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ASSESSING THE THERMAL BEHAVIOR REPRESENTATION OF A SMALL-POLIMITIC-TROPICAL LAKE WITH AN ONE-DIMENSIONAL MODEL

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The thermal behavior of lakes and reservoirs determines the occurrence of stratification and mixing events, on a daily or seasonal pattern. In order to properly use and rely on mathematical models for the assessment of current or future scenarios, the model's performance, limitation and biases must be well known by the modelist. This paper aims to evaluate the capability of a 1DV hydrodynamical model to reproduce reliably the thermal behavior of a small-polimitic-tropical lake. The case study was focused on the Hedberg Dam, located about 90 km from Sao Paulo city, Brazil. It is a 0.23 km²-4.5 m depth pond, built in the beginnings of the 19th century. Its hydrological catchment area is partially protected with some sparse urban occupations. The General Lake Model (GLM) was applied for the simulation. With an hourly time-step, the model used morphology characteristics, atmospheric variables and flow as input data. Thermal profiles from high-frequency sensor data were used for the calibration and validation of the model, 2017 and 2018, respectively, during dry and wet periods, and its results were assessed in the light of the model's performance, limitation and biases. The simulation indicate that the reservoir is well represented by the model, responding to the daily and seasonal patterns observed in a tropical-polimitic-shallow lake, suggesting, however, limitations over the hydraulic representation of extreme flood events and the thermal representation after the occurrence of long-term mixing conditions. The model also seems to overestimate the number of short-term mixing events, mainly during the wet season.

Keywords– thermal behavior, one-dimensional modelling, lakes

INTRODUCTION

The thermal behavior of lakes and reservoirs has been extensively studied over the years, supporting physical, chemical and biological analysis of these environments, as so the design of management

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practices and the foreseeing of different future scenarios. (Amorim, 2020; Goldman & Horne, 1985; Imberger & Patterson, 1989; Kirillin, 2010; Ladwig et al., 2021)

The hydrodynamic processes on these environments rely on morphology characteristics, meteorological conditions and hydrological patterns, whereas the water quality processes are results of these hydrodynamic structures and the watershed incoming loads. (James, 1993) (Tundisi & Tundisi, 2008)

The two main thermal dynamics brought about on these environments are the stratification and mixing processes. As the solar radiation reaches the lake' surface, the water column is heated in a non-homogeneous pattern, generating a thermal-density gradient that, through the buoyancy forces at place, defines a stratified vertical profile. When these vertical buoyancy forces are overcome by the kinetic turbulent energy available in the system, provided by convective cooling, wind stirring and/or internal waves, the mixing processes take place, allowing for the transportation of water, nutrients, dissolved gases and the local biota along the vertical layers. (Imberger & Patterson, 1989) (Tundisi & Tundisi, 2008)

Understanding these processes, predicting their characteristics and assessing their impacts are of great interest for decision-makers, who have been, more and more, relying on mathematical models to support the plan and application of management practices onto lentic environments (Baptistelli, 2008). However, the selection of an adequate model to perform a study must take into account: the study objectives, the available dataset, the model approach on modelling the phenomena of interest, as well as its limitations and biases. (Ji, 2008)

One-dimensional vertical (1DV) models have been widely applied for the study of the physical and chemical characteristics of lakes and reservoirs, whenever the longitudinal dynamics can be overlooked in the light of the predominance of the vertical processes. These models' great computational efficiency and minimal calibration requirements, back their use as an interesting tool for large cross-lakes comparisons and long-term analysis, like climate change impacts assessment. (Bruce et al., 2018; Kirillin & Shatwell, 2016; Read et al., 2014; Saloranta & Andersen, 2007)

This paper aims to discuss the thermal behavior representation of a small-polimitic-tropical lake, the Hedberg Reservoir, through a one-dimensional modelling approach, with the General Lake Model (GLM). The model was simulated between the years 2017 (calibration) and 2018 (validation) and its results were assessed in the light of the model's performance, limitation and biases.

STUDIED SITE

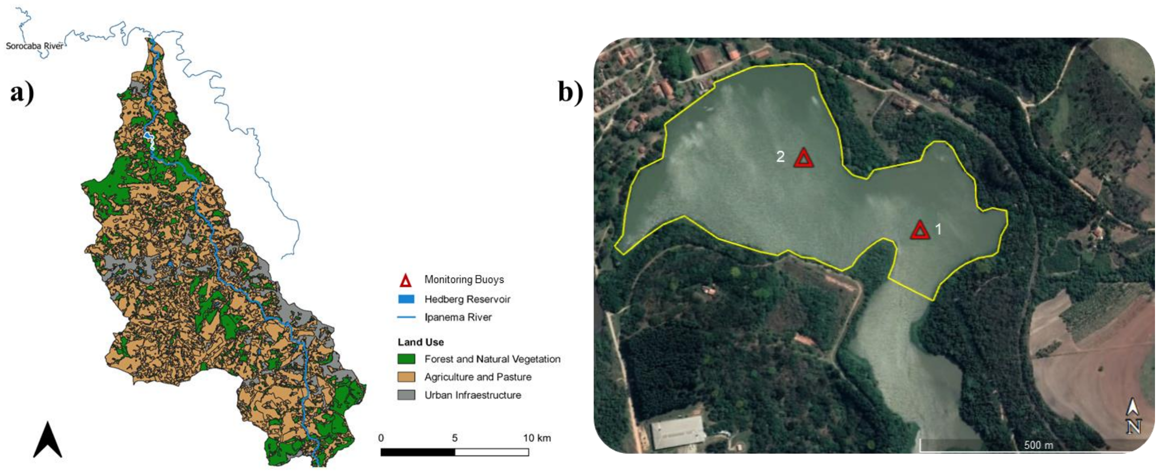
Built in 1811 to provide water for Brazil's first steelmaker and nearby villages, the Hedberg Reservoir is a 0.23km³-surface area dam, enclosed in a 234 km² catchment basin. (Figure 1) With an approximated volume of 1.5 hm³ and average flow from 2 to 5 m³/s, the reservoir presents a detention period between 2 to 10 days, and maximum and mean depths of 5 m and 4.5 m, respectively.

The dam currently integrates the Floresta Nacional de Ipanema area, a Brazilian preserved ecological and historical site, located in Iperó, in the state of São Paulo – Brazil and its main uses are flow regulation, water supply, scientific studies, landscape and recreation. (ICMBio, 2017)

The catchment basin, situated in the tropical zone (23.42° S and 47.6° W), has a temperature range between 15 and 35°C, predominant wind direction as Southeast (SE) and annual precipitation rate of 1500 mm, approximately. It 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. (Mapbiomas, 2020) (Figure 1)

With several events of mixing and stratification along the year, the lake presents a polimitic behavior. Moreover, concerning its water quality evaluations, the lake is considered eutrophic.

Figure 1 - The Hedberg Reservoir. a) Ipanema catchment basin (Mapbiomas 2020); b) Hedberg Reservoir and monitoring buoys



MATHERIALS AND METHODS

The Dataset

The study dataset was composed by morphometric, meteorological, hydrological and monitoring data. The data was obtained and treated in order to provide an accurate dataset, as input data, to the model.

The morphometric data was obtained through the local hypsographic curve, delimited by previous studies on the area.

The meteorological data was gathered from two different stations: one located at the site, placed on the northwest bank of the reservoir, near the spillway, and the other located about 1 km from the lake. The first is maintained by the Sistema de Alerta de Inundação de São Paulo (SAISP) and provides data over a 10 minutes time step, since 2016, lacking data during some periods. The latter is operated by the Instituto Nacional de Meteorologia (INMET) (Code: A7113 – Sorocaba), and its monitoring data is available since 1989, at hourly time-steps.

The main meteorological parameters monitored are: solar radiation, air temperature, relative humidity, wind speed and direction (10 meters above the lake' surface), atmospheric pressure and precipitation. (Figure 2)

The upstream hydrological data, on the other hand, was obtained applying the meteorological drivers (rain and evaporation) on a rain-flow transformation model, the Soil Moisture Accounting Procedure (SMAP) software, calculating the Ipanema River inflow into the reservoir at daily intervals.

At last, the monitoring system implemented on this study is composed by the local meteorological station, a water level sensor and two floats with a set of thermistors attached to each one by a rope and a plummet.

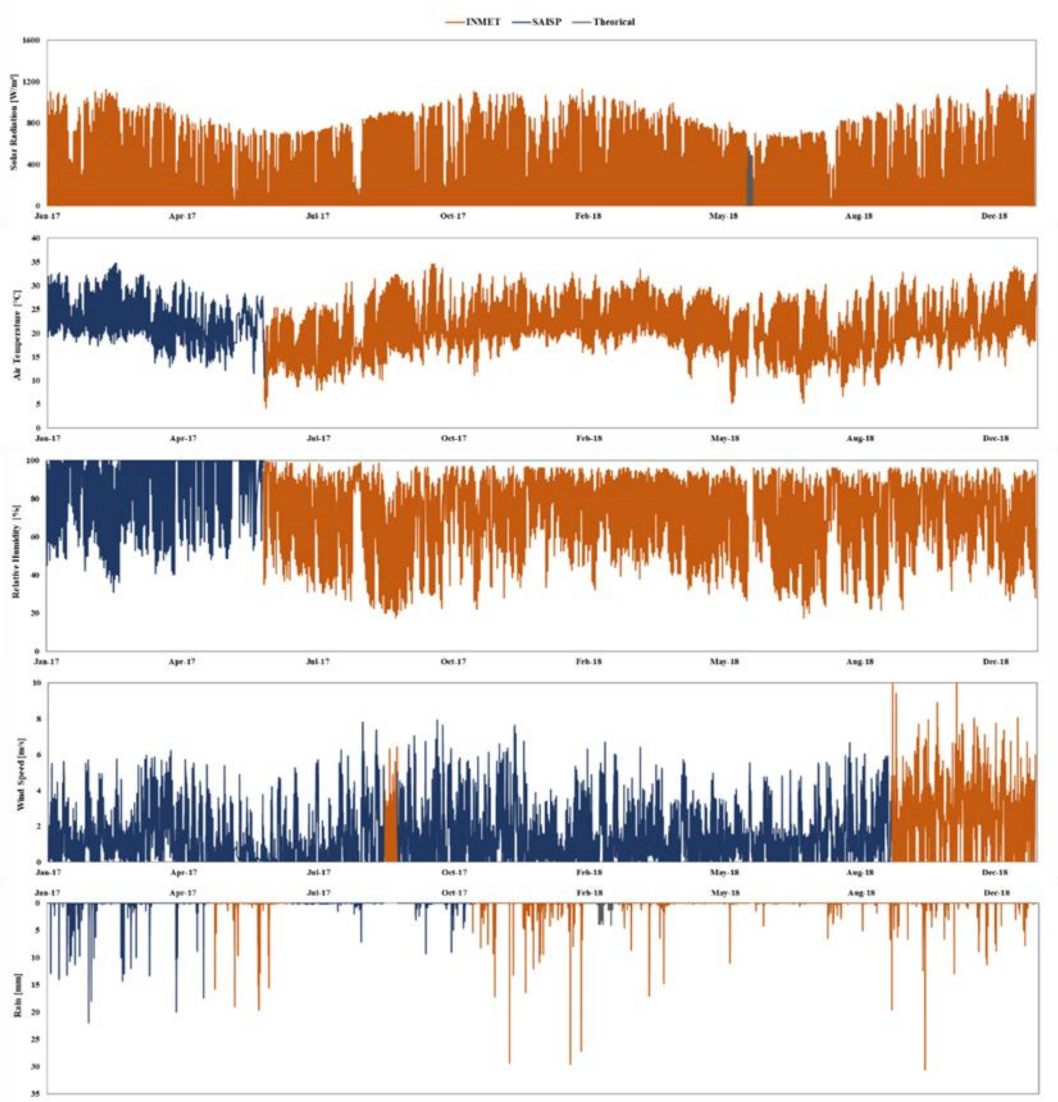
The first float is positioned at the entrance of the Ipanema River on the reservoir. It has one thermistor attached to it, aiming to measure the inflow temperature. The second float is positioned at the center of the lake, where the depth is maximum (around 4.5 m along the year) and the lake's edges does not present relevant influence. With four probes placed in different depths along its vertical profile (from the surface: 0.5 m, 1.5 m, 2.5 m and 3.5 m), the float establishes itself as a representative point of the reservoir.

On both floats, the thermistors used are the HOBO Water Temp Pro v2 Onset Logger (Figure 23), programmed to monitor data in a 2-minutes time-step, with an accuracy of ± 0.2°C.

The maintenance of this monitoring system requires local monthly visits to evaluate the equipment and gather the monitored data, as so to collect water samples and measure the local Secchi depth. These visits are held by a team of researchers that develop studies on the site.

The dataset of the second float, for the period of interest, presents measures from April, 2017, until October, 2018, lacking data on June (2017) and some days of May (2018). The third sensor (2.5 m), however, lacks data from July until September (2017), and the bottom sensor (3.5 m) from September (2017) until January (2018).

Figure 2 -Monitored metheorological data (2017 - 2018)



The General Lake Model (GLM)

The General Lake Model is a one-dimension hydrodynamic model developed by the Aquatic EcoDynamic (AED) group of the University of Western Australia (UWA), in order to support the Global Lake Ecological Observatory Network (GLEON) initiative. (Hipsey et al., 2019)

The GLM uses a deterministic, mechanistic, time-dependent and numerical solving approach, valid for the simulation of stratified and mixed columns, on environments where it is possible to assume the density vertical structure is the dominant one, while the horizontal profile is homogeneous. The GLM numerical model uses a flexible Lagrangian structure to solve the water and energy balance over a vertical dimension, simulating stratification and mixing processes.(Hipsey et al., 2019)

The model has been used in multiple studies across the globe. Bruce et al. (2018) used data from a global observatory network to stress test the GLM against 32 different lakes across the globe, Read et al. (2014), simulated 2368 temperate lakes with the GLM model, within a 33-year time interval, studying the regional coherence of stratification phenology, whereas Farrell et al. (2020), through the GLM model application, coupled with the Aquatic EcoDynamic (AED) library, provided the analysis over the effects of climate warming on nutrient cycling in two distinct lakes.

In the Brazilian context, Silva et al. (2015) modelled the Pampulha Lake (Minas Gerais), evaluating the impact of runoff inflow water on a tropical lake. Soares et al. (2017) studied the Serra Azul reservoir (Minas Gerais) during drought periods and Pinto (2018) evaluated the influence of rainfall and air temperature variations over the thermal regime of the Descoberto reservoir (Distrito Federal). While, Sales (2020) modelled the thermal, chemical and biological regimes of the Passaúna reservoir (Paraná) and Barbosa (2015) simulated the water quality and phytoplankton dynamics on the Paranoá Lake (Distrito Federal). Also, Soares et al. (2020) carried out a study over a subtropical cascade on the Tietê river basin (São Paulo) analyzing six different reservoirs, in order to perform a sensitivity analysis, simulate their thermal regimes and, finally, propose a parametrization strategy for non-monitoring reservoirs.

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 and glmtools.

The simulation time framework was from January 2017 to September 2018, with hourly time-steps. The lake's initial depth was set at 4.1 m, as observed from the monitoring data (for January, 1st, 2017 at 00h00). Whilst the overall lake and inflow salinity was set at 0.0005 mg/L, aiming to reduce its influence over the studied domain, once its impacts are not considered relevant in a freshwater environment.

The optional modes selected were: non_aveg = TRUE; light_mode = 0; rad_mode = 3; cloud_mode = 1; albedo_mode = 1; deep_mixing = 1. Since the cloud cover nor the longwave radiation data were available, the model (rad_mode = 3) estimates the local cloud cover.

Outflow values were, also, not directly provided to the model, but rather, the local spillway was modelled through a surface withdraw structure, placed at the height 548 m. The sediment' mean temperature (19.2 °C), amplitude (9.8 °C) and peak day of the year (30 – Julian) were obtained by the bottom sensor in the second buoy.

Finally, the layers maximum and minimum thickness, as well as the maximum number of layers, were set at: 0.005 m, 1.0 m and 250, respectively.

Calibration and Validation

Observed data from 2017 was used to calibrate the model, whilst the validation was performed during the year 2018. The performance indexes evaluated were the MAE, RMSE and NSE.

For the water balance, two proxies were evaluated: the outflow discharge over the modelled spillway and the lake's water level. The weir performance was calibrated against the outflow values observed for the local discharge curve and the water level with the observed data. Both proxies were analyzed by daily mean values. The calibration parameters adopted were: $c_{D\,weir}$, W_{weir}, f_{ro}, R_L, accounting for the processes of overflow and runoff.

For the energy balance, the water temperature was selected as the proxy (at 0.5, 1.5, 2.5 and 3.5 m) at hourly mean values. The calibration parameters adopted were: K_W, c_e, c_d, C_w, C_{HYP}, K_{soil}, accounting for the processes of surface heating (shortwave radiation and evaporation), wind stirring, diffusive transport on the hypolimnion and sediment heating.

The calibration process was performed manually, applying an interactive trial and error process over the adjustment of the model parameters, through visual evaluation, to identify patterns, and the performance indexes assessment.

RESULTS AND DISCUSSION

Observed Thermal Behavior

Presenting a polymitic pattern, the lake's thermal behavior can be assessed by the daily variations observed along the temperature vertical profile. During the day, the incident solar radiation provides enough energy for the lake's water column to establish the stratification, especially in the first few meters; however, during the night, due to water cooling processes, short mixing events can be observed, lasting for 2 or 3 hours, during the early morning, before the incoming solar radiation restarts the stratification process. Mixing events during the day can also be generated by the wind stirring onto the lake's surface, but those are less frequently observed.

Throughout the year, the seasonal variations influence the Hedberg thermal patterns. The winter is the local dry season (April to August), therefore, lower flow discharges, colder inflow and surface water temperatures, together with the reduction of the solar radiation intensity, bring about the occurrence of long overturning events, which can be maintained for a few days. In the summer, on the other hand, elevated radiation intensities, along with warmer inflow and surface water temperatures, promote stronger stratification profiles and only short mixing events take place.

Measured data at these four depths, observed during the 2017-2018 period showed that the lake's temperature varies between 14°C and 30°C. The most pronounced variations have a daily frequency and take place within the first meters of the water column, being better represented by the 0.5 m and 1.5 m depths; whereas, near the bottom (3.5 m), these daily patterns have a reduced influence over the temperature profile, indicated by a smoother contour.

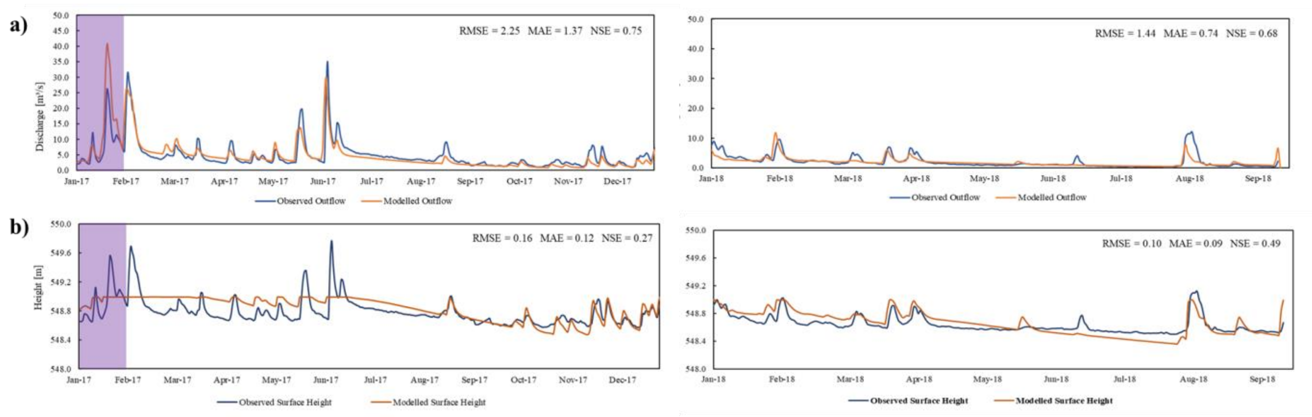
Water Balance

The Hedberg reservoir is a tropical, shallow lake (mean depth 4.5 m), with the local spillway as the main outflow structure, operated as a run-of-river dam. Observed data indicates that, throughout a usual year, the Hedberg outflow discharge varies between 1 and 20 m³/s, as the water level range from 548.5 m to 549.5 m.

Throughout 2017, two unusual flood events were observed, one during the dry and one during the wet period. Regarding the unusual characteristic of both events, mainly the one during the dry season, the calibration focus was to achieve the best representation of the lake's response outside of these periods.

The modelled withdraw structure response is considered adequate, with the modelled outflow fitting well the observed data, even during the extreme events (Figure 3a). The main performance indexes calculated reinforce the models good fit, with the RMSE value of 2.25 m³/s and the NSE of 0.75 (N=344). Yet, the modelled data is slightly smaller than the observed throughout the year.

Figure 3 - Water balance and performance indexes: (a) Spillway discharge (m³/s); (b) Water table height (m); On the left, calibration (2017) and, on the right, validation (2018)



After the outflow calibration, the water level response was analyzed (Figure 3b). Its performance indexes values presented good results, with RMSE of 0.16 m and MAE of 0.12 m (N=344). However, the NSE index was estimated at 0.27, indicating an inefficient representation of the level dynamic, what can be observed for the first semester of the year and explained by the unusual events simulation.

Even with the reliable simulation of the hydraulic structure dynamic, the water level assessment indicates an appropriate fit during most of the year, but fail in to representing the extreme flood events. As the surface water reaches the 549 m height, the water level stops rising and all of the excess water is retrieved from the system. This condition may be due to the large width adopted for the weir (160 m) or the elevated drag coefficient (180.585).

During the validation (2018), both proxies were evaluated and presented suitable results, improving their performance indexes values. (Figure 3)

Energy Balance

The visual analysis of the simulated thermal pattern indicates a good agreement between the observed and modelled data (Figure 4). The seasonal behavior is well represented by the year-long variations, showing decreasing temperature from April to July, and increasing values after August. The daily variations are also well represented in the upper layer; yet, the model displays larger amplitudes than the monitored data.

A quantitative evaluation, for the full vertical profile and at each depth, was performed and the values indicate great fit between the simulation and monitoring data (Table 1).

However, the mixing dynamic of the reservoir is not reliably represented. Due to difficulties in calibrating the bottom layer, which is influenced by the upper layers' dynamic, diffusive processes and the sediment heat exchanges, the 3.5m-depth simulated temperature presented more frequently variations than the observed data, incurring in a coarsen temperature profile. This condition, associated with the larger amplitudes observed in the upper layers, resulted in more frequent occurrences of mixing events, especially during the wet period (Figure 5).

During the dry season, two strong mixing events occur (one each year – end of August, 2017 and beginning of June, 2018). The intense reduction on the lake's energy budget brought about the simulation of colder temperatures along the vertical profile. Although the observed data presented colder temperatures as well, the model results indicated even lower values. This condition impact on the surface and bottom responses during the following days of each event, especially in 2018.

Figure 4 - Energy balance: Calibration (2017) – Surface (0.5 m) and Bottom (3.5 m) layer.

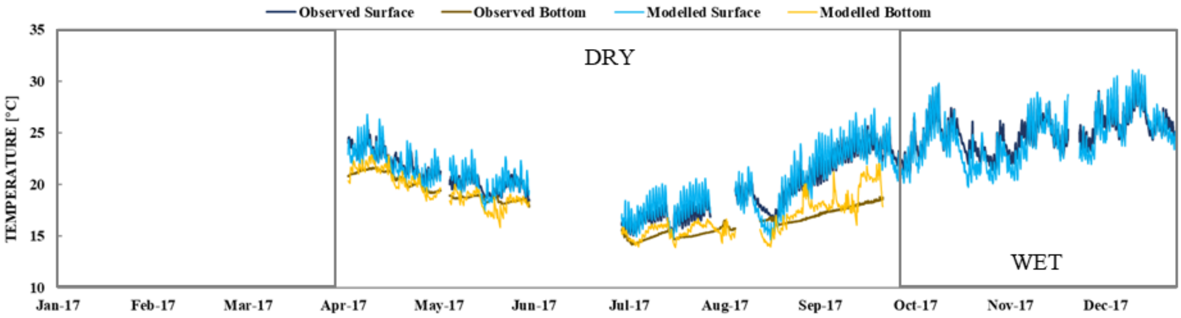
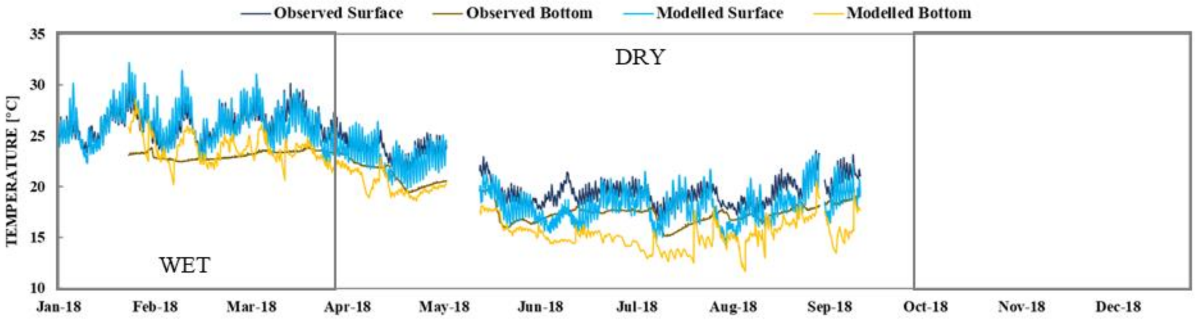


Figure 5 - Energy balance: Validation (2018) – Surface (0.5 m) and Bottom (3.5 m) layer.



As the heating fluxes start to increase, the lake's energy budget is reestablished and the model performance improve. The upper layer recovers first, due to the positive heat fluxes at the surface, whereas the bottom layer presented the worst performance during this period.

The model's behavior can be explained in the light of the provided meteorological data and calibration parameters. However, its deviance from the observed data may indicate that cooling processes, as the surface losses and, more important, in this case, the sediment heating fluxes are not representative for the period.

Table 1 - Performance Indexes: Calibration and Validation (2017 – 2018) - Wet and dry periods

Variable	Dry Season (2017 - 2018)				Wet Season (2017 - 2018)				Whole Year (2017 - 2018)			
	N	RMSE	MAE	NSE	N	RMSE	MAE	NSE	N	RMSE	MAE	NSE
Full Profile	18295	1.11	0.86	0.82	22761	1.71	1.42	0.75	41056	**1.49**	**1.18**	**0.82**
0.5 m	5417	1.06	0.84	0.89	5892	1.46	1.20	0.81	11309	1.28	1.03	0.85
1.5 m	5420	1.12	0.89	0.85	5620	1.75	1.49	0.68	11040	1.48	1.19	0.79
2.5 m	4267	1.24	0.98	0.78	5895	1.67	1.39	0.76	10162	1.50	1.22	0.80
3.5 m	3191	1.02	0.75	0.76	5354	1.97	1.62	0.75	8545	1.68	1.29	0.85

CONCLUSIONS

The model is considered calibrated and validated, over the period of two years and throughout seasons. The water balance is well represented by the modelled spillway and the water level variations, with limitations for the simulation of extreme flood events. As for the energy balance, daily and seasonal responses indicated good agreement with the observed data. Their performance, limitations and biases, into representing the Hedberg reservoir thermal regime, were analyzed.

During the simulated period, the upper layers temperatures showed the most reliable results, responding to the provided meteorological data and exhibiting similar daily patterns to the monitoring data. Still, the daily temperature amplitude was overestimated by the model. In a parallel condition, the bottom layer presented larger temperature amplitude and more frequently variations over its temperature profile than the smooth observed contour.

Both of these modelling performance issues resulted in the overestimation of mixing events by the model, especially during the wet season. Most simulated mixing events had a short duration, taking place at the early hours of the day, in response to the nights' surface heat losses, and being dissipated by the morning solar radiation. The described phenomenon is already observed by the monitoring sensors, though less frequently. This condition suggests that the calibrated model is biased towards the promotion of mixing events.

Apparently contradictory, these issues are also the reason behind the model's poorly representation of strong overturning events. Strong mixing occurrences are brought about by reduced and lasting meteorological conditions, mainly the decline of the heat inputs, onto the lake' surface, during a prolongated period. As, in the daily variations, the heating and cooling processes cause a wider temperature amplitude, the intense reduction of heating will intensify the cooling processes, and the lake's energy budget will decrease, more than the observed data. If low heating conditions are maintained for a few days, the model struggles to reestablish the energy budget necessary to perform well right after the extreme event. Therefore, the calibrated model indicates a limitation over the representation of the lake's temperatures during strong mixing events and in the following days.

Through the understanding of the simulated daily dynamics, the seasonal patterns are better evaluated. The model calibration and validation were considered representative of both seasons, over the two years, however, distinct characteristics were observed. Outside of the intense mixing occurrences, the dry season was better represented by the model, as it was expected due to the short mixing bias, more frequently matched during the winter observed data. For the wet season, on the other hand, even with higher associated errors, the model was coherently over both years, showing a good fit for the surface layer and overestimating the occurrence of short mixing events.

At last, the evaluation of the simulation problems can be discussed in the light of the model limitations, as for: the use of a single parameter to represent season-dependent heat fluxes - the light extinction coefficient and the soil-sediment thermal conductivity are highlighted in this study, as they may vary in time to better represent the characteristics of seasonal fluxes -; the use of inflow data at a daily time step, masking the influence of the inflow temperature over a shallow lake dynamic; and the difficulties in calibrating the bottom layer. Beyond that, the 1DV model approach also carry its own limitations, once it disregards important longitudinal processes.

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