 5. Hovmöller diagram showing seasonal variation in dissolved oxygen (O_2) concentrations

- AOU (Apparent Oxygen Utilization) highlights biological oxygen demand and indicates areas with limited vertical mixing.

(AOU = O_2 saturation – measured O_2)

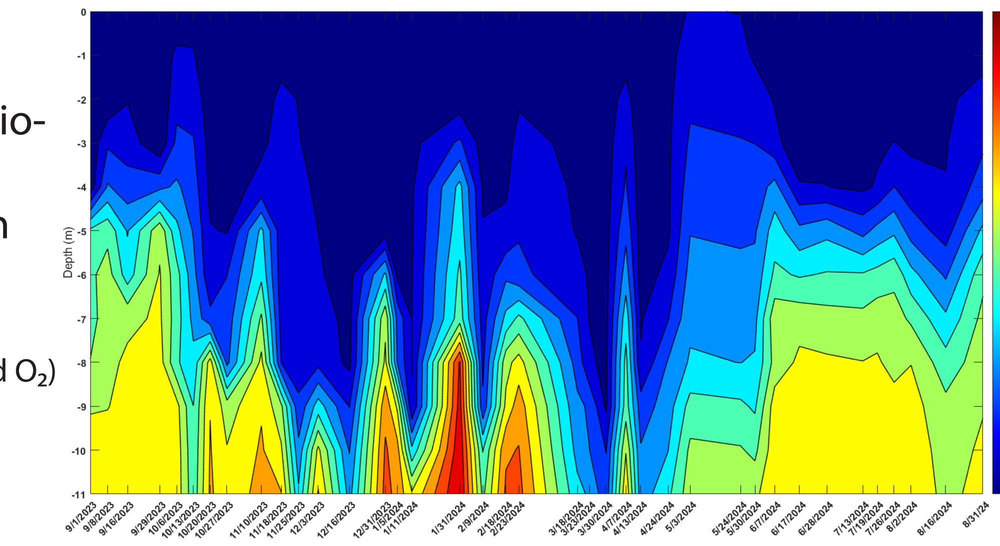


Figure 6. Hovmöller diagram showing vertical and temporal patterns of AOU

Conclusions

The preliminary findings from our ongoing study robustly support our hypotheses concerning the impact of climate variability on Lake Arlington. The accuracy of our one-dimensional (1-D) model in elucidating the lake's thermal dynamics confirms our hypothesis. Seasonal changes significantly influence thermal stratification and oxygen distribution, which our model effectively captures. These observations validate our predictions that increased temperatures and changes in precipitation patterns due to climate variability have a profound impact on the lake's thermal processes.

Future Work

1. Assessment of sources and mixing of stable oxygen isotopes by utilizing a data-driven 1-D diffusion model to better understand evaporative and mixing processes.
2. Prediction of seasonal oxygen distribution with the 1-D diffusion model
3. Explore influence of anthropogenic heat sources (i.e. from natural gas power plant
4. Improve the assessment by replacing the 1-D model with a 3-D general circulation model

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