ASSESSING CLIMATE CHANGE IMPACTS IN TROPICAL RESERVOIRS USING DIFFERENT HYDRODYNAMIC INDICATORS

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Abstract: In the context of climate change, the selection of the proper indicators is fundamental to assess, correlate and compare the impacts of different scenarios onto lentic environments. Once the atmospheric variables are responsible for triggering physical and chemical responses on these environments, the indicators are usually set as measurable response variables. Recent studies discuss which indicators to use and whether the combination of multiple ones can be more effective in overcoming some of the analysis limitations. This work presents a case study of the Hedberg Dam, a 0.23 km²-4.5m depth reservoir, located in Sao Paulo state, Brazil. The hydrodynamic software applied was the General Lake Model (GLM). High-frequency monitored data was used for the calibration and validation of the model (2017 – 2020). The results were considered reliable, as the model represents well the daily and seasonal patterns observed in the Hedberg Dam. For the climate change scenarios, the Eta regional climate model was used. The chosen scenarios represent the RCP 4.5 (optimistic) and RCP 8.5 (pessimistic), proposed by the IPCC. The scenarios were simulated between 2021 and 2100 and their results assessed as three sets of data, near future (2021 – 2039), mid-term future (2040 – 2069) and distant future (2070 – 2100). Five indicators were evaluated throughout the scenarios: the water level, the Schmidt Stability, epilimnion and hypolimnion temperatures and the thermocline depth. Results point to a higher number of mixing and stratification events and longer stratification periods, as expected. The integration of all indicators helped to better understand the predicted trends.

Resumo: No contexto das mudanças climáticas, é fundamental a seleção de indicadores apropriados para avaliar, correlacionar e comparar os impactos de diferentes cenários em ambientes lênticos. Posto que as variáveis atmosféricas são responsáveis por desencadear respostas físicas e químicas nesses ambientes, os indicadores são geralmente definidos como variáveis de resposta mensuráveis. Estudos recentes discutem quais indicadores usar e se a combinação de múltiplos pode ser eficaz para superar limitações da análise. Este trabalho apresenta estudo de caso da Barragem de Hedberg, um reservatório de 0,23km² e 4,5m de profundidade, localizado no estado de São Paulo, Brasil. O software hidrodinâmico aplicado foi o General Lake Model (GLM). Dados monitorados de alta frequência foram utilizados para a calibração e validação do modelo (2017-2020). Os resultados obtidos foram considerados confiáveis, visto que o modelo representa bem os padrões diários e sazonais observados no reservatório. Para os cenários de mudanças climáticas, o modelo climático regional Eta foi utilizado. Os cenários escolhidos são: RCP 4.5 (otimista) e RCP 8.5 (pessimista), propostos pelo IPCC. Os cenários foram simulados entre 2021 e 2100 e seus resultados avaliados

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através de três conjuntos, futuro próximo (2021-2039), futuro de médio prazo (2040-2069) e futuro distante (2070-2100). Cinco indicadores foram avaliados na simulação dos cenários: nível da água, estabilidade Schmidt, temperaturas do epilímnio e do hipolímnio e profundidade da termoclina. Os resultados apontam para maior número de eventos de mistura e estratificação e períodos de estratificação mais longos, como esperado. A integração de todos os indicadores auxiliou no entendimento das tendências previstas.

Palavras-Chave – Climate Change; Hydrodynamic Modelling; Reservoirs.

INTRODUCTION

According to Adrian *et al.* (2009), lakes can be considered sentinels of climate since (1) their environment are well defined and studied in sustained fashion, (2) they respond to climate change variables, not only the ones that directly affect the water body, but also the ones that drive changes within its catchment area, (3) lakes are able to integrate responses over time, filtering random noises, and (4) their worldwide distribution allows them to respond to different climates and geographic locations, capturing different aspects of the phenomena.

Once the atmospheric variables are responsible for triggering a physical, chemical and/or biological response onto the system, the indicators are usually set as a measurable response variable, such as water temperature, dissolved oxygen or algae population. In this context, the selection of the proper indicator is fundamental to assess, correlate and compare the impacts of climate change scenarios onto lakes.

Adrian *et al.* (2009) discussed and proposed indicators to compose this analysis. However, the efficacy of many indicators is affected by regional responses to climate change, the catchment characteristics and the lake mixing regimes. Therefore, combining indicators can be more effective and help overcome some of the limitations.

In the water balance analysis, its main components (precipitation, inflow, outflow and runoff), have their flow rate directly affected by the precipitation regime across the watershed, whereas the evaporation flow depends on the air temperature, relative humidity, wind and the presence of aerosols. These variables impact on the volume and water level of the lake, prompting both responses as indicators (Rocha Junior *et al.*, 2018). The operation of regulated reservoirs is a limitation that may influence the indicators, as well as groundwater levels, changes in vegetation and in the land use of the catchment area (Adrian *et al.*, 2009).

The heat balance, on its turn, is mainly affected by rising air temperatures and changes in the wind conditions. These drivers are responsible for important heat fluxes taking place at the lake surface, as the evaporation and sensible heat, and for influencing current formations and shear production on the upper layer. Therefore, a usually applied indicator is the water temperature, at distinct depths.

The epilimnion temperature, or surface temperature, can be strongly correlated to variations in these atmospheric conditions. As for the hypolimnion temperature, the correlations are not as strong, with the morphology of the lake, sediment characteristics and light penetration conditions having to be considered for the thermal structure assessment. However, both layers temperatures can be understood as indicators of the lake energy integration over time.

The relation between both layer temperatures affects the water density profile and, with that, the thermal gradient of the lake. Long-term changes in the thermal structure can be responsible for significant and lasting alterations in the mixing regime of the lake. As indicators, the increase of the density profile stability can be assessed by the Schmidt Stability number, the depth of the thermocline or by the duration of summer stratifications. The limitations over these indicators are their dependency over the lake's morphology and transparency (for small lakes), and the difficulties in obtaining high spatial and temporal resolution data (Read et al., 2011).

Regarding lentic environments studies, Kirillin (2010) and O'Reilly *et al.* (2003) applied, as indicators, the water temperature on the surface and bottom layer, as did Huang *et al.* (2017), with addition to the thermocline depth, number of stratified days and the start day of the stratification. Woolway *et al.* (2017) and Woolway and Merchant (2019) also used the epilimnion water temperature for analysis and complemented with the ice cover duration assessment.

Since even a small increase in the overall temperature of a lake results on the strengthening of the density gradient and its vertical stability, it is expected that most climate change scenarios will reveal a positive bias towards the occurrence of stratification events (Adrian *et al.*, 2009). In small, shallow lakes these impacts are even more pronounced, impacting their mixing regime; that can shift, for example, in a century-long period, from being a polymictic environment into becoming a monomict one (Kirillin, 2010).

In this scenarios, mathematical modeling can be an important tool for simulating, forecasting, and assessing future climate change conditions and their impacts on lentic environments. Therefore, this paper aims to discuss the analysis of different indicators to assess the impacts of climate change scenarios into a small-shallow-tropical lake.

CASE STUDY

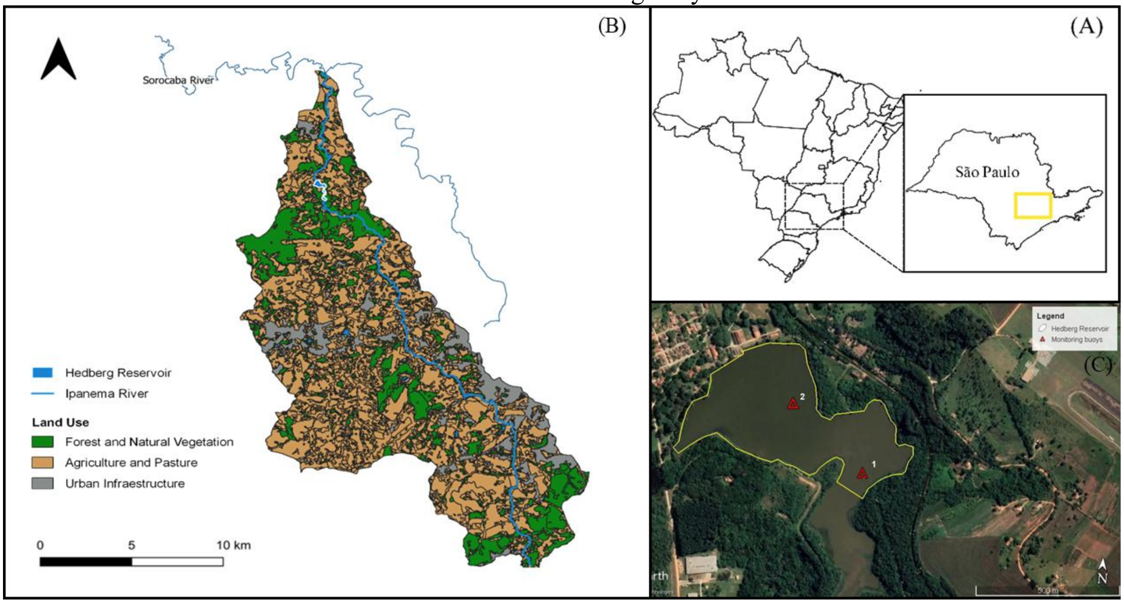
Located in the state of São Paulo - Brazil, the Hedberg reservoir (23°25'39"S and 47°35'39"W) was built in 1811 to provide water for Brazil's first steelmaker and small villages nearby. Currently, with its surrounding area defined as preserved site by the Brazilian government, named Floresta Nacional de Ipanema, its main uses are flow regulation, water supply, scientific studies, landscape and recreation (ICMBIO, 2017).

Downstream of the Ipanema River, the dam resulted in a 0.23 km²-surface area-reservoir, enclosing a catchment area of 234 km². Its basin is characterized by different land uses, with 68.2% of its area classified as rural (agriculture and pasture), 21.5% as forests and natural vegetation and 9.8% as urban. Yet, the growth of the urban sprawl in recent years reflects the anthropogenic influence that the basin has suffered (MAPBIOMAS, 2020).

The Hedberg reservoir (Figure 1) has an approximately volume of 1.5 hm³, an average flow from 2 to 5 m³/s, that determines a detention period of 2 to 10 days. Its maximum depth is 5 m and the mean depth is 4.5 m. The spillway crest elevation is 548.0 m, and the basin width and length at crest elevation are 670 m and 630 m, respectively.

With several events of mixing and stratification along the year, the lake presents a polymictic behavior. Furthermore, concerning its water quality evaluations, the lake is considered eutrophic (ICMBIO, 2017).

Figure 1 – Studied site: The Hedberg reservoir. (A) Ipanema basin location, in the state of São Paulo, Brazil; (B) The Ipanema basin characterized by different land uses and the Hedberg reservoir location; (C) Aerial view of the Hedberg reservoir and the location of the monitoring buoys. Source: Author.



MATHERIALS AND METHODS

This study applied the General Lake Model (Version 3.0.5) to simulate the hydrodynamic behavior of the Hedberg Reservoir, through a one-dimensional approach. The GLM code was compiled in the R environment (R CORE TEAM, 2020) and the following packages were used: GLM3r (Hipsey *et al*., 2019) and glmtools (Read *et al*., 2014).

Observed data from 2017 and 2018 was used to calibrate the model, whilst the validation was performed during the years 2019 and 2020. For the water balance, two proxies were evaluated: the outflow discharge over the modeled spillway and water level of the lake. The weir performance was calibrated against the outflow values observed for the local discharge curve and the water level with the observed data. For the energy balance, the water temperature was selected as the proxy (at depths: 0.5, 1.5, 2.5 and 3.5 m). The calibration was assessed in hourly mean values.

To assess the performance of the lake, the indexes MAE, NMAE, RMSE and NSE (Equations 1 to 4) were evaluated.

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|O_i - S_i| \quad (1)$$

$$NMAE = \frac{MAE}{\bar{O}} \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(O_i - S_i)^2} \quad (3)$$

$$NSE = 1 - \frac{\sum(S_i - O_i)^2}{\sum(O_i - \bar{O}_i)^2} \quad (4)$$

For the climate change scenarios, the Eta regional climate model was used, with a 20 km spatial resolution, being downscaled by the HadGEM2-ES and MIROC5 models. The chosen scenarios represent the RCP 4.5 (optimistic) and RCP 8.5 (pessimistic), proposed by the IPCC, which indicate the increase in mean global temperature by the end of the century of 1.8°C and 3.6°C, respectively. The model was run from 2021 to 2099 (79 years).

In order to use climate change scenarios as input in the GLM, the data had to be transformed to better fit the model's requirements. The inflow characteristics were estimated, based on the predicted rain and air temperature, and the atmospheric variables were discretized into hourly values.

The climate change scenarios assessment was performed through the analysis of four hydrodynamic indicators: water level, epilimnion temperature, hypolimnion temperature and the Schmidt Number. The Lake Analyzer tool (Read et al., 2011) was used for the indicators calculation.

For this study, aiming to better assess the data over 79 years, the hourly results were averaged into year-long values. The limitations implied by this approach are the misrepresentation of seasonal variations and underestimation of extreme events. However, the indicators' tendency and the estimation of their impact over the lake's thermal regime are well represented.

RESULTS AND DISCUSSION

Calibration and validation

The model was calibrated and validated considering mass and heat balances. The water balance is satisfactorily represented by the modeled spillway and the water level variations, with limitations for the simulation of extreme flood events, due to its representation of a run-of-river operation.

For the heat balance, the results indicated good agreement with the observed data. The model performance, limitations and biases were also analyzed. During the simulated period, the upper layers temperatures showed the most reliable results, whilst the bottom layer presented greater temperature amplitudes and fluctuations than the observed data, resulting in the overestimation of mixing events by the model. Nevertheless, the Hedberg reservoir thermal pattern is considered satisfactorily represented by the GLM model, as its daily and seasonal responses characterize a polymictic lake.

Table 1 and 2 summarize the performance indexes RMSE, MAE, NMAE and NSE values calculated for the simulation period (calibration and validation).

Table 1 – Calibration and validation: Performance index values (2017 - 2018) - Water Balance. Source: Author

Variable	Calibration (2017)				Validation (2018)			
	N	RMSE	MAE	NSE	N	RMSE	MAE	NSE
Overflow [m³/s]	334	1.67	1.23	0.86	258	1.23	0.65	0.79
Water Level [m]	334	0.16	0.12	0.25	258	0.10	0.09	0.59

Table 2 – Calibration and validation: Performance indexes values (2017 - 2020) – Energy Balance. Source: Author

Variable	Calibration (2017 - 2018)					Validation (2019 - 2020)				
	N	RMSE	MAE	NMAE	NSE	N	RMSE	MAE	NMAE	NSE
Water Temperature [°C]										
Full Profile	41056	1.20	0.93	0.05	0.82	31032	1.05	0.84	0.04	0.84
0.5 m	11309	0.99	0.79	0.04	0.91	7436	1.23	1.06	0.04	0.70
1.5 m	9887	1.23	0.97	0.05	0.83	8107	0.82	0.66	0.03	0.93
2.5 m	11315	1.39	1.05	0.05	0.77	7383	0.95	0.74	0.03	0.90
3.5 m	8545	1.18	0.92	0.05	0.79	8106	1.18	0.92	0.04	0.81

Climate change scenarios assessment

After the calibration and validation of the GLM model, two different climate change scenarios were simulated, an optimistic one (RCP 4.5) and a pessimistic one (RCP 8.5). The climate change scenarios were analyzed for three sets of data: near future (2021 – 2040), middle-term future (2041 – 2070) and distant future (2071 – 2099).

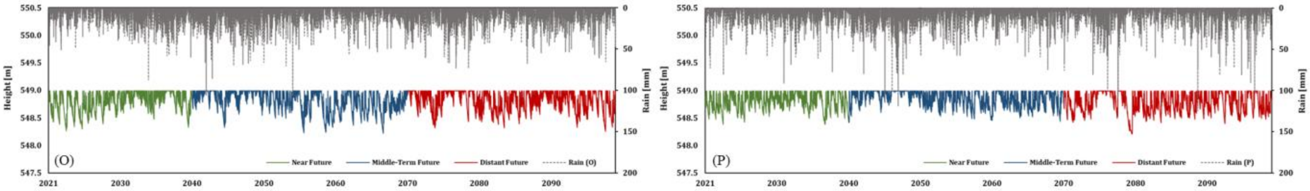
The water level was the selected indicator to assess the impact of climate change scenarios over the Hedberg water balance. The main atmospheric variable influencing the indicator is the rain, which presents intense variations when compared to the observed data.

The model responds to the input of rain and inflow by varying the level of the lake. However, as the reservoir operates as a run-of-river reservoir, when the level reaches over 549 m, the model retrieves all the excess water from the system, imposing an upper limit to the water level representation. Figure 2 presents the water level variations, alternating between drier and wetter conditions, in daily average values.

In the optimistic scenario, these variations are frequent and balanced, for the near future. As the simulation reaches the middle-term future and distant future conditions, the alternation is less frequent, with longer periods of lower (for example, near 2056 and 2074) or higher (2049 and 2077) levels characteristics. The model predicts reductions of up to 0.5 m from the maximum simulated level, with longer periods of reduced levels for the middle-term and distant future. In the pessimistic scenario, the same tendencies are found, however, with more intense characteristics. Longer periods of low (around 2080) and high (around 2047) levels can be noted, and, in its drier conditions, the descent of the water surface goes up to 1 m from the maximum simulated surface.

These predicted tendencies indicate impacts not only over the amount of water available in the reservoir, but also possible impacts over the thermal regime and water quality characteristics in a shallow lake.

Figure 2 – Water balance parameters on the Hedberg reservoir for the optimistic (O) and pessimistic (P) simulations. Source: Author.



For the energy balance assessment, the applied indicators were: the epilimnion temperature, the hypolimnion temperature, the Schmidt Number and the thermocline depth.

Using annual average values, the epilimnion and hypolimnion temperatures are presented in Figure 3, for the optimistic (circle marker) and pessimistic (squared marker) scenarios. The annual average values of the calibrated period (2017 – 2020) are also plotted for comparison.

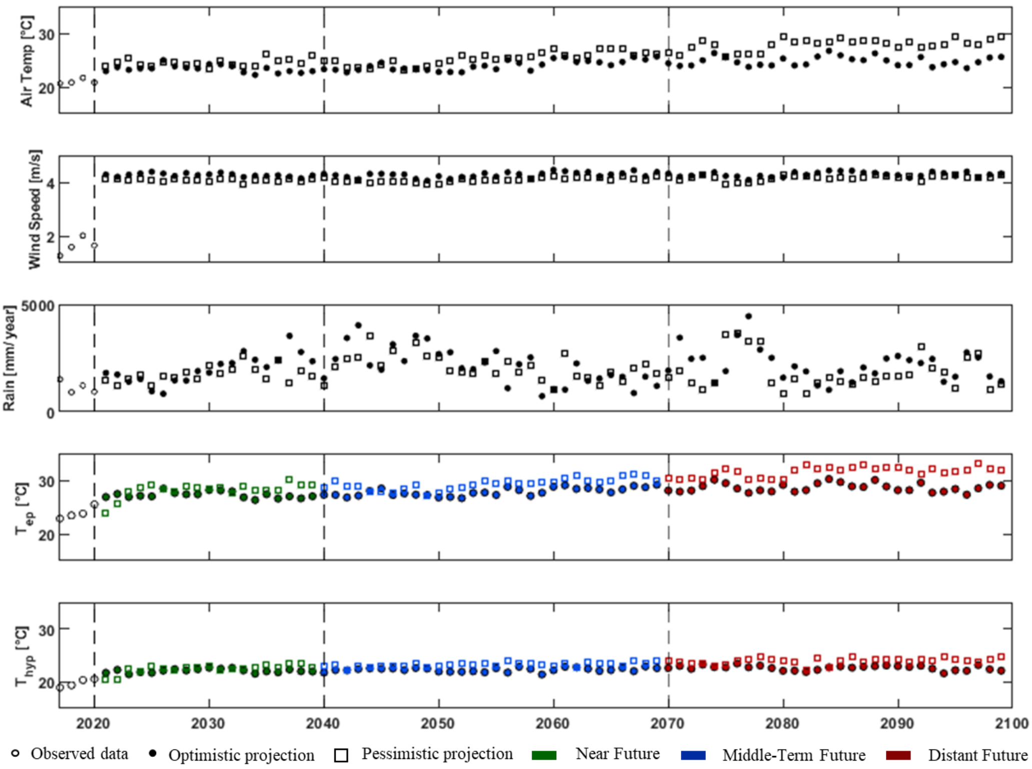
Figure 3 indicates a trend of increasing temperatures for the upper layer of the reservoir, with lower rising rates in the near-future conditions and increasingly higher rates as the simulation progresses. Moreover, the difference between both climate change scenarios is more pronounced in the distant future conditions, when the pessimistic scenario suggests a temperature increase up to 8 °C from the average value of the observed years, in contrast to only 4 °C for the optimistic scenario.

For the hypolimnion temperature, a lower rising rate is predicted, with the temperatures rising up to 2 °C in the optimistic scenario and 4 °C in the pessimistic one. The difference between scenarios is also smaller than the one for the epilimnion.

The surface layer trends strongly relate to the increase of the air temperature over the simulated period, as expected. Nevertheless, the lower rates predicted for the hypolimnetic temperatures suggests a weaker influence on this parameter, once the bottom layer is affected not only by the atmospheric variables, but also by internal processes of energy propagation and dissipation occurring along the water column and on the soil-water interface.

Another factor to be considered is the possible underestimation of colder inflows during the climate change scenarios, once the methodological approach applied in this study estimates the temperature of the inflow based solely on the projected air temperature. The impact of other atmospheric variables, their spatial variations and the influence of the catchment area were not considered. In this context, currents generated by cooler entrainments can be underestimated, as well as their impacts. Therefore, in the light of the identified bias of the projected data and the limitations of the model, even lower rates may be expected for the increase of the hypolimnion temperature.

Figure 3 – Epilimnion and hypolimnion temperatures of the Hedberg reservoir for the optimistic and pessimistic scenarios. Source: Author.

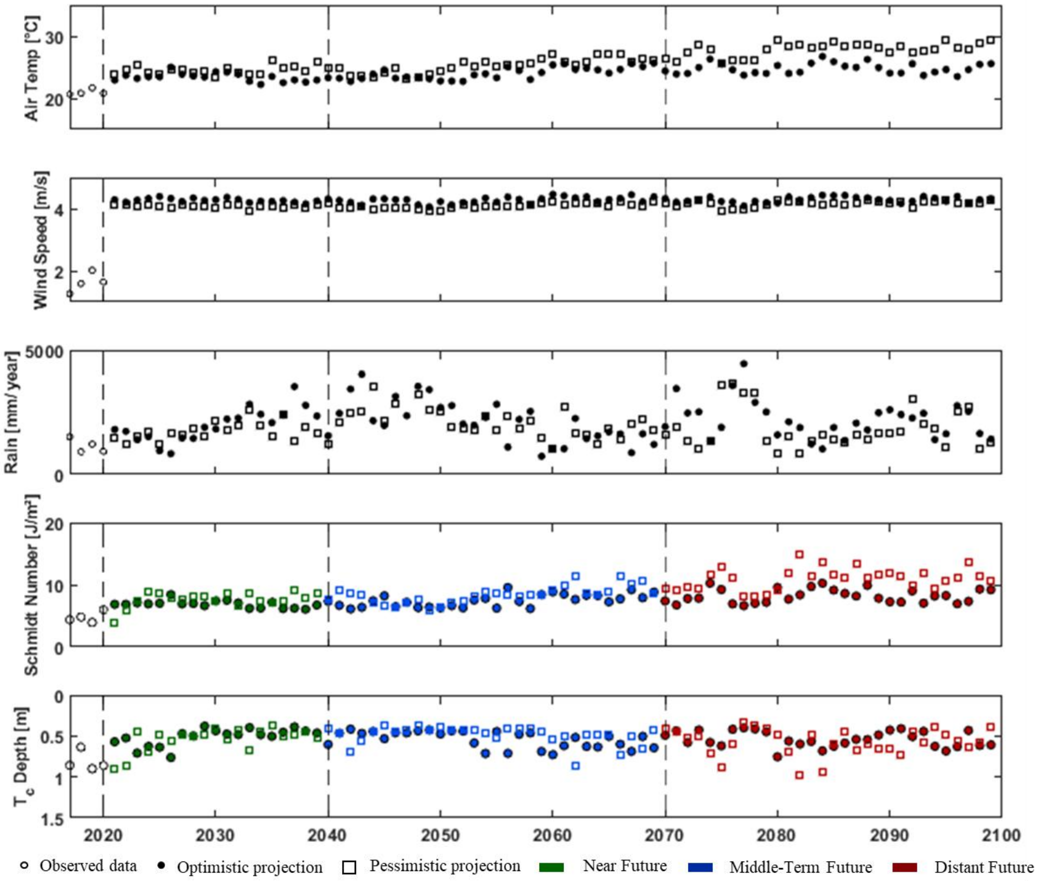


These results allude to the occurrence of stronger stratification events in the Hedberg reservoir. The temperature gradient tends to increase, as temperatures rise at a greater rate on the upper layer than on the bottom one. As a result, the thermal structure establishes a strong density gradient.

These conditions can lead to the occurrence of more stable and lasting stratification events. Stronger density gradients are harder to overcome by daily atmospheric variations, which, in the long term, can suggest changes in the mixing regime of a polymictic lake.

To better assess the changes on the stratification events over time, the Schmidt Number and the thermocline depth were calculated and evaluated for both scenarios (average annual values) (Figure 4). The calculated values from the calibration period were also presented for comparison purposes.

Figure 4 – Schmidt number and thermocline depth for the Hedberg reservoir, for the optimistic and pessimistic scenarios. Source: Author.



During the near-future up to about half of the middle-term future simulation (2055), the Schmidt Number and the thermocline depth indicate an orderly behavior, with small variations and similar tendencies for both climate scenarios. Both indicators indicated low changing rates over time, with the Schmidt Number increasing and the thermocline deepening.

From 2055 onward, mainly for the distant-future conditions, these trends are better defined. The Schmidt Number indicated an increase in the system energy, with the optimistic scenario presenting Schmidt values up to 10 J/m² and the pessimistic one up to 15 J/m². More frequent and greater variations were also observed as more and more extreme events took place.

For the thermocline depth, results indicated great variations between shallow and deep thermoclines, mainly during the pessimistic simulation. The thermocline deepening occurred in both scenarios, with values varying from 0.5 m to 1 m above the surface.

Shallow thermocline depths suggest the predominance of daily conditions over the thermal structure of the lake, related to a polymictic pattern. The deepening of the thermocline, on the other hand, can indicate the strengthening of stratification conditions, since the seasonal characteristics become more relevant. These results are coherent with the previous analysis and indicate the strengthening of the water column stability over time.

Integrating the analysis of all discussed indicators, it is possible to better understand the predicted trends. For the combined occurrence of elevated air temperatures and low rainfall volumes, as the water level of the lake decreased, the stability values increased and the thermocline deepened (for example, around 2073 and 2085), suggesting the occurrence of stronger and lasting stratification events. Whereas, for atmospheric conditions of elevated temperatures and high precipitation rates, the Schmidt Number presented smaller values and the thermocline rose (around 2076 and 2095), indicating lower stability conditions and the predominance of mixed conditions during the year.

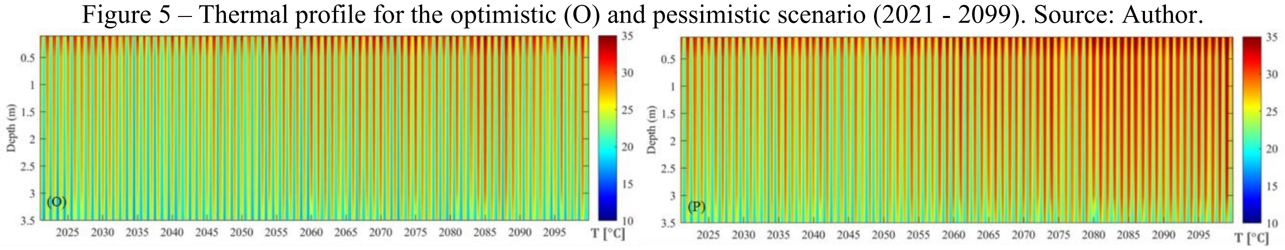
Overall, similar trends were observed on both simulated scenarios:

- Elevation of the lake's temperature, on the upper and bottom layers, with the latter increasing at a lower rate than the first one (epilimnion and hypolimnion temperatures);
- Increase of the density gradient over time;
- Elevation of the lake's overall heat content, resulting on the strengthening of the stratified water column stability (Schmidt Number); and
- More frequent occurrence of deeper thermoclines conditions, suggesting the predominance of long-lasting stratification events, influenced by seasonal variations (thermocline depth).

The optimistic scenario, as expected, presented lower changing rates in relation to the pessimistic one, resulting in smaller variations, for all indicators. The most extreme values were observed during the pessimistic simulation, in response to the more extreme and more frequent atmospheric conditions.

Finally, Figure 5 displays the water temperature along the vertical dimension for the optimistic and pessimistic scenarios, over the 79-year period.

Figure 5 – Thermal profile for the optimistic (O) and pessimistic scenario (2021 - 2099). Source: Author.



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